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Building Life-Cycle Analysis with the GREET Building Module: Methodology, Data, and Case Studies

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by
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ABSTRACT

To holistically address building sustainability, Argonne National Laboratory has expanded its Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) life-cycle model with a new GREET Building Module. This report documents life-cycle analysis (LCA) methodology and foreground data that Argonne National Laboratory compiles and develops to address embodied greenhouse gas (GHG) emissions and energy impacts of a wide range of envelope and structural building materials for new construction and retrofits. The methodology and data form the backbone of the GREET Building Module.

This research effort focuses on developing consistent LCA methodology that conforms to building LCA standards such as the EN 15978 to address embodied GHG emissions and energy impacts of building materials/technologies. We document detailed foreground data for selected building materials and building components that are common for building construction. To test the LCA methodology and the GREET Building Module, this report includes case studies of insulation materials and wall panels for residential building retrofit. We have developed a separate document as a User Guide for understanding and applying the GREET Building Module to conduct detailed, process-level LCA of embodied carbon and energy impacts of emerging building materials and technology solutions that of interest to the Building Technologies Office (BTO) of the US Department of Energy, researchers, and industry stakeholders.

SUMMARY

The GREET Building Module is designed to facilitate detailed, transparent, and consistent LCA of new building materials. As detailed in the User Guide (Cai et al., 2021), the user can make detailed assumptions about energy and material requirement across the supply chain and system boundary of analysis interest. We have developed a transparent and consistent building LCA methodology that conforms to the EN 15978 Standard for conducting sustainability LCA of construction and building materials. We have developed bottom-up, process-level modeling capabilities in the GREET Building Module to address embodied energy and GHG impacts, water consumption, and criteria air pollutant emissions of building materials, components, and technology solutions. Consistent methodology and transparent LCIs incorporated in the GREET Building Module improve consistency, transparency, and comparability of LCA results for different building materials and technology solutions simulated with the Module.

The GREET Building Module includes an extensive, consistent background database that comprises of Cradle-to-Gate life-cycle profiles of typical sustainability metrics including energy consumption, GHG and criteria air pollutant emissions, and water consumption for a wide range of common process energy, such as electricity at the U.S. national average or at the state level, natural gas, etc., and process materials, such as limestone, hydrogen chloride, etc., which are modeled in great detail with the main GREET suite models (Wang et al., 2020). We supplement the GREET-derived database with life-cycle profiles of common building materials that could be

modeled with ground-up data and transparent assumptions to improve transparency and reduce uncertainty. We also include literature data of some common building materials to leverage outcome of the industry and academia efforts to address embodied GHG emissions of building materials. We categorize the LCA results in the GREET database depending on modeling methods and data sources, which allow the user to make informed decisions about which data to use, especially for whole building LCA.

As on-going efforts continue to address new energy and materials that are largely relevant to the transportation sector, the GREET Building Module will benefit from regular updates and expansion that take place in the main GREET suite models to expand and update its background database. LCA results of new building materials that are generated within the Module, as well as incorporation of LCA results reported in literature and by industry are complementary approaches to expanding the background database in the GREET Building Module. These complementary data sources form a strong basis for continuing efforts to address embodied GHG emission impacts, among other sustainability issues of building materials and technology solutions, leveraging best available data and information. In the meantime, the LCA methodology will be updated constantly to incorporate new thinking and guideline developed by the LCA community including ourselves, which is key to holistically addressing emerging LCA issues such as co-product impacts, end-of-life, temporal carbon effects, recyclability, circularity, etc., to understand the full picture of the sustainability performance of building materials and technology solutions.

We conducted case studies of insulation materials with the GREET Building Module to test the methodology and modeling capabilities of estimating embodied GHG emissions of VIP and rigid foam counterparts. We demonstrated that detailed, consistent embodied GHG emission results could be generated with the GREET Building Module for emerging building materials with ground-up LCIs and the GREET LCA methodology, background data, and transparent and holistic modeling framework. The GREET Building Module can generate detailed LCA results that highlight key drivers and opportunities to mitigate the embodied GHG emission impacts of individual building materials or a building system that consists of multiple building materials such as a wall panel. The Module allows the user to access to all the foreground data across the supply chain of interest to make changes to specific assumptions and conduct sensitivity analysis to gauge the impacts of the types and quantities of material/energy inputs, key issues associated with certain life-cycle stages, such as potential leakage of blowing agents during the use phase, and LCA methodological considerations such as choices of co-product handling methods, system boundary of interest, and the functional unit. This gives the user flexibility of considering important details regarding material/energy inputs and outputs along the supply chain of a building material or technology solution that may have an impact on the embodied GHG emissions and other sustainability performances.

With the support of the Building Technologies Office of DOE Energy Efficiency and Renewable Energy Office, the GREET Building Module could empower technology developers, researchers, manufacturers, building designers and architects, and policy makers to holistically address embodied carbon and sustainability performance of novel and conventional building materials with a publicly accessible LCA tool and extensive background data.

1. INTRODUCTION

1.1 BUILDING LIFE-CYCLE ANALYSIS TO ADDRESS EMBODIED CARBON AND ENERGY USE

The buildings sector accounts for 38% of all energy-related CO_2 emissions when adding building construction industry emissions (United Nations Environment Programme, 2020). Owing to its rapid growth and associated higher GHG emissions, the buildings sector has received increasing interest to evaluate its environmental impacts and opportunities to reduce these impacts. Building construction requires manufacturing and use of building materials and components, which may involve resource-intensive processes along the supply chain, including mining and extraction of natural resources, manufacturing, transportation, use, and demolition. Each of these processes consumes large amounts of energy and resources that contribute to the so-called embodied emissions and energy use for buildings. According to Architecture 2030, embodied carbon emissions account for about 28% of the annual carbon emissions of the building sector globally (Architecture30 2020). As the buildings sector continues to improve operational energy efficiency to reach net zero energy buildings, reducing embodied energy/GHGs becomes an integral part of promoting sustainable building components/technologies and whole buildings.

Life-Cycle Analysis (LCA) takes a holistic approach to evaluating embodied carbon and energy impacts across the supply chain of building components, identifying opportunities to mitigate such impacts, and offering insights for choices of low-impact building components for sustainable building designs. With an increase in sustainable manufacturing goals, manufacturers of building products publish LCA data and results for their products using Environmental Product Declarations (EPD) (Galindro et al. 2020; Passer et al. 2015; Rangelov et al. 2021). The EPDs are becoming a popular approach to reporting the embodied energy and emissions of products. EPDs are developed following specific product category rules (PCRs) (American Center for Life Cycle Assessment 2021). Meanwhile, buildings rating programs are becoming popular to evaluate the performances of buildings with pre-defined criteria and threshold values. The commonly used buildings rating systems include Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), ENERGY STAR, and Deutsche gesellschaft für nachhaltiges bauen (DGNB), etc., which are developed and managed by various national and international green council organizations (Vigovskaya, Aleksandrova, and Bulgakov 2018). These rating systems developed lists of criteria encompassing life-cycle environmental impacts, such as Global Warming Potential, Ozone Depletion Potential, Eutrophication Potential, Primary Energy Consumption, etc., as well as quality attributes for economic, construction, operational, maintenance performances, among others, for sustainability certification from design and construction through to operation and refurbishment of various types of buildings. Like EPDs, these green building rating systems also have drawbacks, including disparity in system boundary considered, environmental indicators, and calculation methods (European Commission 2018). Though the EPDs and building rating systems provide high-level environmental impacts scores of buildings materials and whole buildings, to better understand the detailed process level embodied energy and emissions, these impacts need to be analyzed from a life cycle perspective. Over the last few decades, LCA studies have been carried out to evaluate building materials (Rivela et al. 2006; Ingrao et al. 2016; Bergman and Bowe 2008; Bahramian and Yetilmezsoy 2020; 2020; Allan and Phillips 2021; Dascalaki et al. 2021; Salazar and Sowlati 2008) and sustainability performance of buildings (Kylili, Ilic, and Fokaides 2017; Zuo et al. 2017; Hasik et al. 2019; Al-Ghamdi and Bilec 2017).

LCA methodologies that systematically and consistently evaluate the energy and materials required along the supply chain of building components are needed to ensure comparability of the LCA results for different building components that may vary by design, material composition, manufacturing processes, and performance in order to achieve the same or somewhat similar functionality. Meanwhile, a transparent building LCA model that is intuitive-to-use, modify, update, and expand is needed to address embodied GHG emissions and energy impacts for a wide range of building components given specific system boundaries of interest.

To inform the U.S. Department of Energy's (DOE's) Building Technologies Office (BTO) of embodied GHG emission impacts of emerging building materials and technology solutions that are being developed by its Advanced Building Construction (ABC) Initiative, we conduct detailed, transparent, and consistent LCA of the ABC technology solutions. Recognizing the limitations of a few existing building LCA models in modeling capabilities and scopes, lack of transparency, and lack of access to the public free of charge, we are expanding the widely used Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) LCA model (Argonne 2020) with a transparent, detailed building LCA module and apply it to address embodied carbon and energy impacts of ABC building technologies with transparent and consistent methodology and background data (Cai et al., 2021).

This report documents key building LCA methodologies we developed to evaluate the life-cycle energy and environmental impacts of novel building components and their conventional counterparts. Meanwhile, we documented key data, gaps, and issues associated with addressing some common building materials. Furthermore, we applied the LCA methodologies and data that are implemented in the GREET Building Module to estimate embodied greenhouse gas (GHG) emissions of a vacuum insulation panel (VIP) product proposed for use in ABC projects. We present demonstrative LCA results of these building insulation materials in this report.

1.2 REVIEW OF BUILDING LCA METHODOLOGIES

LCA has been defined as a systematic analysis to measure industrial processes and products by examining the flow of energy and material consumption, waste released into the environment and evaluate alternatives for environmental improvement (Abd Rashid and Yusoff 2015). Product category rules (PCRs) have been the primary methodological guidelines for building material LCAs that underpin EPDs. PCRs define the criteria for a specific product category and establish the requirements that must be met when creating an EPD for a product, including rules to be used for the LCA of any product in the category (Gelowitz and McArthur, 2017). PCRs may be developed by any "program operator", who is responsible for both rule creation and third-party verification. However, there is no formal oversight of these Program

Operators, and it is known that there is a lack of harmonization between the PCRs developed (Ingwersen and Stevenson, 2012, Gelowitz and McArthur, 2017), despite on-going efforts of the PCR Committee of the American Center for Life Cycle Assessment to develop more harmonized PCR guidance document. As a result, there has been an increasing number of overlapping PCRs with inconsistencies between very similar products using dissimilar rules for their EPDs such as differences in LCA methodology or reporting (Ingwersen and Subramanian, 2014). The resulting extent and validity of comparison between such products is thus limited to the extent that the underlying PCR parameters are comparable, requiring harmonization efforts to ensure a consistency in quality and information types required by PCRs (Gelowitz and McArthur, 2017). Subramanian et al. (2011) developed a PCR comparison template which led to the conclusion that the deficiencies in comparability were caused by general differences in scope, system boundaries, and environmental impacts. Gelowitz and McArthur (2017) found that a significant percentage of EPD comparisons could not be undertaken for EPDs written to the same PCR, e.g., 50% of comparisons of EPDs written to the same PCR for insulation were invalid. Only a minority of EPD comparisons were valid, e.g., 6% for insulation materials. There are a small number of permissible comparisons (3% for insulation) despite these EPDs having different underlying PCRs. While a small number, this made up half of the total valid comparisons in the insulation category and shows the value of extending comparisons beyond a single PCR, particularly given that the common PCR does not guarantee a valid basis for comparison.

A number of whole building LCA case studies suggested that the LCA methodology varies with materials selection, locations, construction process, building design and usage that will produce a different definition of goal and scope and will bind to certain limitations (Abd Rashid and Yusoff 2015). Variances on goal and scope definition, building structure complexity, and varieties on LCA database and methods are identified as the three main challenges for whole building LCA (Feng, Hewage, and Sadiq 2021). These studies highlight the need for a clear definition of goal and scope as part of a robust LCA methodology.

1.3 REVIEW OF BUILDING LCA TOOLS

Several LCA models and tools are developed to evaluate the embodied energy and emissions of building materials and whole buildings. The EC3 model (Embodied Carbon Construction Calculator) is a tool to report and compare embodied carbon in building materials (CLF 2020). The tool provides carbon emissions data for a range of building materials allowing architects and designers to select low carbon materials and suggest material specification and procurement processes. The EC3 tool incorporates digitized EPDs of building materials to evaluate the embodied carbon in building materials. The tool reports an aggregated embodied carbon emissions of raw material extraction, related transportation, and manufacturing of the building materials. One of the key features of the tool includes its capability to import an entire bill of materials from plug-in models such as Revit or the BIM 360 (CLF 2020). One of the major caveats of this tool is that it does not calculate the environmental metrics for materials rather it is an aggregator of EPDs.

One Click LCA is another LCA tool that calculates environmental footprints of construction projects and products and mostly used by architects, structural engineers, environmental consultants, and green building certification professionals (Bionova 2020). The tool is specialized for building LCA and supports green building rating systems (GBRS) such as leadership in energy and environmental design (LEED) and building research establishment environmental assessment method (BREEAM). One Click LCA uses EPD databases and industry average data to evaluate the embodied carbon in building materials. It has a large geographic coverage including European, North American, Asia Pacific, Middle Eastern, and South American databases. Besides EPDs, the tool uses its own generic construction material database and other databases from American Society for Testing and Materials (ASTM), and Quartz for the North American region. The system boundary is in accordance with the European environmental building declaration EN 15978, including construction products and processes, building use, maintenance, energy and water consumption, end-of-life impacts. The tool is targeted for whole building LCA for different certifications and calculation schemes. The number of the life cycle stages available is restricted to match the requirement of the scheme in question. One Click LCA integrates with building information models in Revit, ArchiCAD, and Tekla structure formats. The software uses both CML and Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methods for life cycle impacts evaluation. A major drawback of the model is that users can not add new processes and datasets into the model on their own. In other words, like EC3, one must use previously defined and recognized products or systems. If a specific material needs to be added, the user needs to send the EPD of that material to the model developers for inclusion into the model.

ATHENA Impact Estimator is another widely used building LCA tool that can model the environmental impacts of choices of building elements, construction assembly, building products for designs of a whole building (ATHENA 2020). The tool is developed specifically for architects, engineers, and sustainable design consultants. The tool is based on the assessment of combinations of choices for different materials, structural, and assemblies. Typically, users introduce information about the different building assemblies manually instructed by the software. Based on the information provided the tool connects its internal life cycle inventory data and other public life cycle data to generate the results for a building design. The background Athena Institute database used in the tool is proprietary and is not publicly available. Typical data sources include in-house, under contract to trade associations, with the cooperation of several manufacturers and plants across North America. The ATHENA Impact Estimator considers the environmental impacts of the following life cycle stages: material manufacturing, including resource extraction and recycled content; related transportation; on-site construction; maintenance and replacement effects; and demolition and disposal. Mid-point environmental impacts are evaluated using the U.S. EPA TRACI database. The tool does not allow users to adjust the energy or material inputs. Furthermore, users cannot adjust the modes of transportation and distance used to deliver materials at different stages of the product life cycle.

Tally building LCA tool was developed by KT Innovations with the partnership of Autodesk and Thinkstep (Kierantimberlake 2020). The model aims to be used as a plug-in model in Revit Architecture or Structure model. It draws information from the Revit model as an automated function and receives a bill of materials. Tally can conduct a full building LCA within the cradle-to-grave system boundary. It uses a database developed in collaboration between KT

Innovations and Thinkstep (GaBi LCI database). It also draws data from EPDs (currently it contains 68 product-specific and 74 industry-wide EPDs). The operational energy calculations are optional in the model. Since it uses the GaBi LCI database, the outputs can be filtered to a specific location, market, and manufacturers. The tool evaluates cradle-to-grave impacts, which include manufacturing, transportation, maintenance and replacement, and end-of-life. It also provides options to include impacts associated with construction and operational energy use for whole-building assessments. It is integrated into the Revit model and uses TRACI 2.1 for impact assessment. Like One Click LCA, Tally does not allow users to add new processes and data. This can only be done by KT Innovations and Thinkstep. However, it allows users to customize the product mix/ingredients and quantities of materials for whole building analysis.

Overall, the above discussed tools facilitate efforts to satisfy requirements by green building certification programs. PCRs serve as the key LCA methodologies and EPDs are the key products of modeling results. Most of the tools do not allow users to add new datasets into the models and users cannot edit or modify the existing data. This limitation makes these tools inadequate to complete and assessment of novel building materials and components such as those being developed under the ABC initiative. To address this gap, we develop a user accessible, streamlined, consistent, and transparent life cycle analysis module in the existing GREET model to evaluate the embodied energy and emissions of building materials across the supply chain, as well as whole buildings and building designs. With such modeling design and capabilities, the GREET Building Module is capable of addressing and incorporating novel building materials, technologies, and designs. Both the background and foreground databases are open to the user for expansion, modification, and maintenance in a transparent and efficient way.

2. ARGONNE BUILDING LCA METHODOLOGY

Recognizing the key methodological issues mentioned above, we focus on defining a consistent, transparent system boundary so that LCA of different building components could be evaluated within the same scope of analysis. Figure 1 shows a complete cradle-to-cradle system boundary within the GREET Building Module. At the same time, we maintain flexibility in the Module to adjust the system boundary in order to address unique and important issues, as summarized in Table 1, which may affect the embodied GHG and energy impacts significantly, e.g., fugitive emissions during the use phase, impacts of end-of-life practices, etc. Despite this flexibility, we note that one should always apply the same system boundary to addressing a new building technology and its counterpart technologies to compare their embodied energy and GHG impacts consistently.

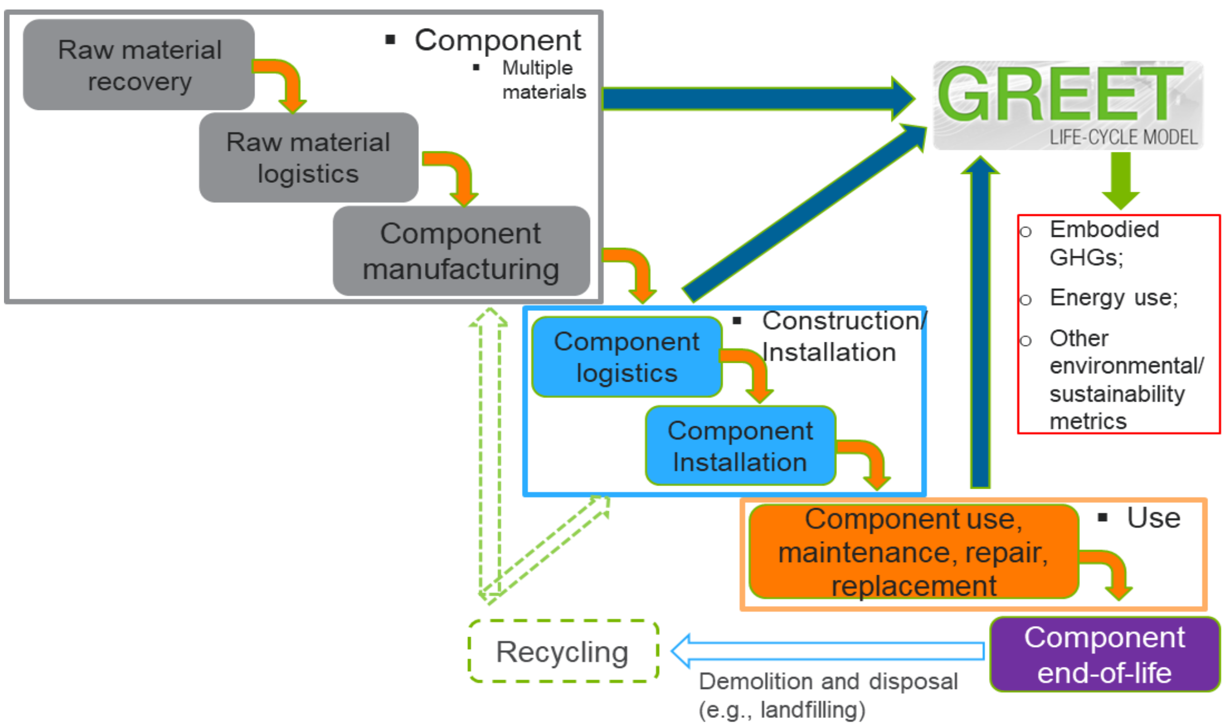


FIGURE 1. Cradle-to-cradle system boundary to address embodied GHG and energy impacts of a building component from raw material sourcing, transportation, manufacturing, construction, installation, use, maintenance, replacement, end-of-life, and recycling and reuse.

