Low Carbon Housing
Using Embodied Carbon as a Design Philosophy

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Abstract

The building industry is the largest emitter of carbon dioxide into our atmosphere when compared with any other industry (USGBC, 2013). This fact has lead the industry to take noticeable steps to reduce their carbon footprint and the green building industry has been a direct response. Green buildings currently focus on reducing operational energy consumption. Yet, aside from operational energy, materials and construction make-up a large portion of a building’s total carbon emissions throughout its life cycle. This report seeks to inform the industry about the impact that embodied carbon has on a building’s carbon footprint and articulates ways in which to use embodied carbon as a design philosophy throughout the design process. Currently, building information modeling (BIM) software informs design decisions during the design process. BIM software highlights opportunities for project teams to reduce their structures environmental impacts. The software is mostly used to educate teams about operational energy consumption, however, it can be used the same way to develop strategies to reduce the embodied carbon footprint. Project teams that neglect to use life cycle assessment (LCA) information to inform their designs are limiting chances to reduce their environmental footprint as much as possible. This study is a housing case study which highlights the effectiveness of BIM software to inform embodied carbon design decisions that result in a reduced carbon footprint. This study analyzes the embodied carbon of a low operational energy house’s envelope and illustrates how reductions can be made during the design phase. This study demonstrates how project teams can significantly reduce their building’s carbon footprint by incorporating LCA into their design process.
The Building Industry’s Contribution to Climate Change

Today there are record amounts of carbon dioxide in the atmosphere. Scientists conclude that these elevated levels are contributing to climate change (Hansen et al., 1981). The rapid change in climate results in unbalanced ecosystems, devastating weather patterns, sea level rise, the extinction of plant and animal species, and more.

The building industry is responsible for a significant portion of the world’s anthropogenic greenhouse gas (GHG) emissions. The emissions generate from the energy production and manufacturing needed to construct, operate, maintain, and deconstruct a building --- polluting the air and contributing to climate change. Currently, buildings account for 41% of energy use within the United States (Fumo et al., 2010) and are associated with 44% of domestic carbon dioxide emissions as shown in Figure 1. Globally, the figure is nearly one-third (USGBC, 2013). GHG emissions will be exacerbated as human population increases and developing countries attain a higher standard of living. According to L. Perez-Lombard et al., the building industry is experiencing a 1.5% increase in CO2 emissions annually, proving their impact on atmospheric carbon will intensify if current standards remain unchanged and the industry continues to operate “business as usual” (2008).

Figure 1. The building industry’s atmospheric carbon dioxide emissions per year
As a primary generator of GHG emissions, the building industry, thus, can have a large impact on curbing anthropogenic climate change. The emergence of Green Buildings have been a response to climate issues and challenge the building industry standard, aiming to reduce environmental harm and overall impacts. According to United States Green Building Council (USGBC) green buildings are defined as:

A holistic concept that starts with the understanding that the built environment can have profound effects, both positive and negative, on the natural environment, as well as the people who inhabit buildings every day. Green building is an effort to amplify the positive and mitigate the negative of these effects throughout the entire life cycle of a building. While there are many different definitions of green building out there, it is generally accepted as the planning, design, construction, and operations of buildings with several central, foremost considerations: energy use, water use, indoor environmental quality, material section and the building’s effects on its site (USGBC, 2016).

The construction market is beginning to adopt and introduce these types of practices, steadily incorporating green building strategies into their business model. In 2005 only 2% of nonresidential construction starts were categorized as “green builds”, 12% in 2008, and 28% to 35% in 2010 (Green Outlook, 2011). With the expected domestic increase in building square footage it is necessary to make sure green building design strategies are considering the entire life cycle and sources of carbon pollution (Ewing et al, 2008).
In many instances the change in strategy from conventional to green solely focus on single attributes (Simonen, 2014), such as adding solar panels to improve operational energy efficiency and reducing reliance on large centralized coal power plants (Carrasco et al., 2006). These approaches reduce a building’s environmental impact and the overall carbon footprint; however, these single strategies are missing the total environmental scope (Simonen, 2014). For example, if a building operates on renewable energy with little to no reliance on fossil the operational impacts will be minimal and “green”, but, that same building could have high embodied impacts. To avoid “green-washing” and ensure a most holistic approach to green building, both operational and embodied impacts need to be considered.

**What Is A Building’s Carbon Footprint?**

A building’s carbon footprint is the total carbon emissions used throughout its lifecycle. Carbon dioxide can be emitted into the atmosphere at any stage of a building’s lifecycle, from raw material allocation, manufacturing, construction, use, and disposal as seen in Figure 2. Transportation associated with these activities is also included in the carbon footprint.

