Whole Building Life Cycle Assessment of a Living Building

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Abstract: A whole building life cycle assessment (LCA) was performed on a Living Building, focusing on impacts from green building materials, a decentralized water system, a net-positive use phase, and the end-of-life of structural materials. The material processes used in this LCA were adjusted from standard to *green* by removing the use of toxic chemicals; results show carcinogenic impacts decreased by up to 96%. The septic system used for wastewater treatment contributes to 41% of the global warming potential [GWP, kg CO_2eq (carbon dioxide equivalent)] over the building's assumed 100-year lifespan due to methane emissions. The on-site solar panels generate more electricity than the site demands, allowing for 44,000 kWh of green energy to be returned to the grid based on 1 year of performance. Lastly, an exploratory scenario analysis performed on multiple waste streams for structural materials shows that the GWP impacts for the end-of-life could vary from +14,000 to −10,500 kg CO_2eq depending on the waste stream. The results of this LCA indicate that the case study building is net-zero energy and water, but not net-zero carbon. **DOI: 10.1061/(ASCE)AE.1943-5568.0000436**.

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Introduction

In the United States, buildings account for 41% of primary energy consumption, 73% of electricity use, 39% of the United States' annual CO_2 emissions, and 45% of the construction and demolition waste stream (USDOE 2012; USEPA 2018). It is clear that buildings exhibit significant environmental impacts, providing opportunities for mitigation and reduction. The impacts of buildings therefore began to be assessed in greater detail in order to establish targeted reduction measures and strategies.

Life cycle assessments (LCA) are one approach that can be used to assist decision makers who aim to reduce environmental impacts of products or processes, or in this research, buildings. LCA quantifies the environmental impacts based on input and output flows (e.g., materials, energy, and emissions) of a given product, process, or system. LCA methodology is standardized by the International Organization for Standardization and has four primary steps: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation and analysis (ISO 2006).

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Whole building LCAs have been performed on various building types. For example, results from a whole building LCA of an office building showed that with respect to global warming potential [GWP, kg CO_2eq (carbon dioxide equivalent)], the use phase accounted for nearly 80% of the total impacts (Junnila and Horvath 2003). Another study conducted a whole building LCA of a new university building, finding that the use phase accounted for 94% of the primary energy consumption, where materials and end-of-life contributed approximately 2% each (Scheuer et al. 2003).

The US Green Building Council, International Living Future Institute (ILFI), and other green building rating system organizations aided in the development of initiatives to improve the energy efficiency of buildings, leading them to recognize that life cycle stages beyond the use phase have a significant effect on building life cycle impacts. Therefore, many rating systems have included additional requirements in their certifications (ILFI 2019; IWBI 2018; USGBC 2018).

The analysis of low-energy buildings continued as use phase impacts decreased due to implementation of energy efficiency measures with motivation and support from green building rating systems, thus shifting the focus to other life cycle stages such as material selection and end-of-life. A materials LCA on another Living Building (a building that has met all the requirements of ILFI's Living Building Challenge, including achieving net-positive energy and water on site while minimizing the impacts of building materials) in Pittsburgh was performed in order to assess the impacts of embodied energy of the various systems within such a high-performing building (Thiel et al. 2013). An LCA of a low-energy building discovered that the materials can account for up to 46% of a low-energy building's total energy (embodied and operational) (Sartori and Hestnes 2007). A similar study assessed a net-zero building and its embodied energy, finding that structural elements accounted for 60% of the embodied energy impacts (Berggren et al. 2013). Furthermore, another study concurred that embodied energy accounts for a large percentage (40%) of low-energy buildings; therefore, the recycling potential of materials is fairly significant in terms of the building life cycle impacts as it

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could equate to up to 15% of the total building energy (Thormark 2002). Lastly, a case study on a low-energy house found that the end-of-life GWP impacts were −8% of the impacts from all other life cycle stages, meaning that the disposal option selected can have potentially offsetting impacts (Blengini 2009).

One shortcoming with respect to these life cycle assessments of high-performance buildings is that unit processes present in commercial or publicly available life cycle databases may not be reflective of novel or *green* materials. A common example of one material that has been improved over the years is the use of asbestos in building insulation. Once the EPA and US Department of Health and Human Services declared asbestos a carcinogen, all new forms of it were banned (USDHHS 2001). Now, safer types of insulation are used. Because these new alternatives are becoming a common practice, some unit processes for these materials exist in LCA databases and can be selected when appropriate. This concept of updated unit processes needs to now be extended to a multitude of other materials as *greener*, healthier options emerge.

Recently, there has been an increase in material transparency, which will streamline the integration of material attributes into LCA databases. ILFI created the material transparency label *Declare* wherein manufactures share various features about a product, including a precise list of ingredients, life expectancy, management at end-of-life, and if it contains any materials on the Red List (ILFI 2018). Also created by ILFI, this list includes chemicals common in building materials that have high potency with respect to environmental pollution, bioaccumulation, and/or negative human health impacts on construction and factory workers. As these transparency efforts continue, databases containing this material information are beginning to emerge; however, there is still a disconnect between the data and the integration of this updated information into databases used during LCA. In order to accurately determine the impacts of buildings that use greener materials, it is imperative that the information used to assess materials reflects the lower impacts of these healthier materials.

This LCA assesses the material impacts, use phase, and end-of-life of a Living Building; this is the first whole building LCA to be performed on a Living Building and therefore aims to elucidate the life cycle impacts of these high-performing instead buildings and to provide guidance for green building rating systems.

Green Building Rating Systems and LCA

Around the 1990s, the green building field *formally* emerged. In 1993, the US Green Building Council formed and released the pilot program of Leadership in Energy and Environmental Design (LEED) in 1999 (USGBC 2018); this rating system was one of the first of its kind in the US. Since the new millennium, the green building design initiative has gained momentum. Following the development of LEED, a plethora of other green building rating systems have emerged domestically, including EnergySTAR, the Living Building Challenge, and the WELL Building Standard and internationally, including Canada's Green Globes, Germany's Passive House, UK's BREEAM (Building Research Establishment Environmental Assessment Method), and Japan's CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) (BRE 2018; GBI 2014; ILFI 2019; IWBI 2018; JSBC 2014; PHI 2018; USEPA 2017; USGBC 2018). Although these are some of the more recognized rating systems, this is not an exhaustive list as more rating systems are continuously emerging and evolving. Each of these green building rating systems was developed in order to target the reduction of either specific building impacts, in the case of WELL which has a focus on human health impacts, or take a more holistic approach, such as the Living Building Challenge. Although the rating systems might have different focuses, they all have the common overarching goal of reducing the impacts of the built environment.

Life cycle assessment (LCA) and life cycle thinking are implemented in various green building rating systems. LEED v4 has a credit involving the completion of a whole building LCA to show a 10% reduction as compared to a baseline building (USGBC 2018). The Living Building Challenge 4.0 requires a 20% reduction as compared to a baseline building; additionally, an LCA must be performed to calculate embodied carbon associated with the building materials and construction, which must be neutralized via carbon offsets (ILFI 2019). Additionally, Green Globes strongly encourages the use of various LCA tools to assess building performance (GBI 2014). Although there are certain challenges associated with integrating LCA into green building rating systems, such as uncertainty and project variability, LCA can still be used as a tool to identify and mitigate high environmental impacts across various life cycle stages (Al-Ghamdi and Bilec 2017).

Living Building Challenge

In 2006, the Cascadia Green Building Council launched version 1 of the Living Building Challenge; due to growing interest in this program over its early years, the Living Building Institute was formed in order to manage the Living Building Challenge and any additional future programs (ILFI 2019). Today, Cascadia works alongside what is now the International Living Future Institute (ILFI), which encompasses the Living Building, Product, and Community Challenges. Each program has similar themes of having a regenerative impact with emphases on promoting social justice, celebrating culture, and ensuring ecological restoration. Because of its extensive and interdisciplinary requirements, this is one of the most challenging building certifications to obtain.

Living Building Challenge requirements are organized into seven petals: Place, Water, Energy, Health and Happiness, Materials, Equity, and Beauty; the three petals that are the focus of this work are Materials, Water, and Energy. Each petal has a series of imperatives, for a total of 20, which all must be met to achieve Living Certification. These imperatives encompass a wide range of concepts, including net-positive energy and water, biophilic environment, and beauty and spirit (ILFI 2019). Achieving this certification requires integrated design strategies, community involvement, and an unprecedented amount of communication between the designers, manufacturers, and contractors, making it a rigorous certification process.

Methodology

This paper details a whole building life cycle assessment performed on an existing Living Building. The impacts from the use phase are lower in Living Buildings than those of conventional buildings, resulting in a change in distribution among the other life cycle impacts and requiring additional analysis to understand a Living Building's impacts. Each material assembly was assessed in detail, including acquiring precise material quantities, removing Red List chemicals from materials used within the building, and integrating the recycled content of products when available. Impacts from both the material preuse and use (replacements) stages that occur over the assumed 100-year lifespan of the building were quantified. Replacement values were extracted from warranties that were

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documented within the various material submittals required for both LEED and Living Building Challenge certification; these values were included in the life cycle inventory to ensure that all assemblies had accurate associated life expectancies for the 100-year lifespan of the building. The use phase impacts of the on-site water treatment and electricity generation systems were calculated from modeling and utility bills, respectively. Lastly, the exploratory quasi-parametric analysis of end-of-life impacts of structural materials included modeling various disposal scenarios. This is a cradle-to-grave life cycle assessment, which includes material manufacturing, operation/use, material replacements, and end-of-life; the only stage omitted is on-site construction due to a lack of sufficient data. Because the construction phase has been found to contribute only a small portion of life cycle impacts (0.4%–12%), it is not a priority of this whole building LCA (Guggemos and Horvath 2006). Also, buildings have site-specific construction impacts that are challenging to model combined with general scenario uncertainty (Singh et al. 2011). The subsequent sections introduce the case study building and explore the methodology used to perform the assessment of each life cycle stage.

