SEAS 2024-2025 Master's Project

Meijer's Embodied Carbon in Construction

by

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1 Executive Summary

1.1 Project Overview

This project was conducted by five graduate students from the School For Environment and Sustainability (SEAS) in University of Michigan as a master's capstone project to assist Meijer in evaluating the embodied carbon emissions from the construction supply chains of its new supercenter. The results include the baseline model and potential strategies of reducing embodied carbon emissions, which could help Meijer further reduce greenhouse gas (GHG) emissions.

1.2 Key Findings

A baseline model of embodied carbon emissions associated with the construction of Meijer's Supercenter was developed using data provided by the Meijer construction team. This data included key project details, material specifications, transportation distances, and on-site energy usage. The analysis identified materials with the highest embodied carbon emissions—particularly during the Product Stage—while also quantifying emissions from the Transport and Construction Stages, which were comparatively smaller in impact. Among all materials, cement emerged as the most significant contributor to embodied carbon. Additionally, the analysis showed that switching to alternative manufacturers, without altering material types, could reduce total embodied carbon emissions by up to 32% compared to the baseline scenario. Building on these findings, a sensitivity analysis was conducted to evaluate the potential of alternative materials and emerging technologies for further emissions reductions.

1.3 Recommendations

In the raw material extraction, processing, and manufacturing stages, the team recommends reducing embodied carbon by using low-carbon cement with industry by-products or Carbon Capture, Utilization and Storage (CCUS)-equipped suppliers, low-emission steel made with biomass, hydrogen direct reduction technology, or from CCUS-equipped suppliers, asphalt with recycled materials, low-carbon insulation sheathing, energy-efficient roofing, and mass timber. In the transport stage, the team recommends using hybrid trucks to reduce transport emissions in the short term and switch to electric trucks in the future. For on-site construction, emissions can be reduced by installing rooftop solar panels on site offices and using biodiesel or green hydrogen in generators.

2 Introduction

2.1 Background

With the global population increasing, the demand for building space is expected to double by 2060(International Institute for Sustainable Development, 2024)— equivalent to constructing a city the size of New York every month for 40 years. Buildings and construction already contribute nearly 40% of global energy-related carbon dioxide emissions, and the majority of future emissions from new buildings will stem from embodied carbon: the greenhouse gases released during the extraction, manufacturing, transport, construction, and disposal of building materials.(New Buildings Institute, 2024). By 2050, embodied carbon could account for half of all emissions from new projects.(KPMG, 2023) Despite this urgency, existing building codes primarily target operational energy consumption, overlooking embodied carbon impacts. This gap is critical, as over half of lifecycle GHG emissions are tied to material management (e.g., extraction, manufacturing). As operational efficiencies improve, the relative share of embodied carbon grows, underscoring the need to address it now. Unlike operational emissions, which can be reduced retroactively, embodied carbon is "locked in" once construction is complete, making early intervention essential to mitigate long-term environmental impacts.(Esau et al., 2021)

2.2 Project Motivation

Meijer was founded in 1934 as a small grocery store by Hendrik Meijer. Meijer has grown into a leading Midwest retailer while maintaining its family-owned values. The company operates more than 500 supercenters,grocery stores,neighborhood markets, and express locations across six states, employing more than 70,000 team members.

Meijer is committed to environmental stewardship and has made significant progress in reducing its carbon footprint through multiple initiatives:

- Energy Efficiency: Achieving a 30% reduction in store energy use since 2005 through advanced lighting, HVAC, and building automation systems.(Meijer, 2025b) — Energy Efficiency
- Sustainable Truck Fleet: Operating an award-winning clean-diesel fleet of 750 trucks, optimizing fuel efficiency across 70+ million annual miles.(Meijer, 2025c) — Truck Fleet
- Refrigerant Management: Consistently recognized by the EPA's GreenChill program for leadership in reducing refrigerant emissions.(Meijer, 2025d) — Refrigerant Management
- Renewable Energy Investments: Expanding solar and other clean energy solutions to power stores and distribution centers.(Meijer, 2025e) — Renewable Energy
- EV Infrastructure: Installing electric vehicle charging stations at 36% of stores to support customer adoption of low-emission transportation.(Meijer, 2025f) — Electric Vehicle Charging

While these operational improvements demonstrate Meijer's commitment to sustainability, the company recognizes that embodied carbon—the emissions tied to building materials and construction—represents the next frontier in climate action. Unlike many retailers that lease their facilities, Meijer maintains control over the design and construction of its buildings, providing a unique opportunity to implement low-carbon materials, optimize supply chains, and adopt innovative building technique

2.3 Project Objective

The aim of this project is to establish a comprehensive framework and methodology for calculating and reducing embodied carbon in Meijer' s construction projects.

3 Literature Review

The literature review process focused on the exploration of the background and calculation methods for embodied carbon emissions. Meijer reached its goal of reducing the emissions of Scopes 1 and 2 50% by 2025 and is expanding efforts on Scope 3, including the engagement of suppliers and the analysis of embodied carbon in its construction supply chain. Thus, the team specifically paid attention to the application of methods in the construction supply chain and reviewed a few company reports about embodied carbon emissions.

3.1 Embodied Carbon in Construction

According to the World Green Building Council, embodied carbon in construction refers to the total GHG emissions associated with the entire life cycle of building materials and construction processes (World Green Building Council, 2022). This includes emissions from raw material extraction, manufacturing, transportation, construction, and end–of–life stages such as demolition and disposal (Hu & Esram, 2021). From McKinsey & Company, embodied carbon can constitute up to 50% of the total life cycle emissions for capital projects (McKinsey & Company, 2022), making it a critical factor in reducing the overall environmental impact of the construction industry. The significance of embodied carbon lies in its "locked-in" characteristic—once a building is constructed, these emissions are irreversible, as they have already been released into the atmosphere. This is in contrast to operational carbon, which refers to emissions from energy use during the building's life and can be reduced over time through energy efficiency measures and renewable energy adoption. Buildings and construction account for nearly 39% of global carbon emissions. The majority of these emissions (about 28%) occur when the building is in operation—from energy use to heat, cool and power them. But a significant amount (about 11%) also comes from embodied carbon emissions due to material manufacturing, construction processes, building maintenance and renovation, and the demolition of buildings by the construction industry. This makes addressing embodied carbon essential for reaching global climate goals. Developed countries have started implementing stricter building codes and standards to reduce embodied carbon, while developing countries are increasingly exploring sustainable construction practices to balance development with environmental responsibility. While policies at the national level are evolving, actions at the industry level—particularly in the retail sector—remain limited. The team did not find past examples of retailers quantifying embodied carbon, which highlights the gap in current industry practices.

3.2 Calculation Tool

From the academic papers and reports the team reviewed, it became evident that while embodied carbon measurement is critical for sustainable construction, its adoption remains limited due to complexities in data collection, lack of standardized methodologies, and the niche nature of life cycle assessment expertise in the industry. Measuring embodied carbon requires accounting for all supply chain stages, from raw material extraction (A1) to construction (A5) that are shown in Figure 1, which involves navigating disparate data sources, inconsistent reporting formats, and gaps in manufacturer transparency.

Multiple tools and frameworks exist to support these calculations, each with varying levels of granularity and accessibility. After evaluating these resources, the team selected the Embodied Carbon Calculator for Construction (EC3) for Meijer's 2024 new supercenter. EC3 is a free, cloud-based, open-access tool, developed by Building Transparency and it leverages construction estimates, Building Information models (BIM), and a comprehensive database of Environmental Product Declarations (EPDs)—third-party verified documents detailing the life cycle environmental impacts of materials. By integrating EPDs with project-specific data, EC3 generates accurate embodied carbon outputs across all supply chain stages (A1-A5), enabling standardized quantification and comparison.

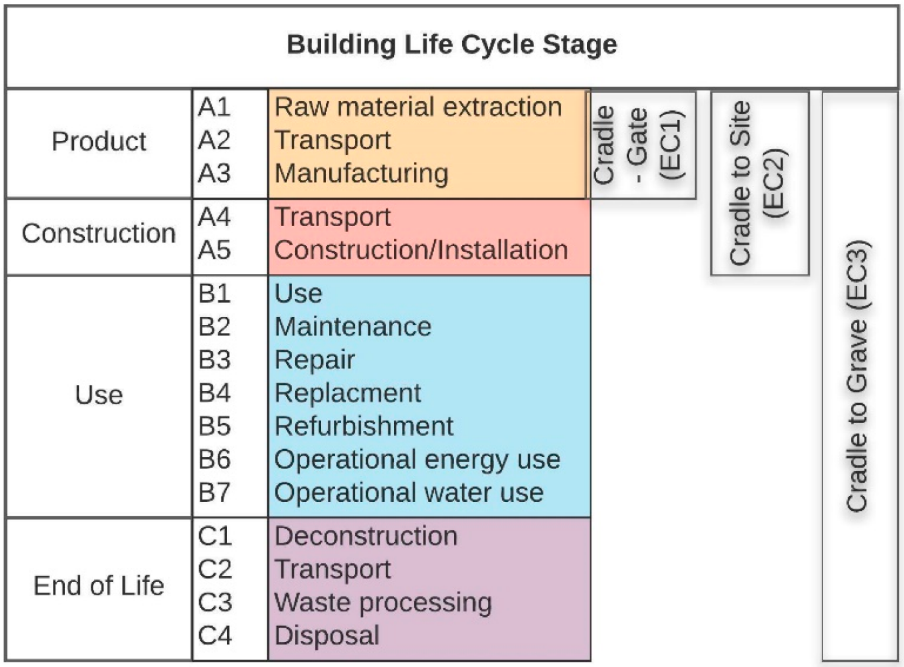

Figure 1: Embodied Carbon and Life Cycle

4 Methodology

4.1 Project Scope

The embodied carbon assessment conducted in this study focused primarily on the building shell and site infrastructure components, which typically represent the largest contributors to upfront emissions in commercial construction projects. The scope of analysis included structural foundations, superstructure, and sitework. Interior fit-outs, fixtures, equipment, and non-structural tenant improvements were excluded from the analysis. This exclusion was based on two considerations:

- Data availability limitations - comprehensive and verified Environmental Product Declarations (EPDs) for interior materials and systems are less consistently available.
- Scope consistency — focusing on the core and shell elements ensures that embodied carbon estimates are representative of the major, permanent construction components and supports comparability across projects.

The calculation boundary was defined to cover upfront phases of a building's life cycle, emphasizing supply chain stages. It accounts for Product Stage (A1-A3) carbon impacts—encompassing raw material extraction to manufacturing—as well as additional impacts from transportation and installation (A4-A5).

4.2 Conceptual Model

The building industry plays a crucial role in addressing climate change linked to construction and material manufacturing- particularly through energy-intensive production processes for steel, cement, and other high-impact materials that account for the majority of embodied carbon. To support sustainable practices, designers, owners, and policymakers require access to verified, third-party-reviewed data on building materials and products. Such data facilitate procurement decisions, decarbonization target setting, and informed design strategies. When evaluating the embodied carbon emissions of a new Meijer supercenter, the SEAS team integrated academic research, industry best practices, and digital tools, particularly the EC3 model. EC3 and its open-access database of EPDs provide a dynamic, continuously updated resource for assessing the carbon impacts of materials and products. As more manufacturers publish EPDs, the availability of embodied carbon data continues to grow. Leveraging EC3's extensive database and external EPDs from material suppliers ensures accurate and transparent carbon footprint calculations for Meijer's projects. To further refine the analysis, the team developed a baseline model and conducted a sensitivity analysis on individual building elements to explore decarbonization strategies. Embodied carbon values are determined using:

$$\begin{cases} \textbf{Embodied Carbon} = \textbf{Material Quantity} \times \textbf{Material EC Intensity} \\ \text{EC}\ (\text{kgCO}_2\text{e}) = Q\ (\text{kg}) \times \text{EC}_{\text{intensity}}\ (\text{kgCO}_2\text{e/kg}) \end{cases} \tag{1}$$

The unit of EC is "global warming potential (GWP) per unit of material". Material embodied carbon intensity values in the formula were derived from construction specifications and material inventories for a representative Meijer project–the Hillsdale, MI Supercenter, which opened in May 2024.