**Figure 2.** Simplified life cycle stages of a building
In general, the total carbon footprint of a building is the sum of two primary categories: operational carbon emissions and embodied carbon emissions. Operational carbon emissions occur when energy is consumed during occupation. Energy is needed for different building systems, such as heating, cooling, ventilation, lighting, equipment, and appliances. Embodied carbon refers to the carbon dioxide emitted during the extraction, manufacturing, transportation, construction and deconstruction of buildings materials, as shown in Figure 3. The total embodied carbon within a building is dependent on material type, quantity, origin, assembly and disassembly method, and maintenance requirement.

![Figure 3. Simplified embodied carbon contributors for buildings](image)

The building type plays a significant role when determining the ratio of the two categories. For example, a building that is passive and uses on-site renewable energy will have nearly 100% embodied carbon. According to Basbagill, embodied carbon in a typical building, however, that relies on fossil fuel consumption for operation energy, accounts for 10-20% of total impacts, with operational impacts making up the difference (Basbagill, 2013). A recent French study found a similar trend when they compared 70 different case study buildings and found 19% of total environmental impacts, over a 100-year life span, were embodied (HQE, 2012).
As building operational systems become more efficient the embodied impacts will become more significant, as shown in Figure 4. This is important to note, and makes embodied carbon accounting vital when trying to achieve a low environmental impact building. The mitigation of “green-washing” can be achieved if both operational and embodied impacts are considered.

Figure 4. Relative impact of a building’s embodied vs operational carbon emissions

Calculating Embodied Carbon: Life Cycle Assessment Fundamentals

The Life Cycle Assessment (LCA) of a building can include all stages of life from cradle to grave. The entire life cycle assessment can be broken into boundaries, looking at different moments throughout a building’s life. Cradle-to-Gate assessments only highlight the environmental impacts from material extraction and manufacturing processes. Cradle-to-Grave, considers the full scope of a building’s life cycle and includes all process from material extraction to demolition.
Many materials can be recycled and plugged back into the system boundary, which is referred to as \textit{Cradle-to-Cradle} as seen in Figure 5. This study analyzes embodied impacts from \textit{Cradle-to-Grave}.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Simplified life cycle stages of a building}
\end{figure}
**Incorporating Life Cycle Assessment Into The Design Process**

Life cycle assessment (LCA) data can be used throughout the design process to highlight environmental impacts of design decisions. The Schematic Design phase is an initial design scheme that defines the general scope and conceptual design of the project including scale and relationships between building components. Prototypes and parti models and drawings are constructed to help visualize ideas. With these conceptual ideas surface level LCA calculations can help the project team make better environmental decisions, see Figures 12 and 13. The same is true for the Design Development phase; this stage is where project teams make material, mechanical, electrical, and plumbing system choices. These choices have significant impact on the embodied carbon footprint and LCA data can help the project team can use this data to help them make informed decisions. LCA data used to inform decisions throughout these two phases can significantly reduce environmental impacts of buildings, see Figures 9 and 16.

**Methodology + System Boundary**

LCA can be used to determine embodied carbon responsibility per building assembly. Material data is derived from Revit, the industry standard building information modeling software for construction plans and details. This program is able to produce area (square feet) and volume (cubic yards) data of different residential systems and assemblies that make up a house. The data from Revit can then be plugged into Athena Eco-calculator for residential construction. Athena is a LCA database and software program.
Athena Eco Calculator results take into account all life cycle stages: resource extraction and processing; product manufacturing; on-site construction of assemblies; all related transportation; maintenance and replacement cycles over an assumed building service life of 60 years; and the demolition and transportation of non-metal materials to landfill.

The study refers to Athena Sustainable Materials Institute (ASMI) for calculating embodied carbon per material assembly. The ASMI tool used was the ATHENA Impact Estimator version 4 (IE4B). A proper LCA is needed for embodied impact calculations, determining where the carbon emissions derive from and in what quantity. Athena LCA is the science behind true environmental footprinting and LCA results on embodied impacts are the basis for achieving sustainability goals and can inform decisions about materials. Thousands of sustainability designers and academics have been trusting Athena software tools since 2002 (Athena, 2017). According to ASMI “LCA methods are always up-to-date, and [their] life cycle data on North American construction materials and processes is the most rigorous, complete, reliable and regionally-specific available.” The National Institute of Building Sciences lists Athena as their sole LCA software tool and credits them for using internationally recognized life cycle assessment methodology (wbdg.org). According to a case study which questioned the validity of ATHENA Impact Estimator, the program has its limitations but is a “workable tool” for calculating embodied carbon impacts of building materials and can be used for comparisons at the schematic level (Stek et al., 2011).
The scope and system boundary of IE4B can model designs at any scale as seen in Table 1. For this case study specific building elements were chosen. The house’s foundation, exterior walls, interior walls, glazing, and roof. IE4B’s geographic coverage includes the United States and Canada. The site for this study is Silverthorne, Colorado which falls within climate zone 6.

ATHENA Impact Estimator has the complex life cycle databases and methodology built right into the program. This makes it simple to import Revit material information into IE4B to calculate specific embodied carbon amounts per material assembly, see Figure 6.