TABLE 1. Building LCA system boundaries to address different issues.

System boundary	Issues to address	Life-cycle stages
Cradle-to-Gate	Building material LCA focusing on energy and environmental impacts of raw material sourcing and material manufacturing	Raw material extraction, transportation, and use for manufacturing of a building material.
Cradle-to-Construction	Building component LCA with consideration of energy and environmental impacts during construction and installation	Cradle-to-Gate, plus finished product transportation and construction/installation
Cradle-to-Use	Building component LCA with consideration of energy and environmental impacts during the service life	Cradle-to-Construction, plus use, maintenance, repair, and replacement
Cradle-to-Grave	Building component LCA with consideration of end-of-life energy and environmental impacts	Cradle-to-Use, plus end-of-life practices
Cradle-to-Cradle	Building component LCA with consideration of energy and environmental impacts of recycling, remanufacturing, and reuse (Re-X)	Cradle-to-Grave, plus Re-X practices

Another key methodological issue we address is to define a performance-equivalent functional unit so that the modeling results can be comparable between a new ABC technology and the counterpart technologies. The desirable functional unit that fully reflects the performance and service functionality of a building component tends to vary among building components, and thus requires specific evaluation for different component groups.

Initial testing of the methodology focused on assessment of embodied GHG emissions and energy use of various types of building insulation, such as vacuum insulation panel (VIP) and its rigid foam counterparts such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral fiber board (MFB), and rigid polyurethane foam (PUR).

These types of building insulation and the prospective ABC envelope systems aim to offer lasting thermal resistance between the exterior environment and the interior living space to maintain a level of comfort for dwellings and reduce their operational energy requirements. The thermal performances of these types of building insulation vary from one another due to different selection, structures, and properties of core materials. Therefore, a thermal performance metric over the service life (functional unit) is needed for consistent comparison of different types of building insulation in the LCA. Details of how we address this issue are presented in the Case Study section.

As it is often the case in LCA of fuel systems, building LCA may need to address the impact and implications of co-products that may be involve in some life-cycle stages, e.g., the manufacturing step, and thus requires rigorous and transparent handling methods to address such co-product impacts. In short, we consider both the allocation-based and displacement-based co-product handling methods as options to address this issue. We discussed details of such co-product handling methods and their implications on LCA results in published journal articles (Wang et al., 2011, Canter et al., 2016, Cai et al. 2018). In the GREET building LCA module, we fully implement such co-product handling methods so that the analyst can decide which particular handling method or a combination of handling methods to choose in the modeling.

To facilitate the effort for building technology developers and manufacturers to identify sources of challenges and develop strategies to address such challenges in terms of tackling embodied GHG emissions, we are considering differentiating Scope 1, 2, and 3 emissions. By definition, Scope 1 emissions are direct emissions that the manufacturer may have from their processes and activities; Scope 2 emissions account for emissions associated with inputs materials and products; and from suppliers along the supply chain, which could be considered as "embedded" emissions and thus may be beyond direct control by the downstream manufacturers. Scope 3 emissions are those associated with use of products (which may not apply to building technologies and buildings, since they are not consumer products). Understanding Scope 1,2 and 3 emissions and their contributions would be helpful to develop plans for mitigating emissions of different causes and origins along the supply chain.

3. LIFE CYCLE INVENTORIES OF COMMON STRUCTURAL AND ENVELOPE BUILDING MATERIALS

Detailed foreground life cycle inventories that inform the material and energy inputs and outputs along the supply chain of a building material or building technology solution are key to thoroughly addressing the embodied GHG emissions and other impacts through a process-level LCA. To address building materials, technology solutions, and whole buildings, we document key material and energy data for common building materials that we have reviewed to this point. We have collected the data from literature and collaboration with manufacturers, trade associations and other stakeholders including subject matter experts. In the Appendix, we summarize literature review, key applications, manufacturing processes, LCI data, and key assumptions of common structural materials, insulation materials, and envelope materials.

It is important to note that these LCI data for individual building materials are incorporated into the GREET Building Module as placeholder values. They could serve as a starting point of conducting detailed, more transparent modeling of Cradle-to-Gate embodied GHG emission impacts of building materials. The results generated with the GREET Building Module with such data are for research purposes only and do not intend to disagree with embodied GHG emissions and other impacts reported in EPDs or other publications by the industry.

In the meantime, we have developed a feature in the GREET Building Module to allow the user to incorporate embodied GHG emissions of building materials that are reported in EPDs and other open literature into the GREET Building Module. Together with detailed LCA and modeling results with the GREET Building Module, such data and information could be used for comparison purposes and to inform whole building LCA.

4. GREET BUILDING MODULE AND USER GUIDE

We have developed a building LCA module on the GREET Excel platform to leverage extensive background data available in GREET. The GREET building LCA module specializes in addressing embodied GHG and energy impacts of individual building components for a given system boundary that could vary from cradle-to-gate to cradle-to-cradle, as well as whole buildings and building designs. The module is designed with a Graphical User Interface, as shown in Figure 2, to be interactive, easy to enter detailed data along the life-cycle stages of interest, transparent to maintain, update, and expand the databases, instructive to help address data gaps and reduce analysis uncertainties, quick to generate and navigate LCA results, and intuitive to illustrate and compare detailed LCA results of selected building components. Refer to a separate User Guide of the GREET Building Module (Cai et al., 2021) for details about how to conduct detailed LCA of building materials, technology solutions, and whole buildings with the module.

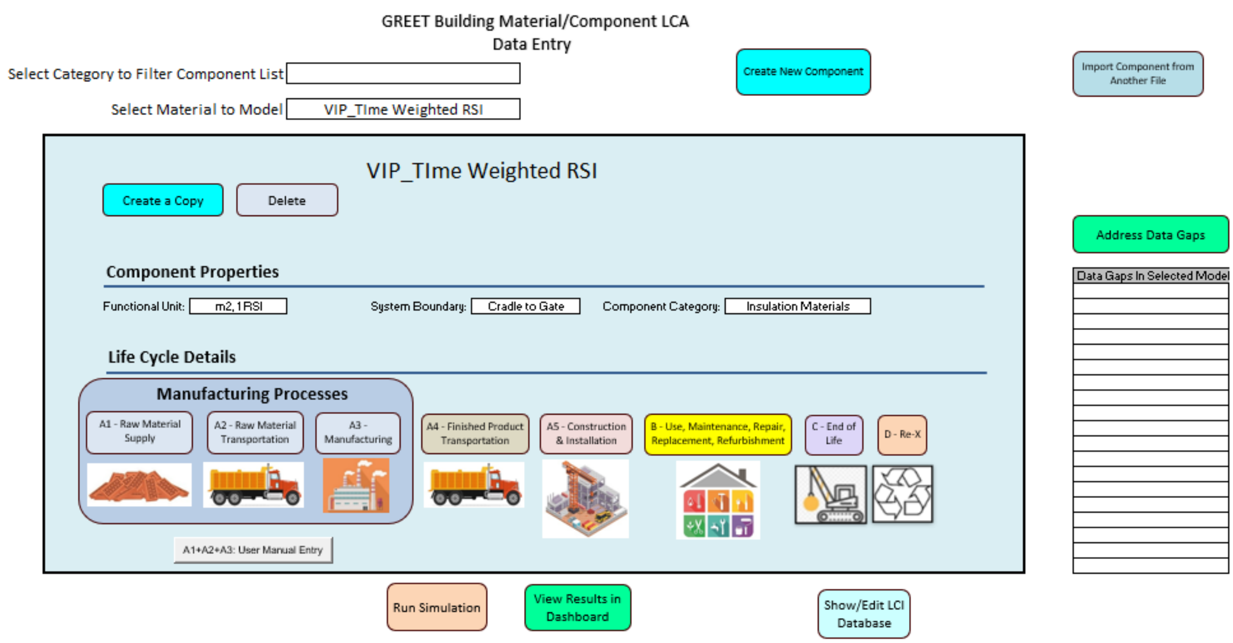


FIGURE 2. Overall Graphical User Interface of the GREET Building LCA module

5. CASE STUDIES OF EMBODIED GHG EMISSIONS OF BUILDING COMPONENTS

We conducted detailed LCA of VIP with a fumed silica core, an emerging insulation material with superior design thermal performance, as well as its conventional counterparts such as EPS, XPS, PUR foam, and a MFB. We collected detailed LCI data for these insulation materials, as presented in Appendix A.2. We aimed to test the LCA methodology as we discussed in Section 2 and the GREET Building Module by applying the methodology and the tool to estimate the embodied GHG emissions of these insulation materials. In this section, we present the modeling results of these insulation materials for demonstration purposes.

5.1 APPLYING ARGONNE LCA METHODOLOGY IN THE GREET BUILDING MODULE

We defined a Cradle-to-Use system boundary to model embodied GHG emissions of VIP and four rigid foam insulation counterparts, i.e., EPS, XPS, MFB, and PUR from the manufacturing of the insulation materials to its use phase. We excluded the end-of-life and potential recyclability of these materials in this case study, which warrant future evaluation. We defined a consistent, performance-based functional unit (FU), which is 1 m^2 of VIP and the counterpart insulation materials with a time-weighted thermal resistance RSI = 1 m^2K/W over a building service life of 60 years. This harmonic average performance throughout the service life for all insulation materials ensures consistent comparison of embodied GHG emissions.

The design R-values of VIP and counterpart insulation materials vary. For VIP, we assumed that a thermal performance of R-40 is designed at the beginning of the service life and it will experience a gradual decline of the thermal resistance over time due to loss of vacuum. We assumed that the VIP product would lose 100% of its vacuum, presenting a thermal performance of a R value of 8 at the end of the 60-year service life. As a result, we estimated a time-weighted R-value of 13.3, which equals RSI=2.35 m^2K/W over a service life of 60 years for VIP. For EPS and MFB, their designed thermal performance of a R value of 4/inch and 3.7 – 4.2/inch would remain the same throughout the service life of 60 years, and thus their time-weighted RSI value remains 1 m^2K/W throughout the service life. For XPS, it is known that its R-value will decline overtime due to loss of the blowing agent. It is estimated that the R-value will decline by as much as 14% over 50 years (EPS Industry Alliance, 2016). With this information, we estimated a time-weighted R-value of 5.3, which equals RSI=0.925 m^2K/W over a service life of 60 years for XPS. For PUR, its R-value may decline from 1.2 RSI to 0.97 RSI, or a 19% decrease in thermal resistance, after 5-10 years due to loss of pentane as the blowing agent during the timeframe (Engineers Edge, 2020). Choi et al. (2018) measured and reported that the thermal resistance of rigid polyurethane decreased by 22.5 % to 27.4 % in comparison with the initial thermal resistance after about 5000 days. Here, we assumed that the R-value would decline by 25% in year 60, which translates to an estimated time-weighted R-value of 4.9, which equals RSI=0.86 over a service life of 60 years for PUR. Figure 3 illustrates that the RSI values of these insulation materials may change over time. In summary, the time-weighted average RSI values of VIP, EPS, MFB, XPS, and PUR are 2.35, 1.0, 1.0, 0.925, and 0.86, respectively, after considering potential decline in thermal performance, in comparison to the initially designed RSI values of 7.0, 1.0, 1.0, 1.0, and 1.0, respectively.

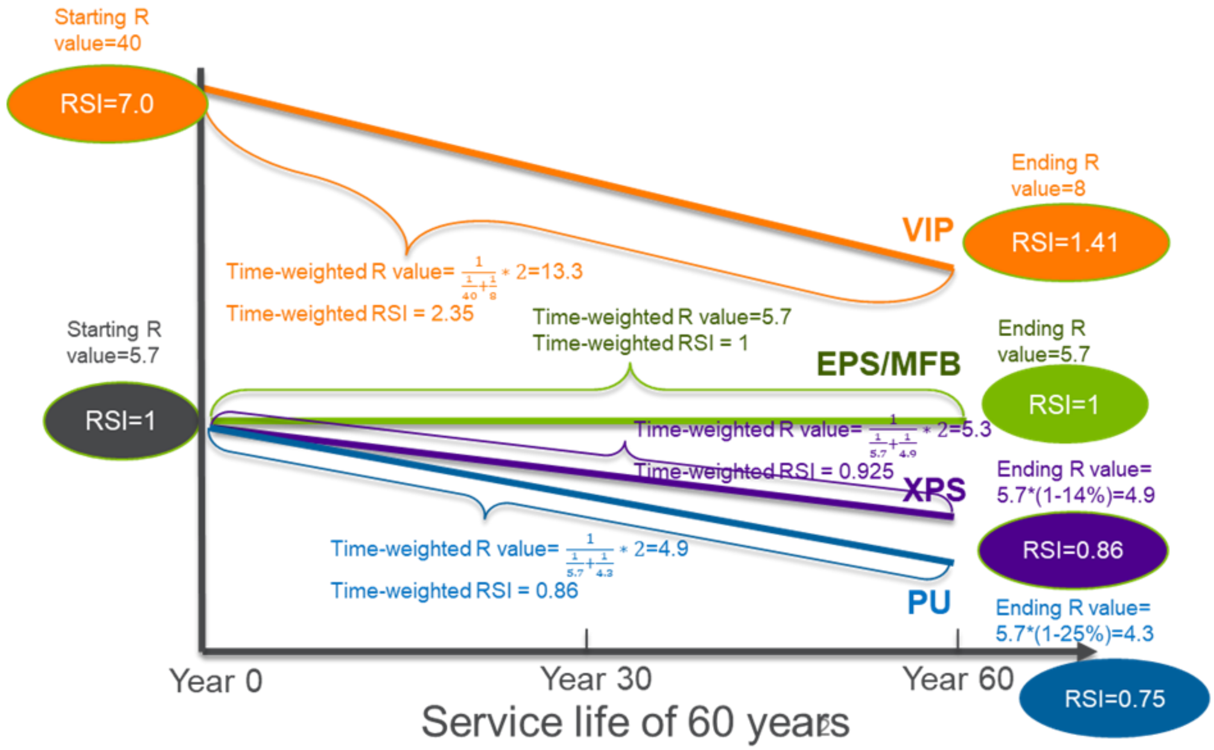


FIGURE 3. Time-weighted RSI values of VIP, EPS, MFB, XPS, and PUR, in comparison to the initial designed RSI value as shown in the y-axis and the estimated RSI value at Year 60.

Note that although the functional unit we used to evaluate the embodied GHG emissions is normalized at 1 m^2 of the insulation material with a given thickness that would offer a lifetime average thermal performance of 1 RSI, the actual thickness of each insulation material varies by design. For example, the designed thickness of the VIP is 1-inch thick, while EPS, XPS, MFB, and PUR can come with a wide range of thicknesses with varying R-values for different building applications. In this case study, we normalized the life-cycle inventories (LCIs) that would be required to make these insulation materials to offer a time-weighted RSI = 1 m^2K/W over a service life of 60 years.

The performance-based functional unit we defined allows for consistent comparison of the Cradle-to-Use embodied GHG emissions of the VIP insulation product and other more conventional insulation materials. However, the embodied GHG emissions of these insulation products, being VIP or PUR or EPS, for actual design dimensions and the thermal performances, would need to be scaled up or down based on the lifetime average RSI value of the product design and its thickness. For example, the embodied GHG emissions of the VIP on a 1 m^2, 1-inch thickness basis, which offers a lifetime weighted average RSI of about 2.35, would require scaling up the estimated embodied GHG emissions of VIP based on a 1 m^2 and a lifetime average RSI of 1 by a factor of 2.35.

We compiled the LCIs of these insulation materials from literature and summarized in Appendix A.2. We incorporated the normalized LCIs into the GREET Building Module across the Cradle-to-Use life-cycle stages. We applied the displacement method to address any co-products that may involve in the production of any raw materials required to manufacture these insulation materials, e.g., 2.4 kg hydrochloric acid that is co-produced during the flame hydrolysis conversion process to produce 1 kg of fumed silica, the core material to produce VIP, and any co-products that may involve in the production of the finished product. Compared to the displacement method, a mass-based allocation method would result in a smaller amount of embodied GHG emissions being attributed to fumed silica, as shown in Figure 4.

We highlighted the impact of choices of different co-product handling methods on the results, but we did not conclude on which particular co-product handling method would be preferred in this particular case. Appropriate choices of method usually depend on the type, quantify, regulatory requirement (if any), and purpose of the co-product from the process design standpoint. Maintaining the transparency and explaining the implications would be key when co-products are involved, especially their impacts are significant.