The baseline analysis followed the following key steps:

- Material Input & Classification: Materials were assigned to corresponding building elements in EC3.
- EPD Selection Criteria: EPDs were chosen based on material type and supplier data.
- Embodied Carbon Calculation: EC3's automated tools computed GWP values using unit conversions and material quantities. Three estimates were provided:
  - Conservative Estimate: A high-end projection assuming no effort to select low-carbon alternatives.
  - Realized Estimate: The actual measured embodied carbon values.
  - Achievable Estimate: A target for achievable reductions based on industry best practices.
- Result Compilation: Embodied carbon values were extracted and visualized using Sankey diagrams.

4.3 Data Collection

The Meijer Design and Construction Team provided data compatible with EC3's input criteria. The datasets included:

a. Project specifications

   i. Project background information: construction start date, building use breakdown, location, floor area, and height. Building use was used to make buildings more comparable. The construction start date was used to verify that EPDs will be valid.
   ii. Project classification: level of development, material quantity source, A5 construction source, construction project scope, primary horizontal gravity system, primary vertical gravity system, podium, primary lateral resistance system, primary foundation system, seismic design category, risk category or importance factor. These factors can affect the assumed uncertainties of the model.

b. Material inventories The material inventories include quantities and types of building elements used in the A1-A5 life cycle stages, categorized as:

   i. Substructure: Foundations
   ii. Shell: Superstructure, Exterior Enclosure, Roofing
   iii. Interiors: Interior Construction
   For accurate EPD selection and comparison, specific subcategories of parent categories were selected. Materials were further grouped by construction function, including:
   iv. Concrete: interior footings, exterior foundation walls and footings, interior and exterior slabs, rebar, wire and mesh, SCM, cement, structural precast
   v. Steel: merchant bar, wire and mesh, prefabricated assemblies, structural steel, cold formed steel
   vi. Openings: glass, extrusions, glazing units
   vii. Thermal/Moisture Protection: membrane roofing, TPO/PVC, insulation
   viii. Sheathing: plywood and OSB, gypsum
   ix. Non-structural Wood
   x. Finishes: cement board, gypsum board, tiling ceramic and glass, ceiling panels, flooring, painting and coatings.
   xi. Other: Asphalt, Network infrastructure

c. Environmental Product Declarations (EPDs)
   EPDs quantify the environmental impacts of materials and products, including their GWP. The selection process for EPDs was primarily based on material performance specifications, geographic relevance, and validity period. The team first prioritizes product-specific EPDs that align with Meijer's suppliers. If an exact match was unavailable, alternative EPDs with similar GWP values were used. When no substitute match could be found, the search criteria would be adjusted to identify a suitable substitute. In such cases, a USA-based industry EPD or an 80% weighted average of relevant product EPDs from the EC3 database was applied. Industry-average EPDs, developed by industry associations, represent the environmental impact of an "average product" within a specific sector or geographic region.

d. Transportation stage
   This stage included supplier locations, material transport distances, and transport methods. EPDs typically trace back to the raw material extraction process, including the initial address, which was used to determine transport distances. For materials without available EPDs, transport distances were calculated based on supplier and construction site locations, using truck routing maps that account for road restrictions. In general, concrete is transported using mixer trucks, while the transport mode for all other materials was set to default values(i.e., standardized emission factors and transport modes were applied when material-specific data was unavailable.).

e. Construction stage
   Energy sources included electricity, natural gas, diesel, gasoline, propane, and welding gases.

4.4 Comparative Analysis

To identify potential reductions in embodied carbon, alternative construction material and methodology scenarios were evaluated. The comparison process relied on a data-driven analysis of different product EPDs to identify multiple alternative options for future use. This involved modifying material performance specifications,which was reviewed to ensure compatibility with the project requirements.

The sensitivity analysis process involved:

a. Comparing each alternative model's total embodied carbon footprint against the baseline.

b. Conducting sensitivity analyses to identify the most influential parameters.

c. Assessing feasibility based on cost, material availability, and implementation challenges.

d. Proposing material specification changes in collaboration with the construction team to ensure compatibility.

By systematically evaluating embodied carbon data and exploring reduction strategies, this study provides actionable insights for minimizing the environmental impact of Meijer's construction projects.

5 Baseline Embodied Carbon Model

5.1 Data Overview

Most data used in the baseline calculations were collected and provided by the Meijer construction team according to the inputs of the EC3 model. In detail, data consisted of four parts:

i. Project Details: type, address, classification, floor area

ii. A1-A3: material types and specifications (used to search for EPDs), quantity

iii. A4: vehicle type, transportation distance

iv. A5: on-site energy consumption

Additionally, the manufacturers of some materials were contacted to request the EPDs of their products as they didn't release them to the public.

5.2 Calculation Process

EC3 calculated embodied carbon emissions by analyzing the GWP from EPDs published by manufacturers. The process started with defining the project scope including address, type, classification and floor area. Then EC3 calculated emissions separately for life cycles: A1-A3, A4 and A5. For A1-A3, EC3 retrieves emissions factors from EPDs for each material and then evaluates emissions by multiplying the quantities by GWP values. For A4, EC3 estimated emissions based on vehicle types and transportation distance. And for A5, EC3 used energy consumption and to quantify the emissions. Among these three steps, A4 and A5 calculations were straightforward, requiring the input data only, while A1-A3 calculation was more complex, as it depended on selecting accurate EPDs based on material specifications and geography. However, in the Meijer Supercenter construction, some materials lacked uploaded EPDs in the EC3 database, or the manufacturers were unknown as the construction team purchased the materials through distributors, which required alternative selection methods to estimate emissions more accurately.

5.2.1 A1–A3: Material EPDs Selection Process

The calculation of embodied carbon emissions for the A1–A3 lifecycle stages was focused on evaluating emissions from material extraction, processing, and manufacturing. As shown in Figure 2, the selection of EPDs followed a hierarchical decision-making process based on the availability of data. A critical consideration in selecting the appropriate EPDs is the distinction between cement and ready-mix concrete, both commonly used in the construction. Cement acts as a binder, typically made from limestone and clay, while Ready-mix concrete is a composite material made by combining cement with other aggregates and water in specific proportions at a batching plant (Big D Ready Mix, 2024). Therefore, even though cement is responsible for the majority of ready-mix concrete's embodied carbon emissions due to its proportion and energy-intensive production, EPDs for ready-mix concrete provide a more complete picture by capturing the full mixture and transport processes. Selecting an EPD that reflects the entire ready-mix product, rather than only cement, is therefore essential for accurate carbon accounting at the A1–A3 stage.

- Product EPDs
  The most ideal scenario for baseline embodied carbon calculation was when a Product EPD was available in the EC3 database for each specific material. A Product EPD provided manufacturer-specific data on the environmental impacts of a particular product, which offered the highest level of accuracy in the embodied carbon evaluation (Building Transparency, 2024). Therefore, Product EPDs were always the top priority in the selection process to ensure precision. However, because uploading EPDs to EC3 is voluntary for manufacturers, Product EPD availability was often limited. In this project, among 44 materials used in the Meijer supercenter construction, only 6 materials had Product EPDs in the EC3 database. This data gap required the use of alternative approaches, such as selecting Industry EPDs or other estimation methods, to ensure a comprehensive assessment of embodied carbon emissions.

- Industry EPDs
  When the Product EPDs were not available, the Industry EPDs were preferred. An industry EPD was created by an industry association by averaging data from multiple manufacturers to represent the typical environmental impact of similar products (Building Transparency, 2024). Hence, the selection of Industry EPDs could help standardize environmental impacts of materials at the industry level and give a comprehensive evaluation when Product EPDs were missing.

- Criteria Adjustments and 80% Default Value
  For some materials, neither the Product nor the Industry EPD were available in the database that could match all performance specifications and geography. In this case, additional adjustments on search criteria were necessary. The first option was to expand geographic scope to USA or Global to increase the chances of finding a relevant Industry EPD. Additionally, some less important specification filters could be deleted in the searching process, keeping only the most essential criteria. For example, for ready-mix concrete, only the specification of compressive strength at 28 days was used as a search parameter. Using these strategies, if Industry EPDs were found, they were selected. If not, 80% default value of all EPDs including Product EPDs from other manufacturers were used.

- EPD Requests to Manufacturers
  If the above strategies failed to find available EPDs, a proactive approach was adopted by directly contacting manufacturers to request EPD documentation or carbon emission information. Since publishing EPDs is not mandatory, some manufacturers may have EPDs available internally that were not publicly available. In this project, one manufacturer provided unpublished EPDs of two materials. To integrate these values into the model, existing EPDs with similar GWP values were selected as approximations.

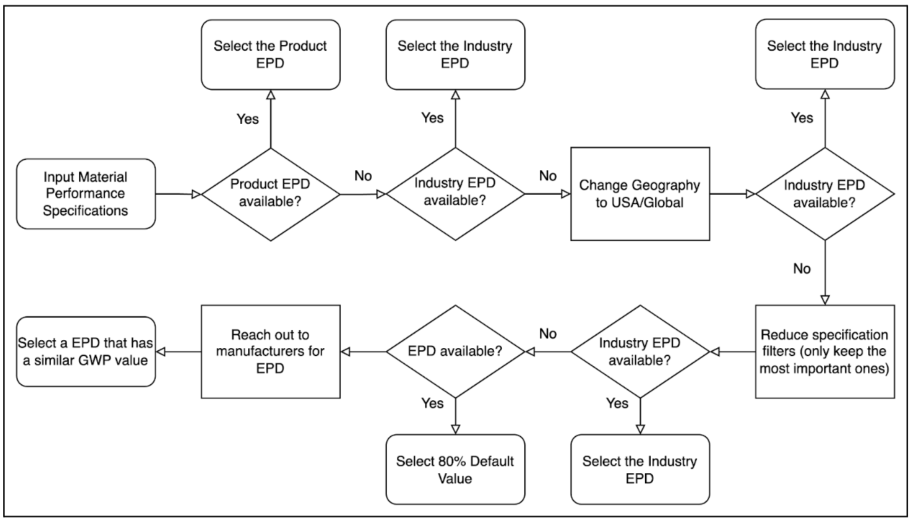

Figure 2: EPD Selection Workflow

5.2.2 A4: Transportation

The estimation of emission in the A4 stage in EC3 required the inputs of vehicle mode and transportation distance. And as shown in Figure 3, the selections were varied based on the material types and EPDs selected in the previous stage.

- Vehicle Mode:
  Since transportation-related data from suppliers were not recorded during the Meijer Supercenter construction, the selection of vehicle mode was based on industry-standard assumptions for typical construction materials. Unspecified trucks were used as the default vehicle mode for most materials. However, for concrete transportation, a mixer concrete truck was specifically chosen to reflect the specialized delivery requirements of ready-mix concrete.

- Transportation Distance:
  The transportation distance was estimated based on the type of EPDs selected. For Product EPDs, EC3 automatically calculated the distance between the manufacturer location recorded in the EPD and the Meijer supercenter site. If an Industry EPD or 80% default value of all EPDs was selected, the online platform TruckMap was utilized to estimate the distance between the supercenter and manufacturer address provided by Meijer Construction Team.