Case Study Building

The Frick Environmental Center is a municipally owned, public building located on the edge of Frick Park in Pittsburgh, Pennsylvania; it is a joint venture between the City of Pittsburgh and the Pittsburgh Parks Conservancy. The Frick Environmental Center serves as a resource for park visitors and is comprised mainly of office space for staff, as well as classrooms used for the numerous educational events (e.g., summer camps and nature classes) hosted by the Pittsburgh Parks Conservancy at this facility. Due to the extensive sustainable features present in this facility, it achieved both LEED Platinum by US Green Building Council and Living Certified by ILFI.

The Frick Environmental Center is a three-story, 1,400 m^2 (15,000 ft^2) building that has steel framing and concrete foundation. Because it is net-positive energy and water, the site contains many sustainable systems and strategies including solar panels, geothermal wells, a rainwater collection and purification system, permeable pavement, passive ventilation, and daylighting. The construction began in 2014, and the facility opened in 2016.

Life Cycle Assessment

Goal and Scope

The goal of this study is to assess the life cycle environmental impacts of a Living Building in order to identify areas for mitigation of the case study building while helping to improve the design of future Living Buildings. The intended audiences are building designers and operators, as well as researchers seeking to reduce the impacts of buildings.

The primary life cycle phases of a building are raw material extraction, material manufacturing and processing, construction, use, and end-of-life. The scope of this whole building LCA includes the stages shown in the system boundary presented in Fig. 1. Construction was not included in this assessment as there was a lack of available data from this stage, such as emissions from construction equipment and transportation distances driven by trucks during construction; the transportation included is that from material manufacturers to the project site. The functional unit for this study is one whole Living Building with a lifetime of 100 years. The results are reviewed on an annualized basis for comparative purposes, and any assumptions made will be addressed throughout the assessment.

Life Cycle Inventory

The life cycle inventory (LCI) is where all input/output data (e.g., material quantities, energy required, and emissions released) for the system are collected. In order to create a comprehensive LCI, a full quantity takeoff (obtaining a full list of materials and their quantities) was performed for the Frick Environmental Center. This takeoff was organized into five main material categories: architectural (e.g., ceiling, flooring, interior walls, and doors/windows), structural (e.g., beams and foundation), and mechanical (e.g., ducts, ventilation units, and piping) assemblies along with the water (e.g., piping, pumps, and cisterns) and energy [e.g., PV (photovoltaic) panels and framing] systems. As-built construction documents were provided by the design team and were uploaded into the takeoff software On-Screen Takeoff (OST 2018). Materials were organized by assembly and type with totals exported to Excel accordingly.

A unit process is the most fundamental element of the LCI and is a critical component of the life cycle impact assessment (LCIA); it contains information regarding all inputs and outputs of a given material or process. These inputs/outputs include energy, water, material resources, and emissions (to air, water, and soil) (ISO 2006). The unit processes and associated data can have numerous sources ranging from existing LCA databases (e.g., ecoinvent, US LCI) to collected and/or experimental data (ecoinvent 2018; NREL 2012). For this assessment, the vast majority of the unit processes were from the ecoinvent database due to its expansive quantity of unit processes; a full list of unit processes used for this LCIA can be seen in Appendix. Because the unit processes determine the

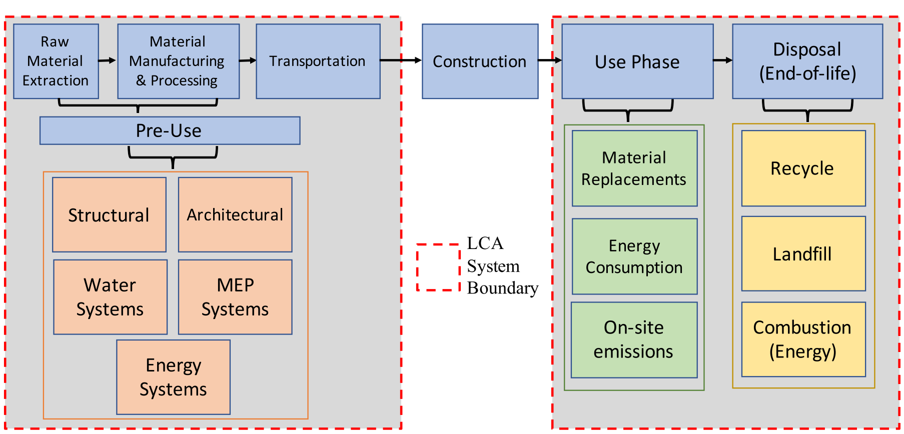

Fig. 1. Life cycle assessment system boundary for case study building.

impacts of each material, it is critical that they are as accurate as possible for the material in question. Material specifications provided by the project team were compared to the options available within ecoinvent in order to select the most accurate unit process, prioritizing material composition and manufacture location since much of the data comes from European sources.

Another quantity assessed for select building materials was their transportation distance. Living Building Challenge 4.0 has detailed requirements regarding transportation distances and material sourcing, where 20% of material sourcing must occur within 500 km, 30% within 1,000 km, 25% within 5,000 km, and the remaining without any sourcing requirements (ILFI 2019). Therefore, all materials used in the project were tracked, and their sourcing distances documented; transportation impacts were therefore included. The unit process for this assessment is a diesel truck. Because transportation impacts are measured in a unit process based on ton-kilometers, the materials with the largest weight were the focus of calculating overall transportation impacts. Structural materials (steel and concrete) account for 98% of the building's total material weight according to the quantity takeoff and therefore were the only materials included in the transportation impact assessment.

Life Cycle Impact Assessment

Lastly, the LCIA is when the LCI data collected is assessed and impacts are analyzed; LCI data are characterized into life cycle impact assessment categories, which for this study are the EPA's TRACI categories seen in Table 1; then, contributions to each category are calculated. Finally, the results of the LCIA are interpreted and contextualized.

Materials Assessment

An additional analysis of this whole building LCA was performing material adjustments to demonstrate how to improve the accuracy of green building LCAs. The more accurate the unit processes are for the materials in question, the more precise the comprehensive LCA results; because the unit processes dictate the defined inputs and outputs required to manufacture a product, the accuracy of these unit processes directly affects a material's life cycle impacts. Therefore, adjustments were made to each material assembly, including Red List adjustments and adding in recycled content percentages. Because Living Building materials cannot contain any Red List chemicals, all of the toxins' impacts were removed. In order to effectively remove these impacts, the contributions of all Red List toxins were subtracted from each material's chemical inventory.

The Red List contains 20 general chemicals and is disaggregated into 815 specific chemicals. For example, the single item *Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs)* encompasses 90 individual chemicals (ILFI 2018). These 815 chemicals were queried and subsequently removed from each material inventory of 2,000 chemicals; since all 10 impact categories were assessed for all material assemblies, 60 inventories were evaluated and adjusted.

Table 1. TRACI v2.1 categories, units, and abbreviation

Impact category	Unit equivalency	Abbreviation
Ozone depletion	kg CFC-11 eq	OD
Global warming potential	kg CO_2eq	GWP
Smog formation potential	kg O_3eq	SFP
Acidification potential	kg SO_2eq	AP
Eutrophication potential	kg Neq	EP
Carcinogens	CTUh	CAR
Noncarcinogens	CTUh	NCAR
Respiratory effects	kg $PM_{2.5}$eq	RE
Ecotoxicity	CTUe	ETX
Fossil fuel depletion	MJ surplus	FFD

Source: Data from Bare (2012).

$$\mathrm{CV} = \sum I_{\mathrm{chem}} \times \sum \mathrm{CF}_{\mathrm{chem}} \tag{1}$$

$$\mathrm{CR} = \sum \mathrm{CV} \times \sum Q_{\mathrm{tot}} \tag{2}$$

where CV = category indicator value; I_{chem} = chemical inventory; $\mathrm{CF}_{\mathrm{chem}}$ = chemical characterization factor; CR = category indicator result; and Q_{tot} = material quantity total.

The inventories contain all chemicals that correspond to a material unit processes, including upstream and downstream flows. These values are the category indicators based on the characterization factors of each chemical; the inventory of indicators was exported to Excel so that totals for each life cycle impact assessment category could be evaluated. Additionally, when the indicator inventories were exported, the values sum to the category indicator value for each life cycle impact assessment category, seen in Eq. (1). This indicator is a multiplier for each life cycle impact assessment category that is ultimately multiplied by the total material quantities to obtain a category indicator result, seen in Eq. (2). Once exported, the contributions to the category indicator value of each Red List toxin for each material assembly were removed, resulting in a new category indicator result for each life cycle impact assessment category. These adjustments consequently produce a more representative category indicator result for the greener materials used and overall more accurate whole building LCA impact results.