Project teams can apply this methodology to their design process which can improve their reduced environmental impact goals.
Table 1. IE4B system boundary capacity

<table>
<thead>
<tr>
<th>Information Module</th>
<th>Supports?</th>
<th>Processes Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 Raw material supply</td>
<td>Y</td>
<td>Primary resource harvesting and mining</td>
</tr>
<tr>
<td>A2 Transport</td>
<td>Y</td>
<td>All transportation of materials up to manufacturing plant gate</td>
</tr>
<tr>
<td>A3 Manufacturing</td>
<td>Y</td>
<td>Manufacture of raw materials into products</td>
</tr>
<tr>
<td>A4 Transport</td>
<td>Y</td>
<td>Transportation of materials from manufacturing plant to site, and construction equipment to site</td>
</tr>
<tr>
<td>A5 Construction-installation process</td>
<td>Y</td>
<td>Construction equipment energy use, and A1-A4, C1, C2, C4 effects of construction waste</td>
</tr>
<tr>
<td>B1 Installed product in use</td>
<td>N</td>
<td>n/a (currently insufficient consensus in methodology and data for this module to be addressed)</td>
</tr>
<tr>
<td>B2 Maintenance</td>
<td>Partial</td>
<td>Painted surfaces are maintained (i.e. repainted), but no annual maintenance aspects are included</td>
</tr>
<tr>
<td>B3 Repair</td>
<td>N</td>
<td>n/a (not currently well-supported with data)</td>
</tr>
<tr>
<td>B4 Replacement</td>
<td>Y</td>
<td>A1-A5 IM effects of replacement materials, and C1, C2, C4 effects of replaced materials</td>
</tr>
<tr>
<td>B5 Refurbishment</td>
<td>N</td>
<td>n/a (this module applies to known future refurbishment and needs to be addressed on a case-by-case basis if applicable)</td>
</tr>
<tr>
<td>B6 Operational energy use</td>
<td>Y</td>
<td>Energy primary extraction, production, delivery, and use</td>
</tr>
<tr>
<td>B7 Operational water use</td>
<td>N</td>
<td>n/a</td>
</tr>
<tr>
<td>C1 De-construction demolition</td>
<td>Y</td>
<td>Demolition equipment energy use</td>
</tr>
<tr>
<td>C3 Transport</td>
<td>Y</td>
<td>Transportation of materials from site to landfill</td>
</tr>
<tr>
<td>C3 Waste Processing</td>
<td>N</td>
<td>Most material data does not include waste processing effects, however, the newer metals “voided burden” methodology data does include waste processing effects, but not is it not separated into its own C3 module (see Metal Recycling on page 38)</td>
</tr>
<tr>
<td>C4 Disposal</td>
<td>Y</td>
<td>Disposal facility equipment energy use and landfill site effects</td>
</tr>
<tr>
<td>D Benefits and loads beyond the system boundary</td>
<td>Y</td>
<td>Carbon sequestration and steel recycling</td>
</tr>
</tbody>
</table>

Figure 6. How the impact estimator for buildings works

Industry Strategies to Reduce a Buildings Total Carbon Footprint

Green building standards, established institutionally, primarily focus on operational energy reduction and offsets, giving little attention to embodied carbon. For example, the popular green building rating system, Leadership in Energy and Environmental Design (LEED), awards points for sustainable building practices with the most points achievable in categories related to operation energy. 110 points are possible for new building projects striving for LEED v4 BD+C certification, of those, 33 points are reserved for Energy and Atmosphere. This category addresses strategies used to reduce the environmental impact a building has during its operation, with 18 of those possible points reserved for Optimize Energy Performance. In contrast, LEED only offers 13 possible points for the Materials and Resources category, and of the 13 only 9 address strategies that reduce embodied carbon (USGBC, 2016). Embodied carbon accounts for a good portion a buildings lifetime carbon emissions- especially in structures with good operational efficiency, like LEED certified buildings. However, only 9% of the possible points can be attained by implementing embodied carbon reduction into the design, while 30% can be achieved for achieving certain levels of operational efficiency, as seen in Figure 22.

Government agencies are also focusing on operational carbon reductions. In 2007, the California Public Utilities Commission (CPUC) adopted goals that all new residential construction will be net zero energy by 2020. The standard defines a net zero energy (NZE) building as one that produces as much energy as it consumes over the course of a year (“California Zero Net Energy - ZNE Homes” 2016). The CPUC suggests four strategies to achieve the NZE goals: high performance walls; high performance attics; improved water heating system efficiency; energy efficient appliances.
The CPUS’s goals isolate the two impact categories, favoring operational impacts and paying little to no attention on embodied impacts. For example, high performance walls require more insulation material compared with standard walls. Therefore, the embodied carbon associated with high performance walls is greater than standard walls. In this case, an embodied carbon analysis could be done to determine how the increase of insulation material will affect the carbon footprint. The ease of measurability may be the cause for the isolation. Operational impacts are easily monitored and measured, where as the measurability of embodied impacts are more difficult and dependent on many variables. These variables are site specific. For example, since embodied carbon includes transportation of materials, every project site will have a different embodied carbon number for that assembly. For example, the same exact house using the same materials was built on Site A and Site B.