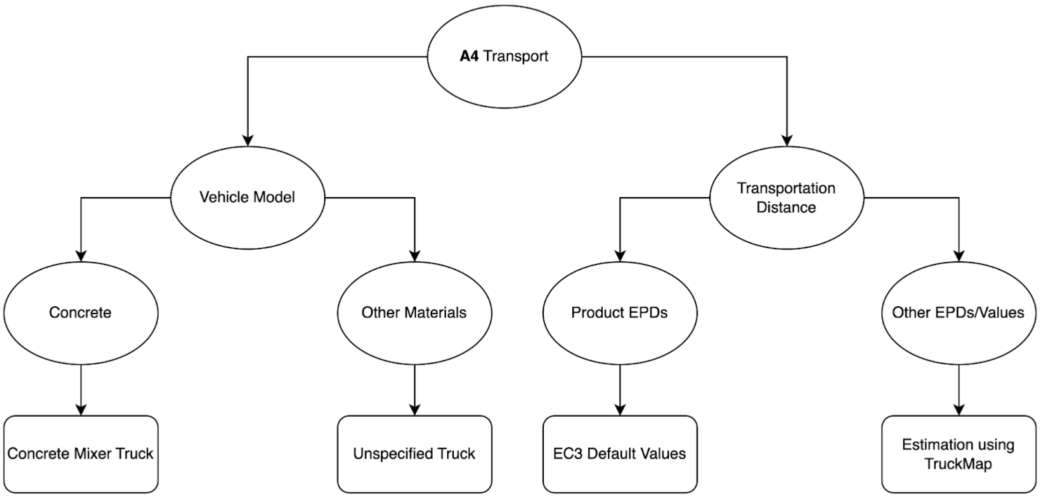

Figure 3: A4 Vehicle Mode and Transportation Distance Measurement Process

5.2.3 A5: Energy Consumption

The energy consumption data recorded in the construction process were the amount of diesel for generators. Specifically, the two sources were job trailer generators and site/building generators used before the site's utility connection.

5.3 Results

5.3.1 Emission Results

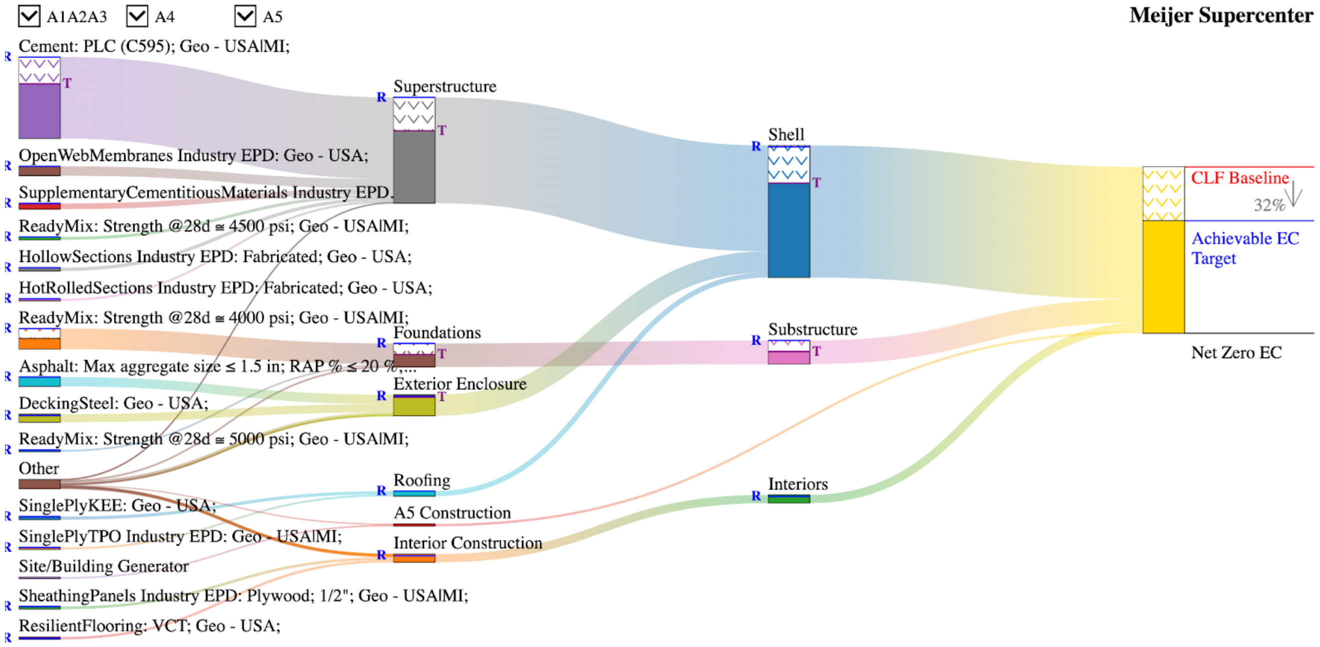

Figure 4: Global Warming Potential Sankey Diagram of A1-A5 stages in Meijer Supercenter Construction

The Sankey diagram (Figure 4) generated from EC3 illustrates the embodied carbon flows within the project, detailing the contributions from materials, subassemblies, and assemblies. Among all materials, cement accounted for the highest embodied carbon emissions. At the structural level, the majority of emissions were attributed to the superstructure and shell components. Additionally, EC3 analyzed the potential for embodied carbon reduction by considering all EPDs associated with the materials. This analysis, shown on the right side of the chart, indicated that by switching to different manufacturers—without changing material types—the project's embodied carbon emissions could be reduced by up to 32% compared to the baseline. To further examine the sources of embodied carbon emissions for a Meijer Supercenter, two pie charts were created to show the breakdown across life cycle stages and materials (Figure 5 and 6). The A1–A3 stages (raw material supply, transport, and manufacturing) were responsible for the largest share, contributing approximately 87% of total emissions. This was followed by 12% from stage A4 (transportation) and 1% from stage A5 (construction and installation processes). These findings highlight that current decarbonization efforts should prioritize the A1–3 stages, particularly through the selection of alternative products or materials. Building on this, material-specific contributions were analyzed (Figure 6), revealing that concrete products, including cement and ready-mix concrete, were responsible for over half of the project's embodied carbon emissions, followed by asphalt and steel products. Given their significant impacts, subsequent decarbonization strategies should focus primarily on these key materials.

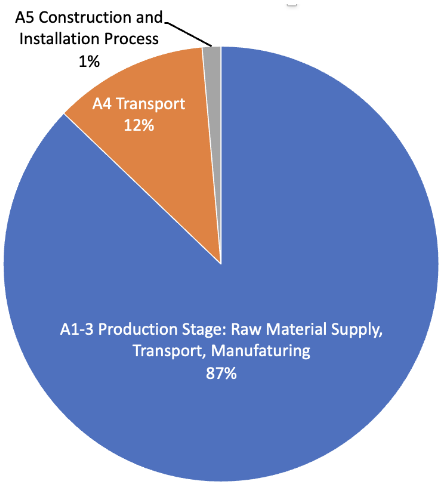

Figure 5: Embodied Carbon Emissions from A1-5 lifecycle stages in Meijer Supercenter Construction

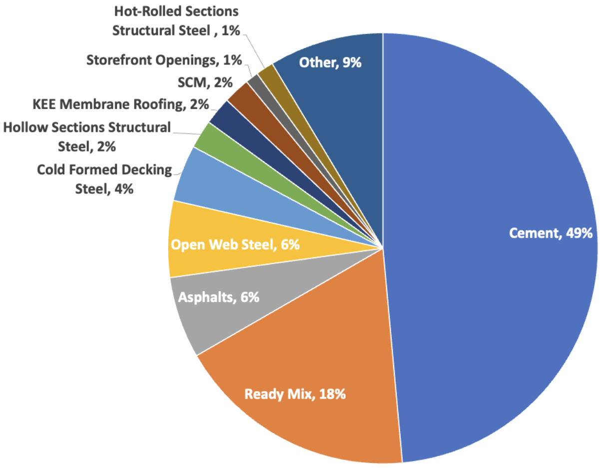

Figure 6: Embodied Carbon Emissions from Top 10 sources in Meijer Supercenter Construction

5.3.2 Comparison to the Operational Emissions

Operational carbon significantly dominates the total lifetime greenhouse gas emissions of Meijer supercenters. Considering an annual operational emission of approximately 2,900 metric tons of CO_2-equivalent (mtCO_2e), a Meijer supercenter accumulates about 87,000 mtCO_2e over a typical 30-year building lifespan, accounting for 91.8% of its total carbon footprint as seen in Figure 7. These operational emissions are driven mainly by the high-energy demands of heating, ventilation, and air conditioning (HVAC) systems, refrigeration units, and extensive lighting required to maintain optimal store conditions and customer comfort. In contrast, upfront embodied carbon emissions, which arise from the production, transportation, and construction of building materials, represent 8.2% of the total emissions, totaling around 7,795 mtCO_2e (Figure 7). Reducing embodied carbon upfront is critical, particularly given that embodied emissions contribute 7,795 mtCO_2e (8.2%) of Meijer supercenter's total emissions which occur immediately and are irreversible once the building is constructed. Prioritizing reductions in this initial stage ensures immediate climate impact mitigation, as these emissions become fixed at construction completion. Conversely, operational emissions, though comprising the larger share (91.8%), can be strategically and gradually managed throughout the facility's lifetime through technology upgrades and efficiency measures. Therefore, early intervention on embodied carbon significantly complements ongoing operational improvements, optimizing overall emission reductions for retail infrastructure.

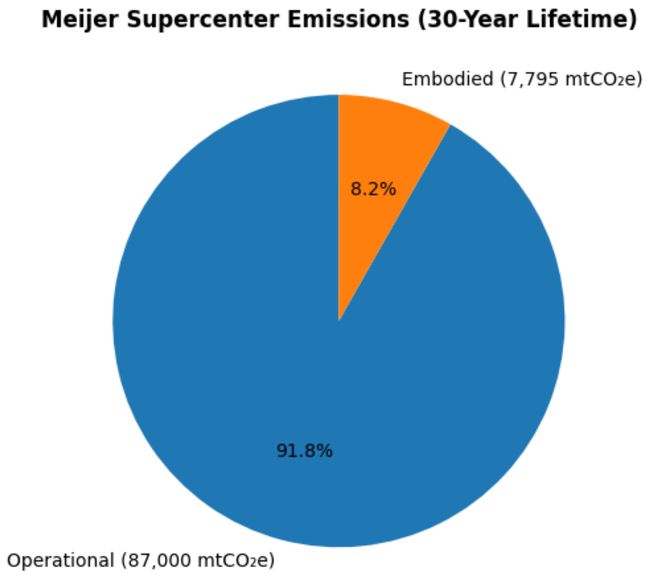

Figure 7: Distribution of Operational vs. Embodied Carbon Emissions for Meijer Supercenter (30-Year Lifetime).

5.3.3 Benchmarking Analysis

To contextualize the modeled embodied carbon emissions at both national and global levels, a benchmarking study was conducted using data from the 2017 Embodied Carbon Benchmark Study by the Carbon Leadership Forum.