Use Phase

As a Living Building, the Frick Environmental Center is required to have a net-positive energy and water profile, meaning that it generates more energy and collects more water on site than it uses on an annual basis. This results in significantly different use phase impacts than that of a traditional building, where use (operational energy) has been found to account for 80% of total life cycle impacts (Junnila and Horvath 2003). The three primary components of the use phase for this study are material replacements, electricity, and water system impacts. The electricity profile for the Frick Environmental Center only consists of offsetting (net-positive) impacts. These offsets are a function of the surplus electricity that is generated on site and subsequently sent back to the local electricity grid. This offsets electricity that was otherwise generated using fossil fuels, resulting in significant amounts of avoided global warming potential impacts (7,700 kg CO_2eq annually). As for the water system, research into on-site treatment systems is continuous because there are many tradeoffs when it comes to decentralized systems. One study found that they are not the most sustainable option with respect to scale, and more centralized, community-scale systems have lower embodied energy impacts and smaller carbon footprints (Cornejo et al. 2016); another study found that decentralized systems can have lower energy (operational) impacts when compared to centralized water treatment (Hendrickson et al. 2015). Lastly, a comparable study of the water system of another Living Building in Pittsburgh found that a standard building modeled with low-flow water fixtures had the potential to have lower life cycle impacts than a building with a complete wastewater treatment system on site (Hasik et al. 2017); this study uses a model based on the work in Hasik et al. (2017) with material quantity and systems adjustments made to reflect the system at the Frick Environmental

Center. The impacts of the Frick Environmental Center's on-site water treatment system were assessed to determine its sustainability.

Recurring Embodied Impacts from Replacements

In order to obtain comprehensive results for the entire life cycle of the building, it was imperative to factor material *replacements* into this LCA. Because all product submittals were provided, the warranties for all products assessed could be acquired and thus used to calculate the number of replacements required over the course of the assumed 100-year lifespan of the building. These impacts are critical to include because there is potential for the building to have relatively higher embodied impacts from material replacements, especially when the energy use impacts are so low. These impacts are considered during the use phase because they occur periodically over the course of the building's lifespan. Comprehensive impacts from material replacements are further discussed in the "Case Study LCA Results" section.

Frick Environmental Center Water System and a Comparison

The Frick Environmental Center has three primary water systems on site: potable, stormwater, and wastewater. These water systems are extensive and designed to meet net-positive water criteria from the Living Building Challenge, which demands all water used onsite needs to be collected from precipitation or other natural systems (ILFI 2019). Therefore, rainwater and snowfall are collected via three rain barrels placed throughout the site: two at the foot of the solar panel parking coverage and one beside the barn. This water is collected and stored in one large 57,000 L (15,000-gal.) cistern located underground in the middle of the site. Two UV purification systems are present on site to treat this collected water.

Due to Pennsylvania water regulations, water reclaimed and treated on site can only be used for *nonpotable purposes* (ICC 2015). However, the Frick Environmental Center treats its reclaimed water up to potable standards with the expectation that state regulations progress over the life of the building. A portion of the stormwater collected is treated to potable standards but used for nonpotable uses in the building; this semi-closed-loop system with storage allows the net-positive target to be achieved with ease. Because there are only roughly 20 regular occupants in the space, Pittsburgh receives ample rain and snowfall to meet their daily demands, with the cistern assisting on peak days when summer camps or community events are held.

A large problem that the city of Pittsburgh faces is the issue of combined sewer overflow. Because Pittsburgh has older infrastructure, most parts of the city have combined sewers where both stormwater and sewage are transported in the same pipe. Therefore, during average or large rain events, these systems exceed capacities leading to combined sewer overflow events in which sewage is then discharged into local water bodies; this results in significant environmental impacts, including ecosystem damage and negative human health impacts. The City's public infrastructure entities are working to reduce the frequency of these combined sewer overflow events by improving the city's infrastructure and reducing the peak volumes these systems face. The Allegheny County Sanitary Authority, the municipal authority in Pittsburgh for water treatment, entered a consent decree with the EPA in 2008 pledging to perform drastic improvements to the sewage system in an effort to prevent these combined sewer overflow events; this agreement included a \$1.2M penalty for Clean Water Act violations and a \$3M pledged investment by the Allegheny County Sanitary Authority into environmental projects (USDC 2007). In order to avoid contributions to this significant environmental vulnerability, the Frick Environmental Center project is not connected to the Pittsburgh stormwater or sewer system; all rainwater is either collected as previously explained or redirected into the nearby park.

An LCA was performed on the water system of another Living Building in Pittsburgh, the Center for Sustainable Landscapes located at Phipps Conservatory and Botanical Garden (Hasik et al. 2017). The Center for Sustainable Landscapes' main purpose is to provide office space for employees of Phipps; it therefore has less foot traffic and visitors in general than the Frick Environmental Center. The assessment of the Center for Sustainable Landscapes was adjusted for the Frick Environmental Center, including material quantity adjustments and removal of systems the Center for Sustainable Landscapes has that the Frick Environmental Center does not; this assessment was then incorporated into the whole building LCA results for the Frick Environmental Center. The primary discovery from this assessment is the amount of emissions from the septic system. The Center for Sustainable Landscapes has a closed-loop system that includes sand filters, constructed wetlands, and solar distillation. However, the Frick Environmental Center does not have a closed-loop system as the treated wastewater ultimately infiltrates into the soil via a septic system that feeds into a drip field. Although this is allowed by ILFI and is a natural way of treating wastewater, the Frick Environmental Center does not use an aerator; therefore, anaerobic digestion occurs which leads to high associated methane emissions when not captured. Because methane is a greenhouse gas that is 25 times more potent than carbon dioxide, it is critical to minimize its emissions, especially when they could be mitigated via aeration of the septic system (USEPA 2014). Note that septic system emissions for both the Center for Sustainable Landscapes and Frick Environmental Center were based off of published values and were adjusted to volumetric rates that passes through each system (Leverenz et al. 2010).

End-of-Life

As the use phase impacts of high-performance buildings decline, research is now focusing on both materials and end-of-life (EOL) impacts. Depending on how significant the EOL environmental effects are, factoring these impacts in earlier in the design of a building could affect the overall life cycle impacts; specifically, due to their embodied impacts, choosing a structural material with lower end-of-life impacts could result in a significant reduction in the total environmental impacts. Even though recycled steel has a higher embodied energy than concrete (13 MJ/kg compared to 1 MJ/kg), steel has a larger recycling potential than concrete, which could result in lower life cycle impacts for steel, thus making it a preferred material over concrete (Hammond and Jones 2008). Additionally, the waste stream the material enters affects its EOL impacts; therefore, disposal scenarios for each structural material were analyzed.

EOL Assessment of Structural Materials

There is an important conversation occurring regarding sustainable building material selection, specifically as it applies to structural lumber. It is agreed that man-made materials such as steel and concrete have significant environmental impacts due to extensive energy and resources required for extraction, processing, manufacturing, and distribution. These impacts are compared to the theoretically carbon-neutral impacts of lumber. The reason that lumber is the appealing choice is because it is thought of as a carbon sink, capturing CO_2 during its life and storing it over the course of its use as a structural material. Therefore, researchers are starting to detail the importance of factoring in the impacts of this biogenic carbon into the life cycle assessment of structural lumber (Fouquet et al. 2015; Levasseur et al. 2013; McKechnie et al.

2011; Simonen 2014). When a timber house was assessed, the carbon stored via landfilling offset nearly one-third of the building life cycle impacts; when the lumber was incinerated with energy recovery, greater offsets were seen; however, the release of carbon when burned resulted in an overall greater net GWP (Fouquet et al. 2015). This illustrates the complicated balance when using structural lumber and the significance of factoring in biogenic carbon impacts at end-of-life.

Another significant aspect of this discussion is the impacts on deforestation. Although land-use impacts are outside of the scope of this LCA, it is an important consideration for the design of Living Buildings in general. Recently, the Sierra Club published an open letter calling for a need to focus on reducing the embodied carbon of building materials, while warning that a drastic shift to timber products could be damaging if not done in a thoughtful, sustainable manner (Sierra Club 2018). They specifically call out cross-laminated timber as this material is a common wood product used in larger construction projects, referred to in this letter as *Tall Timber*.

As with most sustainability issues, this debate demonstrates how the best option has to be optimal for the project in question and evaluated with tools such as life cycle assessment. In order to determine which disposal option has the lowest environmental impacts, exploratory scenario analyses for the EOL impacts of steel with concrete (as-built) and lumber with concrete (modeled) were assessed. Two Revit models were constructed, one with a steel structure (as-built) and one with a lumber structure, as seen in Fig. 2. Linear quantities from the Revit models were exported for each material and converted into mass quantities based on the density of each material. A generic constructability analysis was performed for each model within Revit in lieu of a time- and resource-intensive structural analysis, which was out of scope for this exploratory EOL assessment. The details of those models are as follows:

1. *Steel* (as-built, left): steel beams, concrete columns, concrete foundation; and
2. *Lumber* (right): lumber beams, lumber columns, concrete foundation

To perform this assessment, four primary assumptions were made: only structural elements were considered (beams, foundations, and columns); when lumber is replaced for steel in the modeled assessment, the lumber connections are assumed to be designed for disassembly; the concrete foundation is unchanged from one frame to the other; steel is always modeled with a 100% recycling rate at its end-of-life.