Figure 7. LEED point allocation by category
However, site B is 5 miles further away from where the materials come from. The house on site B will have a larger embodied carbon footprint. Another variable that is very difficult to calculate is maintenance requirements. For example, damages that are not intended but take place due to destructive behavior can not be accounted for in embodied carbon calculations, however, these can occur and increase the embodied carbon.

**Current Green Building Strategies to Reduce Embodied Carbon**

The embodied carbon footprint of a building can never reach absolute zero without carbon storage, carbon sequestration, or carbon offsetting. Carbon storage and sequestration is the extraction and storage of carbon dioxide from the atmosphere. Trees are a simple and proven way to extract to accomplish storage. It is estimated that within urban USA 700 million tonnes of carbon is stored within trees (Nowak, 2002). This has been a popular method used by designers and builders who wish to reduce their building’s embodied carbon, purchasing offsets through tree planting programs. Second to tree programs, is the purchasing of renewable energy certificates to offset carbon emissions. Smith College Bechtel Environmental Classroom, a LBC building located in Whately, Massachusetts explains this. The structure is a state-of-the-art 2,500 square foot single-story wood-framed building. In order to offset these emissions the project team purchased carbon offsets from the Clean Air Action Program (Living Building Challenge, 2016). The Clean Air Action Corporation works with subsistence farmers in Africa and India on a tree planting model. According to the website over 78,000 farmers are taking care of more than 16 million trees and also plant new trees everyday. The program began in 1999 and claims their trees have sequestered over 3 million tonnes of carbon dioxide from the atmosphere (cleanairaction.com, 2016).
These types of programs help buildings offset their footprint and reach absolute zero in theory, however, the building still has an embodied carbon footprint of 29 tonnes – it is not really zero. These programs offset carbon emissions, however, do nothing to achieve reduction of actual emissions.
Purpose and Goal of Study

The purpose of this study is to inform the building industry, especially residential designers and engineers, on the importance of incorporating an embodied carbon reduction strategy into their schematic design process, as seen in Figure 8 and Figure 9. Designing with embodied carbon in mind is the only way to achieve actual carbon reductions. This study demonstrates how BIM software in tandem with LCA software programs, like Athena, can inform design teams on carbon reduction strategies for their structure. Embodied carbon can be accounted and designed for in the SD phase of the construction process and reduce the total carbon footprint.

This study is a comparative life-cycle assessment and compares embodied carbon of two different house structures. Decisions realized in the schematic design phase of residential structures can directly reduce or increase environmental impacts such as atmospheric carbon emissions. The study was developed to understand how embodied carbon can be increased or decreased during the schematic design phase of residential buildings.

This study is intended for use by architects, engineers, contractors, and any designer seeking to understand how the awareness of embodied carbon can inform design decisions.

This comparative assessment covers specific assemblies and does not consider mechanical systems and is to be integrated into a more comprehensive LCA, see Table 2 for the scope of this study. The information benefits architects, engineers, and contractors looking to understand how the design phase of residential construction can influence total
Figure 8. Project teams develop massing models in the early design phases. An LCA performed during this process can give teams the information needed to compare the embodied carbon potential of different building forms. For example, Massing Form B may have a smaller embodied carbon footprint than Massing Form A.

Which siding options provide the lowest embodied carbon footprint?

Which glazing system provides the lowest embodied carbon footprint?

Which roofing material will provide the lowest embodied carbon footprint?

Figure 9. Project teams can use LCA data in the design development phase to compare material, electrical, and plumbing system options. Teams can make informed decisions based on this data and can reduce the design’s embodied carbon footprint.


Methods

Analyzing Embodied Carbon Using A Comparative Study

This study compares two houses, both having the same living square footage area of 1,800 square feet. The first house, named “Baseline House” takes advantage of standard green practices to achieve a net-zero operational emissions baseline. The second house, named “New House”, is a response to the Baseline House, with a shift in focus towards total carbon footprint. The second house still achieves net zero operational energy, but goes a step further and reduces embodied carbon through a number of design changes. Using the material takeoffs and construction documents from BIM software, information on material type and quantity was collected, which was plugged into Athena Eco-calculator to calculate total Global warming potential – measured by total carbon dioxide embodied (tCO2e). The second house was designed with an embodiedcarbon reduction design philosophy and responds to the total embodied carbon calculations of the baseline house’s chosen assemblies: Foundation; Floor; Interior Walls; Glazing, Exterior Walls; Roof.