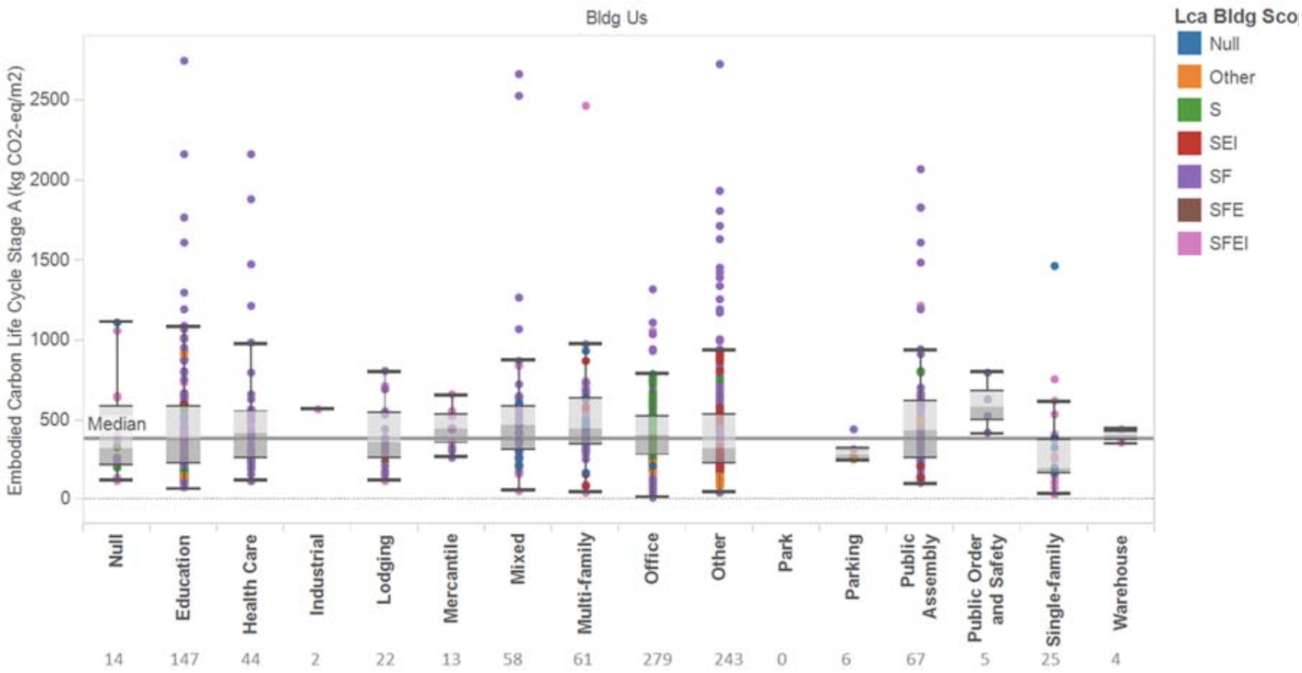

Figure 8: Embodied Carbon from Lifecycle Stage A per m2 (1,007 buildings). Adapted from the 2017 Embodied Carbon Benchmark Study by the Carbon Leadership Forum.

Figure 8 showed Stage A embodied carbon per square meter across more than 1,000 buildings, categorized by building type. Among all building types, the warehouse was selected for comparison, which was the most comparable to Meijer's supercenter. Although only four warehouses were included in this study, the spread and median values provided valuable references for benchmarking. Compared to the values about warehouses in the chart, the modeled embodied carbon emissions from Meijer's supercenter fell within the range but slightly above the median, suggesting that Meijer's current baseline was relatively typical but still could be optimized. Therefore, to explore possible reductions, a sensitivity analysis was subsequently conducted to evaluate alternative design and procurement scenarios.

6 Alternative Models

The built environment contributes approximately 39% of global carbon dioxide (CO_2) emissions, with 11% attributed to embodied carbon emissions from material extraction, processing, transportation, and construction activities (Hart et al., 2021). While operational carbon emissions are being addressed through efficiency improvements and renewable energy integration, embodied carbon remains a critical challenge. The life cycle assessment (LCA) methodology, as defined by EN 15978, categorizes emissions across different life cycle stages, including product (A1–A3), transport (A4), and construction (A5) stages (Hawkins et al., 2021). This paper examines alternative embodied carbon reduction strategies within each LCA stage, focusing on material substitution, process efficiency, and emerging low-carbon technologies.

6.0.1 Product Stage (A1–A3): Raw Material Extraction, Processing, and Manufacturing

The product stage is the most carbon-intensive phase, as it encompasses raw material extraction, transportation, and manufacturing processes. Sensitivity analyses indicate that material selection has the highest impact on whole-life embodied carbon (WLEC). Engineered timber exhibits significantly lower embodied carbon than steel and concrete due to its carbon sequestration potential during growth. Studies have shown that cradle-to-gate emissions for timber buildings can be 9–56% lower than mineral-based structures, depending on the energy mix used in processing (Hawkins et al., 2021). For steel structures, decarbonization efforts focus on transitioning from traditional basic oxygen furnaces (BOF), which produce approximately 2.32 t of tCO_2 per ton of steel, to electric arc furnaces (EAF), which reduce emissions to 0.67 tCO_2 per ton (Patlán Manjarrez et al., 2025). Similarly, alternative cementitious materials, such as fly ash and slag, can replace clinker in concrete, reducing emissions by up to 40% (Suwondo & Keintjem, 2024). Prefabrication and modular construction techniques further contribute to minimizing material waste and optimizing resource utilization in manufacturing processes (Hawkins et al., 2021).

6.0.2 Transport Stage (A4): Logistics and Distribution

Emissions from the transport stage (A4) primarily result from fossil fuel consumption in material distribution. Sensitivity analyses demonstrate that reducing transportation distances significantly lowers emissions, emphasizing the importance of local sourcing. Optimized logistics, including consolidating material deliveries and adopting electric or hydrogen-powered transport fleets, can further contribute to carbon reductions (Hawkins et al., 2021). Lifecycle modeling of different material sourcing strategies reveals that for every 100 km reduction in transportation distance, embodied carbon can decrease by 3–5%, depending on the material type (Patlán Manjarrez et al., 2025). Regional supply chain optimization and just-in-time delivery methods have been identified as effective strategies for mitigating emissions in this stage.

6.0.3 Construction Stage (A5): On-Site Activities

The construction stage (A5) accounts for emissions due to heavy machinery use, energy consumption, and material waste. Digital construction tools such as Building Information Modeling (BIM) have been shown to optimize material usage and prevent reordering, reducing overall emissions (Suwondo & Keintjem, 2024). Prefabrication and off-site manufacturing methods further contribute to reducing waste and emissions by improving construction precision and minimizing on-site energy use (Patlán Manjarrez et al., 2025). Sensitivity analyses highlight that transitioning construction site operations from fossil fuel-based generators to renewable energy sources (e.g., solar-powered machinery or biodiesel-based generators) can reduce emissions by up to 30% (Hawkins et al., 2021).

7 Sensitivity Analysis

Sensitivity analysis is a crucial tool for evaluating the impact of different carbon reduction strategies. Comparative assessments of structural materials reveal that timber consistently exhibits lower embodied carbon at the product and construction stages but may generate higher emissions at end-of-life due to potential carbon re-release (Hawkins et al., 2021). However, this effect is offset when timber is sourced from sustainably managed forests. For concrete structures, carbonation, a natural process where concrete absorbs CO_2 over time can partially offset emissions, reducing net carbon impact when recycled instead of landfilled . Additionally, structural optimization studies indicate that frame geometry plays a crucial role in WLEC, with optimized lightweight structural systems achieving reduction in embodied carbon compared to conventional designs (Hart et al., 2021). Further analysis of floor slab materials indicates that cross-laminated timber (CLT) floors reduce overall structural mass and emissions compared to traditional reinforced concrete slabs. Sensitivity modeling suggests that for every 1% reduction in structural mass, embodied carbon can decrease by 0.8–1.2%, depending on material efficiency and reinforcement strategies (Hawkins et al., 2021). A holistic approach to embodied carbon reduction requires targeted interventions at each LCA stage. Material substitution emerges as a primary strategy, with engineered timber presenting a viable alternative to conventional steel and concrete structures. Additionally, advancements in steel and concrete technology, such as electric arc furnaces and supplementary cementitious materials, offer significant decarbonization potential. Transportation and logistics optimizations further contribute to emissions reduction, particularly through regional material sourcing and low-carbon transport solutions. Construction-phase strategies, including prefabrication, BIM integration, and renewable energy adoption on-site, can lower emissions and improve efficiency. Sensitivity analyses confirm that a combination of these approaches can reduce embodied carbon by up to 30–40% across the A1–A5 life cycle stages. Future policy measures could incentivize low-carbon material procurement, sustainable construction methodologies, and circular economy principles to accelerate the transition to a net-zero built environment. The integration of carbon taxation on high-emission materials, mandatory LCA reporting, and performance-based building codes could be impactful in achieving global decarbonization targets.

7.1 Sensitivity Analysis Framework for Meijer Superstore Construction Project

The sensitivity analysis evaluates how different assumptions and parameters impact the embodied carbon footprint of Meijer's construction project. By identifying the most influential variables, this study provides a roadmap for effective carbon reduction strategies.

Key Variables for Sensitivity Analysis

- Material Selection: The choice of materials, such as low-carbon cement, mass timber, and recycled asphalt, significantly influences embodied carbon.
- Transportation Distance and Mode: Emissions vary with transportation distance and the type of vehicle used (diesel vs. electric trucks).
- Energy Use in Construction: Fuel consumption and alternative energy sources at construction sites impact overall emissions.

7.2 Sensitivity Analysis Approach

A scenario-based approach was applied, adjusting one variable at a time to measure its impact on the total embodied carbon footprint.

7.2.1 Material Substitution Scenarios

Baseline Scenario:

Baseline Scenario: This scenario assumes traditional concrete and steel construction methods without any modifications. These materials have high embodied carbon due to energy-intensive production processes and contribute significantly to the heat island effect due to their thermal mass and low albedo.

Optimized SCM Scenario:

This scenario considers replacing 20% of cement with supplementary cementitious materials (SCMs) such as fly ash and slag. In the Meijer Supercenter project, EC3 calculations indicate that concrete contributes 785,339 $kgCO_2$ from ready-mix,2,333,530 from cement, 108,179 from SCM and 34,083 $kgCO_2$ from precast elements, totaling 3,261,133 $kgCO_2$. Research suggests that substituting 20% of cement with SCMs reduces emissions by approximately 22%. This estimate is derived from an analysis of local EPDs and literature on SCM impact (Knight et al., 2023)., which report a range of 18-25% reduction based on specific cement types and replacement ratios.

Mass Timber Scenario:

Traditional steel and concrete construction is assumed for the baseline scenario, with steel contributing 884,570 $kgCO_2$ (based on EC3 data for the Meijer project). Steel production is highly emissions-intensive, generating approximately 1.4-1.85 tons of CO_2 per ton of steel (Sustainable Ships, 2022). To reduce embodied carbon, mass timber- specifically cross-laminated timber (CLT) and glue-laminated timber (glulam)- can replace steel beams and columns. Life cycle assessment (LCA) studies indicate that CLT reduces embodied carbon by 30–40% compared to steel, with additional benefits from biogenic carbon storage.(Younis & Dodoo)(Allan & Phillips, 2021). For a project of Meijer's scale, partial substitution (e.g., in roof trusses and interior framing) could achieve an estimated 30% reduction in steel-related emissions. Furthermore, CLT acts as a carbon sink, storing approximately 643.6 kg CO_2eq/m^3 (based on EPD averages from Younis & Dodoo, 2022). When accounting for biogenic carbon, Meijer's project could sequester 220–250 kg CO_2eq/m^2 (cradle-to-gate), consistent with research demonstrating a 40% lower global warming potential (GWP) for timber compared to steel (Allan & Phillips, 2021).

Overall, as shown in Figure 9, our analysis shows that substituting conventional materials with low-carbon alternatives can lead to significant savings:

- Concrete: Using 20% fly ash reduces emissions by 22%—that's 717 fewer tonnesof CO_2 per supercenter.
- Steel: Switching to mass timber (CLT) slashes emissions by 40%, saving 354 tonnes of CO_2.
- Asphalt: Opting for recycled mixes cuts emissions by 25%, or 104 tonnes of CO_2.