After the quantities from each of the models were obtained, the waste scenarios for each material were established. These various scenarios assessed are shown in Table 2. Because steel has a high recycling rate in construction of nearly 90%, no alternative waste scenarios were considered (Hammond and Jones 2008; SRI 2017). Concrete, on the other hand, is either landfilled or recycled to be used for aggregate. Lastly, wood products can either be landfilled (with or without landfill gas capture), recycled, or combusted for energy. Regarding each scenario for concrete and lumber, an analysis was performed using four 25% increments, with the supplementary percentages defaulting to the *landfill* option. In the scenarios where lumber is landfilled, it was assumed that there was no landfill gas (LFG) recovery; this way, the number of scenarios is simplified and the effect that recovery has on lumber landfilling can be isolated in other scenarios. Emissions factors for each EOL scenario for concrete and lumber were extracted from EPA's WARM tool; the recycling emissions factor for steel was extracted from the ecoinvent database (ecoinvent 2018; USEPA 2016).

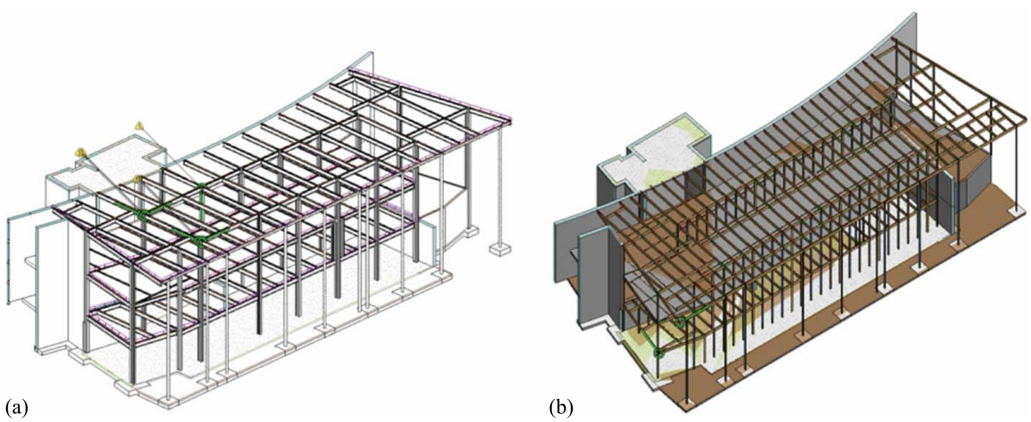

Fig. 2. Revit models of (a) steel model; and (b) lumber model.

Table 2. Tabulated Scenarios 1–8 and their frame type and waste stream per material

Scenario no.	Frame type	Steel waste stream	Concrete waste stream	Lumber waste stream
Scenario 1	Steel	100% Recycled	Increasing recycling with decreasing landfilling	N/A
Scenario 2	Lumber	N/A	Increasing recycling with decreasing landfilling	100% Landfilled (no LFG capture)
Scenario 3	Lumber	N/A	100% Landfilled	Increasing lumber reuse with decreasing landfilling (no LFG capture)
Scenario 4	Lumber	N/A	100% Recycled	
Scenario 5	Lumber	N/A	100% Landfilled	Increasing lumber combustion for energy recovery with decreasing landfilling (no LFG capture)
Scenario 6	Lumber	N/A	100% Recycled	
Scenario 7	Lumber	N/A	100% Landfilled	Increasing lumber LFG capture with decreasing combustion for energy recovery
Scenario 8	Lumber	N/A	100% Recycled	Increasing lumber LFG capture with decreasing landfilling

Note: Each scenario analysis includes four 25% increments of an increase to a particular waste stream, e.g., Scenario 1 includes concrete recycled at a percentage of 0%, 25%, 50%, 75%, and 100%. Landfill gas (LFG) can potentially be captured, modeled in Scenarios 7 and 8.

Case Study LCA Results

Materials

The preuse phase results of the building present impacts from materials, including adjustments made such as Red List removal and incorporated recycled content. The structural materials have the most significant environmental impact, and the removal of Red List chemicals had the greatest effect on the TRACI impact category carcinogens.

Structural Materials Dominate Preuse Impacts as Expected

Material/preuse impacts are disaggregated per assembly in Fig. 3 and reflect the Red List adjustments. As expected, structural systems dominate the preuse stage impacts, contributing 21%–57% of each category. Although these materials have comparable category indicator values to those of the other assemblies, the immense quantities required result in dominating impacts. The primary materials in the structural assembly are concrete masonry unit blocks, steel (reinforcing, beams, and plates), and concrete, with weights around 270, 90, and 2,200 metric tons, respectively; the substantial weight of concrete results in the structural assembly contributing to the majority of the GWP category. The choice of the structural materials of a building significantly affects the overall impacts and should therefore be done with great consideration.

The remaining assemblies compose a small to moderate percentage of each impact category. The geothermal assembly contributes to carcinogens (44%) as a result of the hydronic piping used in this system; the chromium and stainless-steel pipes used see high carcinogenic impacts but are not Red List chemicals and therefore their impacts remain, resulting in dominating carcinogenic impacts. Although the architectural assembly encompasses the largest number of material types, it has smaller contributions to fossil fuel depletion (21%), respiratory impacts (18%), and acidification (17%). The PV system only consists of the solar panels and their supporting structure, yet still notably contributes to eutrophication potential (24%), respiratory impacts (18%), and ozone depletion (17%); the larger eutrophication potential results are due to the large volume of water required to manufacture the silicon for the photovoltaic panels. The only significant impact category for the water systems materials is carcinogens (26%), which is attributed to some complex filtration and pumping systems that contain a substantial amount of metal components. Lastly, the mechanical assembly sees moderate impacts to each category, primarily due to metals used to manufacture the ductwork.

Red List Adjustments Decrease Carcinogen Impact

As seen in Fig. 4, there were substantial reductions in the overall impacts for each assembly in the TRACI categories: carcinogens, noncarcinogens, ecotoxicity, and ozone depletion as a result of the Red List adjustments. These reductions shown for each assembly are calculated by assessing the percent change in total impacts from standard material adjustments, which include recycled content, and Red List Free. The adjustment results in average reductions for all assemblies in the life cycle impact assessment categories of as much as carcinogens (86%), noncarcinogens (47%), ozone depletion (16%), and ecotoxicity (15%).

There is not one material assembly that saw significantly larger reductions across the board for each impact category. Overall, however, the structural, PV, and water assemblies were affected the most by the removal of Red List chemicals. Structural components see large reductions because of the large quantity of these materials; any small decreases in the category indicators are therefore amplified.

Use Phase

The use phase results of the building synthesize impacts from materials' replacements, building energy consumption, and water system use. The methane emissions from the water system via the septic system are the most significant impact to this stage, with electricity sent to the grid resulting in significantly offsetting impacts.

Material Replacement Impacts Distributed among Mechanical, PV, and Architectural Systems

The distribution of replacement impacts is slightly different, as seen in Fig. 5; these results include the Red List adjustments previously

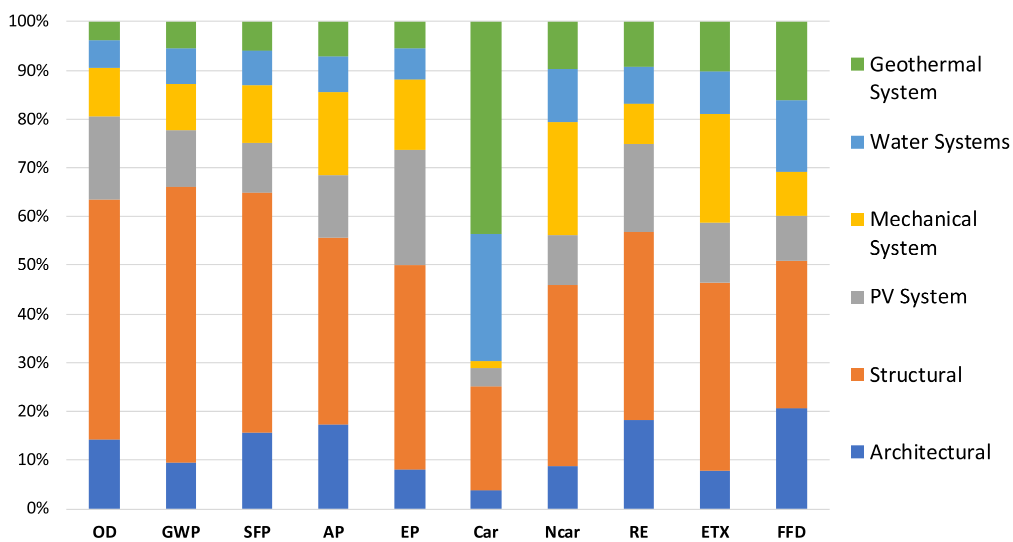

Fig. 3. Life cycle impact assessment results percentages from preuse/material impacts per assembly for each TRACI v2.1 impact category (Bare 2012). Categories left to right are: OD = ozone depletion; GWP = global warming potential; SFP = smog formation potential; AP = acidification potential; EP = eutrophication potential; CAR = carcinogens; NCAR = noncarcinogens; RE = respiratory effects; ETX = ecotoxicty; and FFD = fossil fuel depletion.