1. The first step was designing and modeling the Baseline House to achieve net-zero operational energy. The livable area of the house is 1,800 square feet and the assembly abides to the standard building code for residential construction. The house is three bedrooms, two bath. The house’s envelope was the focus of the study and, therefore, the design does not include interior furniture, appliances, or mechanical systems – although there is enough space to accommodate these features when desired. See Figure 10 and Figure 11 for the energy analysis, floor plans, layout, general design features and guidelines of the baseline house.
2. The Baseline House was modeled in Revit. Different assemblies were assessed for embodied energy. This study focuses on the house’s envelope and assemblies were chosen accordingly. The assemblies analyzed were the house’s foundation, exterior walls, interior walls, floor, roof, and glazing. A material takeoff, which gives square footage and cubic volume quantities, was produced in Revit for each assembly. The information was then plugged into Athena to calculate the embodied carbon (EC) of each assembly, as seen in Figure 12.

3. The embodied carbon information was used to create a graphical display highlighting the carbon responsibility of each assembly, shown in Figure 13.

4. Without altering the square footage or the program the New House was re-designed and modeled in Revit, as seen in Figure 14. Massing manipulations were prototyped and modeled in Revit, as seen in Figure 15 and 16. The material information from the new Revit models was plugged into Athena. Changes that achieved a reduction in embodied carbon were kept. The aluminum windows were replaced with wood windows and the metal roofing material was replaced with asphalt shingles, as seen in Figure 17. The envelope of the house was unchanged throughout these design changes, as seen in Figure 18.

5. The New House was modeled in Revit after all design changes were made. Material takeoffs were re-produced in Revit for each assembly. The information was then plugged into Athena to calculate the embodied carbon of each assembly, as seen in Figure 19.

6. The New House’s operational energy was then modeled in Open Studio to determine if the design changes increased the Energy Use Intensity (EUI) compared with the Baseline House, this can be seen in Figure 20.

7. The New House was then rendered to display the aesthetic appeal and features of the low carbon house, this is shown in Figure 21, 22, 23 and 24.
Baseline House

The Baseline House was designed as a case study on how to reduce a house’s carbon footprint during the schematic design phase (SD) of construction. Originally the focus was on renewable energy sources and passive strategies to achieve sustainability. Located in a heating dominated climate, the house is able to achieve a high standard of operational efficiency. After operational energy was achieved the designer realized more could be done to further reduce the house’s total carbon footprint. Embodied Carbon was not accounted for during the original design phase. Utilizing Lifecycle Analysis to inform design during SD phase can significantly diminish the total carbon footprint.

Original Goal:
To design a low carbon house, reducing the carbon footprint as much as possible.

Original Schematic Design Strategies Include:

What’s Missing?
The Embodied Carbon of the house was never considered during the schematic design phase. Using embodied carbon as a design philosophy can significantly reduce the overall carbon footprint.

Operational Energy Analysis
Total EUI after all design iterations was reduced from 86 to 19.

Figure 10. Baseline House energy analysis, project goals, and design guidelines
Location and Layout: Silverthorne, Colorado

Figure 11. Baseline House general design and layout

- Elevation: 9,201 feet
- Single Family: 3 bedroom, 2 bath
- Square Footage: 1,850 feet
- Revitalized Grey Field Site: Ranch land restored, re-introducing native habitats
Embodied Carbon Analysis: Base House

**Roof**
- Wood Joist: Aluminum Finish
- EC: 48 tCO2eq
- kgCO2 Per sq': 17.82
- Area sq': 2710

**Exterior Walls**
- Wood Stud 2x6 24” OC
- EC: 15 tCO2eq
- Per sq': 17.82 kgCO2
- Area sq': 2258

**Glazing**
- Aluminum and Operable
- EC: 77 tCO2eq
- Per sq': 67.17 kgCO2
- Area sq': 621

**Interior Walls**
- Wood Stud 2x4 16” OC
- EC: 02 tCO2eq
- Per sq': 1.17 kgCO2
- Area sq': 1304

**Floor**
- Wood Joist w. Plywood Decking
- EC: 15 tCO2eq
- Per sq': 8.39 kgCO2
- Area sq': 1758

**Foundation**
- CIP Concrete, 2% Steel
- EC: 11 tCO2eq
- Per sq': 5.14 kgCO2
- Area cubic': 1,656

Embodied Carbon Total: **168 tCO2eq**

*Figure 12. Baseline House embodied carbon*
Figure 13. Embodied carbon footprint of Baseline House’s envelope

Figure 14. New House floor plans and general program layout - square footage unchanged
Before
1 Level

After
2 Levels

**Figure 15.** Massing manipulation

**Roof Reduction**
The roof was reduced by 1,082 square feet.

**Foundation Reduction**
The foundation walls were reduced by 436 square feet. The footer was reduced by 282 cubic feet.

*The percentage of embodied carbon (tCO₂eq) reduced.