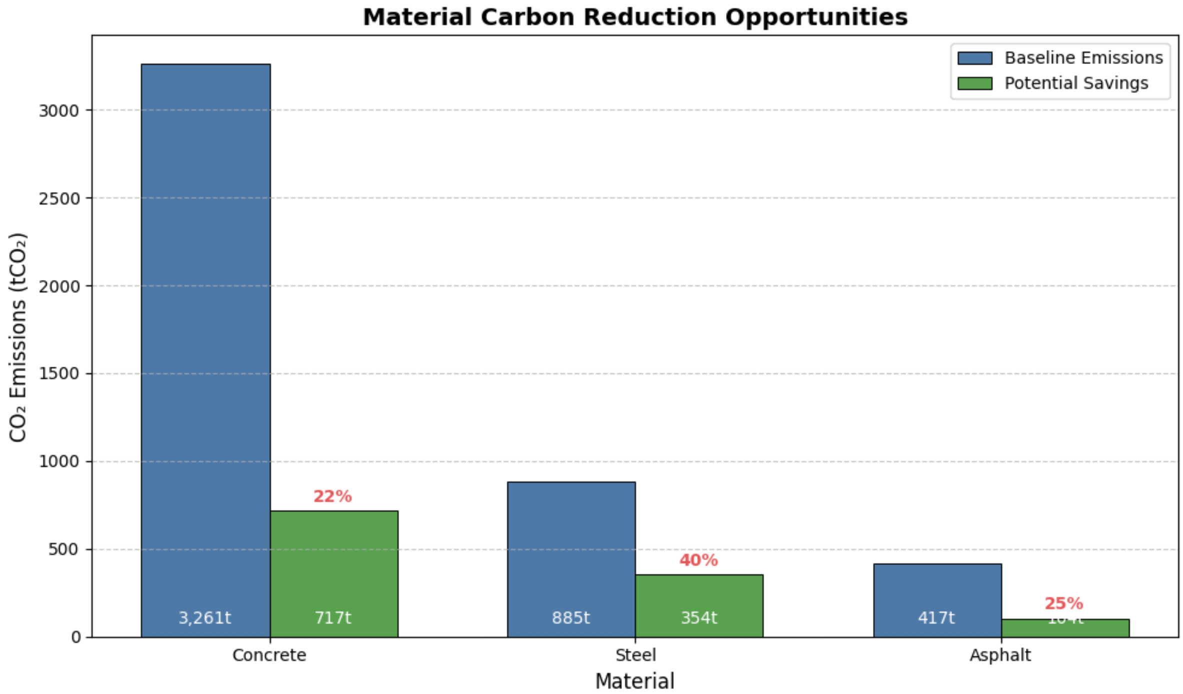

Figure 9: Percentage CO_2 Reduction- Material Substitution Scenarios

7.2.2 Transportation Emission Scenarios

For the Meijer project, three flooring materials—Vinyl Composition Tile (VCT), Polymer Flooring, and Luxury Vinyl Tile (LVT)—must be transported 597 miles from 1401 N Hobbie Ave, Kankakee, IL 60901 to the construction site of meijer supercenter.

Various scenarios analysed are described below.

- **Baseline Scenario (Diesel Truck Transport):**
  This scenario assumes the use of diesel-powered semi-trucks with an average fuel efficiency of 6.5 mpg and an emission factor of 10.1 $kgCO_2$ per gallon of diesel. The total CO_2 emissions per truckload are 927 kg, resulting in 46.4 $kgCO_2$ per ton-mile. For 100 tons of flooring transported, the total emissions amount to 4.6 tCO_2, with 5 truckloads required.

- **Electric Truck Scenario (Battery-Electric Semis):**
  In this scenario, Tesla Semi trucks are used, with an energy efficiency of 1.7 kWh/mile. Given the grid's carbon intensity of 0.38 $kgCO_2/kWh$, the total CO_2 emissions per trip are 386 kg, or 19.3 $kgCO_2$ per ton-mile. For 100 tons of flooring, the total emissions are 1.9 tCO_2, resulting in a 58% reduction in emissions compared to diesel trucks.

- **Rail-Intermodal Scenario (Train + Last-Mile Trucking):**
  This scenario uses electric freight trains for the primary 500-mile haul, with diesel trucks covering the last 97 miles. The train emits 230 $kgCO_2$ per trip, while the truck contributes 151 $kgCO_2$. The total CO_2 per trip is 381 kg, or 19.05 $kgCO_2$ per ton-mile. For 100 tons of flooring, the total emissions are 2.1 tCO_2, representing a 54.35% reduction compared to diesel trucks.

- **Local Sourcing Scenario (Reduced Distance by 50%):**
  Here, the supplier is relocated to 300 miles away, reducing the transportation distance by half. Using diesel trucks with the same efficiency as the baseline, the emissions per truckload are 466 kg, or 23.3 $kgCO_2$ per ton-mile. For 100 tons of flooring, the total emissions are 2.3 tCO_2, resulting in a 50% reduction in emissions compared to the original 597-mile diesel haul.

A summary of the results is provided in Table 1, while Figure 9 illustrates the CO_2 reduction percentages relative to the baseline scenario.

Table 1: Comparison of Transport Scenarios for 100 Tons Flooring Delivery

Scenario	**$kgCO_2$/Ton-Mile**	**Total CO_2 (100 Tons)**	**Reduction vs. Diesel**
1. Diesel Truck (Baseline)	46.4	4,635 kg (4.6 t)	–
2. Electric Truck	19.3	1,930 kg (1.9 t)	58%
3. Rail + Truck	19.05	1,905 kg (1.9 t)	54.35%
4. Local Sourcing (300 mi)	23.3	2,330 kg (2.3 t)	50%

This analysis,as described above evaluates the carbon impact of transporting vinyl composition tile (VCT), polymer flooring, and luxury vinyl tile (LVT) over 597 miles to the Meijer construction site, comparing four scenarios: diesel trucks (baseline), electric trucks, rail-intermodal, and local sourcing (50% distance reduction).Detailed calculations are attached in the Appendices section. Results,as captured in Figure 10, show that electric trucks offer the greatest reduction (58% lower emissions vs. diesel), followed by rail-intermodal (55%) and local sourcing (50%). The baseline diesel scenario emits 4,635 $kgCO_2$ per 100 tons of flooring, while electric trucks cut this to 1,930 $kgCO_2$.Key recommendations include prioritizing electric truck adoption where feasible, leveraging rail for bulk shipments, and sourcing regionally to minimize transport distances. These strategies align with Meijer's sustainability goals by significantly lowering embodied carbon in material logistics.

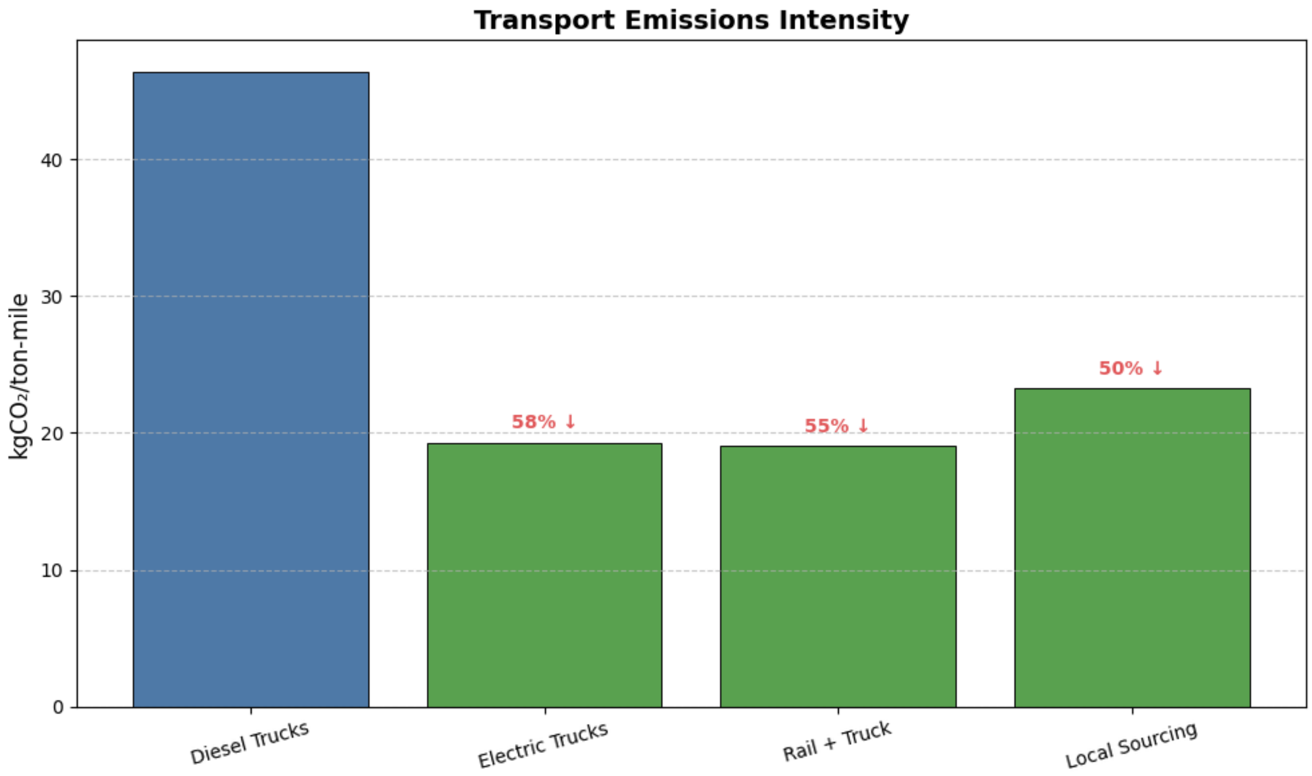

Figure 10: Percentage CO_2 Reduction- Transportation Emission Scenarios

7.2.3 On-Site Energy Consumption Scenarios

This analysis evaluates carbon emissions from construction power systems, comparing three alternative approaches against the baseline diesel generator scenario.

1. Baseline Scenario (Diesel Generators Only): In this scenario, diesel generators power both the job trailer and site/building operations throughout the construction period. The job trailer runs for 36 weeks using 2,880 gallons of diesel, while the site generator operates for 20 weeks consuming 6,000 gallons. Total emissions from diesel consumption amount to 89.7 tCO_2, serving as the reference point for comparing alternative strategies.

2. Early Utility Tie-In Scenario (Reduced Generator Use): This approach transitions the job trailer and site operations to grid electricity partway through the project—after 20 and 12 weeks, respectively. While some emissions still result from diesel use (52.5 tCO_2), the remaining energy demand is met by grid power, resulting in 28.4 tCO_2. The total emissions under this scenario are 80.9 tCO_2, reflecting a modest reduction of about 10% compared to the baseline.

3. Solar-Assisted Hybrid Scenario (50% Diesel Offset): By integrating on-site solar panels to meet 50% of energy needs, this hybrid model reduces diesel usage significantly. Diesel emissions drop to 44.8 tCO_2, while solar's embodied carbon contributes an additional 2.6 tCO_2, bringing the total to 47.4 tCO_2. This represents a 47% reduction in emissions compared to the diesel-only baseline, offering the most substantial benefit among the evaluated options.

4. Biodiesel Blend Scenario (B20 Adoption): In this scenario, generators run on a B20 biodiesel blend, which lowers the carbon intensity of fuel use by 20%. The total fuel consumption remains the same (8,880 gallons), but emissions drop to 71.8 tCO_2. This strategy achieves a 20% reduction from the baseline, offering a practical improvement with minimal operational change.

A summary of the results is provided in Table 2, while Figure 11 illustrates the CO_2 reduction percentages relative to the baseline scenario.