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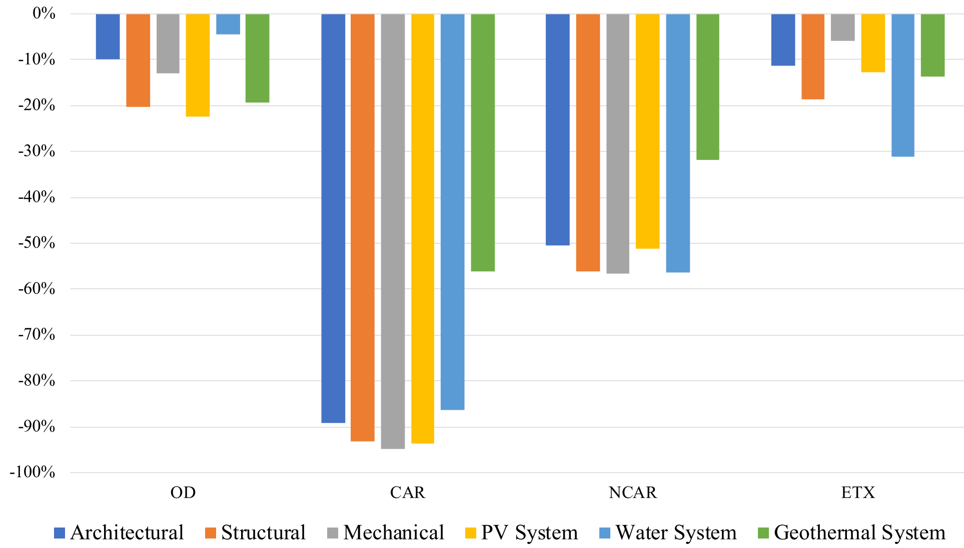

Fig. 4. Overall percent change in material impacts per material assembly. Categories left to right are OD = ozone depletion; CAR = carcinogens; NCAR = noncarcinogen; and ETX = ecotoxicity. Categories with <1% change are not shown.

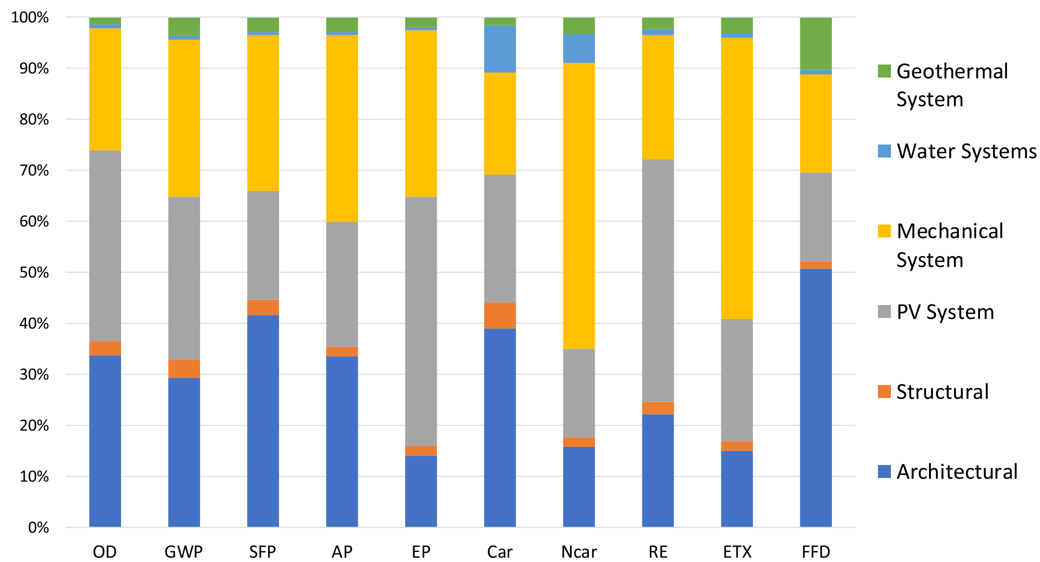

Fig. 5. Life cycle impact assessment results percentages from use (replacement) impacts, per assembly. Categories left to right are: OD = ozone depletion; GWP = global warming potential; SFP = smog formation potential; AP = acidification potential; EP = eutrophication potential; CAR = carcinogens; NCAR = noncarcinogens; RE = respiratory effects; ETX = ecotoxicity; and FFD = fossil fuel depletion (FFD).

described. Because structural elements do not require substantial replacements but only minimal maintenance of exterior materials, other assemblies see an increase in relative significance.

First, the architectural components are in general higher than in the material/preuse phase; this is because there are various components within this assembly (e.g., carpeting, windows, and interior walls) and most of these elements have lifespans much shorter than 100 years per their documentation and therefore need to be replaced from two to five times over the course of the building's life.

Similarly, because the photovoltaic (PV) assembly also already has substantial preuse impacts, it follows that its impact would be significant during the replacement phase as well; the lifespan of this assembly is 25 years, meaning that over 100 years, it would see three full replacements, assuming that there are no additional replacements needed due to malfunctions or other reasons for panel degradation.

The mechanical system contributes significantly to noncarcinogens (56%) and ecotoxicity (55%) as most of these elements require three replacements; these metal materials have high contributions to these specific TRACI categories because chemicals used to manufacture mechanical products, such as the stainless steel used in the ductwork, have high carcinogenic impacts but are not on the Red List. Therefore, they remain in the inventory, resulting in this assembly dominating nearly each category that is otherwise diminished by Red List chemical removal. Lastly, the geothermal system sees minor replacements, resulting in minimal impacts during this stage.

PV Generation Creates Significant Offsets

As a net-zero building, the Frick Environmental Center has minimal impacts associated with the energy of the use phase due to its on-site generation. Because there are minimal impacts associated with the operation of solar panels, the use phase of the Frick

Environmental Center with respect to its energy consumption results in high offsets. An estimated 43,600 kW · h are put back into the grid by the Frick Environmental Center on an annual basis. Based off the grid mix of the Pittsburgh region, the electricity is equivalent to 7,700 kg CO_2eq offset each year.

On-Site Water System Causes Large Emissions

The use phase for the water systems has a large contribution to the overall building life cycle impacts. The primary hotspot within the use phase of the water systems is the emissions from the septic system; they account for 98% of the wastewater GWP and 41% of the entire building life cycle GWP. This is a significant contribution from a life cycle perspective and should be mitigated moving forward.

End-of-Life

With respect to the exploratory analysis of the steel and concrete (as-built) models in Fig. 2, concrete recycling has the potential for a significant effect on the EOL impacts, shifting the GWP contributions from +14,000 kg CO_2eq when 0% of the concrete recycled to −10,500 kg CO_2eq with 100% of the concrete is recycled, as seen in Fig. 6. When the percentage of lumber reuse rises, the offsets significantly increase, as seen in Scenarios 3 and 4 in Fig. 7; conversely, as more lumber is combusted for energy as landfilled lumber decreases, the offsets lessen as seen in Scenarios 5 and 6. This is due to the high negative emissions factor of reuse (−1.23 kg CO_2eq/kg lumber) compared to landfill without LFG capture (−0.46 kg CO_2eq/kg lumber). Lastly, in Scenarios 7 and 8 from Table 2, when landfill gas is captured and used to generate electricity, the offset emissions increase slightly due to an emissions factor of −0.51 kg CO_2eq/kg lumber (USEPA 2016). This high-level assessment of structural materials is meant to illustrate how critical considering end-of-life impacts is when analyzing which materials have lower environmental impacts.

Overall Life Cycle Impacts

Including the materials/preuse, transportation to site, and use phases of materials, along with the energy and emissions from the water system, the normalized life cycle impact distribution can be seen in Fig. 8. Despite their high embodied impacts, structural materials no longer dominate any TRACI impact categories. The mechanical system sees high replacement impacts, therefore having significant impacts in categories such as ecotoxicity (33%) and noncarcinogens (35%). As discussed previously, the geothermal system's carcinogenic impacts (28%) are still notable

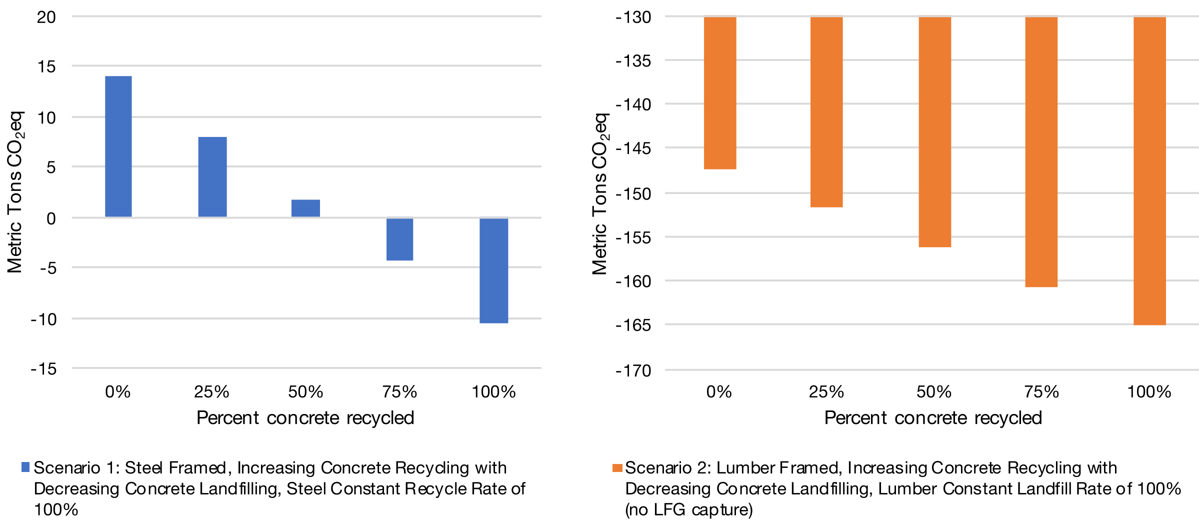

Fig. 6. Total kg CO_2eq for EOL impacts of increasing concrete recycle rate for steel (Scenario 1) and lumber (Scenario 2) model as referenced in Table 2.