**Figure 16.** Massing manipulation resulting in roof and foundation EC reductions

**Glazing System : Aluminum to Wood**
An achieved a reduction

**Roof Finish : Aluminum to Asphalt Shingles**
An achieved a reduction of 5 tCO₂eq.

**Figure 17.** Material changes applied to glazing and roof system
Material and Construction: Envelope Assembly

Asphalt Shingle Roof
Beam
3/4" Charred wood Siding
Furring
1" Rockwool Exterior Board Insulation
Metal Flashing
U 2.5 Glazing
3/4" Plywood Sheathing
Drainage Vapor Barrier
8" Rockwool Batt Insulation
3/4" Blue Pine Interior Finish
Warmboard Flooring
Foam Insulation
Metal Flashing
2x
5 % Grade away from structure
Crawl Space
Concrete Footer
Gravel
6" Perforated pipe
Natural Soil

Figure 18. The Anatomy of the assembly was unchanged throughout the SD changes
Embodied Carbon Analysis: New House

**Roof**
Wood Joist: Aluminum Finish
EC: 24 tCO2eq
kgCO2 Per sq’: 17.82
Area sq’: 1628
- 24 tCO2eq

**Exterior Walls**
Wood Stud 2x6 24” OC
EC: 15 tCO2eq
Per sq’: 17.82 kgCO2
Area sq’: 2528
+ 02 tCO2eq

**Interior Walls**
Wood Stud 2x4 16” OC
EC: 02 tCO2eq
Per sq’: 1.17 kgCO2
Area sq’: 1304
0 tCO2eq

**Glazing**
Wood and Operable
EC: ? tCO2eq
Per sq’: 67.17 kgCO2
Area sq’: 621
-21 tCO2eq

**Floor**
Wood Joist w. Plywood Decking
EC: 15 tCO2eq
Per sq’: 8.39 kgCO2
Area sq’: 1758
0 tCO2eq

**Foundation**
CIP Concrete, 2% Steel
EC: 07 tCO2eq
Per sq’: 5.14 kgCO2
Area sq’: 684
Area cubic: 450
- 04 tCO2eq
- 40 tCO2eq compared with base.

Figure 19. New House embodied carbon

EMBODIED CARBON TOTAL = 121 tCO2eq
New House

The New House was able to further reduce its carbon footprint during the schematic design phase beyond what was originally considered, by implementing embodied carbon reduction design strategies.

Operational Energy Analysis:

<table>
<thead>
<tr>
<th>Information</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Name</td>
<td>Building 1</td>
<td>building_name</td>
</tr>
<tr>
<td>Net Site Energy</td>
<td>59,675</td>
<td>kBtu</td>
</tr>
<tr>
<td>Total Building Area</td>
<td>1,945</td>
<td>ft²</td>
</tr>
<tr>
<td>EUI (Based on Net Site Energy and Total Building Area)</td>
<td>30.68</td>
<td>kBtu/ft²</td>
</tr>
</tbody>
</table>

Figure 20. New House energy analysis

Figure 21. South elevation
Figure 22. East elevation
Figure 23. Southern dusk rendering
Figure 24. Southern snow storm rendering
Results

The methods led to a decrease in embodied carbon from the baseline house design. The envelope of the Baseline House had 168 tonnes of CO2 embodied (tCO2e). The LCA for the house’s glazing determined that by changing the framing from aluminum to wood there would be a reduction of 21 tCO2e. Similar results were seen with the roofing system. The metal finish material of the joist roof was replaced with asphalt shingles, reducing the roof’s embodied carbon by 8 tCO2e. Massing the house from a one story to a two story house reduced the foundation walls square footage from 1,120 square feet to 684 square feet and the footer material volume from 732CF to 450CF. This massing change also led the roof size to decrease from 2,710 square feet to 1,628 square feet. This resulted in a 4 tCO2e reduction in the foundation and a 16 tCO2e reduction in the roof. Changing the Baseline House from one to two stories caused an increase of 2 tCO2e in the exterior walls. Schematic design decisions based on LCA results and embodied carbon calculations resulted in the Baseline House reducing its embodied carbon footprint by 48 tCO2e, from having 168 tCO2e to now having 121 tCO2e, a 28% reduction. See Table 3 for embodied carbon calculations on the Baseline House and Table 4 for the New House calculations. The two houses embodied carbon comparisons can be seen side by side in Figure 25, or refer to Figures 12 and 19.
### Table 2. Scope of assemblies analyzed in comparative LCA study