Key Findings and Recommendations

- **Best Environmental Option:** The solar hybrid scenario achieves the greatest emissions reduction (47%), though it requires significant capital investment. This aligns with Meijer's long-term sustainability goals.
- **Immediate Feasibility:** Biodiesel (B20) offers a straightforward 20% reduction with minimal operational changes, suitable for near-term implementation while planning larger investments.

Table 2: Comparison of On-Site Energy Scenarios

Scenario	**Total CO_2 (tCO_2)**	**Reduction vs. Baseline**	**Key Advantage**	**Implementation Challenge**
1. Baseline (Diesel Only)	89.7	–	Simple setup	High emissions
2. Early Grid Tie-In	80.9	9%	Uses existing infrastructure	Requires early utility coordination
3. Solar Hybrid	52.2	47%	Renewable integration	High upfront cost
4. Biodiesel (B20)	71.8	20%	Drop-in solution	Limited supply chains

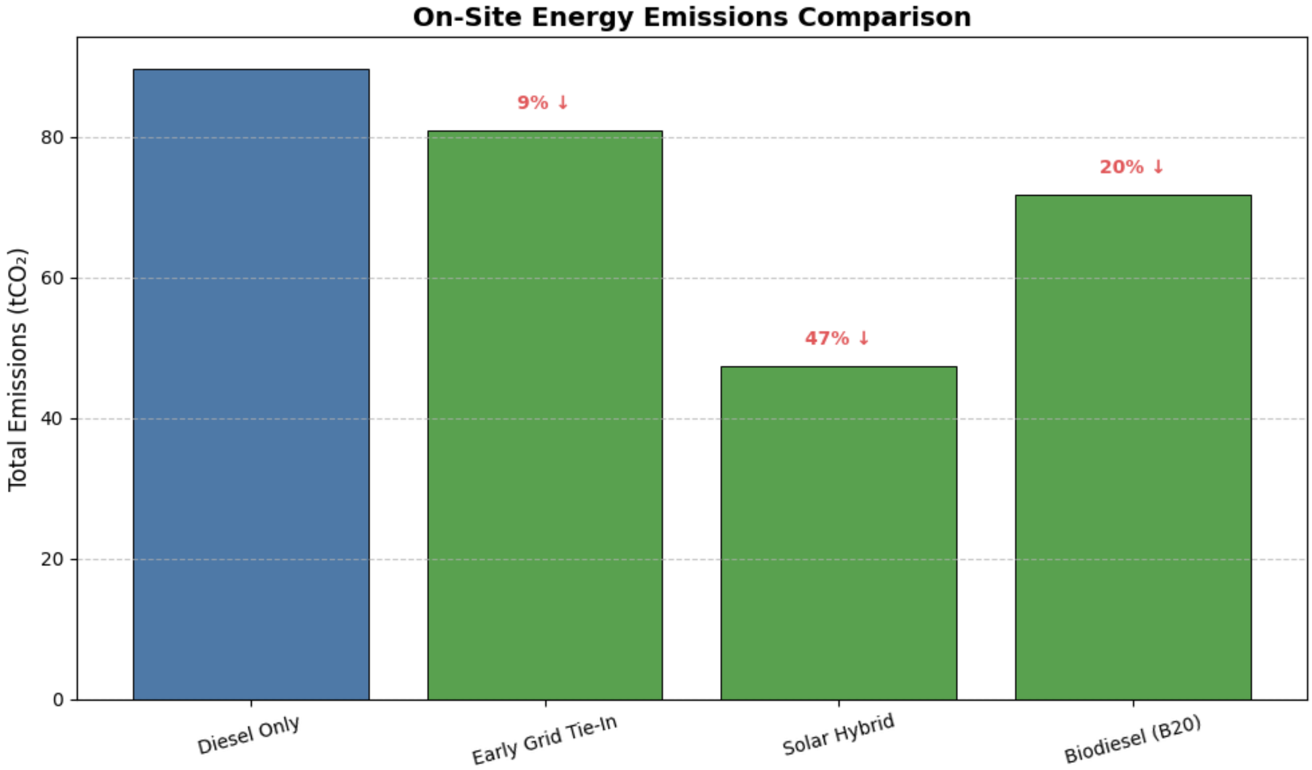

Figure 11: Percentage CO_2 Reduction- On-Site Energy Consumption Scenarios

- **Counterintuitive Result:** Higher grid emissions (0.552 kgCO2/kWh) diminish benefits of early tie-in: Only 9.8% reduction vs. diesel-only. This suggests that:
  - With cleaner grid, reduction improves
  - Generator efficiency matters.Using 14 kWh/gal (vs. 11 kWh/gal) increases grid demand, but also shows higher sensitivity to grid carbon intensity.
- **Hybrid Approach Recommended:** A combination of:
  1. Immediate B20 adoption
  2. Phased solar installation
  3. Combine early tie-in with renewable energy procurement to maximize reductions.
- **Policy Lever:** The 47% solar reduction potential supports pursuing:
  - Inflation Reduction Act tax credits (30% for solar)
  - USDA Rural Energy for America Program grants

Note: All scenarios assume 36-week job trailer operation and 20-week site generator use. Solar estimates include cradle-to-gate embodied carbon.

8 New technologies and recycled materials in decarbonization

Based on the building life cycle stage and baseline model results, the SEAS team mainly focused on construction materials with the highest 10% of embodied carbon emissions and researched emerging carbon reduction technologies at different stages to help Meijer enhance the environmental sustainability of the supercenter.

8.1 A1-A3 Stages:

8.1.1 Concrete and Cement:

In the baseline model, “Concrete–Cement” had the highest quantity and embodied carbon emissions, making it the primary choice for emission reduction. “Concrete–Ready Mix–Interior Slabs” ranked second, so it became the secondary focus. Since cement is the main upstream material used in ready-mix concrete, reducing its embodied carbon will also lower concrete emissions. Therefore, the following discussion covers both. The Technology Roadmap–Low–Carbon Transition in the Cement Industry of International Energy Agency (IEA) (2018) pointed out that the CO_2 emissions from cement production can be reduced by using supplementary cementitious materials (SCMs) to lower the clinker to cement ratio. These SCMs include gypsum, natural volcanic materials, limestone and industrial by–products (Jain, Sancheti, & Jain, 2021). This project used Portland Limestone Cement (PLC) combined with fly ash (FA). PLC is produced by blending regular clinker with 15% limestone (The Euclid Chemical Company, 2022), while FA is a by-product of the coal industry (Herath, Gunasekara, Law, and Setunge, 2020). Although the use of limestone and FA helped reduce a portion of CO_2 emissions in the project, the team found that incorporating additional SCMs into clinker, as well as implementing carbon capture, utilization, and storage (CCUS), could further reduce emissions (Danish, Salim, & Ahmed, 2019).

1.Different SCMs:
SCMs other than FA can also be used to reduce CO_2 emissions while maintaining concrete performance. Several studies have analyzed these materials and their optimal replacement ratios.

a. Rice Husk Ash (RHA): As an SCM, RHA can improve the strength and durability of concrete. Besides, by replacing part of the cement, it also reduces the need of clinker required in cement production, which lowers the associated emissions. Furthermore, since RHA is made from rice husks, a by-product of rice production, its use promotes recycling waste into building materials and lowers construction costs. The recommended level is 30% (Siddika, Al Mamun, Alyousef, & Mohammadhosseini, 2021).

b. Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBS): Incorporating 50% GGBS and 10% SF, which are recycled materials and waste, in cement can improve durability and reduce CO_2 emissions in concrete by about 40% (Mouna, Batikha, & Suryanto, 2021).

c. Clay Brick Powder (CBP): CBP comes from construction and demolition waste. The CO_2 emissions and energy consumption associated with CBP and CBP concrete are significantly lower than those of OPC and OPC concrete (Wu, Gao, Liu, Guo, & Luo, 2024).

2.CCUS technology: CCUS is a necessary complementary measure because 65% of the CO_2 emissions in the cement sector come from manufacturing processes. Post–combustion CO_2 capture technology is the optimum option, with chemical absorption using liquid solvents is the most mature technology. This method has already achieved large–scale demonstration in cement plants (Plaza, Martínez, & Rubiera, 2020).

8.1.2 Steel:

“Steel–Prefab Assemb–Open Web Steel Joists” and “Steel–Cold Formed–Decking” were the third and fifth sources of embodied carbon emissions in the baseline model, so they were identified as the next priorities for emission reduction. Both of these materials are derived from the same material—raw steel, so they are discussed together. According to the EPD report from the suppliers, the raw steel in this project was sourced from the major steel mill companies that utilize both Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) processes. The EAF process primarily uses steel scrap as its raw material, which can be utilized up to 100%, while the BOF process uses iron ore and coal (Odenthal, Kemminger, Krause, Sankowski, Uebber, &

Vogl, 2017). Furthermore, the EAF process is mainly powered by electricity, with small amounts of coal (less than 5%) and natural gas (25–30%) while the BOF process is powered by electricity and fuel oil (Karlsson, Rootzén, Toktarova, Odenberger, Johnsson, & Göransson, 2020; Ruth, 2004). Thus, the overall CO_2 emissions of the EAF process are lower than those of the BOF process (Nidheesh & Kumar, 2019), but the team also found that there are other innovative technologies that could further reduce CO_2 emissions. One of the advanced technologies is hydrogen ironmaking, which can reduce emissions associated with natural gas use during production in the EAF process. The hydrogen ironmaking technologies include hydrogen plasma smelting reduction (HPSR), hydrogen flash smelting, hydrogen–enriched blast furnace ironmaking, and shaft furnace hydrogen direct reduction (H–DR). Among these, the H–DR technology is considered the most promising and has the greatest potential to reduce carbon emissions by 80–90% (Wang, Zhao, Babich, Senk, & Fan, 2021). Other breakthrough technologies, such as sorption-enhanced water-gas shift technology, producing advanced high strength or lighter steel to replace traditional steel, and using biomass like charcoal or torrefied biomass instead of coke and coal in BOF, can also decrease CO_2 emissions. Moreover, carbon sequestration can further help control emissions (Nidheesh & Kumar, 2019).

8.1.3 Asphalt:

Carbon emissions from "Asphalt" in the baseline model are also significant. The carbon footprint of asphalt is significantly influenced by the materials used and the production processes. For a virgin asphalt mixture with 95% aggregates and 5% asphalt blender content produced at a typical asphalt plant, 57% of the total cradle–to–gate emissions comes from raw materials (A1) and 38% from mix production (A3) (Shacat, Willis, and Ciavola, 2024). To reduce carbon emissions, recycled materials such as reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS) can be used to replace part of the aggregates or blender in asphalt mixtures. Emissions associated with processing RAP are 0.7 kg CO_2e per ton, and 3.2 kg CO_2e per ton for RAS. Other recycled materials and industrial byproducts that may be used in asphalt mixtures include steel slag, blast furnace slag, ground tire rubber, recycled fibers, and coal combustion products (Shacat, Willis, and Ciavola, 2024). Additionally, Warm Mix Asphalt (WMA) technologies (including chemical-, foam-, and wax-based) also reduce the environmental impacts of asphalt mixtures. If coupled with RAP materials they may lead to approximately 20% reduction in environmental impacts (Shatnawi, Ali, and Almutairi, 2025). In the market nowadays, companies such as CRH Americas and Granite Construction offer asphalt with recycled materials. Moreover, Recycled Asphalt Pavement also provides asphalt recycle service by reclaiming aggregate and bituminous material from deteriorated pavements, the need for new materials is appreciably reduced and the overall cost of the new pavement will be decreased. Except for the materials and technologies mentioned above, biomass-based asphalt may be another effective alternative. The CO_2 emissions of bio–asphalt mixtures with 5%, 10%, and 35% lignin will reduce by 13.9%, 27.7%, and 96.6% compared to that of the conventional asphalt mixture respectively (Tran, Aoki, Watanabe, Miyawaki, Nuruki, & Shakuno, 2024). Moreover, the LCA of biochar modified bioasphalt (BMBA) indicated that BMBA derived from waste wood have lower energy consumption compared to petroleum-based asphalt and it is the most environmentally friendly option (Zhou, Baghaee Moghaddam, Chen, Wu, Adhikari, Xu, & Yang, 2020). Although bioasphalt has great potential to reduce CO_2 emissions, there are no products on the market currently. As research progresses and technology advances, more asphalt mixture products incorporating lignin may emerge in the future.