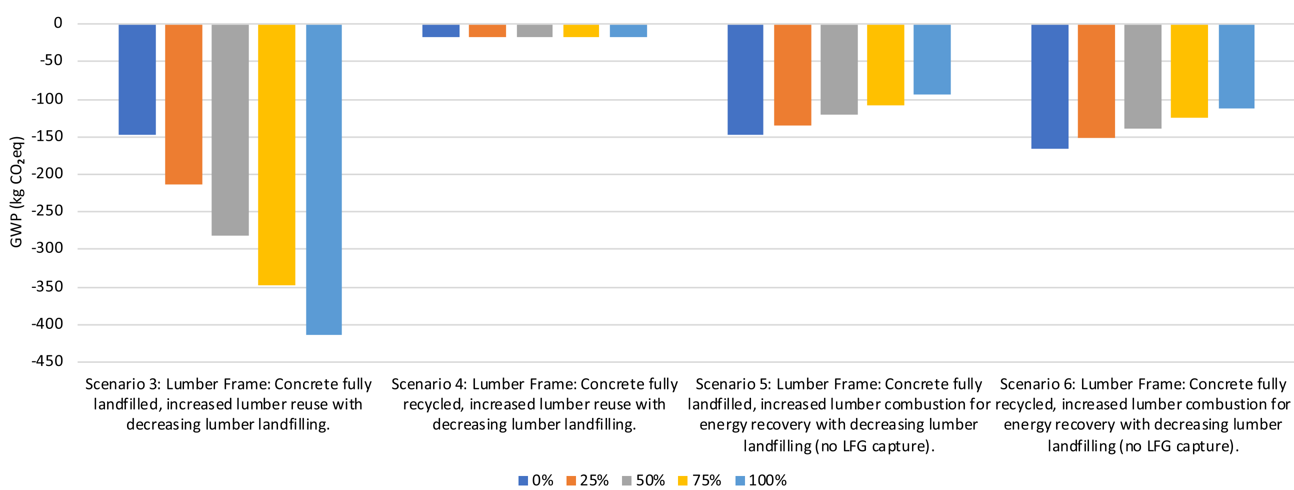

Fig. 7. Global warming potential in kg CO_2eq for EOL impacts for waste scenario options for lumber frame.

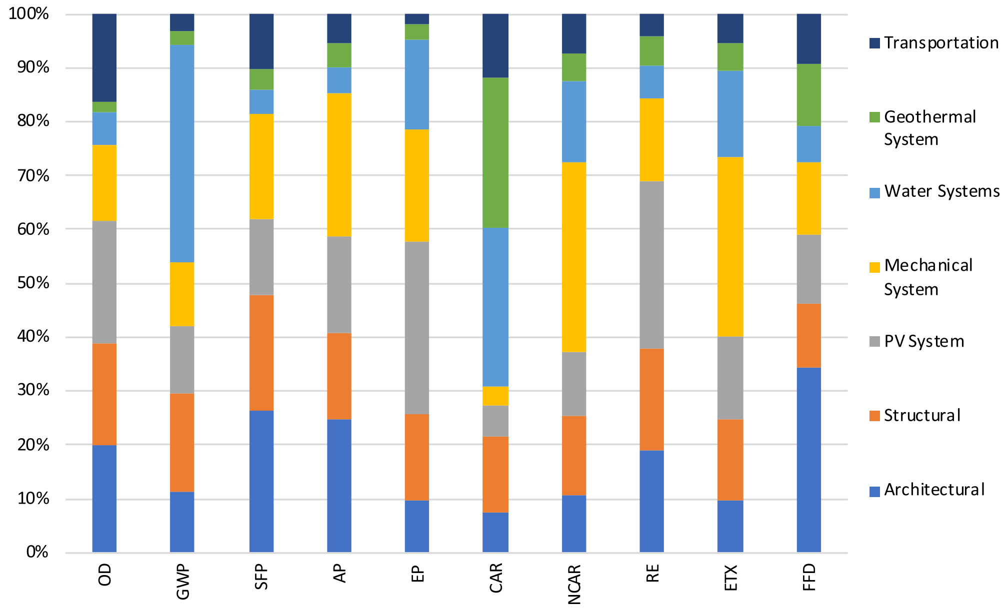

Fig. 8. Life cycle impact assessment results percentages from preuse and use stages, per assembly. Categories left to right are: OD = ozone depletion; GWP = global warming potential; SFP = smog formation potential; AP = acidification potential; EP = eutrophication potential; CAR = carcinogens; NCAR = noncarcinogens; RE = respiratory effects; ETX = ecotoxicity; and FFD = fossil fuel depletion.

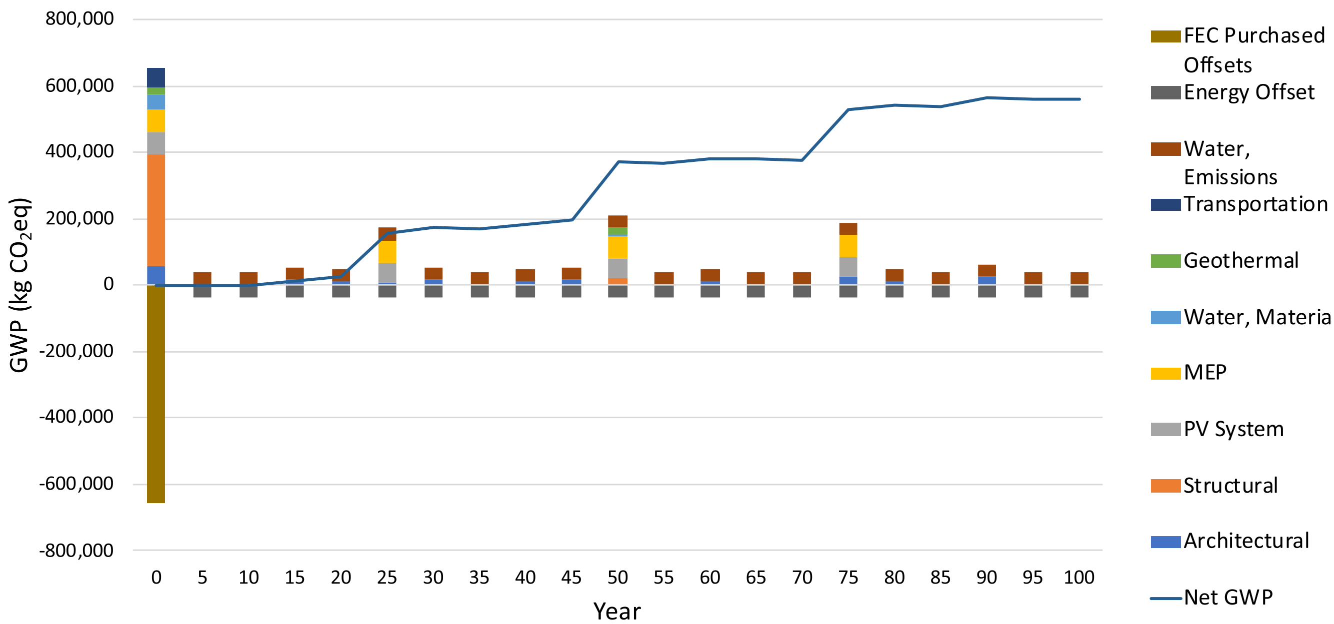

Fig. 9. Total global warming potential in kg CO_2eq by life cycle stage for preuse, transportation to project site, use (material replacements, and water system emissions/electricity offsets), and end-of-life (steel frame, steel 100% recycled, and concrete 50% recycled/50% landfilled). Assumed 100-year lifespan.

on a life cycle scale. Also, the transportation impacts from structural materials see notable contributions to ozone depletion (16%), carcinogens (12%), and smog formation potential (10%), which are attributed to trucks' consumption of diesel fuel. The methane emissions from the water system can be seen in the GWP impacts, accounting for 41% of this category. Finally, the increases in architectural material impacts are a result of their multiple replacements over the lifespan of the building.