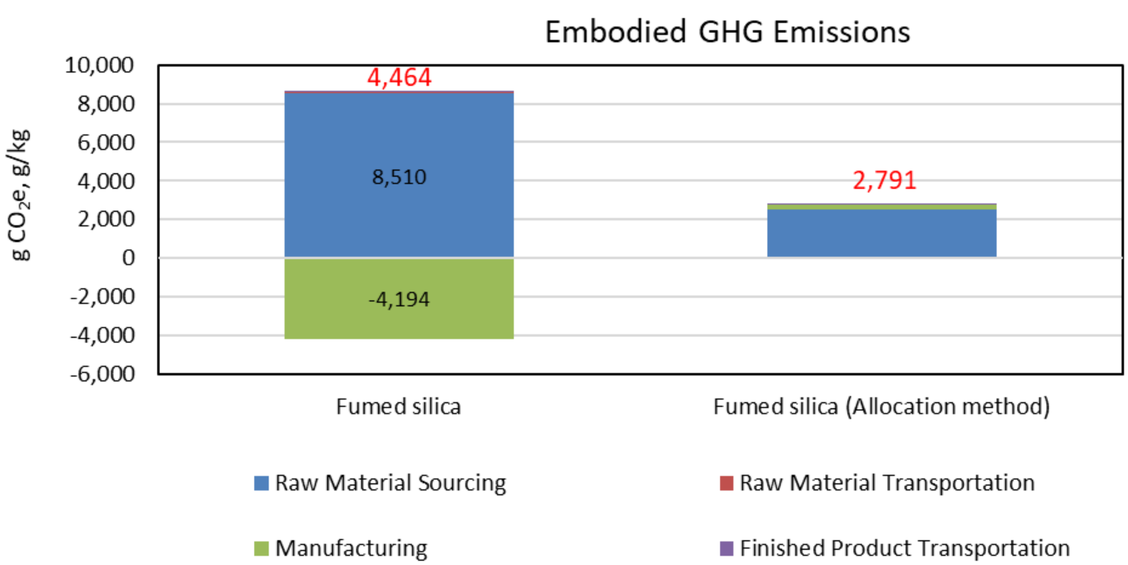
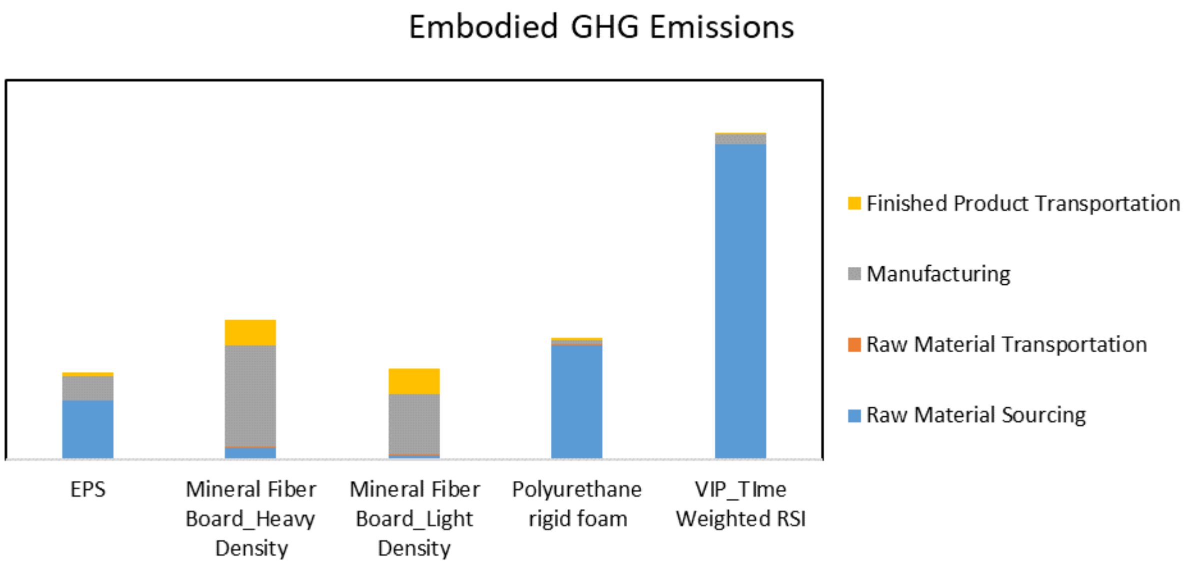


FIGURE 4. Impact of choices of co-product handling methods on embodied GHG emissions of fumed silica, produced via the flame hydrolysis process that co-produces a significant amount of hydrochloric acid.

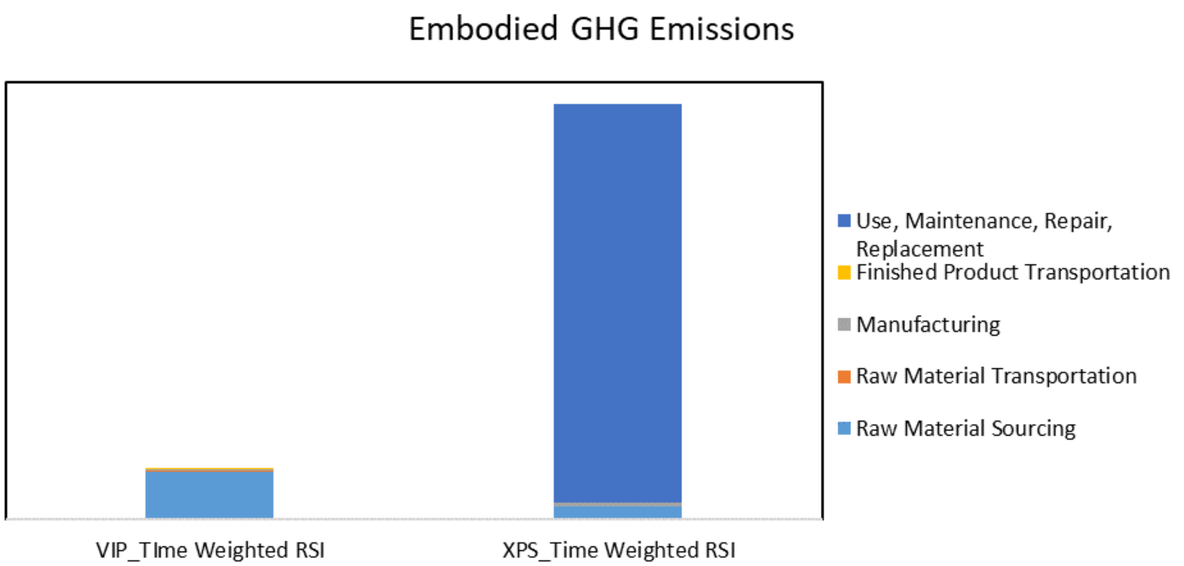
5.2 ILLUSTRATIVE EMBODIED GHG EMISSIONS OF VIP AND COUNTERPARTS

We present the embodied GHG emissions of the fumed silica-based VIP and the rigid foam counterparts, as well as the key drivers in sensitivity analysis in Figures 5-6. Note that these estimated embodied GHG emissions are not intended for comparison to what may be reported in EPDs due to differences in the scope, assumptions, and background data adopted in the underlying LCA studies. Rather, these sample results are illustrative of the outputs of applying the methodology to conduct LCA of building materials with the GREET Building Module.

Figure 5 shows that fumed silica-based VIP is more GHG-intensive than other rigid foam counterparts except for XPS. XPS stands out as the most GHG emission intensive insulation material compared to other rigid foam insulations including VIP, owing to our assumption that it contains HFC-134a as a blowing agent, which leaks during the use phase that could be 1,430 times as potent as CO_2 for global warming effect. XPS historically used CFC-12 as the blowing agent, and then predominantly transitioned to HCFC-142b/22 blends. In developed countries, HFC-134a and HFC-152a have replaced some ozone-depleting substances use, although other low-GWP options—isobutane, di-methyl ether, blends of those two agents, and CO_2—are also used. There are challenges associated with the adoption of various low-GWP alternatives. For example, hydrocarbons and di-methyl ether expose high flammability; CO_2 increases quantities of foam required to accommodate lower insulation value, has poor stability when used as sole blowing agent, has poor gas and foam thermal conductivity, and exhibits high permeability through cell walls. Hydrofluoroolefin (HFO) is being evaluated for this application but is not commercially available. In the current analysis, we assumed that the blowing agent used for the XPS is 100% HFC-134a. If other blowing agents were used in different designs of XPS, the embodied GHGs and thermal insulation performance need reevaluation and would likely be different.



(a)



(b)

FIGURE 5. Embodied GHG emissions of fumed silica VIP, in comparison to (a) EPS, light density and heavy density mineral fiber board, and polyurethane rigid foam; and (b) XPS. The comparison is on a relative basis and serves for illustrative purposes.

Figure 5 also shows sources of embodied GHG emissions of fumed silica VIP, in comparison to those of the counterparts. VIP, PUR, and EPS can attribute their emissions largely to the raw material sourcing stage, while the manufacturing stage is the key source of emissions for high density and low density MFB. Embodied GHG emissions of XPS is dominant by the release of blowing agent HFC-134a during the use phase.

Figure 6 further shows key drivers of cradle-to-construction embodied GHG emissions of fumed silica VIP, in comparison to those of the counterparts. These insights help identify hotspots and key emission drivers for opportunities to tackle the emission hotspots and mitigate the emission impacts of a product. For example, fumed silica VIP is driven by use of the core material, fumed silica, which undergoes an energy-intensive flame hydrolysis that involves silicon tetrachloride as a reagent that takes metallurgical grade silicon to make. Polyurethane rigid foam is also driven by the two major reagents, polyether polyol and methylene diphenylene diisocyanate (MDI). For EPS, the virgin quality EPS resin, or polystyrene, is a key emission driver, together with the electricity requirement during the manufacturing step. For mineral fiber board, energy consumption during the manufacturing step could be the major contributor, which needs to be confirmed with updated data from the industry. Transportation is shown as another major emission source, due to underutilization of the truck payload, as well as long distance transportation (>1,000 miles) of the finished product to the construction sites.

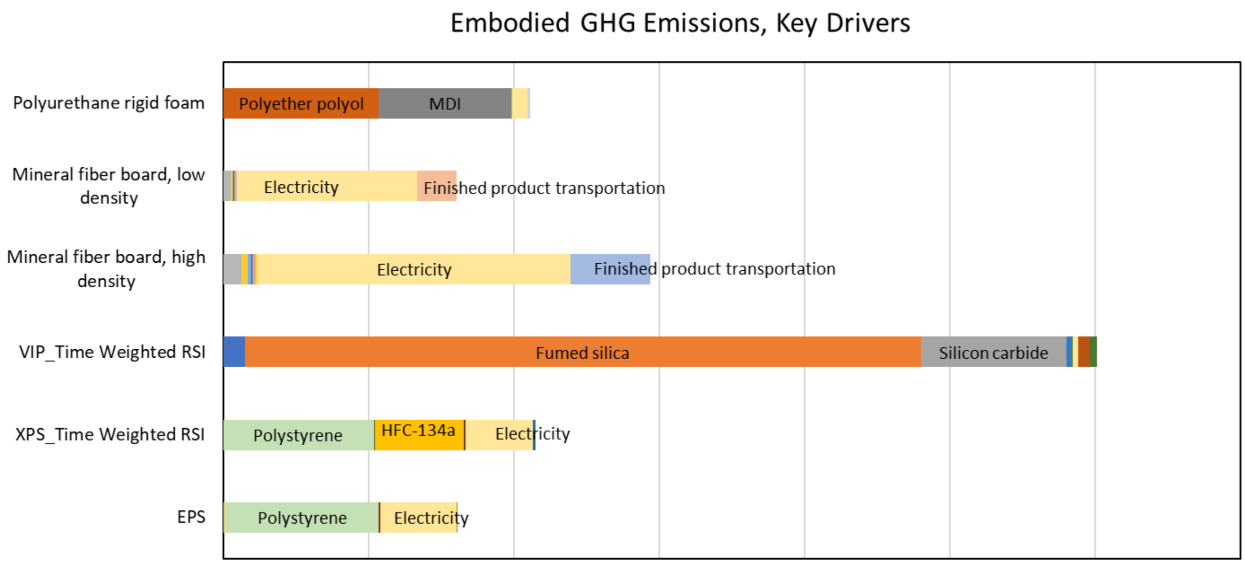


FIGURE 6. Key drivers of cradle-to-construction embodied GHG emissions of fumed silica VIP, in comparison to those of the counterparts. Note that the impact of blowing agent leakage during the use phase is excluded here for XPS.

5.3 SENSIVITY ANALYSIS OF EMBODIED GHG EMISSIONS OF VIP AND COUNTERPARTS

Figure 7 illustrates sensitivity analysis of the potential embodied GHG emissions impacts of durability and thermal performance of VIP throughout its service life of 60 years. Depending on possible failure and degradation modes of VIP and the resulting time-weighted thermal performance that could deviate significantly from the originally designed thermal performance, the embodied GHG emissions of VIP to achieve an average thermal performance of 1 RSI could vary widely. The more durable and reliable of the thermal performance, the less embodied GHG emission impacts VIP would have.

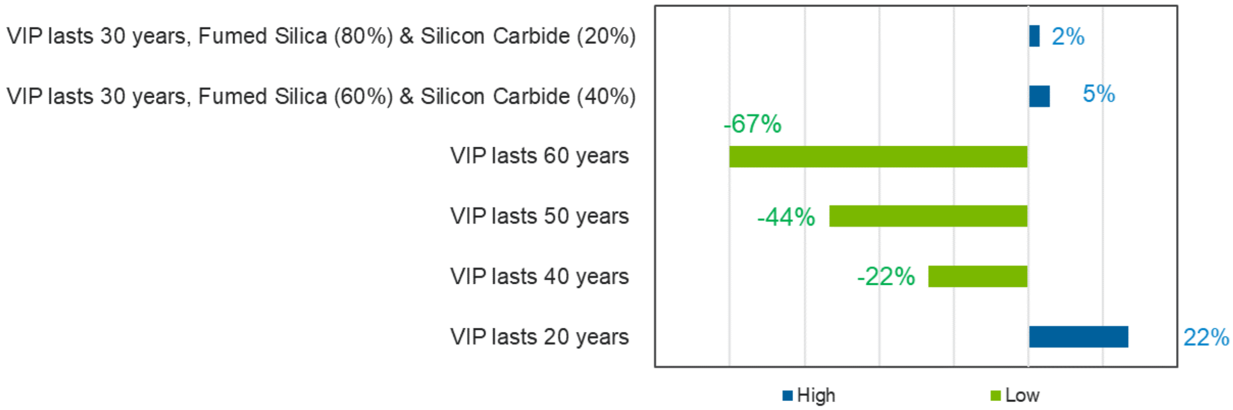


FIGURE 7. Sensitivity analysis of embodied GHG emissions of VIP: durability of VIP is a key factor that could vary its embodied GHG emissions significantly.

Figure 8 shows that increasing the recycled EPS resin content for EPS may offer the greatest opportunity to reduce the embodied GHG emissions. Improvement in energy efficiency and reduction in electricity consumption during the manufacturing step could be another major opportunity to mitigate the emissions.

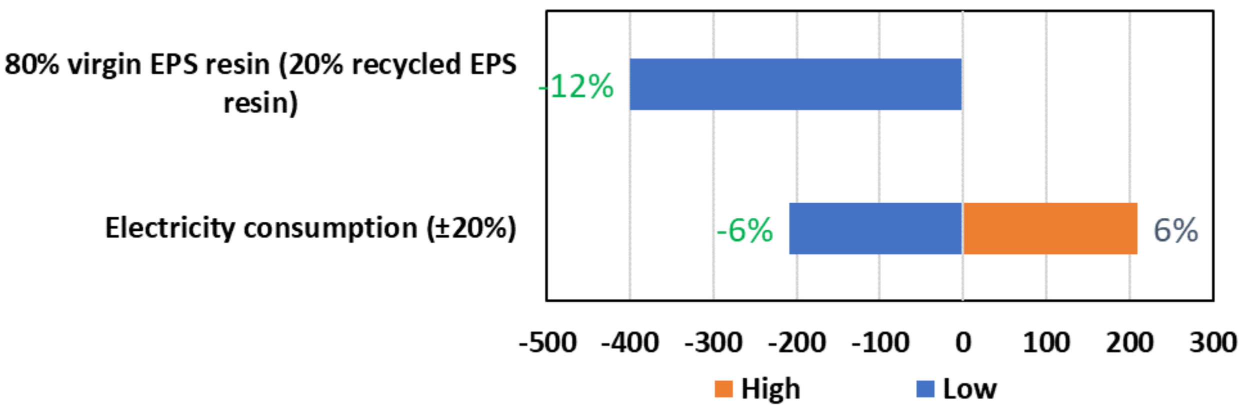


FIGURE 8. Sensitivity analysis of embodied GHG emissions of EPS: material composition, i.e., the share of virgin EPS resin, and electricity consumption during manufacturing are key factors that could vary the embodied GHG emissions significantly for EPS.

Figures 9 and 10 shows that reducing electricity consumption could be an effective measure to reduce embodied GHG emissions of mineral fiber boards. Transportation related emissions could be curbed if production of MFBs near construction sites.

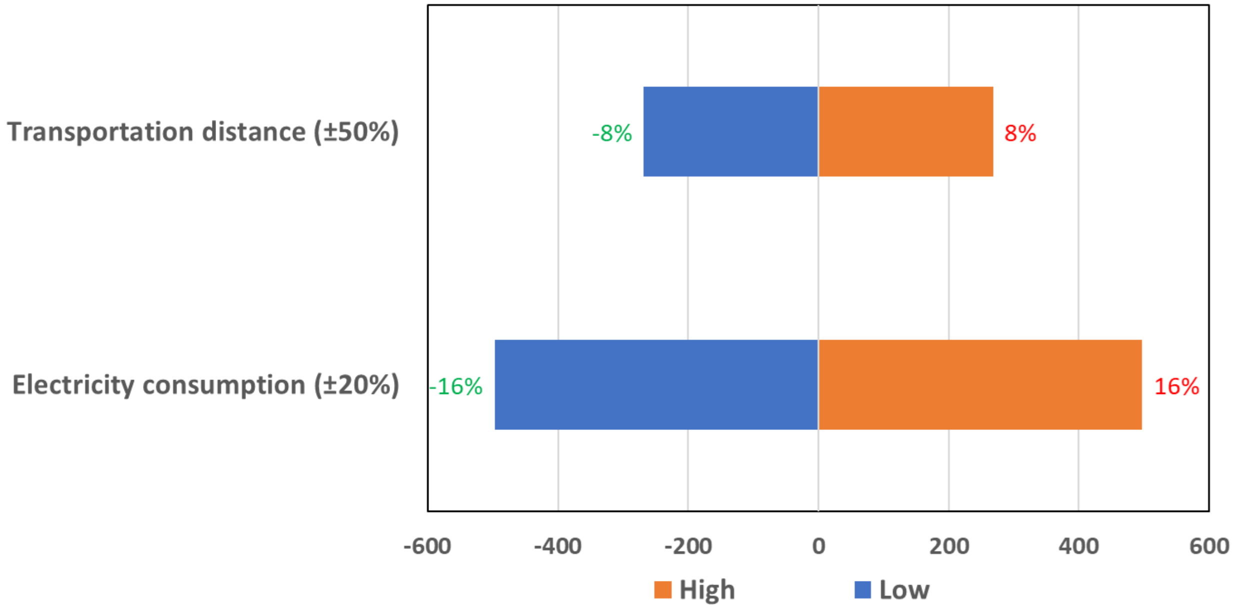


FIGURE 9. Sensitivity analysis of embodied GHG emissions of MFBs: transportation distance and electricity consumption during manufacturing are key factors that could vary the embodied GHG emissions significantly for light density MFB.

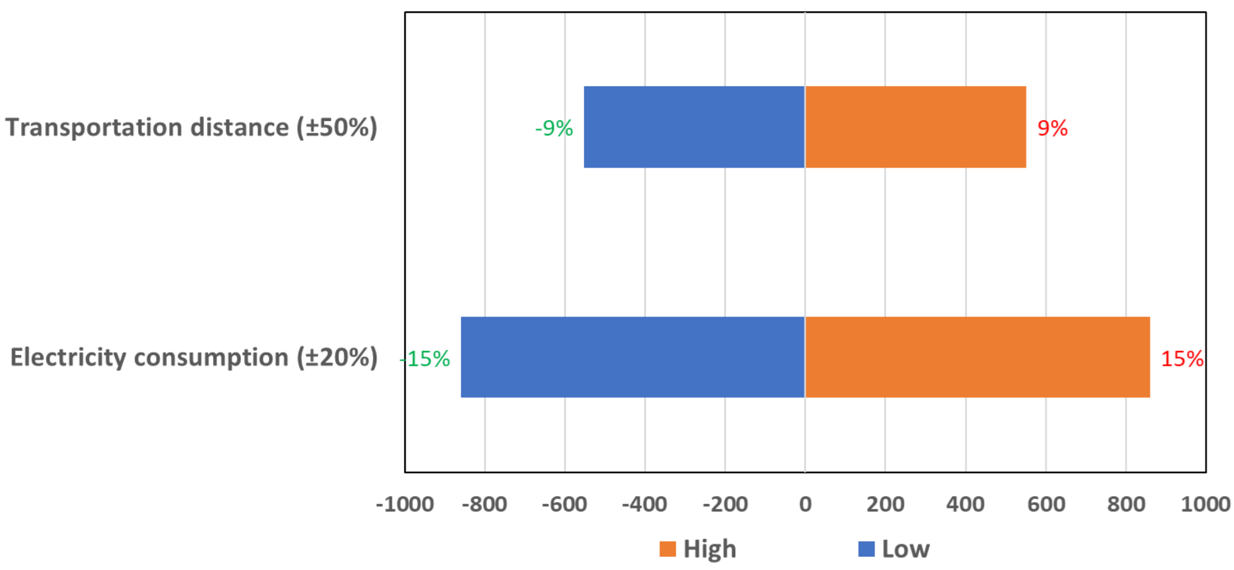


FIGURE 10. Sensitivity analysis of embodied GHG emissions of MFB: electricity consumption during manufacturing and transportation distance are key factors that could vary the embodied GHG emissions significantly for high density MFB.