8.1.4 Sheathing:

The team also studied the decarbonization ability of sheathing. An analysis of International Code Council (ICF) (2024) comparing EPDs and embodied carbon of the most used cavity and exterior sheathing insulation materials. They found cellulose loose fill, fiberglass loose fill, and unfaced batts are the top low-carbon insulation products. Other notable materials include:

- Fiber Cement Sheathing – Durable, fire-resistant, and made from recyclable materials, fiber cement sheathing is an excellent sustainable option.
- Recycled and Composite Sheathing – Sheathing products incorporate recycled materials, reducing waste and promoting circular economy practices.

8.1.5 Roofing:

For Roofing, a new study completed by Polyisocyanurate Insulation Manufacturers Association (PIMA) and ICF (2024) demonstrated that code-compliant levels of roof insulation installed entirely above deck as part of a roof replacement project can help building owners cost-effectively reach energy reduction goals while cutting costs and carbon emissions. Other roofing systems such as cool roofs, wood shingles, metal roofing, and solar roofing can also be considered (Roofline Supply, 2022). Among these, Insulative Cork Board (ICB) is the best performing one regarding both carbon absorption, lightweight density, and thermal capabilities. Using ICB will allow for carbon to be absorbed from the built environment and still perform thermally while being the most sustainable material. The only negative is that the market is available more in the European area, however the United States would be capable of growing the Cork Oak in a simulated climate. The next contender among the innovative insulation materials is Mycelium. Mycelium is still a new product to the market and there has not been any certification performed to ASTM standards (Mollohan, Mansy, and Yowell, 2025).

8.1.6 Mass Timber:

In addition to studying the existing materials in the project, mass timber can also be used to reduce CO_2 emissions. Mass timber is a type of construction that uses large, solid wood panels for walls, floors, and roofs. It offers a more sustainable option compared to materials that rely heavily on fossil fuels, as it uses renewable resources. Mass timber includes Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT), Glued-Laminated Timber (Glulam), and Dowel-Laminated Timber (DLT) (reThink Wood, n.d.). Using mass timber instead of steel structures and concrete floors leads to a significant reduction in carbon footprint. Mass timber buildings can cut carbon emissions by 19% from A1 to A4 stages (Hemmati, Messadi, Gu, Seddelmeyer, & Hemmati, 2024). Another LCA study on A1-A3 stages of mass timber shows that the average embodied GHG emissions of reinforced concrete buildings are 42.68% higher than those of mass timber alternatives. Besides, mass timber buildings generally have lower GWP and life cycle primary energy consumption compared to reinforced concrete and steel structures. This suggests that replacing traditional materials with mass timber can help reduce climate impact and promote sustainable construction (Duan, Huang, and Zhang, 2022). The prefabricated character of mass timber panels also leads to a safer and cleaner building process because it simplifies the on-site construction process (Ahmed & Arocho, 2020). In the United States, there are several suppliers of CLT and GLT, including Mercer Mass Timber (Washington), Timberlab (Oregon), Lam-Wood Systems (Colorado), SmartLam North America (Montana, Alabama), and Vaagen Timbers (Washington). In Canada, companies like Kalesnikoff, Western Archrib, Element5, and DowelLam also provide CLT and DLT products for the North American market. From the information available on these companies' websites, the team found that mass timber is mostly used for roofing, floor, beams and interior walls.

8.2 A4 Stage:

During the transportation of building materials, battery-electric trucks or electric semi-trucks can replace traditional trucks to help reduce carbon emissions. For electric trucks, their life–cycle energy use and GHG emissions are lower than diesel trucks (Lee, Thomas, & Brown, 2013). For electric semi-trucks, the Environmental and Energy Study Institute's research highlighted their benefits, including lower carbon emissions, reduced costs, and enhanced safety (Agrawal, 2023). This study also mentioned that the electric semi-truck models available in the U.S. include: Kenworth T680E, Peterbilt 579EV, Freightliner eCascadia, Volvo VNR-Electric, Nikola Tre BEV, Tesla Semi. The range of most models are 150 to 275 miles, with some reaching up to 500 miles. This aligns with the project's building material transportation needs. But transitioning to electric trucks encounters several challenges. One study found that in order to use electric trucks, companies need to build their own charging infrastructure, which can be very expensive. A charger costs around $50,000, and infrastructure upgrades will cost $55,000. In addition to the fixed cost, companies also have to cover the maintenance cost of electric trucks. All in all, it is a significant cost for businesses (Giuliano, Dessouky, Dexter, Fang, Hu, and Miller, 2021).

To address these issues, both state and national governments have started implementing incentive measures:

- Inflation Reduction Act (IRA):Purchasing 14,000 pounds or more (typically large vehicles like school buses and semi-trucks) can receive credit maximum to $40,000. In addition, if companies install qualified vehicle refueling and recharging property, including electric vehicle charging equipment, they may be eligible to receive a credit of up to $100,000 for each qualified item of property (Electrification Coalition, 2025; Internal Revenue Service, 2025).
- Bipartisan Infrastructure Law (BIL):The BIL establishes a National Electric Vehicle Infrastructure Formula Program ("NEVI Formula") to provide funding to States to strategically deploy electric vehicle (including trucks) charging infrastructure and to establish an interconnected network to facilitate data collection, access, and reliability (Federal Highway Administration, 2025).

8.3 A5 Stage:

In addition to reducing the embodied carbon of building materials and transportation, carbon emissions from energy use on construction sites also deserve attention. Studies indicate that solar panels, as a renewable energy source with nearly 100% carbon reduction potential, are an efficient and feasible option. Installing solar panels on the roofs of site offices can significantly reduce electricity consumption, potentially supplying up to 72% of the electricity demand for site offices. However, the initial investment in solar panels is relatively high (Zhang, Li, Chan, Li, Fan, Dai, & Shi, 2023).

9 Recommendations

The team formulated the following recommendations based on insights from the sensitivity analysis:

9.1 A1-A3 Stages:

9.1.1 Cement and Concrete:

- Procuring cement products containing FA, SF, GGBS, RHA, and CBP based on local supply conditions.
- Procuring products from cement suppliers that have CCUS facilities.

The supply of FA, GGBS, and SF is widely available in the current market:

- FA: Titan America, HeidelbergCement, CEMEX, ARGOS
- GGBS: Buzzi Unicem USA, St Marys Cement, Titan America, HeidelbergCement, CEMEX, ARGOS
- SF: St Marys Cement

All of these suppliers have factories and distribution terminals within the United States to ensure the supply of cement. Moreover, Titan America has also tried using climate–friendly alternative fuels and materials, as well as implementing strict energy management measures to reduce CO_2 emissions during the production by cutting electricity use (Titan America, n.d.). In terms of CCUS technology, Holcim has already deployed mature CCUS technologies and committed to capturing over 5 million tons of carbon annually by 2030 (Holcim, 2025). HeidelbergCement is also optimizing its products and processes through research and technological efforts to ensure the lowest possible CO_2 emissions (HeidelbergCement, n.d.).

9.1.2 Steel:

- Purchasing steel produced by H–DR technology or sorption-enhanced water-gas shift technology in the future.
- Purchasing products from steel manufacturers that have deployed CCUS facilities.
- Purchasing products from suppliers who source raw materials from EAF or BOF that use biomass as fuel.

9.1.3 Asphalt:

- Prioritizing the use of asphalt with RAP and RAS.
- Purchasing asphalt with WMA technologies combined with RAP materials.
- Procuring bioasphalt products to replace traditional asphalt in the future.

9.1.4 Sheathing:

- Meijer could prioritize the use of low-carbon insulation products such as cellulose loose fill, fiberglass loose fill, and unfaced batts.
- Meijer could use fiber cement sheathing due to its durability, fire resistance, and recyclability.
- Recycled and composite sheathing options, which incorporate recycled materials, could also be considered as alternative plans to reduce emissions.

9.1.5 Roofing:

Meijer could consider incorporating ICB into their roofing structure due to its excellent performance in carbon absorption and thermal efficiency. Other roofing options, such as cool roofs, wood shingles, metal roofing, and solar roofing, can also reduce carbon emissions.

9.1.6 Mass timber:

- Mass Timber could be used for roof structure, floor slabs, and interior walls. This can reduce the carbon footprint while ensuring structural stability.
- Using NLT would reduce more emissions, but it is important to assess its accessibility. Meijer can choose suppliers based on the delivery costs and the supplier's production capacity to ensure the project meets its environmental and economic goals. If NLT supply is not available or too expensive, CLT or DLT could be considered as alternatives.

9.2 A4 Stage:

Considering infrastructure development and project cost evaluation, the team recommends that Meijer can adopt hybrid trucks to reduce some of the transportation carbon emissions in the short term. In the future, after assessing the initial costs, Meijer can consider using electric trucks to gradually replace conventional trucks. This approach will not only help improve the company's green image but also align with environmental regulations and market expectations.

9.3 A5 Stage:

The team recommends that Meijer can reduce carbon emissions on construction sites by:

- Installing rooftop solar panels on site offices to generate clean electricity, while considering the initial investment costs.
- Using biodiesel in all generators to help lower emissions and promote the use of clean energy.
- Using green hydrogen to power fuel cell generators for zero-emission electricity generation.

10 Discussion

10.1 Limitations

This study on reducing embodied carbon in Meijer's construction projects provided valuable insights into emissions from materials, transportation, and construction processes. However, several limitations should be acknowledged. First, data availability posed a significant challenge. Some manufacturers have not yet published EPDs, leading to reliance on industry-average data or estimations, which may not fully capture regional or supplier-specific variations (Building Transparency, 2024). Second, while the EC3 is a robust tool, its database is continuously evolving. The inclusion of new EPDs over time may alter the results if re-evaluated in the future. Additionally, the study was constrained by project timelines, limiting the extent of sensitivity analysis and the ability to test a wider range of alternative materials and methodologies. Another key limitation relates to the geographic and logistical constraints of material procurement. While our analysis explored the potential of alternative materials, such as mass timber and SCMs, their availability in Meijer's operational regions was not fully assessed. The feasibility of transitioning to these materials would require further supplier engagement and lifecycle cost analysis.

10.2 Challenges

Implementing the recommended strategies presents several challenges. A major hurdle is the cost associated with transitioning to low-carbon materials and technologies. While the Inflation Reduction Act and other policy incentives may help mitigate these costs, upfront investment in sustainable materials, electric fleets, and carbon capture technologies remains substantial (Internal Revenue Service, 2025). Additionally, industry-wide inertia and lack of supplier readiness pose barriers to adopting new practices. Many construction stakeholders are unfamiliar with the latest low-carbon materials, and resistance to change can slow progress. A further challenge is ensuring consistency in carbon accounting methodologies across Meijer's supply chain. The voluntary nature of EPD publication means that material suppliers may use different LCA methodologies, leading to variability in reported data (Ming Esram, 2021). Standardizing these reporting practices through supplier engagement and policy advocacy would be necessary for accurate carbon accounting. From a practical standpoint, integrating mass timber into Meijer's construction framework requires structural redesign considerations and adherence to building code regulations, which vary by jurisdiction (Ahmed Arocho, 2020). Similarly, scaling up SCM usage in concrete must align with structural performance requirements and local availability of materials like fly ash and ground granulated blast furnace slag (Jain et al., 2021).