Analyzing the material preuse and use phases on a life cycle scale illustrates a different context. The specific replacements for each assembly were plotted over the assumed 100-year lifespan of the structure, with continual contributions from architectural materials and septic emissions combined with the constant negative GWP from the electricity offset, seen in Fig. 9. The carbon offset from surplus electricity generated on-site was modeled from the first year and was assumed to be constant; it is conceivable that this offset will vary based on the on-site generation and the energy sources used in the electricity generation for this region. The embodied CO_2eq from the materials is outweighed by the offsets from the solar electricity generation. If there were minimal septic emissions, the annual GWP would be negative via the electricity offsets unless there is a substantial material replacement; however,

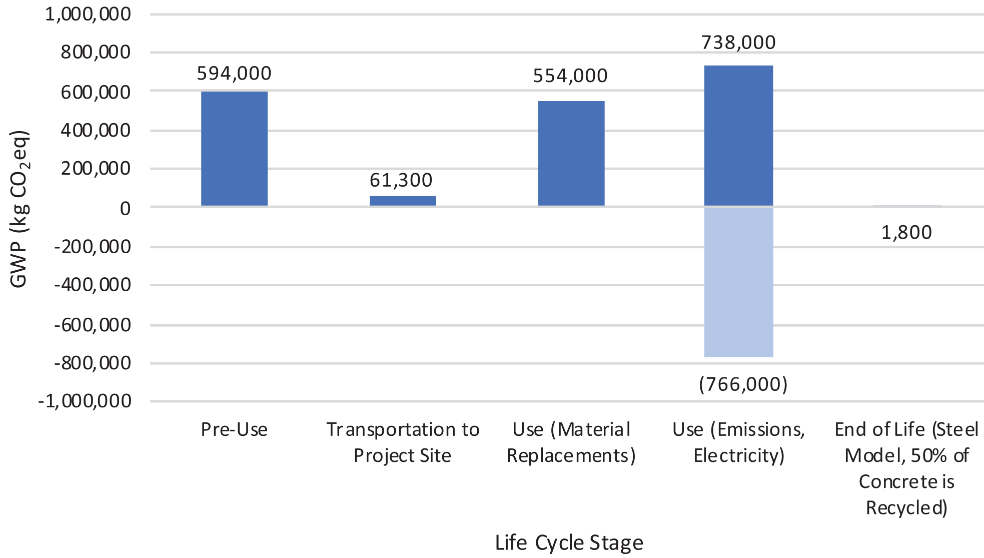

Fig. 10. Total global warming potential in kg CO_2eq by life cycle stage for preuse, transportation to project site, use (material replacements, and water system emissions/electricity offsets), and end-of-life (steel frame, steel 100% recycled, and concrete 50% recycled/50% landfilled). Assumed 100-year lifespan.

when the septic emissions are included, the electricity can only offset these material-related emissions, resulting in a positive net GWP each year. This brings up the ongoing discussion of how buildings truly achieve *net-zero* status from a carbon life cycle perspective. Based on this assessment, when the septic emissions are combined with the offsets that were purchased to offset initial material and construction impacts, the Frick Environmental Center is not a net-zero carbon building despite the significant number of sustainable features it implemented; for this study, the purchased offsets are assumed to equal the calculated impacts of the preuse impacts. The question of how and when carbon offsets should be purchased over the lifespan of a building in order to achieve net-zero carbon is important and should be considered in future rating systems. Generally, offsets are one-time purchases near the beginning of a building's life, as seen here and required in the Living Building Challenge (ILFI 2019). However, impacts from material replacements and in this case the emissions from the septic system exacerbate this increase in GWP, and it could be argued that recurring offsets should be purchased in order to allow a building to be truly *net-zero* with respect to life cycle carbon impacts.

The GWP for each life cycle stage is plotted in Fig. 10. Impacts from the use phase of materials (replacements) are nearly equal those of the preuse (install) stage; this is reasonable because many assemblies have two to five replacements over the building's lifespan, thus negating the absence of replacement impacts for structural materials, which have the highest preuse impacts. Having such detailed submittal information permitted an in-depth investigation of material replacements. Transportation emissions accounted for only 8% of overall GWP, illustrative of the positive impacts of sourcing local materials, as required by the Living Building Challenge. The emissions from the water system are the largest. The EOL impacts are minimal, accounting for only 0.1% of the building's life cycle GWP. This is attributed to the negative impacts resulting from steel recycling (−2,300 kg CO_2eq), combined with minor concrete impacts when the waste stream scenario is modeled at 50% recycled (4,100 kg CO_2eq). Concrete landfilling only emits 0.01 kg CO_2eq per pound and recycling prevents 0.005 kg CO_2eq per pound, whereas production releases 0.07 kg CO_2eq per pound; it follows that when half of the concrete is recycled, the EOL impacts are significantly lower than those of the preuse stage.

Conclusion

This research included a whole building LCA of a Living Building that focused on the impacts from materials, a decentralized water system, a net-positive use phase, and the disposal of structural materials. The material processes used in this LCA had the impacts of Red List chemicals removed per the product submittals, with results showing carcinogenic impacts were decreased by up to 96%. The lack of aeration of the septic system used for wastewater treatment results in methane emissions that contribute to 41% of the global warming potential for the building's lifespan. The solar panels on-site produce a net-positive energy profile, generating an annual surplus of 44,000 kWh of electricity that is returned to the grid, offsetting 7,700 kg CO_2eq annually (based on the first year of performance). Lastly, an exploratory scenario analysis with limitations was performed on multiple waste streams for the structural materials of two Revit models (as-built steel and modeled lumber) both with a concrete foundation. Results showed that based on the frame and waste stream selected, the end-of-life GWP impacts could vary from +14,000 kg CO_2eq to −10,500 kg CO_2eq for the as-built structure depending on the waste stream. Finally, even with offsets purchased for the preuse impacts, the Frick Environmental Center is not net-zero carbon as a result of the methane emissions from the septic system combined with recurring material replacement impacts; should the methane emissions be mitigated, net-zero carbon on a life cycle scale is within reach for the Frick Environmental Center.

The results of this research could impact the future design of Living Buildings. The hotspots identified in this life cycle assessment are likely present in other green buildings. It is recommended that more emphasis is placed on material selection during the design phase of Living Buildings due to their high global warming potential impacts throughout the lifespan of the building combined with their high potential for offsetting impacts during material end-of-life. Architects, material manufacturers, and engineers should work together to form a comprehensive material database including information on green building materials compatible for life cycle assessment. Additionally, any water systems used on site should be vigilantly monitored to ensure there are limited fugitive greenhouse gas emissions from those systems. Embodied impacts from material selection as well as all emissions seen on site should be considered in calculating a Living Building's "net-zero" carbon footprint. It is imperative to consider the building from a life cycle perspective in order to minimize holistic impacts. Green building rating systems can use these recommendations to update their standards, thus allowing future projects to avoid facing similar challenges. These results can be used to improve the design of green and high-performance buildings to continuously reduce the impacts of future Living Buildings.

Future Work

Future work for this LCA includes additional assessment of Red List chemicals. This work presents a methodology wherein these highly toxic chemicals were removed in order to show a more accurate chemical profile for a Living Building material. However, future work includes integrating substitutions wherever manufacturers replace Red List chemicals with another ingredient, while ensuring no regrettable substitutions were made. Because substitution data is not readily available, it was not within the scope of this LCA to include this within the assessment; however, it is suggested that manufacturers work towards more transparency in order to better understand the chemical profiles of green building materials.

Additional future work includes comprehensive statistical analysis regarding the uncertainty of this LCA. A Monte Carlo simulation is suggested to assess the uncertainty of the parameters set for this case study. Because many life cycle assessments use a variety of data sources and tools, understanding the variability of the results is helpful when it comes to comparing completed whole buildings LCAs. The end-of-life modeling was exploratory in nature with limitations; recommendation for future work includes an equivalent structural analysis for the comparative structures but was outside the scope of this project.

Appendix. LCIA Unit Processes

This appendix shows all life cycle inventory data used to obtain LCA impact results. These LCIA tables include values and unit processes selected for structural (Table 3), MEP (Table 4), PV system (Table 5), geothermal system (Table 6), architectural (Tables 7–9), and use phase (Table 10) materials and processes.

Table 3. Structural unit processes and additional data

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
CMU blocks	Portland cement (no fly ash)	ecoinvent 3.4	Cement, Portland {US}, market for, Alloc Def, U	20	—	100
	River sand	ecoinvent 3.4	Sand {GLO} market for Alloc Def, U	40	—	100
	River gravel	ecoinvent 3.4	Gravel, crushed, {ROW}, market for, Alloc Def, U	40	—	100
Concrete	Portland cement (incl. fly ash)	ecoinvent 3.4	Cement, pozzolana and fly ash 15%–40%, US only, market for, Alloc Def, U	10	—	100
	Gravel	ecoinvent 3.4	Gravel, crushed, {ROW}, market for, Alloc Def, U	30	—	100
	Natural sand	ecoinvent 3.4	Sand {GLO} market for Alloc Def, U	60	—	100
Steel beams	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	—	83%	100
Steel plates	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	—	78%	100
Reinforcing steel	Steel	ecoinvent 3.4	Reinforcing Steel, market for, Alloc Rec, U	90	99%	100
	Steel alloys	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	10	—	100
Steel trellis	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	—	82%	75

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 4. MEP unit processes and additional data