Figure 11 shows that if highly GHG-intensive blowing agents, i.e., HFC-134a, could be replaced with a low-GHG blowing agent, or its usage could be reduced, the GHG emission impact during the use phase could be greatly mitigated. Research on developing low-GHG impact substitute blowing agents could be a key to minimize such impacts during the use phase.

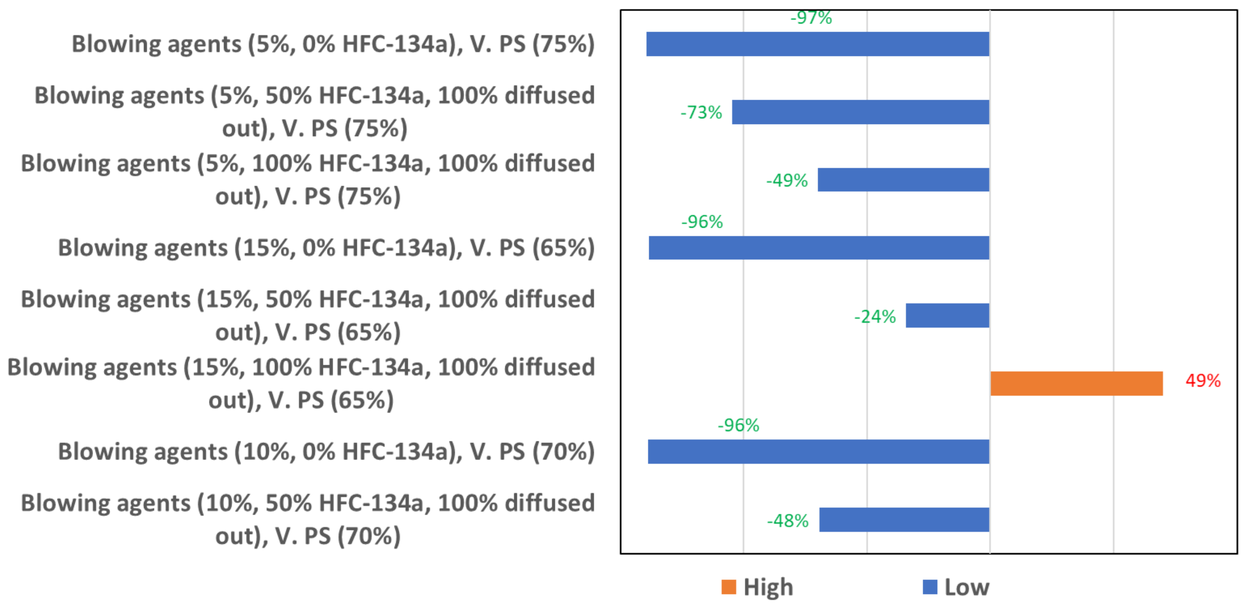


FIGURE 11. Sensitivity analysis of embodied GHG emissions of XPS: choice, usage, and fate of blowing agents during the use phase are key factors that could vary the embodied GHG emissions significantly for XPS. PS represents polystyrene.

APPENDIX.
MATERIAL AND ENERGY DATABASE OF BUILDING MATERIALS

A.1 STRUCTURAL MATERIALS

A.1.1 Steel

Introduction and applications: Steel is widely used as a major supporting material in residential and commercial buildings. The most common applications of steel in building infrastructure includes structural sections, reinforcing bars and rods, and sheet products. The structural sections provide a frame, bars and rods are used for foundations and basements along with concrete, and sheets are used as roofing material, walls, ceiling, and cladding. The world steel institute estimated about 44% of the steel used in a building is rods and bars, followed by 31% sheets and 25% structural form (Worldsteel 2020). The construction sector is the largest consumer of steel in the U.S. (43%), followed by the automotive industry (27%), machinery and equipment (10%), energy sector (7%), appliances (5%) and other (8%) (USGS, 2019).

System boundary and manufacturing: Typically, steel plants use two routes to manufacture steel products – a) primary steel via integrated mills and b) secondary steel via mini-mills. The primary steel production uses basic oxygen furnaces (BOF) to process iron (or hot metal) from iron ore (Worldsteel 2017). Secondary steel production generally refers to the recycling route, which converts scrap steel into new steel by re-melting in an electric arc furnace (EAF). While the BOF plants were common until the mid-1970s, because of the development of effective recycling and processing technologies, the EAF routes of steel production are increasing (Hua et al., 2019). The use of the EAF route now accounts for nearly two-third of steel production in the United States (Statista 2020).

In the U.S., most steel manufacturing companies (over 50 companies) utilize the EAF route in mini-mills, whereas only three major companies utilize the BOF route in integrated steel mills (USGS 2019). Regardless of the steel production routes, the molten steel produced by both BOF and EAF processes follows similar routes after leaving the furnace. Figure A1 provides a visual description of the flow of materials through the steel production system. Since the majority of steel for buildings is produced via the EAF route using recycled steel, we consider this route and highlight that scrap steel (recycled scrap) is a major input to the EAF process. Additionally, the transportation stages for materials must be included for an inclusive accounting of energy inputs.

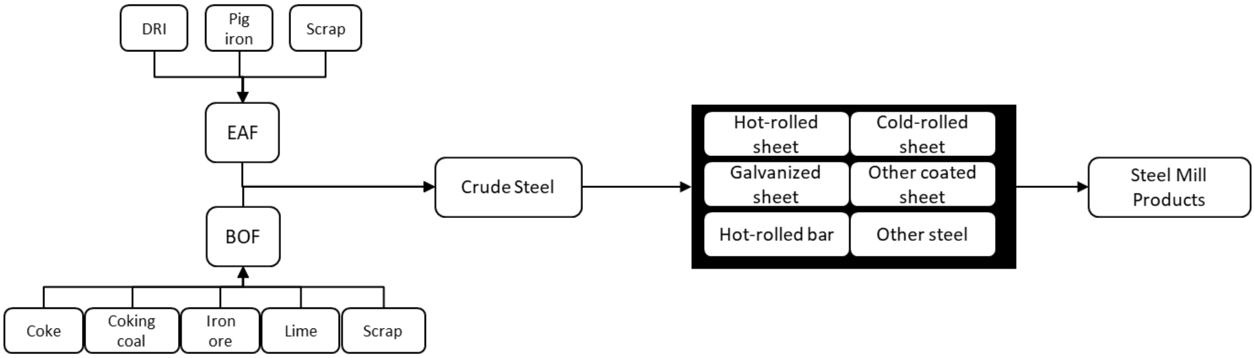


FIGURE A1. System boundary of steel production considered in the analysis.

In an EAF production route, steel scraps are collected as either post-consumer scrap from the industrial market or from runaround (in-house) scrap. Scrap from the market is transported to an EAF facility whereas runaround scrap can often be remelted within the home facility. In either case, the scraps are charged to the furnace in batches. The scraps are melted to generate a foamy slag. The crude steel is cast on a casting machine then controlled cooling is allowed. The cooled slab is then transported to the hot strip mill, reheated in the reheating furnace, and rolled into hot bands. The hot bands may be cold-rolled, annealed, and prepared in a finishing mill. Depending on the desired specifications of the final product, the hot bands from the hot rolling mill may be further processed in various ways, such as annealing, heat-treating (tempering), galvanizing, coating, or painting. Based on our communication with subject matter experts at the American Institute of Steel and Iron (AISI), the residential buildings mostly do not require additional processing such as annealing and galvanization. Therefore, we only consider up to the cold rolled and hot rolled steel sheets and rod and bars production. Figure A2 shows the manufacturing process of steel products via the EAF route. One of the important features of the EAF process is that since it primarily uses steel scrap; it uses less direct input energy to produce a ton of steel compared to the BOF route. It should be noted that EAF can also use direct reduced iron (DRI) or even pig iron, which are more energy-intensive feedstocks. We assume that the EAF plant does not use any DRI, which is not necessary to serve the building sector that may be more tolerant of lower grades of steel (as opposed to the automotive sector which requires high grades of steel and utilizes DRI to increase the steel grade).

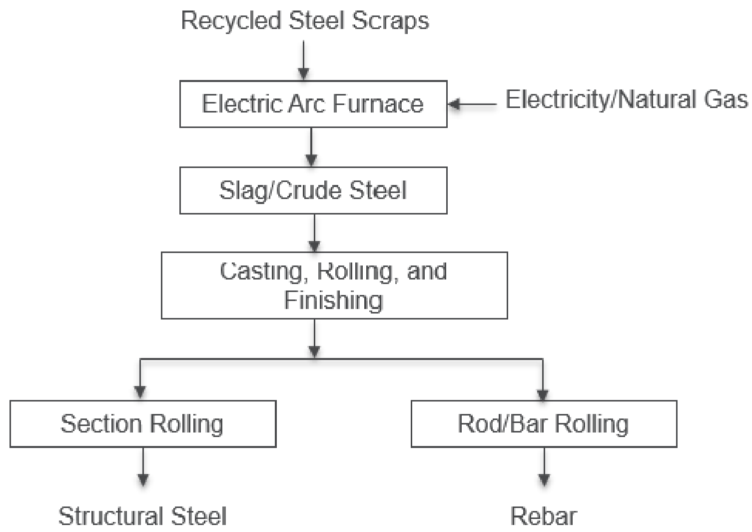


FIGURE A2. Typical manufacturing process of the steel using EAF route.

Life cycle inventory data: Argonne has been developing and updating process-level manufacturing data for steel production via both the BOF and EAF routes that are modeled in GREET2, our vehicle cycle life-cycle model (Burnham et al., 2006; Keoleian et al., 2012; Dai et al., 2017). These analyses focused on the automotive sector based on the historical focus of the GREET model on transportation. Given this focus, the life cycle inventory data developed for GREET utilized both BOF and EAF steel data available from the steel industry and focused on the routes that were dominant in the automotive industry. BOF steel has traditionally been utilized for automotive steel products with upwards of 80% of the vehicle's steel being virgin. But EAF steel is also used in the automobile and that manufacturing technique was also modeled using data from industry reports. In GREET, recycled steel is assumed to consume scrap steel and energy (coke, natural gas, and electricity) in the EAF process, it is then processed through a rod and bar mill, and finally subjected to machining. The rod and bar mill requires 1.043 tons of input steel per ton of output steel, while the machining process is assumed to be lossless.

As we noted, the grades of steel used within buildings is different than that used within the automotive sector. Therefore, while the EAF approach used in GREET may be representative of the recycled steel used within buildings, we conducted a literature and industry review to understand the energy inputs required within that sector.

Literature review:

Athena Sustainable Materials Institute (2002) collected and modeled the life cycle inventory of steel products produced by different mill types in Canada and the US. Inventory data is developed for products including 1) welded wire mesh, ladder wire, 2) rebar, rod, light sections, 3) hot rolled sheet, 4) cold rolled sheet, 5) galvanized sheet, 6) galvanized studs and others. The data is representative of US average recycled contents and is summarized in Table A1.

TABLE A1. Life cycle inventory of steel products (per tonne of product)

Inputs	Nails	Welded wire mesh, Ladder wire	Rebar, Rod, Light sections	Hot rolled sheet	Cold rolled sheet	Galvanized sheet	Galvanized studs	Screws, Nuts, Bolts	Unit
Materials									
Lime	70.82	56.82	53.38	61.02	60.17	65.31	71.56	68.71	kg
Limestone	41.48	11.49	7.08	38.95	20.47	39.50	59.44	29.68	kg
Iron ore (pellets)	997.97	252.39	153.27	1106.70	491.41	791.27	1190.66	754.51	kg
Prompt Scrap	185.97	342.72	354.82	131.80	289.20	160.41	32.27	274.19	kg
Obsolete Scrap	313.57	546.51	563.48	226.86	466.37	272.27	79.64	447.13	kg
Scrap Prompt and Obsolete	499.54	889.22	1155.04	358.66	755.57	432.67	111.92	721.32	kg
Coal Total	395.69	109.56	67.54	371.51	195.21	348.67	524.65	276.38	kg
Energy									
Chemical Heat	2064.29	330.71	97.29	2181.54	873.95	1856.11	2944.01	144.32	MJ
Embodied Energy - Prompt Scrap	3253.15	6832.78	7087.53	1345.71	5539.53	3249.15	717.56	4867.31	MJ
Energy from Coal	11874.21	3287.89	2026.76	11148.64	5857.89	10463.10	15744.07	8293.74	MJ
Energy to pellets	74.36	4.18	0.00	45.71	442.06	17.91	0.00	108.88	MJ
Electricity	6763.66	4638.80	2464.54	4668.06	4104.86	5205.45	5306.15	5515.21	MJ
Natural gas	7578.88	6266.68	5419.48	4237.80	4487.04	3036.28	1849.35	7968.88	MJ
Bunker oil	350.46	97.04	59.82	329.03	172.89	308.80	464.70	244.80	MJ
Oxygen	320.94	156.61	129.94	291.38	204.28	106.43	405.35	262.47	MJ
Diesel fuel	148.42	163.63	178.43	225.78	185.27	106.43	136.24	154.09	MJ
Light fuel oil	174.07	48.20	27.62	163.43	85.89	153.20	230.80	121.59	MJ
Coke	122.80	246.21	256.70	74.40	202.23	101.66	0.00	192.86	MJ
Gasoline	2.26	0.63	0.39	3.36	1.35	2.00	3.00	1.58	MJ

The AISI publishes LCA studies of various steel products manufactured via EAF and BOF-EAF mixed plants (Montalbo 2017). Moreover, we also reviewed several EPDs published by multiple steel manufacturers. The AISI LCA study on steel production based on EAF reported a total energy requirement of 10.8 mmBtu/ton, which is within the range as incorporated in the GREET model (10.1 mmBtu/ton). Table A2 shows the life cycle inventory data of steel products used in the building sector. Table A2 summarizes the input materials and energy associated with the EAF process as well as the input energy and loss factors to produce rebar/rods along with a machining process. GREET categorizes recycled steel as progressing through the EAF process, rebar/rod stage and through machining.

TABLE A2. Life cycle inventory of structural steel and rebar production via the EAF route.

Inputs	**Units**	**EAF process**	**Rebar/Rods**	**Machining**	**Total**
Loss Factor			1.043	1.00	
Energy					
Coke	mmBtu	0.17	-	-	0.17
Natural gas	mmBtu	1.19	2.15	-	3.34
Electricity	mmBtu	4.99	1.07	0.54	6.60
Outputs	short tons	1	1	1	1

A.1.2 Concrete

Introduction and applications: Concrete is the one of the most important and widely used building materials. Its unparalleled advantages, such as its strength, durability, fire stability, versatility, cost-effectiveness, recyclability and others, made it the predominant material for infrastructure systems including buildings, bridges, highways and others. Worldwide, over 10 billion tons of concrete is produced each year, while in the United States only, the annual shipment of ready-mixed concrete is about 378 million cubic yards in 2020 (Concrete Financial Insights, 2021). Concrete is produced in four basic forms: ready-mixed concrete, precast concrete, cement-based materials, and advanced products incorporating fibers and special aggregates (Portland Cement Association, 2021). Ready-mixed concrete designs that vary by the mix of cement, aggregate, sand, water, among other ingredients, can be modeled with the GREET Building Module to address their embodied GHG emissions.
To better understand the designs of ready-mix concretes and their associated applications, we reached out to National Ready Mixed Concrete Association (NRMCA) and received informative inputs from Mr. Lionel Lemay and Mr. James Bogdan. Typical 28-day strengths in pounds per square inch (psi) of different ready-mixed concrete designs for different applications are summarized in Table A3.

TABLE A3. Ready-mixed concrete designs of different strengths for different applications

Category	Type	Detail	Region	Concrete PSI
Pavement	Highway		North climate zone	4,750
			South climate zone	4,500
	Local roads/streets		North climate zone	4,750
			South climate zone	4,500
	Public parking lots		North climate zone	4,750
			South climate zone	4,500
Building, residential	Single-family houses	Footers		3,000
		Basement slab/Slab on grade		3,000
		Basement wall		3,000
		Driveways, patios, sidewalks	North climate zone	4,000
			South climate zone	3,000
	Multi-family apartment buildings (low rise)	Foundation		3,000
		Basement wall		4,000
		Above grade walls		4,000
		Elevated slabs		4,000
		Parking lots, patios and sidewalks	North climate zone	4,000
			South climate zone	3,000
	Multi-family apartment buildings (high rise)	Post-tensioned slab		5,000
		Mat foundation		6,000
		Basement walls		5,000
		Floors		5,000
		Shear walls		6,000
		Columns		8,000
Building, commercial	Low rise	Post-tensioned slab		5,000[1]
		Mat foundation		6,000
		Basement walls		5,000
		Floors		5,000
		Shear walls		6,000
		Columns		8,000
	High rise	Post-tensioned slab		5,000
		Mat foundation		6,000
		Basement walls		5,000
		Floors		5,000
		Shear walls		6,000
		Columns		8,000
Stationary/Industry	Power plants	Coal-/natural gas-fired power plants		5,000[2]
		Hydropower dams		3,000-5,000[3]
		Nuclear power plants		5,000[2]
	Petroleum refineries			5,000[2]

TABLE A3. (Cont.)

Category	Type	Detail	Region	Concrete PSI
Stationary/Industry	Power plants	Coal-/natural gas-fired power plants		5,000[2]
		Hydropower dams		3,000-5,000[3]
		Nuclear power plants		5,000[2]
	Petroleum refineries			5,000[2]

[1] Typically post tensioned slab for mid/high-rise residential buildings has a strength of 5,000 psi at 28 days as the design criteria, but developers may require 8,000 psi concrete instead;
[2] Rough estimation
[3] 3,000 to 5,000 psi at 28-days is typical, but 8,000 to 10,000 psi depending on type of structure and design life is widely used. Large mass concrete structures can be on the order of 2,500 to 3,500 psi at 90-days (1,500 to 2,000 psi at 28-days) to reduce heat of hydration.

System boundary and manufacturing process: Four types of technologies for cement production, wet, dry, dry with preheater, and dry with precalciner, are considered. The production process of concrete involves cement production, gypsum quarrying, clay quarrying, sand and gravel quarrying, and concrete ready-mix production. Figure A3 shows the manufacturing process of concrete (Hawkins et al., 2020).