<table>
<thead>
<tr>
<th>Foundation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>structure</td>
<td>Wall: 8&quot; CIP Concrete, 2% steel (square feet)</td>
</tr>
<tr>
<td>structure</td>
<td>Footer: Poured Concrete, 2% steel (cubic yards)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Floors</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>structure</td>
<td>Wood Joist w/ Plywood decking (square feet)</td>
</tr>
<tr>
<td>envelope</td>
<td>Batt Cavity Insulation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exterior Walls</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>structure</td>
<td>Wood Stud 2x6 24&quot; OC Plywood (square feet)</td>
</tr>
<tr>
<td>envelope</td>
<td>Cedar Bevel Siding</td>
</tr>
<tr>
<td></td>
<td>Batt Cavity Insulation</td>
</tr>
<tr>
<td></td>
<td>1/2&quot; gypsum board + 2 coats latex paint</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>windows</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt.1</td>
<td>Aluminum- operable (square feet)</td>
</tr>
<tr>
<td>Opt.2</td>
<td>Wood- operable (square feet)</td>
</tr>
<tr>
<td>Opt.3</td>
<td>Vinyl-clad Wood - operable (square feet)</td>
</tr>
<tr>
<td>curtain panel</td>
<td>Aluminum- operable (square feet)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interior Walls</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>structure</td>
<td>Wood Stud 2x4 16&quot; OC (square feet)</td>
</tr>
<tr>
<td>envelope</td>
<td>1/2 Gypsum board + 2 Coats Latex Paint</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roof</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt.1</td>
<td>Wood Joist: Metal Roofing (square feet)</td>
</tr>
<tr>
<td>Opt.2</td>
<td>Wood Joist: Asphalt shingles (square feet)</td>
</tr>
<tr>
<td>Opt.3</td>
<td>Wood Truss Pitched: Metal (square feet)</td>
</tr>
<tr>
<td>Opt.4</td>
<td>Wood Truss Pitched: Asphalt shingles* (square feet)</td>
</tr>
<tr>
<td>envelope</td>
<td>Plywood Decking</td>
</tr>
<tr>
<td></td>
<td>Cavity Insulation</td>
</tr>
<tr>
<td></td>
<td>Vapor Barrier</td>
</tr>
<tr>
<td></td>
<td>1/2&quot; Gypsum board w/ 2 coats Latex paint</td>
</tr>
</tbody>
</table>
Operational Energy Modeling

The Baseline House was modeled in Open Studio and according to the software had an EUI of 19, as shown in Figure 7. After making design changes to the Baseline House to achieve the desired decrease in the embodied carbon footprint, the New House was modeled in Open Studio. According to Open Studio the New House has an EUI of 30, as seen in Figure 17. According to our energy models the solar panels generate enough energy to keep the house operating at net-zero energy.

28% Reduction

168 tCO2e 121 tCO2e

Figure 25. Embodied carbon comparison of the Baseline House and the New House
<table>
<thead>
<tr>
<th>TABLE 3. Results of LCA and embodied carbon calculation for Baseline House</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BASELINE HOUSE</strong></td>
</tr>
<tr>
<td>Foundation</td>
</tr>
<tr>
<td>structure</td>
</tr>
<tr>
<td>structure</td>
</tr>
<tr>
<td>Floors</td>
</tr>
<tr>
<td>structure</td>
</tr>
<tr>
<td>envelope</td>
</tr>
<tr>
<td>Exterior Walls</td>
</tr>
<tr>
<td>structure</td>
</tr>
<tr>
<td>envelope</td>
</tr>
</tbody>
</table>
| | | | | | | Batt Cavity Insulation
| | | | | | | 1/2” gypsum board + 2 coats latex paint
| windows | | | | | | |
| Opt. 1 | Aluminum- operable | 621sq’ | 77t | | | 118 |
| Opt. 2 | Wood- operable | | 42t | 67.17kg | | |
| Opt. 3 | Vinyl-clad Wood - operable | | 22t | 35.45kg | | |
| curtain panel | Aluminum- operable | 525sq’ | | 35t | 67.17kg | |
| Interior Walls | | | | | | |
| structure | Wood Stud 2x4 16° OC | 1304sq’ | | 2t | 1.17kg | 120 |
| envelope | 1/2 Gypsum board + 2 Coats Latex Paint | | | | | |
| Roof | | | | | | |
| Opt. 1 | Wood Joist: Metal Roofing | 2710sq’ | 48t | | 17.82kg | 168 |
| Opt. 2 | Wood Joist: Asphlat shingles | 2710sq’ | 40t | | 14.61kg | |
| Opt. 3 | Wood Truss Pitched: Metal | 445sq’ | | | | |
| OPT.4 | Wood Truss Pitched: Asphalt shingles* | ? | | | 15.56kg | |
| envelope | Plywood Decking | | | | | |
| | Cavity Insulation | | | | | |
| | Vapor Barrier | | | | | |
| | 1/2” Gypsum board w/ 2 coats Latex paint | | | | | |
| | *organic felt based, 30yr | | | | | |
| Highest Impact | | | | | | |
| Lowest Impact | | | | | | |
| | 168t | 168,000kg | | | | |
| | 139t | | | | | -29t |
Table 4. Results of LCA and embodied carbon calculation for New House