10.3 Future Research

Future studies should aim to refine embodied carbon reduction strategies by addressing these limitations and challenges. One area of focus should be expanding the dataset of regionally sourced EPDs to improve material-specific emissions estimates. Partnering with manufacturers and suppliers to develop product-specific EPDs could enhance data granularity and reduce reliance on industry averages. Another avenue for future research involves deeper life cycle assessments of emerging technologies, such as bio-asphalt and CCUS in cement production (Plaza et al., 2020). As these technologies mature, comparative studies should assess their long-term economic viability and scalability within Meijer's construction model. Additionally, further research should explore the integration of renewable energy sources at construction sites. While the present study highlighted the potential of rooftop solar panels, future work could evaluate additional strategies such as on-site battery storage for microgrid applications to further reduce emissions during the construction phase (Zhang et al., 2023) Future studies could also explore quantifying embodied carbon across different Meijer store formats beyond the supercenter model. This would help evaluate variation in emissions based on building size, design, and material use, providing more targeted strategies for diverse retail layouts. Lastly, a broader exploration of policy and incentive structures could help identify regulatory mechanisms that support sustainable construction transitions. Government policies play a critical role in shaping industry practices, and aligning Meijer's strategies with upcoming environmental regulations could provide financial and operational benefits.

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13 Appendices

13.1 Supporting Documentations

13.1.1 Sensitivity Analysis - Transportation Emission Scenarios Calculations

1. Baseline Scenario-Diesel Truck Transport

Assumptions:

- Transport via diesel-powered semi-trucks (average fuel efficiency: 6.5 mpg)
- Emission factor: 10.1 $kgCO_2$/gallon diesel (EPA SmartWay) [**epa_smartway**]
- Payload capacity: 40,000 lbs (20 tons) per truckload

Calculations:

$$\text{Fuel consumed per trip} = \frac{597\text{ miles}}{6.5\text{ mpg}} = 91.8\text{ gallons}$$
$$\text{CO}_2\text{ per trip} = 91.8\text{ gal} \times 10.1\text{ kgCO}_2/\text{gal} = 927\text{ kgCO}_2/\text{truckload}$$
$$\text{CO}_2\text{ per ton-mile} = \frac{927\text{ kgCO}_2}{20\text{ tons}} = 46.4\text{ kgCO}_2/\text{ton}$$
$$\text{Total emissions (100 tons)} = 5\text{ truckloads} \times 927\text{ kgCO}_2 = 4{,}635\text{ kgCO}_2\text{ (4.6 tCO}_2)$$

2. Electric Truck Scenario (Battery-Electric Semis)

Assumptions:

- Tesla Semi (e-truck) efficiency: 1.7 kWh/mile [**(U.S. EIA, 2025)-CO$_2$ Emissions per Kilowatthour**]
- Grid carbon intensity: 0.38 $kgCO_2$/kWh (U.S. national avg.) [**eia_grid_2023**]
- Payload capacity: 20 tons (same as baseline)

Calculations:

$$\text{Energy per trip} = 597\,\text{miles} \times 1.7\,\text{kWh/mile} = 1{,}015\,\text{kWh}$$
$$\text{CO}_2\text{ per trip} = 1{,}015\,\text{kWh} \times 0.38\,\text{kgCO}_2/\text{kWh} = 386\,\text{kgCO}_2/\text{truckload}$$
$$\text{CO}_2\text{ per ton-mile} = \frac{386\,\text{kgCO}_2}{20\,\text{tons}} = 19.3\,\text{kgCO}_2/\text{ton}$$
$$\text{Total emissions (100 tons)} = 5\,\text{truckloads} \times 386\,\text{kgCO}_2 = 1{,}930\,\text{kgCO}_2\,(1.9\,\text{tCO}_2)$$
$$\text{Reduction vs. diesel} = 58\%\,\text{lower emissions}$$

3. **Rail-Intermodal Scenario (Train + Last-Mile Trucking)**
   Assumptions:

- Primary haul: 500 miles by electric freight train (0.023 kgCO_2/ton-mile) [**(Climatiq, 2025)-Rail Freight Emission**
- Last-mile: 97 miles by diesel truck (same parameters as baseline scenario)
- Total distance: 597 miles (consistent with other scenarios)
- Payload capacity: 20 tons (maintained for comparison)

Calculations:

$$\begin{aligned}
\text{Train emissions} &= 500\,\text{miles} \times 0.023\,\text{kgCO}_2/\text{ton-mile} \times 20\,\text{tons} = 230\,\text{kgCO}_2 \\
\text{Truck emissions (last 97 miles)} &= \frac{97\,\text{miles}}{6.5\,\text{mpg}} \times 10.1\,\text{kgCO}_2/\text{gal} = 151\,\text{kgCO}_2 \\
\text{Total CO}_2\text{ per trip} &= 230\,\text{kgCO}_2 + 151\,\text{kgCO}_2 = 381\,\text{kgCO}_2/\text{truckload} \\
\text{CO}_2\text{ per ton-mile} &= \frac{381\,\text{kgCO}_2}{20\,\text{tons}} = 19.05\,\text{kgCO}_2/\text{ton} \\
\text{Total emissions (100 tons)} &= 5\,\text{truckloads} \times 381\,\text{kgCO}_2 = 1{,}905\,\text{kgCO}_2\,(1.9\,\text{tCO}_2) \\
\text{Reduction vs. diesel} &= 54.35\%\,\text{lower emissions}
\end{aligned}$$

4. **Local Sourcing Scenario (Reduced Distance by 50%)**
   Assumptions:

- Supplier distance: 300 miles (50% reduction from baseline)
- Transport mode: Diesel trucks (same 6.5 mpg efficiency as baseline)
- Payload capacity: 20 tons (consistent with other scenarios)
- Emission factor: 10.1 kgCO_2/gallon diesel (EPA SmartWay)

Calculations:

$$\begin{aligned}
\text{Fuel per trip} &= \frac{300\,\text{miles}}{6.5\,\text{mpg}} = 46.2\,\text{gallons} \\
\text{CO}_2\text{ per trip} &= 46.2\,\text{gal} \times 10.1\,\text{kgCO}_2/\text{gal} = 466\,\text{kgCO}_2/\text{truckload} \\
\text{CO}_2\text{ per ton-mile} &= \frac{466\,\text{kgCO}_2}{20\,\text{tons}} = 23.3\,\text{kgCO}_2/\text{ton} \\
\text{Total emissions (100 tons)} &= 5\,\text{truckloads} \times 466\,\text{kgCO}_2 = 2{,}330\,\text{kgCO}_2\,(2.3\,\text{tCO}_2) \\
\text{Reduction vs. 597-mile diesel} &= 50\%\,\text{lower emissions}
\end{aligned}$$

13.1.2 Sensitivity Analysis - On-Site Energy Consumption Scenarios Calculations

1. Baseline Scenario (Diesel Generators Only) Assumptions:

- Job Trailer Generator:
  - Duration: 36 weeks (April–January)
  - Consumption: 80 gallons/week
  - Total diesel: 2,880 gallons
- Site Generator:
  - Duration: 20 weeks (May–October)
  - Consumption: 300 gallons/week
  - Total diesel: 6,000 gallons
- Emission factor: 10.1 $kgCO_2$/gallon [**(U.S. EPA, 2023)-Emission Factors for Greenhouse Gas Inventories**]

Calculations:

$$\begin{aligned}\text{Job trailer emissions} &= 2{,}880\,\text{gal} \times 10.1\,\text{kgCO}_2/\text{gal} = 29{,}088\,\text{kgCO}_2\,(29.1\,\text{tCO}_2)\\ \text{Site emissions} &= 6{,}000\,\text{gal} \times 10.1\,\text{kgCO}_2/\text{gal} = 60{,}600\,\text{kgCO}_2\,(60.6\,\text{tCO}_2)\\ \text{Total emissions} &= 29.1\,\text{tCO}_2 + 60.6\,\text{tCO}_2 = 89.7\,\text{tCO}_2\end{aligned}$$

2. Early Utility Tie-In Scenario (Reduced Generator Use) Assumptions:

- **Generator Usage Reduction:**
  - Job trailer: Grid power after 20 weeks (vs. 36 weeks)
  - Site generator: Grid power after 12 weeks (vs. 20 weeks)
- **Remaining Diesel Consumption:**
  - Job trailer: 20 weeks × 80 gal/week = 1,600 gal
  - Site: 12 weeks × 300 gal/week = 3,600 gal
- **Grid Parameters:**
  - Emission factor: 0.552 $kgCO_2$/kWh [**(U.S. EPA, 2025a)-Greenhouse Gas Equivalencies Calculator**]
  - Generator efficiency: 1 gal diesel = 14 kWh

Calculations:

$$\begin{aligned}\text{Diesel emissions} &= (1{,}600 + 3{,}600)\,\text{gal} \times 10.1\,\text{kgCO}_2/\text{gal} = 52{,}520\,\text{kgCO}_2\,(52.5\,\text{tCO}_2)\\ \text{Grid energy demand} &= \begin{cases} 16\,\text{weeks} \times 80\,\text{gal/week} \times 14\,\text{kWh/gal} = 17{,}920\,\text{kWh (job trailer)}\\ 8\,\text{weeks} \times 300\,\text{gal/week} \times 14\,\text{kWh/gal} = 33{,}600\,\text{kWh (site)}\end{cases}\\ \text{Total grid emissions} &= 51{,}520\,\text{kWh} \times 0.552\,\text{kgCO}_2/\text{kWh} = 28{,}439\,\text{kgCO}_2\,(28.4\,\text{tCO}_2)\\ \text{Total emissions} &= 52.5\,\text{tCO}_2 + 28.4\,\text{tCO}_2 = 80.9\,\text{tCO}_2\end{aligned}$$

3. Solar-Assisted Hybrid Scenario (50% Diesel Offset) Assumptions:

- Solar panels provide 50% of energy demand
- Diesel consumption reduced proportionally:
  - Job trailer: 2,880 gal × 50% = 1,440 gal
  - Site: 6,000 gal × 50% = 3,000 gal

- **Solar System:**
    - Capacity: 100 kW
    - Annual output: ~51,520 kWh
    - Embodied carbon: 50 gCO_2/kWh [**solar_lca_2023**]

Calculations:

$$\begin{aligned}
\text{Diesel emissions} &= (1{,}440 + 3{,}000)\,\text{gal} \times 10.1\,\text{kgCO}_2/\text{gal} = 44{,}844\,\text{kgCO}_2\,(44.8\,\text{tCO}_2) \\
\text{Solar embodied carbon} &= 51{,}520\,\text{kWh} \times 0.05\,\text{kgCO}_2/\text{kWh} = 2{,}576\,\text{kgCO}_2\,(2.6\,\text{tCO}_2) \\
\text{Total emissions} &= 44.8\,\text{tCO}_2 + 2.6\,\text{tCO}_2 = 47.4\,\text{tCO}_2 \\
\text{Reduction vs. baseline} &= 47\%\,\text{lower emissions}
\end{aligned}$$

4. **Biodiesel Blend Scenario (B20 Adoption) Assumptions:**

- B20 fuel blend (20% biodiesel, 80% diesel)
- Emission factor: 8.08 $kgCO_2/gal$ (20% reduction) [**biodiesel_epa_2023**]
- Total consumption: 8,880 gallons (2,880 + 6,000)

Calculations:

$$\begin{aligned}
\text{Total emissions} &= 8{,}880\,\text{gal} \times 8.08\,\text{kgCO}_2/\text{gal} = 71{,}750\,\text{kgCO}_2\,(71.8\,\text{tCO}_2) \\
\text{Reduction vs. baseline} &= 20\%\,\text{lower emissions}
\end{aligned}$$