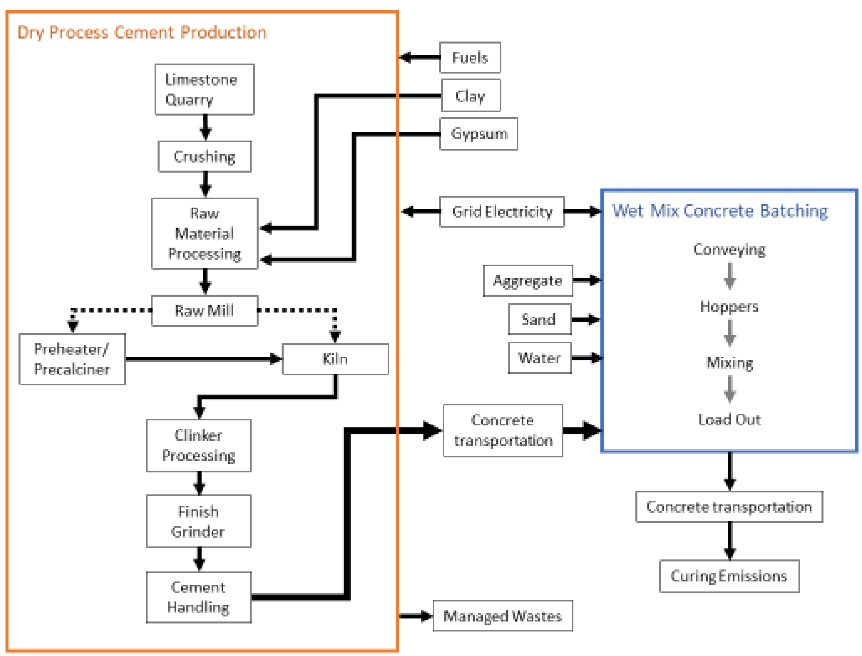


FIGURE A3. Typical manufacturing process of cement and concrete

Functional unit: The functional unit for ready mixed concrete is one cubic yard.

Literature review: Compared to studies focusing on the European or Asian markets, few studies and databases have reported the life cycle GHG emissions of concrete products in North America. One recent study commissioned by NRMCA (Athena Sustainable Materials Institute, 2020) collected inventory data from the United States and Canada. It conducted Cradle-to-Gate assessments for 72 ready-mixed concrete products. It also reported results for US national average and 8 regions. For example, the life cycle GHG intensity for normal weight concrete of 4,000 psi (27.6 MPa, 28-day strength) is 0.148 ton of GHG per ton of concrete, while the result for light weight concrete of the same strength is 0.445 ton of GHG per ton of concrete. Studies have also been conducted on concrete masonry unit. For example, Canadian Concrete Masonry Producers Association (CCMPA) reported an intensity of 0.116 ton of GHG per ton of concrete for normal weight concrete masonry unit and that of 0.148 ton of GHG per ton of concrete for light weight concrete masonry unit.

Life cycle inventory: The cement LCA results modeled with GREET2, which was based on facility-level data from EPA NEI and Greenhouse Gas Reporting Program (GHGRP) databases, together with production capacities, utilization rates, and other facility-specific technology details from the Portland Cement Association and the USGS Minerals Yearbook (Wang et al., 2019), are incorporated into the GREET Building Module. LCI of material composition and energy consumptions of different ready-mixed concrete designs that possess different strengths are collected from NRMCA's national benchmark studies (Athena Sustainable Materials Institute, 2020) and summarized in Table A4.

Table A4. Life cycle inventory of material composition and energy consumption of ready-mixed concrete designs of different compressive strengths

Compressive Strength	2500	3000	4000	5000	6000	8000	3000 LW	4000 LW	5000 LW	Unit
Material										
Portland Cement	354	394	475	576	610	719	394	475	556	lbs
Fly Ash	62	69	83	101	107	126	69	83	97	lbs
Slag Cement	17	19	23	28	30	35	19	23	27	lbs
Mixing Water	305	305	305	315	341	341	308	308	308	lbs
Crushed Coarse Aggregate	1,126	1,115	1,083	1,029	1,061	1,018	0	0	0	lbs
Natural Coarse Aggregate	553	547	531	505	521	499	0	0	0	lbs
Crushed Fine Aggregate	169	167	162	154	159	152	161	149	136	lbs
Natural Fine Aggregate	1,282	1,270	1,233	1,171	1,208	1,159	1,225	1,130	1035	lbs
Lightweight Aggregate	0	0	0	0	0	0	1386	1279	1171	lbs
Total Weight	3,867	3,886	3,895	3,878	4,037	4,049	2,178	2,168	2159	lbs
Energy										
Electricity	3.22									kWh
Natural gas	11.98									Cubic ft
Diesel	0.32									gal
LPG	0.01									gal
Fuel oil (other than diesel)	0.01									gal
Water										
Water	23.03									gal

The energy requirements for crushed coarse aggregate and crushed fine aggregate are approximated by the energy for crushing limestone (US Department of Energy, 2002), which is 2,655 btu/ton aggregate.

A.2 INSULATION MATERIALS

A.2.1 Fiberglass

Introduction and applications: Insulation is found in almost all modern buildings, with fiberglass insulation being the most popular type of insulation (US DOE 2020). Fiberglass insulation is an important building material, which is mostly used as a wall insulation material to maintain temperature or for acoustic purposes. Traditional insulation materials include glass fiber, expanded polystyrene, mineral wools, and polyurethane foam, etc. Fiberglass insulations are applied in different forms and types. Some of the commonly used fiberglass insulation types are loose fill, batts, Kraft faced batts, duct tape, pipe and duct board (PE International 2011). The characteristics of these fiberglass insulation products vary depending on the intended applications.

System boundary and manufacturing process: The production of fiberglass begins with batch preparation and the melting of raw materials in a furnace. Raw materials include soda ash, borax, cullets, limestone, and binders among others. At the furnace, raw materials are melted at a very high temperature and the melt outputs are turned into fibers. The fibers are then glass coated and collected on conveyers. The curing oven provides required heat to cure the fibers, which then are sawn or cut to the required sizes for batts. In the case of loose fill, the same production method is used except the insulation material is kept loose and unbonded. Scrap materials are typically recycled back into the production process (PE International 2011). Figure A4 shows the fiberglass manufacturing process and system boundary considered in this study.

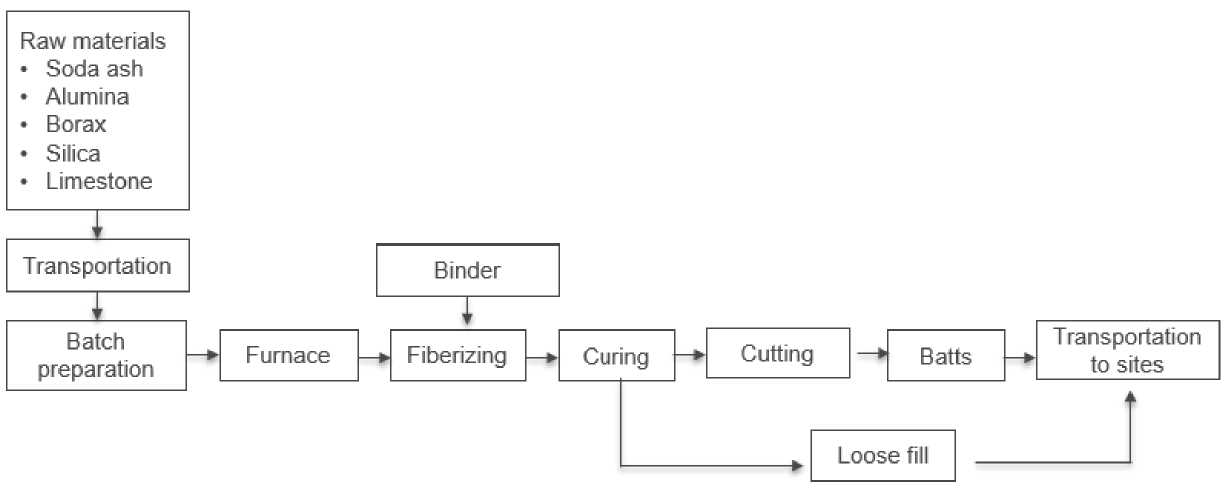


FIGURE A4. System boundary of the study and fiberglass manufacturing process as described in literature.

Functional unit: The major function of fiberglass products is insulation, which varies by several factors such as thickness and insulation capacity. Therefore, the functional unit selection is important in energy and emissions calculation for fiberglass products. Because the standard units of these materials do not have the same insulating capacity, the comparison of the results on a per-unit-of-output basis is not appropriate. This highlights that a fair comparative functional unit for fiberglass insulation should account for the thermal performance of the products. The thermal performance is measured in terms of R-value. Typically, when the operation stage of the building is considered, the functional unit for insulation materials including fiberglass is one square meter of insulation with a thickness that provides an average thermal resistance of 1 m^2K/W. The R values considered by residential insulation range from R-11 to R-38 (PE International, 2011). Since our focus is to document the manufacturing of the building materials, we consider a functional unit of 1 kg of fiberglass production. The thermal performance-based functional unit, which considers the thermal conductivity of fiberglass during its service life as an insulation material in a building, will be included in the upcoming reports.

Life cycle inventory: We reviewed several EPDs, existing building LCA models, trade association LCA reports, and literature to collect the life cycle inventory of fiberglass production. As highlighted in previous sections, the EPDs and existing building LCA models do not provide material and energy inputs data at process level. After the review of the available data sources, we decided to use the LCI data based on the fiberglass trade association – North American Insulation Manufacturer's Association (NAIMA). NAIMA is a trade association representing over ten insulation manufacturers in the U.S., Canada and Mexico. In 2011, the NAIMA published an LCA study of fiberglass production for loose fill and batts. The industry wide average LCI data, which were reported by NAIMA, are more representative of fiberglass industry in the U.S (PE International 2011). Since the NAIMA LCA report is based on relatively old technology, we also validated the NAIMA LCI data with recently published individual EPDs and existing building LCA models such as BEES. The life cycle inventory is representative of a weighted average for the fiberglass industry, and not specific to a product dimension. Table A5 shows the raw material inputs by percentage considered in the reviewed sources. For instance, BEES data assumes 9% of soda ash in the fiberglass batt and loose fill types. This soda ash composition varies between 25-50% as reported in the EPDs. This higher range of soda ash composition reported in the EPDs are mainly due to the variations in products specifications manufactured by individual manufactures. The NAIMA LCA report uses 8% composition of soda ash in fiberglass batt and loose fill. Similarly, another important raw material borax composition share is about 12% for batts and 13% for loose fill in BEES, whereas the EPDs report the borax composition to be below 15%. The NAIMA LCA report considered in this report assumes 13% of borax for batts and 11% for loose fill. The composition of cullet in fiberglass reported in EPDs, BEES, and NAIMA LCA report are also within the same range with 25-50%, 35%, and 34%, respectively. Overall, we found that the material composition data reported among EPDs, BEES model, and NAIMA are in the same ballpark for fiberglass manufacturing.

TABLE A5. Composition of key raw materials in fiberglass production based on reviewed studies

	Composition (%)			
Data sources	NAIMA (PE International 2011)	BEES (Lippiatt 1998)	EPDs (CertainTEED 2014; Owens Corning 2012; Johns Manville 2016)	Eco-invent
Inputs				
Soda ash	8	9	6-15	7%
Borax	11-13	12-13	10-30	-
Cullet	34	35	25-50	-

The furnace can use different technologies. Based on the NAIMA survey with the manufacturers, the loose fill Melter uses technology mix of oxy-fuel (49%), natural gas (27%), and electric (24%), whereas the batt Melter uses oxy-fuel (31%), natural gas (15%), and electric (54%) (PE International, 2011). Table A6 presents the LCI inventory of the fiberglass loose fill, and batts and rolls based on the NAIMA LCA report. We used a cutoff value of 1% to exclude raw materials that are required in low quantity. The NAIMA database includes energy required for overhead (e.g., lightings, heating, etc.). We excluded the overhead energy in this report as it is not directly used in the manufacturing of the product.

TABLE A6. Life cycle inventory data for fiberglass production (per kg of fiberglass)

Process units/inputs	***Unit***	***Products***	
Batch preparation [a]		Loose fill	Batts and rolls
Inputs			
Borax	Kg	0.12	0.14
Dolomite	Kg	0.053	0.035
Soda	Kg	0.03	0
Cullet	Kg	0.337	0.402
Limestone	Kg	0.006	0.02
Nepheline syenite	Kg	0.036	0.02
Burnt dolomite lime	Kg	0.006	0.023
Soda ash	Kg	0.084	0.085
Calcinated quicklime	Kg	0.007	0.006
Feldspar	Kg	0.033	0.004
Sand	Kg	0.324	0.3
Ulexite	Kg	0.015	0.009
Electricity (handling/mixing)	mmBtu	0.000043	NA
Major outputs			
Batch	Kg	1.06	1.045
Waste	Kg	1.16E-03	NA
Furnace/Melter			
Inputs			
Electricity	mmBtu	0.0022	0.0024
Natural gas	mmBtu	0.0042	0.0036
Major outputs			
Molten glass	Kg	0.96	0.94
Waste	Kg	2.47E-04	2.31E-04
Binding[a]			
Inputs			
Phenolic resin	Kg	NA	0.06
Ammonia	Kg	NA	0.001
Urea	Kg	NA	0.016
Oil emulsion	Kg	NA	0.007
Acrylic resin	Kg	NA	0.0045
Major outputs			
Binder	Kg	NA	9.27E-02
Finishing			
Inputs			
Lubricant/oils	Kg	0.04	
Electricity	mmBtu	0.0013	0
Natural gas	mmBtu	0.0042	0.0028
Major outputs			
Fiberglass	Kg	1.00	1.00
Waste	Kg	0.01	0.03

NA = Not applicable, [a]= materials less than 1% are excluded

The upstream energy and emissions associated with the raw materials required in the fiberglass production are available in the GREET database. The exception is borax, which constitutes over 10% of the total raw materials. The current GREET model does not have LCI data for borax manufacturing. We reached out to Rio Tinto, one of the major borax manufactures in the U.S. Due to proprietary issues, Rio Tinto was not able to provide the data, however, it provided the production process. Borax acts as an aiding agent during the fiberizing process and improves durability in use. The production of borax is made from borate minerals and brines (Smith 2000). In Europe, particularly in Turkey, colemanite is used while in the United States mainly sodium borate minerals (borax, kernite) are used as raw minerals for borax production.

Anhydrous borax that is produced by dehydration of hydrated sodium tetraborates (e.g. sodium borates like Tincal or kernite). A rotary kiln is used for partial dehydration then large fusion furnaces are used to eliminate all the remaining water. After cooling down, crystalline forms can be achieved. The sodium borate extraction process begins with open pits mining. Based on the same process, the eco-invent LCI database provides the energy and material inputs for borax production based on California. Table A7 shows the input and output data for one kg of anhydrous borax production data adopted from the eco-invent database (Althaus et al. 2007).

TABLE A7. Input/output data to produce 1 kg of anhydrous borax based on eco-invent data

Inputs	Unit	Amount
Sodium borates	Kg	1.705
Electricity	kWh	0.944
Natural gas	MJ	13.6

The transportation of raw materials involves different modes and distances. Table A8 shows the transportation modes and distances for raw materials used in fiberglass production. The data is based on the NAIMA LCA report.

TABLE A8. The distance and modes of transport of raw materials for fiberglass production

Process units/inputs	**Loose fill**		**Batts**		
Batch preparation	Truck (miles)	Rail (miles)	Truck (miles)	Rail (miles)	Water (miles)
Borax	0	1904	49	1870	1054
Dolomite	201	366	166	643	0
Sodium sulfate	346	0	322	0	0
Cullet	168	340	140	307	0
Limestone	193	0	167	0	0
Nepheline syenite	130	879	0	1470	0
Lime burned high calcium	60	53	239	42	0
Soda ash	55	1818	118	1928	0
Sand	106	638	114	360	0
Sodium nitrate	60	0			0
Magnesium oxide	1289	0			0
Binder					
Phenolic resin	NA	NA	816	0	0
Urea	NA	NA	169	0	0
Ammonium sulfate	NA	NA	781	0	0
Lubricants	NA	NA	371	0	0
Ammonia	NA	NA	213	0	0
Acrylic resin	NA	NA	0	924	0
Amino silane	NA	NA	1846	0	0

Limitations: We compiled the fiberglass batts and loose fill manufacturing life cycle inventory data based on the best available resources. The data reported here are representative of industry average, so they do not represent any specific fiberglass product. The thermal performance of fiberglass insulation is not considered in this report, which we intend to incorporate in the upcoming models and reports. Furthermore, borax production data requires additional validation. In the meantime, according to PE International (2011), the Cradle-to-Gate embodied GHG emissions are 2.31 kg CO_2 equivalent and are 1.96 kg CO_2 equivalent for producing 1 kg of loose fill fiberglass and fiberglass batts, respectively.

A.2.2 Expanded Polystyrene

Introduction and applications: Expanded Polystyrene (EPS) insulation is a lightweight, rigid, closed-cell insulation. It is available in several compressive strengths to withstand load and back-fill forces. The closed-cell structure provides minimal water absorption and low vapor permanence (Insulation Corporation of America, 2020). We focus on EPS insulation, ASTM C578 (Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation) Type I. Type I EPS thermal insulation has a minimum density of 0.9 pounds per cubic foot with a minimum thermal resistance of 3.6 per inch thickness at 75 degrees Fahrenheit, and is used as a thermal insulator for floors, walls, and roofs (Franklin Associates, 2017).

System boundary and manufacturing process: The manufacturing of EPS includes the production of polystyrene resin and the production of EPS insulation. The manufacturing of polystyrene resin starts from the production and processing of natural gas, which is used as both feedstock and process energy. Natural gas is then used as a feedstock to produce ethylene and pygas, which are precursors of ethylbenzene and styrene. Styrene monomer is polymerized to polystyrene by the process of suspension polymerization. Suspension polymerization utilizes an aqueous system with the monomer in a dispersed phase, which results in a dispersed solid phase polymer. This dispersion is maintained through the use of agitation and water-soluble stabilizers. The product from suspension polymerization is a polymer bead impregnated with a blowing agent N-pentane. Flame retardants is then added to the resin. At the insulation manufacturing plant, EPS beads go through an expansion process, which uses steam to expand the beads, releasing some of the pentane. They are then sent to a dryer where the steam moisture is evaporated from the bead surface. The beads are stored in large bags allowing the product to stabilize. After the aging is completed, the beads are sent to the molding process, where they go into a mold cavity. Steam further expands the EPS beads, filling the mold space and forming a solid mass (block) of EPS. The EPS block is aged prior to cutting. The molded block is cut into sheets of specified size and thickness and then stored for distribution (Franklin Associates, 2016 and Franklin Associates, 2017). Figure A5 shows the production process.