<table>
<thead>
<tr>
<th>New House</th>
<th>Area</th>
<th>Volume</th>
<th>GWP</th>
<th>CO2kg/sq'</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1t</td>
</tr>
<tr>
<td>Wall: 8&quot; CIP Concrete, 2% steel</td>
<td>584sq'</td>
<td>7t</td>
<td>5.14kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Footer: Poured Concrete, 2% steel</td>
<td>450CF</td>
<td></td>
<td>211.62kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Floors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0t</td>
</tr>
<tr>
<td>structure</td>
<td>1758sq'</td>
<td>15t</td>
<td>8.39kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>envelope</td>
<td>Batt Cavity Insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Exterior Walls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2t</td>
</tr>
<tr>
<td>structure</td>
<td>2528sq'</td>
<td>17t</td>
<td>6.74kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>exterior</td>
<td>Cedar Bevel Siding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batt Cavity Insulation</td>
<td>1/2&quot; gypsum board + 2 coats latex paint</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>windows</strong></td>
<td>621sq'</td>
<td>58t - 77t</td>
<td>67.17kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt.1</td>
<td>Aluminum- operable</td>
<td>42t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt.2</td>
<td>Wood- operable</td>
<td>22t</td>
<td>35.45kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt.3</td>
<td>Vinyl-clad Wood - operable</td>
<td>21t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>curtain panel</td>
<td>Aluminum- operable</td>
<td>525sq'</td>
<td>35t</td>
<td>67.17kg</td>
<td>0t</td>
</tr>
<tr>
<td>curtain panel</td>
<td>wood- operable</td>
<td>525sq'</td>
<td>?</td>
<td>67.17kg</td>
<td></td>
</tr>
<tr>
<td><strong>Interior Walls</strong></td>
<td>1304sq'</td>
<td>2t</td>
<td>1.17kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>structure</td>
<td>Wood Stud 2x4 16&quot; OC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>envelope</td>
<td>1/2 Gypsum board + 2 Coats Latex Paint</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-19t</td>
</tr>
<tr>
<td>Opt.1</td>
<td>Wood Joist: Metal Roofing</td>
<td>1628sq'</td>
<td>29t</td>
<td>17.82kg</td>
<td>-16t</td>
</tr>
<tr>
<td>Opt.2</td>
<td>Wood Joist: Asphalt shingles</td>
<td>1628sq'</td>
<td>24t</td>
<td>14.61kg</td>
<td></td>
</tr>
<tr>
<td>Opt.3</td>
<td>Wood Truss Pitched: Metal</td>
<td>1684sq'</td>
<td>26t</td>
<td>15.56kg</td>
<td></td>
</tr>
<tr>
<td>OPL.4</td>
<td>Wood Truss Pitched: Asphalt shingles*</td>
<td>1684sq'</td>
<td>21t</td>
<td>12.35kg</td>
<td></td>
</tr>
<tr>
<td>envelope</td>
<td>Plywood Decking</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cavity Insulation</td>
<td></td>
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<tr>
<td>Vapor Barrier</td>
<td></td>
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<tr>
<td>1/2&quot; Gypsum board w/ 2 coats Latex paint</td>
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</tr>
</tbody>
</table>

*organic felt based, 30yr
Conclusion

A building’s carbon footprint is comprised of two categories: embodied carbon emissions and operational carbon emissions. The green building industry currently rewards architects, engineers, and project teams for reducing their operational carbon footprint. Because of this, the design phase process utilizes BIM software to inspire design decisions which increase operational efficiency thus reducing carbon emissions. However, embodied carbon which is responsible for a significant portion of an operationally efficient building’s carbon footprint is often forgotten during the schematic design phase. Project teams can introduce LCA and embodied carbon analysis into their design process to reduce their structures carbon footprint in addition to the operational carbon reductions already being considered.

LCA embodied carbon calculations can be used throughout the construction design process. When a project is in the early phases, LCA data can be used to help inform schematic design (SD) decisions such as; massing design, programatic design, and general scope of the project. As shown in this report, an LCA conducted during the SD phase provides valuable information about potential environmental impacts of design decisions and possible techniques to reduce those impacts. Also, the LCA can inform decisions and influence design amid the Design Development (DD) phase. LCA during the DD phase emphasizes the environmental impact of project materials, mechanical, electrical, and plumbing systems. Teams can use this data as a tool for incorporating embodied carbon reduction strategies, as seen in this study.

This study illustrates how a significant reduction in the carbon footprint of a residential building can be achieved when using BIM software and Athena Impact Estimator to conduct LCA during the SD and DD phases.
As the green building industry efforts to further reduce their environmental impacts it is necessary for the total carbon footprint to be considered; both embodied carbon and operational carbon. The New House in this study does not achieve absolute zero carbon, however, the footprint was considered in its entirety during the design process and represents a method moving towards reaching absolute zero carbon residential structures.
References