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
Air terminal units	Steel	ecoinvent 3.4	Galvanized steel sheet, at plant/RNA	95	—	25
(VAVs)	Fiberglass insulation	ecoinvent 3.4	Glass fibre {GLO}, market for, Alloc Def, U	5	—	25
Air vent	Cast iron	ecoinvent 3.4	Cast iron {GLO}, market for, Alloc Def, U	80	—	25
	Brass	ecoinvent 3.4	Brass {GLO}, market for, Alloc Def, U	10	—	25
	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	10	—	25
Diffusers	Steel	ecoinvent 3.4	Steel, stainless 304, {GLO} scrap/lb	40	—	25
	Iron (pig iron)	ecoinvent 3.4	Pig iron {GLO}, market for, Alloc Def, U	40	—	25
	Bronze	ecoinvent 3.4	Bronze {GLO}, market for, Alloc Def, U	20	—	25
Fan	Aluminum	ecoinvent 3.4	Aluminum removed by drilling, conventional {GLO}, market for, Alloc Def, U	—	60%	25
	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	—	90%	25
Fan coil units	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	40	—	25
	Copper	ecoinvent 3.4	Cooper {GLO}, market for, Alloc Def, U	20	—	25
	Galvanized steel	ecoinvent 3.4	Galvanized steel sheet, at plant/RNA	40	—	25
Ducts	Stainless steel	ecoinvent 3.4	Galvanized steel sheet, at plant/RNA	95	—	25
	Biosoluble glass mineral wool	US LCI	Glass wool mat {GLO}, market for, Alloc Def, U	5	—	25

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 5. PV unit processes and additional data

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
Aluminum gutter	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	—	60	75
Panels	Monocrystal	ecoinvent 3.4	Silicon, single crystal, Czochralski process, electronics {GLO}, market for, Alloc Def, U	—	—	25
Inverter	Inverter (600 W)	ecoinvent 3.4	Inverter, 0.5 kW {ROW}, production, Alloc Def, U	—	—	15
Structure—Concrete	Portland cement (incl fly ash)	ecoinvent 3.4	Cement, pozzolana, and fly ash 15%–40%, US only, market for, Alloc Def, U	20	—	75
	Gravel	ecoinvent 3.4	Gravel, crushed {ROW}, market for, Alloc Def, U	20	—	75
	Natural sand	ecoinvent 3.4	Sand {GLO} market for Alloc Def, U	60	—	75
Structure—steel	Steel	ecoinvent 3.4	Reinforcing steel {GLO}, market for, Alloc Def, U	—	96	75

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 6. Geothermal unit processes and additional data

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
Piping network	HDPE	ecoinvent 3.4	Polyethylene pipe, DN 200, SDR 41 {GLO}|market for earth tube heat exchanger, polyethylene, DN 200|Alloc Def, U	—	—	50
Grout	Cement mortar	ecoinvent 3.4	Cement mortar {GLO} market for, Alloc Rec, U	90	—	75
	Silica sand	ecoinvent 3.4	Silica sand {GLO}, market for, Alloc Rec, U	5	—	
	Activated bentonite	ecoinvent 3.4	Activated bentonite {GLO}, market for, Rec, U	5	—	75
HVAC piping	Steel	ecoinvent 3.4	Chromium Steel pipe {GLO}, market for, Alloc Def, U	—	—	25

Note: WB = weight breakdown; RC = recycled content; PL = product lifespan (years).

Table 7. Architecture unit processes and additional data

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
Ceiling—ACT	ACT tiles	ecoinvent 3.4	Glass fibre {GLO}, market for, Alloc Def, U	80	—	25
	Steel suspension	ecoinvent 3.4	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1 lb, {GLO} S	15	—	25
	Aluminum 3005 alloy suspension	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	5	60	25
Ceiling—gypsum wallboard	Sheathing	ecoinvent 3.4	Gypsum wallboard product, regular, 0.5 in./m^2/RNA	—	30	50
Ceiling—metal decking	Steel	ecoinvent 3.4	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1 lb, {GLO}	80	—	100
	Fibrous glass	ecoinvent 3.4	Glass fibre {GLO} market for, Alloc Def, U	20	—	100
Door—aluminum	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	—	60	100
Door—HM	Steel	ecoinvent 3.4	Steel, low-alloyed {GLO}, market for, Alloc Def, U	2.5 lb	—	100
	Polystyrene core	ecoinvent 3.4	Polystyrene, general purpose {GLO}, market for, Alloc Def, U	5 lb	—	100
Door C—wood	Wood (maple)	US LCI	Lumber, softwood, borate treated, SE/m3/RNA	3.065 lb	—	100
Door E—wood and glass	Wood	ecoinvent 3.4	Lumber, softwood, borate treated, SE/m3/RNA	2 lb	—	100
	Glass	ecoinvent 3.4	Flat glass, uncoated {GLO}, market for, Alloc Def, U	20 lb	—	100
Door F—glass and aluminum	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	44 lb	—	100
	Glass	ecoinvent 3.4	Flat glass, coated {GLO}, market for, Alloc Def, U	32.5 lb	—	100

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 8. Architecture unit processes and additional data, cont'd

Assembly	Material	Database	Unit process	WB (%)	PL
Door G—glass and aluminum	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	32 lb	100
	Glass	ecoinvent 3.4	Flat glass, coated {GLO}, market for, Alloc Def, U	17.5 lb	100
Door H—alum, glass, wood	Wood	ecoinvent 3.4	Lumber, softwood, borate treated, SE/m3/RNA	3 lb	100
	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	44 lb	100
	Glass	ecoinvent 3.4	Flat glass, coated {GLO}, market for, Alloc Def, U	32.5 lb	100
Flooring—carpet	Nylon squares (Type 6)	ecoinvent 3.4	Nylon 6 {GLO} market for, Alloc Def, U	20	15
	Polypropylene base	ecoinvent 3.4	Polypropylene, granulate {GLO}, market for, Alloc Def, U	80	15
Flooring—resilient	Rubber base	ecoinvent 3.4	Synthetic rubber {GLO} market for, Alloc Def, U	80	15
	Limestone	ecoinvent 3.4	Limestone, crushed, washed {GLO}, market for, Alloc Def, U	10	15
	Limestone (recycled)	ecoinvent 3.4	Limestone, crushed, washed {GLO}, market for, Alloc Rec, U	10	15
Flooring—tile	Tile	ecoinvent 3.4	Ceramic tile {GLO}, market for, Alloc Def, U	—	100
Furnishings—cabinetry	Veneer exterior	ecoinvent 3.4	Veneer, hardwood, dry, at veneer mill, E/lb/RNA	50	25
	Plywood walls	ecoinvent 3.4	Plywood, for indoor use {RER}, market for, Alloc Def, U	50	25
Guard rail	Steel	ecoinvent 3.4	Steel, unalloyed {GLO}, market for, Alloc Def, U	0.9	75
Roofing	Thermoplastic	ecoinvent 3.4	Polypropylene, granulated {GLO}, market for, Alloc Def, U	0.5	20
	Thermoplastic	ecoinvent 3.4	Polyethylene, low density, granulated {GLO}, market for, Alloc Def, U	0.5	20

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 9. Architecture unit processes and additional data, cont'd

Assembly	Material	Database	Unit process	WB (%)	RC (%)	PL
Steel grate	Galvanized steel	ecoinvent 3.4	Galvanized steel sheet, at plant/RNA	—	96	75
Wall—aluminum frame	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3$ {GLO}, market for, Alloc Def, U	—	60	15
Wall—gypsum wall board	Glass fibre	ecoinvent 3.4	Glass fibre {GLO}, market for, Alloc Def, U	20	—	20
	Gypsum board (5/8″)	ecoinvent 3.4	Gypsum wallboard product, regular, 0.675 in./m^2/RNA	80	30	20
Wall—polycarbonate	Polycarbonate	ecoinvent 3.4	Polycarbonate {GLO}, market for, Alloc Def, U	—	—	50
Wall—exterior lumber	Lumber	US LCI	Lumber, softwood, borate treated, SE/m3/RNA	—	—	25
Window frame—wood	Lumber	US LCI	Lumber, softwood, borate treated, SE/m3/RNA	—	—	25
Window frame—aluminum	Aluminum	ecoinvent 3.4	Aluminum alloy, $AlMg_3${GLO}, market for, Alloc Def, U	—	60	15
Window—tempered/spandrel	Coated glass	ecoinvent 3.4	Flat glass, coated {GLO}, market for, Alloc Def, U	—	—	20
Window—standard	Glass	ecoinvent 3.4	Flat glass, uncoated {GLO}, market for, Alloc Def, U	—	—	20
Wood—black locust envelope	Black locust lumber	US LCI	Lumber, softwood, borate treated, SE/m3/RNA	70	—	25
	Sheathing (1″)	ecoinvent 3.4	Gypsum, mineral {GLO}, market for, Alloc Def, U	5	—	25
		ecoinvent 3.4	Glass fibre {GLO}, market for, Alloc Def, U	5	—	25
	Gypsum board (5/8″)	ecoinvent 3.4	Gypsum wallboard product, type x, 0.625 in./m^2/RNA	10	30	25
	Mineral wool insulation (5″)	ecoinvent 3.4	Glass wool mat {GLO}, market for, Alloc Def, U	10	—	25

Note: WB = weight breakdown; RC = recycled content; and PL = product lifespan (years).

Table 10. Use phase unit processes and additional data

Assembly	Unit	Database	Unit process	%
Grid electricity	kW · h	ecoinvent 3.4	Electricity, high voltage {RoW}|electricity production, hard coal|Alloc Def, U	35
	kW · h	ecoinvent 3.4	Electricity, medium voltage {RoW}|market for|Alloc Def, U	29
	kW · h	ecoinvent 3.4	Electricity, nuclear, at power plant/US	26

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request, including takeoff quantities, Red List adjustment quantities, and additional life cycle inventory assessment data.

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