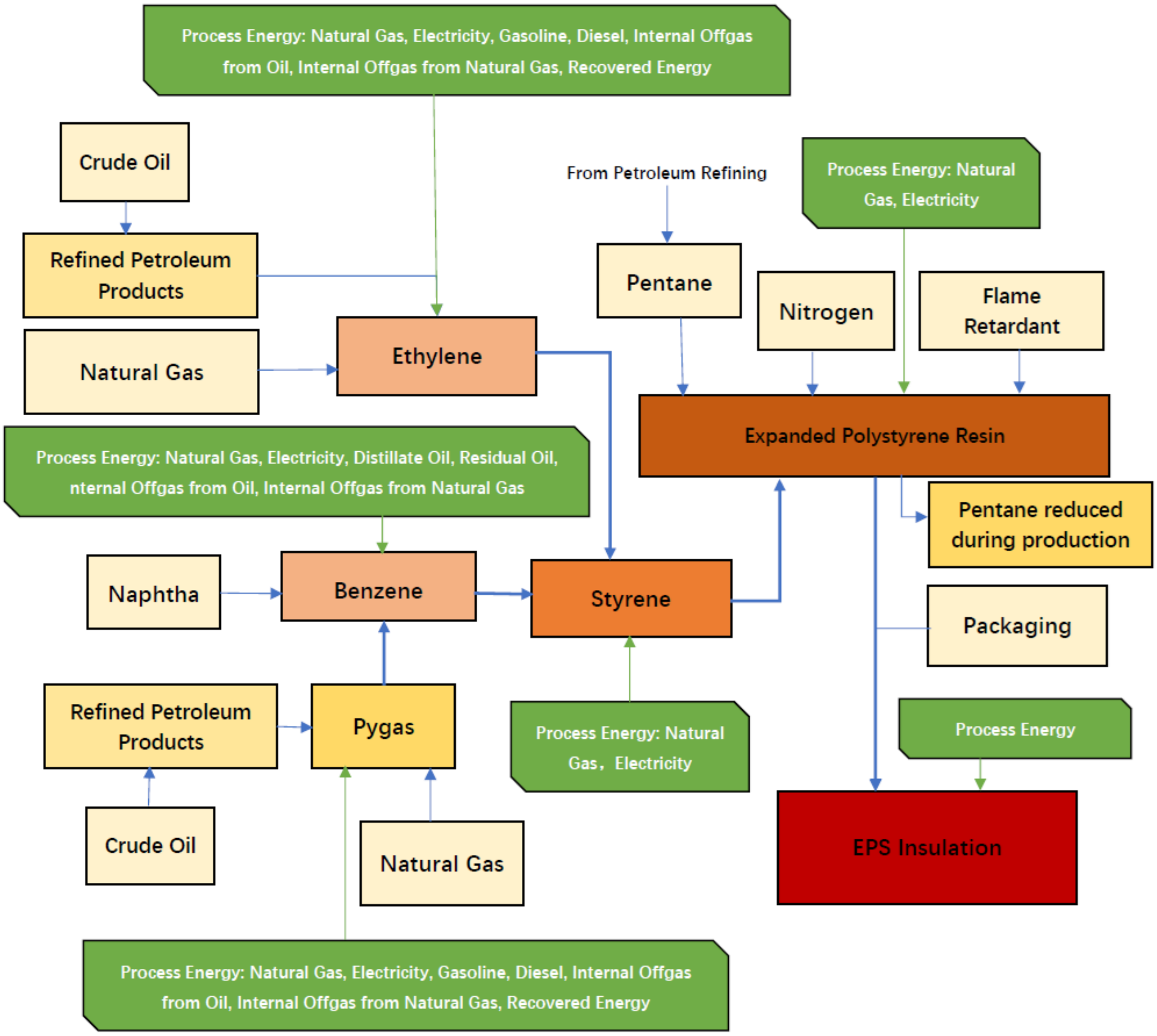


FIGURE A5. Manufacturing process of EPS as described in literature.

Functional unit: The functional unit is 1 m^2 of EPS insulation with a thermal resistance RSI = 1 m^2K/W and with a building service life of 60 years. Note that RSI is a metric system unit of measurement (in m^2K/W), as opposed to the R-value, which is an imperial system unit of measurement (in $ft^2 \cdot °F \cdot h/BTU$). I RSI equals a R-value of 5.678.

Literature review: Franklin Associates (2016, 2017) and EPS Industry Alliance (2017) collected and published process-level life cycle inventory data from North American industry partners and conducted Cradle-to-Gate life cycle assessment for EPS resin and Cradle-to-Grave assessment for EPS insulation. They also explained specific issues such as electricity/heat cogeneration, co-product credits, the release of blowing agent pentane, post-consumer recycling allocation, and end-of-life management in their reports and EPDs. Their results showed that 71.4 MJ of cumulative energy was consumed and 2.79kg CO_2e emissions were generated to produce 1 m^2 of EPS insulation with a thermal resistance RSI=1 m^2K/W and with a building service life of 60 years.

In addition to LCA of general EPS resin and insulation, researchers from Europe also conducted LCA for different specific EPS products and applications, such as EPS granulates, lightweight concrete with regranulated EPS and high-density EPS board (Gomes et al., 2019 and 2020), EPS for flat roofs (Gomes et al., 2019 and 2020), EPS as part of an external thermal insulation composite system (ETICS) for retrofitting (Silvestre et al., 2019), EPS insulation with alternative exterior wall designs (Monteiro & Freire, 2012), and EPS-based ETICS with different rendering types (Michałowski et al., 2020).

Life cycle inventory: The data is extracted and summarized from Franklin Associates (2016) and Franklin Associates (2017). According to these reports, EPS resin data was collected from one plant from each of three EPS resin-producing companies from Canada, the United States, and Mexico, thus representing the three North American countries. The EPS resin is transported to EPS insulation producers throughout North America. Information on the production of EPS insulation was collected from six participating EPS-IA member companies, who provided data from 29 plants from the U.S. and Canada. The primary data provided by the plants includes grinding and densifying EPS from internal and external sources. Approximately half of the participating companies include some percentage of external regrind in their insulation. Overall, external regrind comprised 2 percent of the EPS insulation. Some insulation producers also generate internal scrap that is reground and recycled back into the process. EPS insulation is made primarily of virgin EPS resin that includes an average of 5.2 percent (by weight) of pentane blowing agent at the time of insulation manufacturing. The average plant operating data includes use of natural gas thermal oxidizers in some plants to destroy pentane emissions released during the processing. Overall, approximately 80 percent of the pentane was reduced during production and storage of the insulation (25 percent captured and burned in emission control systems, 55 percent released without combustion), and the remaining 20 percent released during the use phase over its service life of 60 years. Table A9-10 summarizes the life cycle inventory data (Franklin Associates, 2017).

TABLE A9. Life cycle inventory data to produce 1 kg of polystyrene

Material and Energy Inputs	Unit	Mass or Energy Values
Ethylene	kg	0.29
Benzene	kg	0.78
Electricity (grid)	MJ	0.59
Electricity (cogeneration)	MJ	0.00079
Natural gas	MJ	15.6

TABLE A10. Life cycle inventory data to produce one functional unit of EPS

Material and Energy Inputs	Unit	Mass or Energy Values
Polystyrene (virgin)	kg	0.60
Polystyrene (recycled)	kg	0.012
Foam spacers	kg	0.0014
Nylon	kg	0.00012
Polyethylene	kg	0.0019
Polypropylene	kg	0.0021
Natural gas	MJ	1.76
Electricity	kWh	0.12

According to Franklin Associates (2017), Cradle-to-Grave life cycle GHG emissions of 1 m^2 EPS insulation with a thermal resistance of RSI=1 m^2K/W and with a building service life of 60 years is 2.79 kg CO_2 equivalent.

A.2.3 Extruded Polystyrene

Introduction and applications: Similar to EPS, Extruded Polystyrene (XPS) is also made from polystyrene but is manufactured using an extrusion process instead of an expansion process. Products are available in a range of compressive strengths to suit varied application needs (Green Building Solutions, 2016). There are several types of XPS insulation board, insulating sheathing and fanfold siding underlayments that can be installed directly over existing siding. It is rigid and closed-cell, air and moisture resistant, light weighted, and durable (Extruded Polystyrene Foam Association, 2020). Owens Corning's XPS product FOAMULAR, which is the primary XPS insulation product discussed here, is available for a variety of applications including sheathing, foundation, under slab, re-siding, commercial roofing, under road plaza deck and commercial walls (Owens Corning, 2013).

System boundary and manufacturing process: XPS foam begins as a solid granule of polystyrene resin. The plastic granules are fed into an extruder, where they are melted and mixed with critical additives to form a viscous fluid. Next, a blowing agent is injected to enable the plastic product's expansion. Under carefully controlled heat and pressure conditions, the plastic mixture is forced through a die into the desired shape. The rigid foam plastic is then trimmed to the final product dimensions and is usually recognized as boards. This continuous process produces a closed-cell structure that looks like a mass of uniform bubbles with common walls between them. A continuous smooth skin on the top and bottom also forms (Green Building Solutions, 2016). Figure A6 shows the manufacturing process (Owens Corning, 2013).

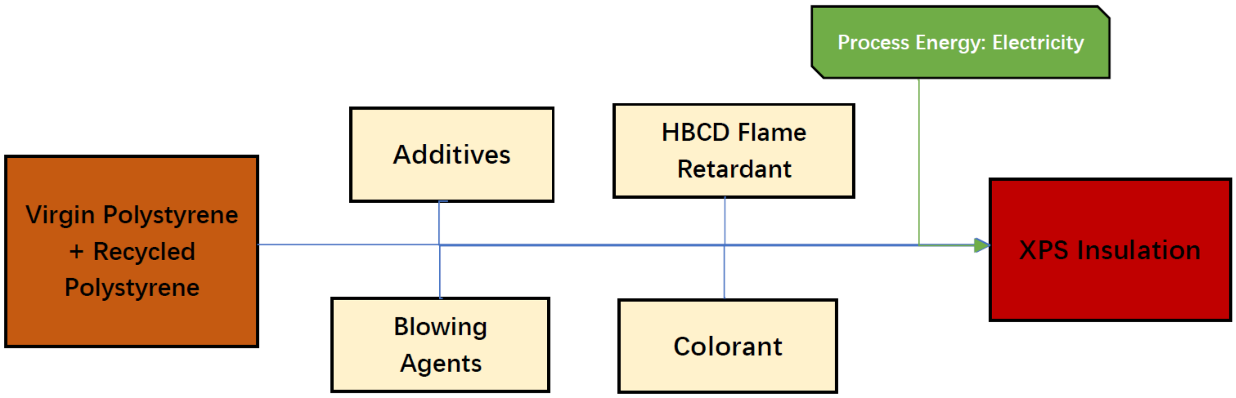


FIGURE A6. Manufacturing process of XPS as described in literature.

Functional unit: The functional unit is 1 m^2 of insulation material with a thickness that gives an average thermal resistance of RSI = 1 $m^2 \cdot K/W$ and with a building service life of 60 years.

Literature review: In Owens Corning (2013)'s EPD of FOAMULAR XPS insulation with an HFC blowing agent, they collected life cycle inventory data from four Canada and US manufacturing plants and reported a total cradle-to-grave primary energy use of 80.7MJ eq and a global warming potential (GWP) of 60.8kg CO_2eq per 1m^2 of XPS insulation with a thermal resistance RSI=1 m^2K/W and with a building service life of 60 years. While the reported embodied energy of XPS was slightly higher than EPS, its GHG emissions were more than 20 times higher compared to the data reported by Franklin Associates (2017). Since XPS and EPS have the same resin (polystyrene), many studies compared their LCA and, likewise, reported a much higher GHG emissions from XPS (Silvestre et al., 2011, Pargana et al., 2014, Nicolae & George-Vlad, 2015, Biswas et al., 2016, Saadatian et al., 2016, Llantoy et al., 2020, Monteiro et al., 2020). Specifically, Biswas et al. (2016) compared the Cradle-to-Grave GWP of EPS and XPS with different blowing agents (HFC-134a, HFC-152a, CO_2), and found that the significant fugitive emissions of high-GWP blowing agents was the major contributor of GHG emissions. Moreover, Vo & Paquet (2004) found that the concentration of initial blowing agents (CFC-12, HCFC-142b, HFC-134s, HFC-152a, CO_2) right after manufacturing varied significantly among XPS products with different blowing agents. Additionally, the thermal performance of XPS changed as the residual concentration of blowing agents changing over time, which might increase the complexity of LCA modeling.

Life cycle inventory: Owens Corning North American manufacturing locations can be found across the United States and Canada. Primary data provided in this declaration is based on the weighted average of production for four facilities in Ohio, Illinois, Oregon, and Quebec (Owens Corning, 2013). The life cycle inventory data is summarized in Table A11.

TABLE A11. Life cycle inventory data to produce one functional unit of XPS

Material and Energy Inputs	Unit	Mass or Energy Values
Blowing agents	kg	0.084
Polystyrene (virgin)	kg	0.59
Polystyrene (recycle)	kg	0.16
Hexabromocyclododecane flame retardant	kg	0.0028
Additives	kg	0.0028
Colorant	kg	0.0028
Electricity	MJ	7.85

According to (Owens Corning, 2013), the cradle-to grave GHG emissions of1 m^2 of XPS insulation material with a thickness that gives an average thermal resistance of RSI = 1 $m^2 \cdot K/W$ and with a building service life of 60 years is 60.8 kg CO_2 equivalent.

Limitations: The data is based on one single EPD and does not necessarily represent the industry average.

A.2.4 Mineral Fiber Board

Introduction and applications: Mineral fiber board (MFB) insulation products are comprised of semi-rigid and rigid boards and batts. It resists mold, fungi, and is vermin proof due to its being an inorganic material (Owens Corning, 2019). The R-value of Thermafiber® mineral wool insulation, for example, ranges from 3.7 – 4.2 per inch of thickness. It is available in multiple thicknesses, densities, and various facings by product type. Reflected by its R-value, mineral wool's insulating performance is achieved by its densely packed fibers. Mineral fiber board products are used in residential and multi-family construction as nonstructural thermal-insulating materials in floor-ceiling assemblies, attics, crawl spaces and walls. In exterior walls, it can be used as continuous insulation in the building envelope, and within interior walls, it can be used as acoustic insulation for partitions.

System boundary and manufacturing process: The manufacturing process diagram below for Thermafiber® mineral wool insulation is representative of the manufacturing processes of mineral fiber board in the US. Although minor differences exist due to the availability of specific suppliers for materials, there are no significant process differences among manufacturing locations.

Figure A7 shows the Cradle-to-Gate system boundary and the manufacturing process in particular.

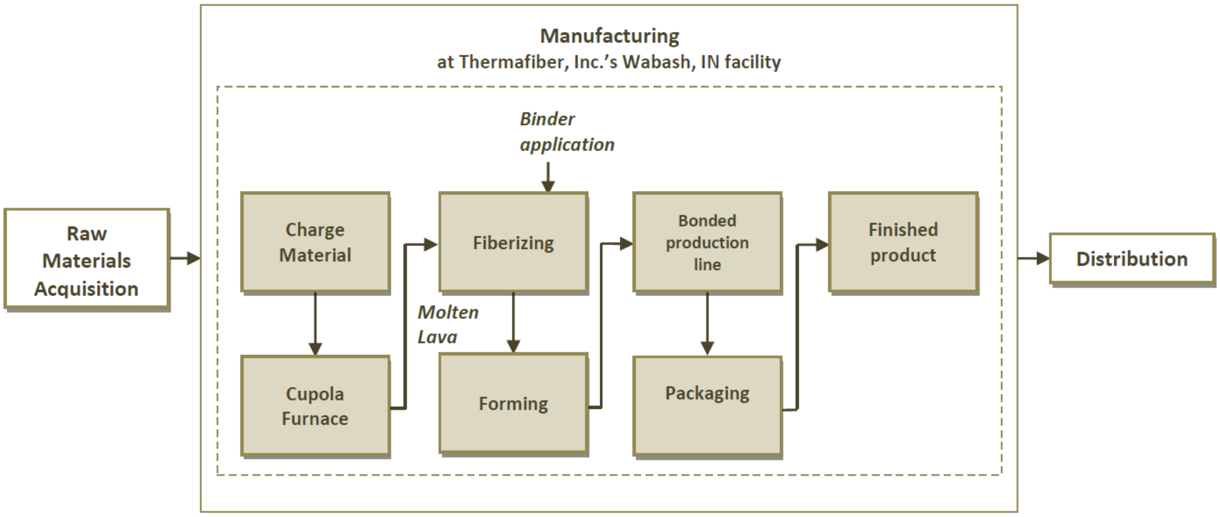


FIGURE A7. Manufacturing process of Thermafiber® mineral wool insulation as an example (Owens Corning, 2014)

Functional unit: The functional unit for mineral fiber board is 1 m^2 of the insulation material with a thickness that gives an average thermal resistance RSI = 1 m^2K/W and with a building service life of 60 years.

Life cycle inventory: Primary data we collected are based on Thermafiber® light and heavy density mineral fiber boards (Owens Corning, 2019). The life cycle inventory data is summarized in Table A12.

MFB, regardless of light density (<4.3 lb/ft3) or heavy density (>4.3 lb/ft3), is volume-limited in the transportation stage. It is reported that the light density and heavy density MFB utilize about 63% of the truck loading capacity during the transportation. Since raw materials (e.g. the slag) are sourced locally (Owens Corning, 2019), we assume a transportation distance of 100 miles for raw material transportation. It is reported that the finished product transportation to construction site is by diesel truck for 1,090 and 1,100 miles, respectively, for heavy and light density mineral wool boards.

Table A12. Life cycle inventory data to produce one functional unit of light density and heavy density mineral fiber boards

	Low density board	High density board	Low density board	High density board	
		Material Inputs			Unit
Blast furnace slag (byproduct from steel production)	69%	69%	1.15	2.39	kg
Feldspar	60%	6%	0.10	0.21	kg
Trap rock	23%	21.5%	0.39	0.75	kg
Binders, phenolic resin	1.5%	2.0%	0.025	0.070	kg
Binders, urea	1.0%	2.0%	0.017	0.070	kg
			Process Energy*		
Electricity (grid)			20.3	36.0	MJ

* Electricity use is based on data revealed in the 2014 EPD (Owens Corning, 2014).

According to Owens Corning, (2019), the Cradle-to-Gate GHG emissions for 1 m^2 mineral fiber board with a thickness that gives an average thermal resistance RSI = 1 m^2K/W and with a building service life of 60 years is 10.8 kg CO_2 equivalent for heavy density board and 5.3 kg CO_2 equivalent for light density board.

Limitations: The energy requirement during manufacturing is not disclosed in the 2018 EPD.

A.2.5 Rigid Polyurethane Foam

Introduction and applications: Polyurethane (PUR) foams exist as both rigid and flexible foams. Rigid polyurethane foams usually have closed-cell foam structures and cell gases that resist heat transfer, which give them good thermal insulating properties. They are widely used as roof and wall insulation, insulated windows, doors and air barrier sealants (American Chemistry Council, 2018).

System boundary and manufacturing process: The production of rigid PUR foam requires two main liquid components - a polyol and a polyisocyanate, typically methylene diphenylene diisocyanate (MDI) - and a blowing agent. The blowing agent is usually added to the polyol together with further auxiliary components such as activators (reaction accelerators), foam stabilizers and flame retardants. The polyaddition reaction that takes place when the polyol and polyisocyanate are mixed together results in macromolecules with urethane structures (polyurethanes). During the reaction a considerable amount of heat is released which is used partly to evaporate readily volatile liquids (blowing agents). As a result, the reaction mix is expanded to form a foam. Various quantities of water are normally added to the polyol. The water reacts with the polyisocyanate to form polyurea and carbon dioxide, which serves as a co-blowing agent but can also be the sole blowing agent (Kapps and Buschkamp, 2004).

Figure A8-A10 show the manufacturing process of polyether polyol, MDI (Franklin Associates, 2011), and rigid PUR (Keoleian, 2012), respectively.

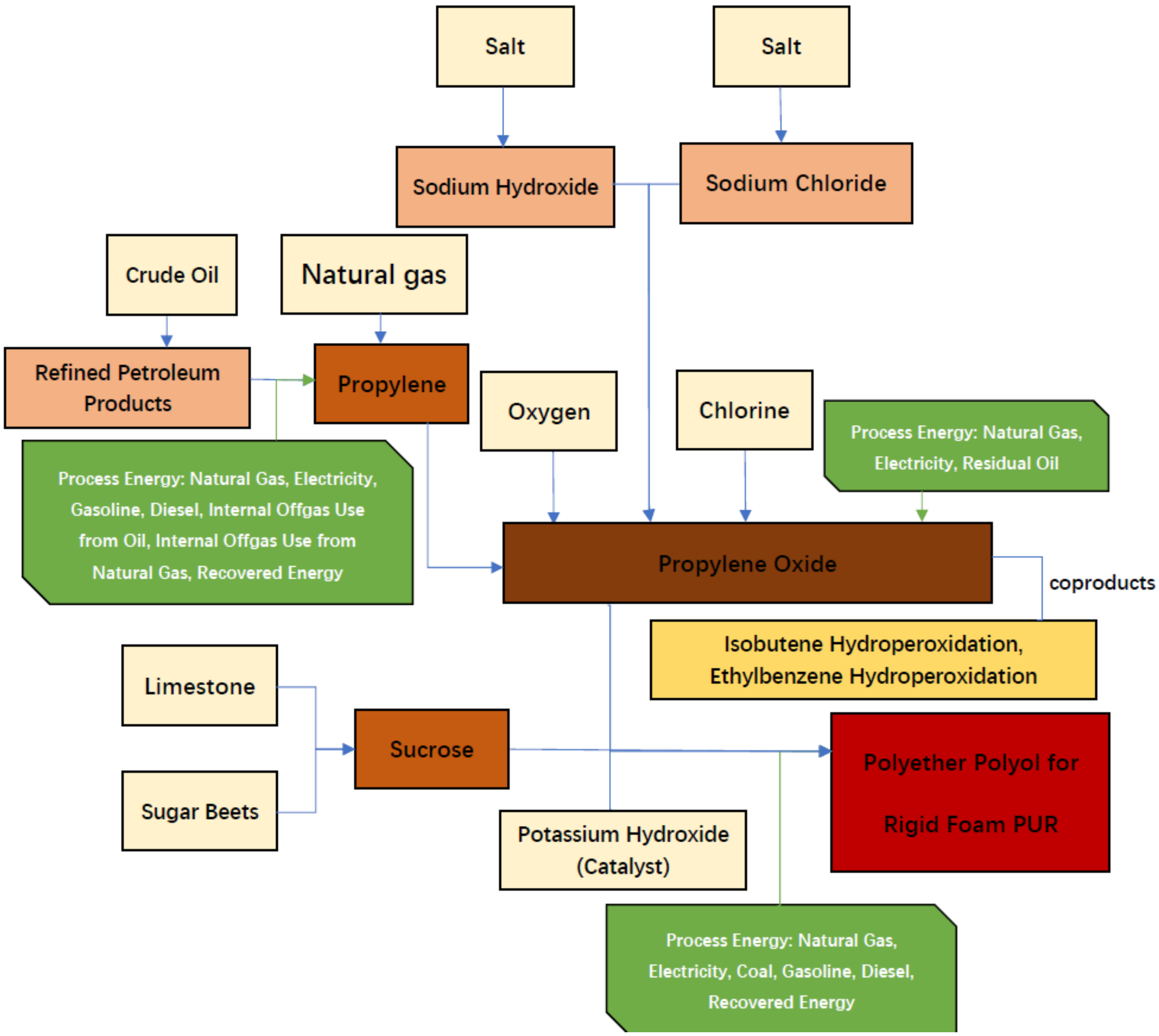


FIGURE A8. Manufacturing process of polyether polyol as described in literature.

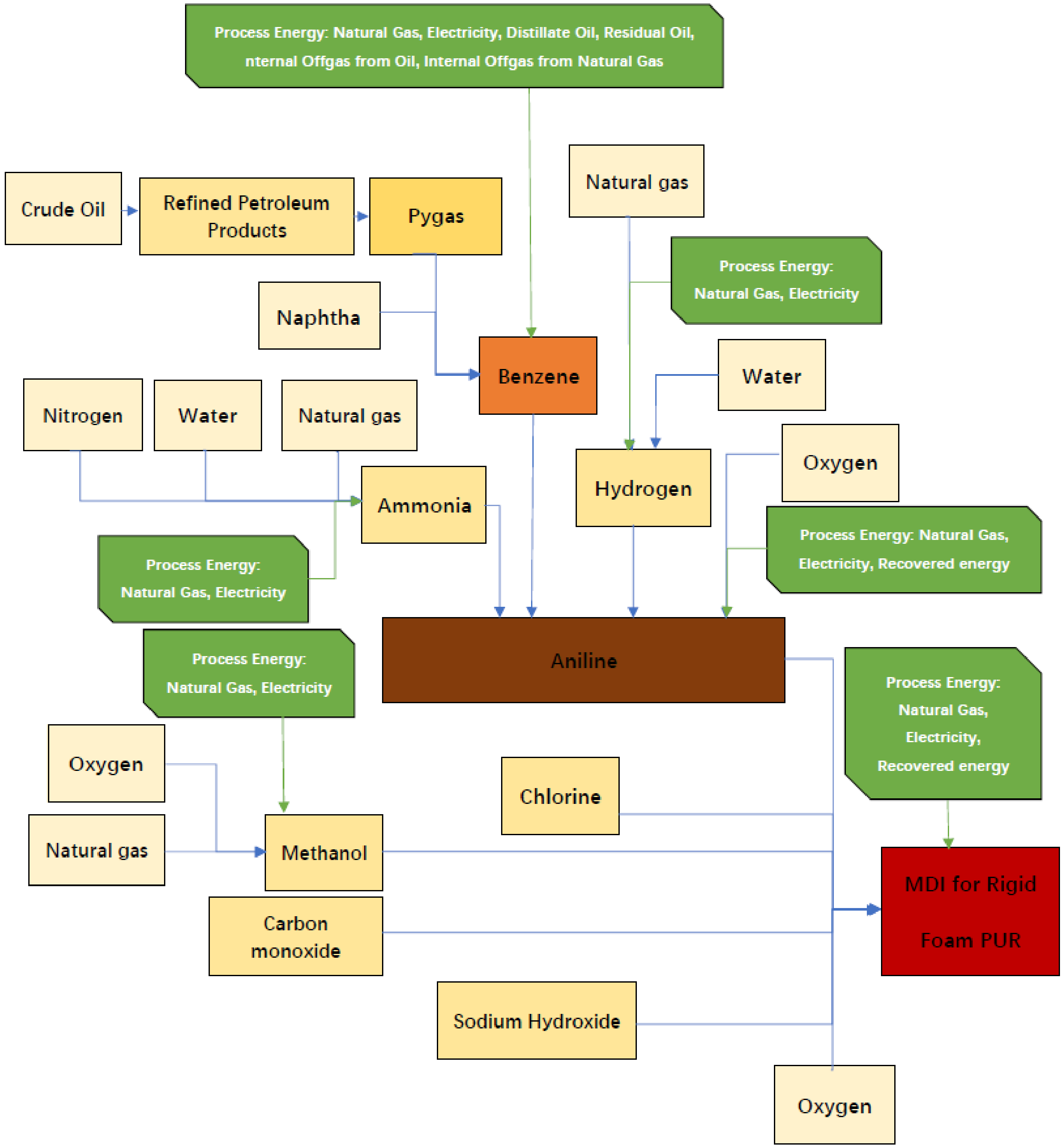


FIGURE A9. Manufacturing process of methylene diphenylene diisocyanate (MDI) as described in literature.

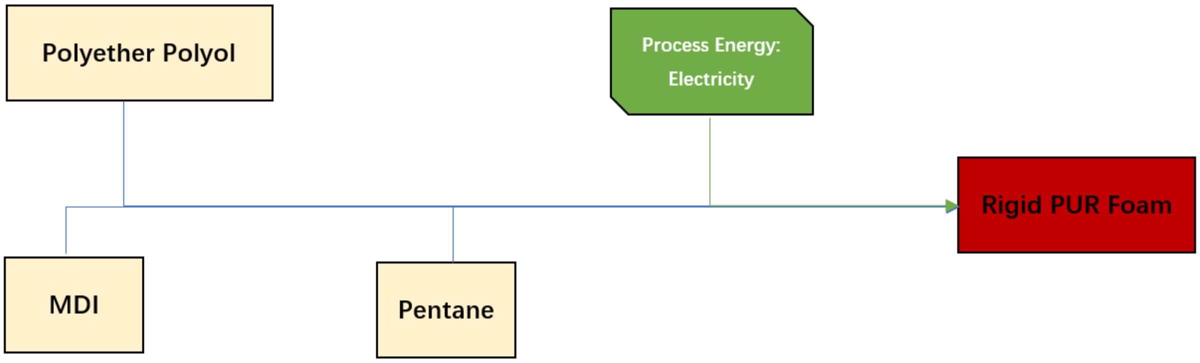


FIGURE A10. Manufacturing process of rigid polyurethane (PUR) as described in literature.

Functional unit: The functional unit is 1 m^2 of insulation material with a thickness (1 inch) that gives an average thermal resistance of RSI = 1 $m^2 \cdot K/W$.

Literature review: Researchers have conducted LCA for various types of polyols and PUR insulation products. Fridrihsone et al. (2020) compared rapeseed oil-based and petrochemical polyols, and found that those bio-based polyols had a better cradle-to-gate environmental performance and lower embodied energy. Another study (Fridrihsone et al., 2020) further found that the bio-based feedstock was the main contributor to the better environmental performance of bio-polyol production process. Assen & Bardow (2014) also investigate the use of CO_2 as feedstock during the manufacturing of polyols, and found it less carbon and energy intensive. As for PUR insulation products, there are limited research publications and EPDs available. One EPD (Stiferite, 2018) reported a total emissions of 8.68 kg CO_2eq of GHG emissions per 1m^2 with an average thickness of 49mm and R=1.76m^2K/W.

The environmental performance of PUR is also often compared with other insulation materials discussed in this report. Pargana et al. (2014) compared the Cradle-to-Gate life cycle environmental impact and embodied energy of some insulation materials with the same R-value in Europe, including the mostly used EPS, XPS, and PUR. The results showed that EPS and PUR had low contribution to all impact categories and low embodied energy, while XPS presented high global warming potential (GWP) and photochemical ozone creation potential (POCP). Many other studies (Silvestre et al., 2011, Nicolae & George-Vlad, 2015, Saadatian et al., 2016, Llantoy et al., 2020, Monteiro et al., 2020) assessed both embodied and operational energy of these three materials with the same thermal resistance for various applications or under multiple scenarios, and presented very different results on the environmental performance of PUR compared to EPS and XPS. For example, researchers took the impact of insulation thickness, ventilation level, exterior wall alternatives (double brick, concrete and wood walls) and building occupancy patterns into consideration, and assessed the trade-offs between embodied and operational impacts for some insulation materials including PUR, EPS and XPS (Monteiro et al., 2020).

Life cycle inventory: Data in Table A13 and A14 represents the production of precursors polyether polyol and MDI comes from multiple plants in the US (Franklin Associates, 2011), while data for the final stage, production of rigid polyurethane foam, as shown in Table A15, is collected from one European site in 1996 (Keoleian, 2012). According to PlasticsEurope (2020), the European data used is also the newest version.

TABLE A13. Life cycle inventory data to produce 1 kg polyether polyol

Material and Energy Inputs	Unit	Mass or Energy Values
Propylene oxide	kg	0.760
Potassium hydroxide	kg	0.0130
Limestone	kg	0.0725
Sugar beets	kg	1.215
Water	liter	0.00417
Electricity (grid)	kWh	0.106
Electricity (co-generation)	kWh	0.292
Natural gas	MMBtu	0.00268
Coal	kg	0.0544
Gasoline	liter	0.0254
Diesel	liter	0.0152
Recovered energy	MJ	0.0228

TABLE A14. Life cycle inventory data to produce 1 kg MDI

Material and Energy Inputs	Unit	Mass or Energy Values
Aniline	kg	0.480
Methanol	kg	0.104
Chlorine	kg	0.378
Caustic	kg	0.0582
Carbon monoxide	kg	0.150
Oxygen (from air)	kg	0.0520
Electricity (grid)	kWh	0.114
Electricity (co-generation)	MJ	0.640
Natural gas	MJ	4.84
Recovered energy	MJ	0.763

TABLE A15. Life cycle inventory data to produce one functional unit of rigid PUR foam

Material and Energy Inputs	Unit	Mass or Energy Values
Polyol	kg	0.394
MDI	kg	0.628
Pentane	kg	0.055
Electricity	MJ	1.530

Limitations: The LCI data for rigid PUR foam production, as shown in Tables A13-A15, is based on relatively old European data, which may not be representative of the current US manufacturing process.

A.2.6 Polyisocyanurate Insulation

Introduction and applications: Polyisocyanurate (Polyiso) insulation boards can be used in residential, commercial and industrial roof and wall constructions on new buildings and retrofits. It is the most widely used type of insulation in above-deck commercial roof applications in the United States and Canada (Polyisocyanurate Insulation Manufacturers Association, 2020).

System boundary and manufacturing process: Both polyiso roof and wall insulations are comprised of a foam core and two facers. The foam core consists of MDI, which reacts with polyester polyol and blowing agent, flame retardant, surfactant, catalyst and water. The facers are typically made from glass fiber (Polyisocyanurate Insulation Manufacturers Association, 2020). Figure A11 illustrates the manufacturing process of polyiso wall and roof (Polyisocyanurate Insulation Manufacturers Association, 2020).

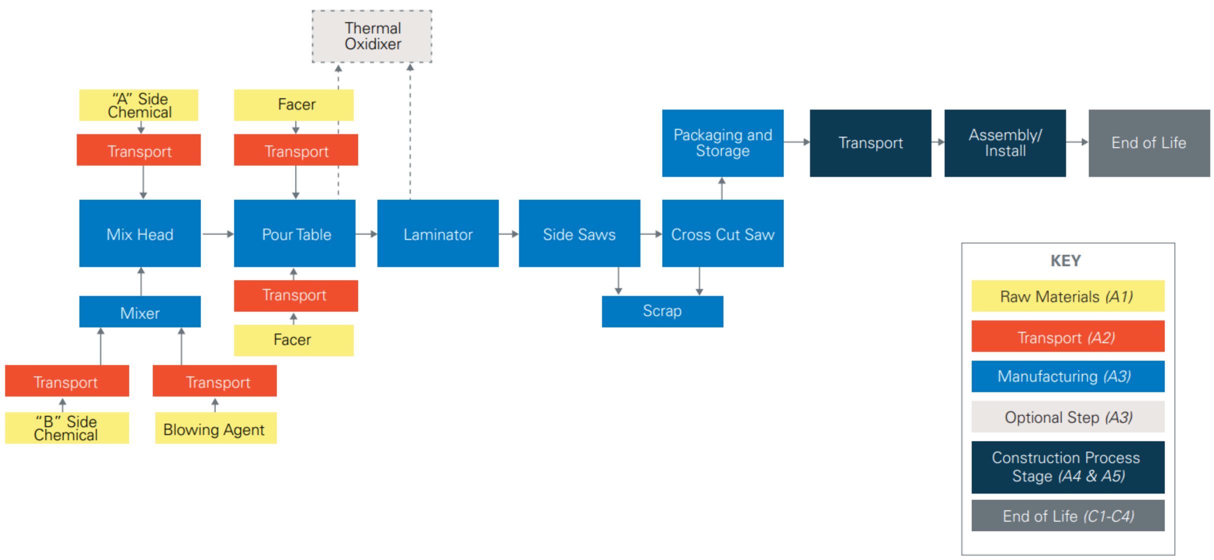


FIGURE A11. Manufacturing process of polyiso wall and roof insulation (Polyisocyanurate Insulation Manufacturers Association, 2020)

Functional unit: 1 m^2 of installed insulation material with a thickness that gives an average thermal resistance RSI = 1 $m^2 \cdot K/W$ and with a building service life of 75 years.

Literature review: Polyisocyanurate Insulation Manufacturers Association (2020) reported a Cradle-to-Gate industry average GHG emissions of 4.36 kg CO_2eq for polyiso roof insulation and 4.29 kg CO_2eq for polyiso wall insulation with the functional unit stated above.

Life cycle inventory: The inventory for producing polyiso insulation foam core is collected from 36 manufacturing facilities in the United States and Canada. The data is summarized in Table A16. For polyiso roof insulation, 1.9 replacements are assumed during the 75-year building service life; while for polyiso wall insulation, no replacement is required (Polyisocyanurate Insulation Manufacturers Association, 2020).

TABLE A16. Life cycle inventory for polyisocyanurate roof and wall foam core

Input	Roof	Wall	Unit
Material			
MDI	0.49	0.67	kg
Polyester polyol	0.25	0.26	kg
Blowing agent (pentane)	0.058	0.061	kg
Flame retardant (TCPP)	0.032	0.069	kg
Surfactant	0.0042	0.0059	kg
Catalyst	0.015	0.019	kg
Water	0.0008	0.0022	kg
Transportation			
From production to building site	652 km of unspecified freight semi truck (diesel)		
From building site to landfill	32 km of unspecified freight semi truck (diesel)		

According to Polyisocyanurate Insulation Manufacturers Association (2020), the Cradle-to-Grave life cycle GHG emissions of polyiso roof insulation with a glass fiber reinforced cellulosic facer is 4.36 kg CO_2 equivalent for 1 m^2 insulation with a thickness that gives an average thermal resistance RSI = 1 $m^2 \cdot K/W$ and with a building service life of 75 years, and 5.96 kg CO_2 equivalent for the same functional unit of coated glass facer polyiso roof insulation. For polyiso wall insulation, the value is 4.29 kg CO_2 equivalent.

Limitations: The inventory data does not include the production and transportation of facers.

A.2.7 Vacuum Insulation Panel

Introduction and applications: Vacuum Insulation Panels (VIPs) with a fumed silica core as designed by the Oak Ridge National Laboratory (ORNL) team possess outstanding insulation efficiency with a R-value of 40 $ft^2 \cdot °F \cdot h/BTU$, which means that this VIP product can resist to a heat flux of 1 BTU per hour in one square foot of the VIP from the warmer (inner) surface of the VIP to the outer surface that is 40 °F colder. VIPs were robust if installed with care. The great thermal performance can offer favorable payback in one-story buildings in regions with extreme climates and high utility costs (Howett et al, 2014). The extremely low thicknesses (10 mm to 25 mm) of VIPs make them a great solution for retrofitting without compromising on the space, and for new constructions to benefit from space and energy savings. VIPs have already been used in buildings to insulate floors and doors as well as dormer windows and glazed facades. The technology has also been applied to facades in new construction as well as retrofits, including both exterior and interior facades. One of the most common applications is on the exterior of existing walls. Other specialized applications include attic hatches and stairs. VIPs have even been used in saunas. It is also very useful on roofs where adding bulk is costly (VIPA, 2020). A Vacuum Insulation Panel consists of a rigid, highly porous core material encased in a thin, gas-tight outer envelope. The core materials must have a sufficiently high compressive strength to withstand the mechanical pressure load. Core material classes basically comprise three structures as microporous powders, fibers, and foams. Common core materials include fumed silica and fiberglass. The envelope is evacuated and sealed to prevent outside gases from entering the panel. Important factors in the selection of envelope materials for VIPs includes gas impermeability, impermeability to water vapor, low thermal conductivity, and sufficient puncture resistance (VIPA, 2020).

System boundary and manufacturing process: The fumed silica core of VIPs is produced by the flame hydrolysis of silicon tetrachloride ($SiCl_4$) at high temperatures, as shown in Figure A12 (Schonhardt et al., 2003). Primary particles of amorphous silicon dioxide, which do not exist outside of the reactor, fuse together producing chain-like, branched aggregates. These aggregates further form loosely bound agglomerates (BRENNTAG Solutions Group, 2020).

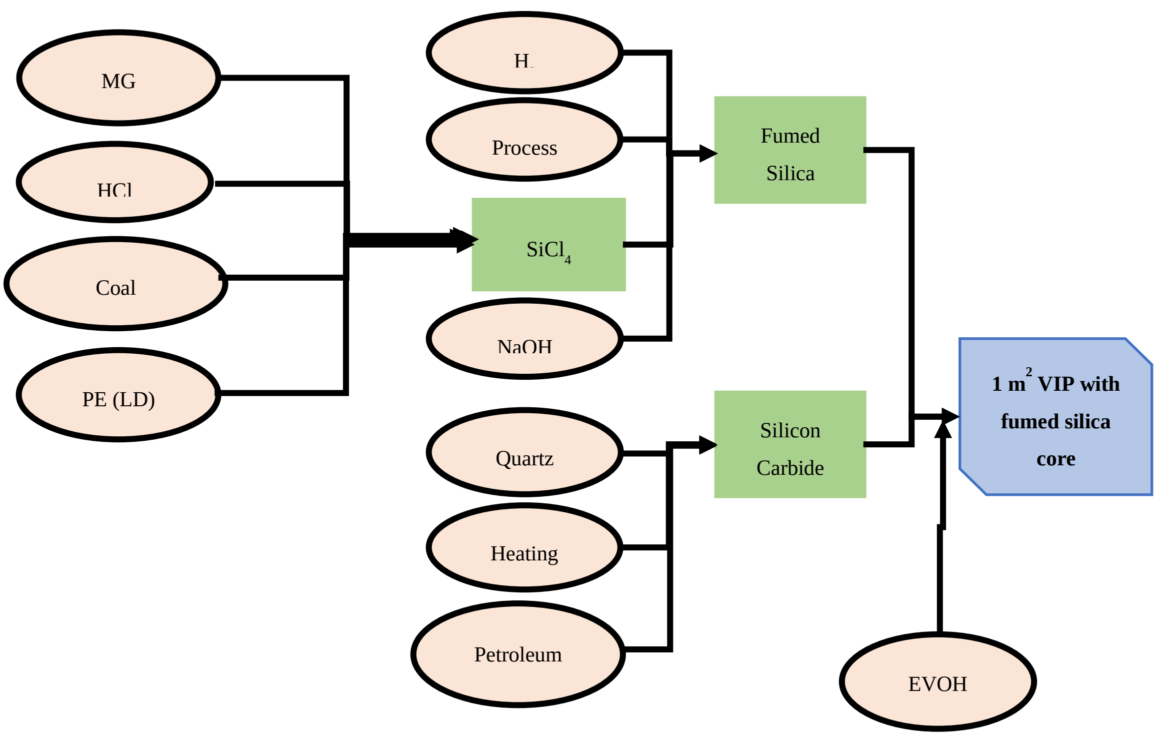


FIGURE A12. System boundary considered in this study and manufacturing process of VIP as described in literature.

Functional unit: The functional unit is 1 m² of VIP insulation with a time-weighted thermal resistance of 1 RSI over a building service life of 60 years. 1 RSI, or 1 m²K/W equals a R-value of 5.678, or 5.678 ft^2·°F·h/BTU. In the following life cycle inventory, data for the functional unit of 1 m² VIP insulation with a designed thermal resistance (R=40, equivalent to 7.04 RSI) is collected, and then standardized to a time-weighted RSI=1 m²K/W over a service life of 60 years, assuming a gradual loss of vacuum and degradation of thermal performance, which would perform at R=8 (equivalent to 1.41 RSI) at year 60.

Literature review: IEA-EBC Annex 65 is a research project to investigate the potential long-term benefits and risks of super insulation materials including VIP. Their multiple reports reviewed state-of-the-art of LCA for fumed silica VIP (Heinemann et al., 2020, Wallbaum & Kono, 2020). From their summary of existing VIP LCA projects, all the LCA studies and EPDs only covered the production stage and the end-of-life stage, except for one project that covered operational energy use. However, no reference was provided for that project. Meanwhile, though the LCA results from these existing studies varied, it was still clear that VIP was not competitive with conventional insulation materials cellulose fiber, fiberboard, foam glass, stone wool, PUR, EPS, or XPS in terms of Gradle-to-Gate GHG emissions. The reports also repeatedly stressed that due to the lack of LCA for VIP, the potential for better representation of its environmental performance could be expected (Heinemann et al., 2020). In terms of comparing VIP with other innovative insulation materials, Wallbaum & Kono (2020) analyzed a retrofitting modeling in four European cities and showed that VIP outperformed aerogel in all cities on economic payback time and GHG emissions.

In addition to those covered by IEA-EBC, there are several other publications studying the LCA of fumed silica VIP from different perspectives. Karami et al. (2015) compared the environmental impact of a standard residential building, a regular well-insulated building and a building insulated with VIPs, and found that VIP had the highest Cradle-to-Gate GHG emissions and embodied energy mainly because of the considerable impact of its core material, and it had a comparatively lower operational energy. Similarly, Papadaki et al. (2019) collected actual LCI data and conducted LCA for a conventional demo house and a house covered with phase change materials (PCMs) and VIPs, and reported that the operational energy savings compensated the higher embodied energy of the latter house within one year.

Life cycle inventory: We reviewed EPDs and reached out to fumed silica and VIPs manufacturers in the US and in Europe to collect up-to-date life cycle inventory data, but were not able to receive process-level data that was detailed enough to model the embodied GHG emissions of fumed silica core VIP. Instead, we used data from a German study (Schonhardt et al., 2003) and confirmed its consistency with consolidated energy and material input data provided by a leading fumed silica VIP manufacturer. The data is shown in Table A17-A19.

TABLE A17. Life cycle inventory data to produce 1 kg of fumed silica

Material and Energy Inputs	Unit	Mass or Energy Values
H_2 (assuming SMR production)	kg	0.066
Silicon tetrachloride ($SiCl_4$)	kg	2.79
Process air	kg	0.53
NaOH	kg	0.24
Natural gas	MJ	4.15
Electricity	MJ	5.68

TABLE A18. Life cycle inventory data to produce 1 kg of silicon carbide

Material and Energy Inputs	Unit	Mass or Energy Values
Quartz sand	kg	1.55
Heating oil	kg	1.02
Petroleum coke	kg	1.07
Electricity	MJ	23.0

TABLE A19. Life cycle inventory data to produce one functional unit of VIP

Material and Energy Inputs	Unit	Mass or Energy Values (1m^2 VIP)	Mass or Energy Values (Time-weighted 1m^2 RSI=1 VIP)
Fumed Silica	kg	4.90	2.09
Silicon Carbide	kg	0.91	0.39
EVOH	kg	0.09	0.09
Electricity	kWh	0.40	0.17
Natural gas	MJ	11.70	4.98

Limitations: Though validated by a manufacturer, this data is extracted from a 2003 German study, which may not be best representative of manufacturing practices and energy efficiency of manufacturers in the US today.

A.3 ENVELOPE MATERIALS

A.3.1 Vinyl siding

Introduction and applications: Vinyl siding is an important building material as it is widely used as a building envelope. It is mostly used as an exterior wall finish for both new and renovated buildings. In 2018, out of 840,000 single-family dwellings constructed in the U.S., about 26% of the buildings used vinyl siding, followed by stucco 25%, brick 21%, and fiber cement 20%. (Onaran et al. 2019). Typically, vinyl siding is composed of two layers namely the substrate and capstock. The capstock is exposed to the outside environment and designed for weather resistant. The capstock can be made of polyvinyl chloride (PVC) and acrylonitrile styrene acrylate (ASA). We consider three major vinyl siding types– a) vinyl, b) insulated vinyl, and c) polypropylene siding.

System boundary and manufacturing process: The production of vinyl siding begins with the raw material extraction, transportation, manufacturing and finishing, and transportation to the construction site. The manufacturing process includes an extrusion process, which requires energy. Insulated vinyl sidings are also manufactured in a similar manner to vinyl siding; however, it requires addition of a foam backing layer to the vinyl siding layer. On the other hand, polypropylene siding manufacturing requires melting of beads and injected into molds. Then, various pigments can be added for color variations. Figure A13 shows the Cradle-to-Gate system boundary diagram of vinyl siding production considered.

FIGURE A13. System boundary of vinyl siding production

Functional unit: The functional unit is defined as a 100 square feet of vinyl siding with a R-value of 3.2, and a service life of 50 years. This functional unit is commonly used in vinyl siding life cycle studies and EPDs (SSC 2016).

Life cycle inventory: We took several approached to collecting the life cycle inventory data for vinyl siding production. Specifically, we reviewed EPDs, trade association LCA reports, and literature. Like fiberglass, the Vinyl Siding Institute (VSI) is a trade association representing over 30 vinyl siding manufactures based on North America. The VSI published an LCA study of vinyl siding manufacturing in 2016. After reviewing existing EPDs by individual manufacturers and other LCA reports, we decided to incorporate the industry-wide average life cycle inventory data prepared by the VSI. The VSI LCA study reports the raw material requirements by percentage of the total inputs (SSC 2016). It also provides the product weight (19.23 kg for vinyl siding, 22.37 kg for insulated vinyl siding, and 32.34 kg for polypropylene) per functional unit. We utilized this information to estimate the raw material inputs by weight. We validated the VSI data with available EPDs and LCA models on vinyl siding production. For instance, PVC resin is used about 80% for the PVC vinyl siding in BEES and VSI LCA report, while EPDs provide a range between 74-90%. The BEES model and EPDs report the composition of ASA to be 7%, while the VSI report uses 11%. Calcium carbonate, another important raw material, is assumed to be 11% in BEES and 9-11% in EPDs. The VSI report also uses the same 11% share of calcium carbonate in vinyl siding production. All the reviewed sources report the similar additives use in the production. In summary, our review of vinyl siding LCI studies shows that the raw material and energy requirements are within the same range. Table A20 shows the life cycle inventory data for vinyl siding production based on the VSI LCA study.

TABLE A20. Life cycle inventory data for sidings production for one hundred square feet

Inputs	Unit	Vinyl siding		Insulated vinyl siding		Polypropylene siding
Materials		PVC Capstock	ASA Capstock	PVC Capstock	ASA Capstock	
PVC	Kg	16.24	13.94	16.24	13.94	0
ASA	Kg	0.00	2.42	0.00	2.42	0
Calcium carbonate	Kg	2.24	2.02	2.24	2.02	4.07
Impact modifier	Kg	0.38	0.22	0.38	0.22	0
Titanium dioxide	Kg	0.28	0.18	0.28	0.18	0
Stabilizer	Kg	0.12	0.14	0.12	0.14	0
Process aid	Kg	0.1	0	0.1	0	0
Lubricant	Kg	0.34	0.34	0.34	0.34	0
Chlorinated polyethylene	Kg	0.14	0.48	0.14	0.48	0
Sealant	Kg	0.16	0	0.16	0	0
Calcium stearate	Kg	0.12	0	0.12	0	0
Pigments	Kg	0.02	0.04	0.02	0.04	1.02
Polypropylene	Kg					28.86
Foam insulation	Kg	0	0	3.05	3.05	0
Glue	Kg	0	0	0.23	0.23	0
Energy						
Electricity	mmBtu	0.0163	0.0163	0.019	0.019	0.176
Natural gas	mmBtu	0.002	0.002	0.00242	0.00242	0.065
Propane	mmBtu	0.001	0.001	0.0017	0.0017	0.00009
Gasoline	mmBtu	0.0000008	0.0000008	0.000001	0.000001	0

According to (SSC 2016), the Cradle-to-Grave life cycle GHG emissions of vinyl siding is 92 kg CO_2 equivalent, and that of insulated vinyl siding and polypropylene siding are 110 kg CO_2 equivalent and 170 kg CO_2 equivalent, respectively.

Limitations: The VSI LCA report provides industry average raw materials inputs in percentage. We used the density information provided in the report to calculate the material inputs in mass units. While converting this information in mass, potential loss factor is not accounted for in this report. Furthermore, one of the benefits of vinyl siding, particularly insulated vinyl siding, is to provide insulation to the building. The comparison of vinyl siding types may need to consider the thermal performance of vinyl sidings.

A.3.2 Gypsum Wallboard

Introduction and applications: Gypsum wallboard (also called drywall, plasterboard, sheetrock, etc.) is used as an interior wall finish in buildings. It is made of a non-combustible core primarily of gypsum with a paper facing (ASTM International 2018). Typically, the gypsum industry uses two most common gypsum wallboards namely ½" (12.7 mm) Regular and 5/8" (15.9mm) Type X gypsum wallboard. As the name refers, the Type X gypsum board has greater thickness and special core additives, which provides additional fire resistance, higher rigidity and enhanced sound attenuation as compared to ½" Regular gypsum board. Due to its additional fire rating characteristics, the Type X conventional gypsum board is used primarily in commercial applications while the Regular gypsum board is typically used in residential applications.

System boundary and manufacturing process: The production of gypsum wallboard begins with the natural or crude gypsum ore extraction, gypsum paper manufacture, transportation, finishing, and transportation to the construction site. The crude gypsum, which is rock-like mineral, is quarried or mined underground by drilling and blasting. The quarry process begins with the removal of overburden (earth) over the gypsum deposit. The gypsum rock is crushed and then transported to the gypsum wallboard manufacturing site. The gypsum paper facings are produced using recycled papers such as old corrugated containers (OCC) and mixed recovered papers. The manufacturing process involves feeding the recycled paper into a pulper and dissolving them to make a slurry of paper fiber. The paper slurry is cleaned and fed into the paper making machine (Gypsum Association 2020).

Using these two key raw materials (gypsum and paper facing) the gypsum wallboard is manufactured. The crushed gypsum is heated and partially dehydrated, which is then mixed with several additives, foaming agents, and water to prepare a gypsum slurry. The slurry is moved fast at the production line where it is covered with face and backing papers. The raw gypsum board after is cut to the desired sizes. Figure A14 shows the Cradle-to-Gate system boundary of gypsum wallboard production.

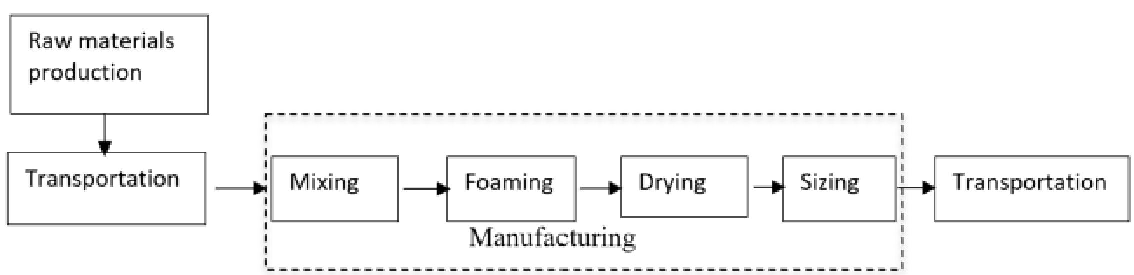


FIGURE A14. System boundary and manufacturing process of gypsum wallboard

Functional unit: The functional unit used for gypsum wallboard is one thousand square feet (1 MSF) or 92.9 square meters with a service life of 60 years.

Life cycle inventory: We reviewed EPDs, trade association LCA reports, and literature to collect the life cycle inventory of the gypsum wallboard production in the U.S. The Gypsum Associations (GA) is a trade association representing gypsum manufacturers in the U.S. Recently, in early 2020, the GA published an LCA report on Regular (1/2") and Type- X (5/8") gypsum wallboard. After reviewing published studies, literature and EPDs, we decided to incorporate the industry-wide average life cycle inventory data based on the recent GA LCA report. Table A21 presents the weighted average material content of gypsum boards.

TABLE A21. Key material inputs, in kg, for 1 MSF of gypsum wallboard production (Gypsum Association 2020)

Raw materials	1/2" Regular	5/8" Type- X
Natural gypsum	182	359
Synthetic gypsum (FGD)	383	558
Post-consumer	4.2	3.5
Paper (facing and backing)	40.4	37.1
Starch	4.7	3.8
Vermiculite	0	0.55
Fiberglass	0.52	2.65
Potash	0.16	0.0041
Dextrose	0.36	0.59
Dispersant	1.46	1.63
Retarder	0.24	0.22
Potassium Sulfate	0.022	0.02
Clay, kaolin	0	0.28
Boric acid	0.36	0.12
Foaming agent (soap)	0.27	0.25
Ball mill accelerator (BMA)	3.1	2.4
Edge paste	0.21	0.2
Sodium Trimetaphosphate	0.27	0.036
Shredded paper	0.027	0.029
Water	422	610

The transportation of raw materials to the manufacturing site involves different modes and distances. Table A22 shows the transportation mode and distances for the key raw materials used in the gypsum wallboard production.

TABLE A22. The distance and modes of transport of raw materials for gypsum wallboard production (Gypsum Association 2020)

Materials (one way)	Rail (miles)	Road (miles)	Barge (miles)
Mined natural gypsum ore	-	-	12,400
Quarried natural gypsum ore (domestic)	-	22.1	1,340
Quarried natural gypsum ore (imported)	-	-	-
Synthetic gypsum (FGD)	0.0245	23	1,020
Post-consumer gypsum	-	125	112
Starch	530	472	-
Fiberglass	60.9	594	-
Edge glue	-	404	-
Retarder	-	656	-
Dispersant	162	650	-
Boric acid	198	158	-
Soap form	169	774	-
BM accelerator	-	58.8	-
Shredded paper	157	0.817	-
Potassium sulfate	-	446	-
Ammonium sulfate	-	56	-
Sugar	-	573	-
Talc	-	218	-
Clay	-	12.5	-
Gypsum facing paper	177	452	-
Gypsum backing paper	200	456	-

According to Gypsum association (2020), the Cradle-to-Gate life cycle GHG emissions of 1/2’’ lightweight gypsum board is 207 kg CO_2 equivalent, while the value for 5/8’’ Type X conventional gypsum board is 277 kg CO_2 equivalent.

Limitations: FGD synthetic gypsum is a by-product of coal-fired power generation process - a result of SO_2 scrubbing and is a recovered waste material. The GA LCA report assumes that FDG has the same molecular composition and has market value for various applications. Therefore, the study considers it as a co-product and treats as a credit generator by displacing crude gypsum on a one-to-one basis. Though this assumption needs further investigation, at this point, we take the GA study approach on handling the FDG. In the future reports, we will thoroughly review this assumption and update the life cycle inventory accordingly.

A.3.3 Asphalt Shingles

Introduction and applications: Roofing systems are important building components because these structures enclose the building exposures. Asphalt shingle roofing systems protect building structures from the elements and severe weather. Asphalt shingles are commonly made from fiberglass mats with a mixture of asphalt and mineral filler. Asphalt shingles are available in strip (3-Tab) and laminated types (ARMA 2016).

Functional unit: The functional unit used to quantify energy and emissions of asphalt shingles is one square meter area covered with a service life of 20 years.

System boundary and manufacturing process: Manufacture of fiberglass asphalt shingles begins with impregnation and coating of a fiberglass mat with a filled asphalt coating. The filled coating mixture is produced separately by mixing oxidized asphalt and mineral stabilizer in appropriate proportions. Minerals and granules are added to the top surface on areas that will be exposed in the building. Asphalt-based adhesive is applied to the finished shingle, which serves to bond individual shingles to each other. In the case of laminated shingles, the individual layers are combined during manufacturing using a laminating adhesive. Finally, the shingle is cut to size and packaged for shipment. Underlayment is an important component of asphalt shingles installation. Typically, asphalt-impregnated organic felt is used in the asphalt shingle industry, however, self-adhering polymer modified bituminous sheet materials have also been used. The manufacturing of underlayment involves production of an organic felt mat that typically incorporates paper, cardboard, and sawdust (ARMA 2016; BEES 2010) . Figure A15 shows the asphalt shingles manufacturing process and system boundary.

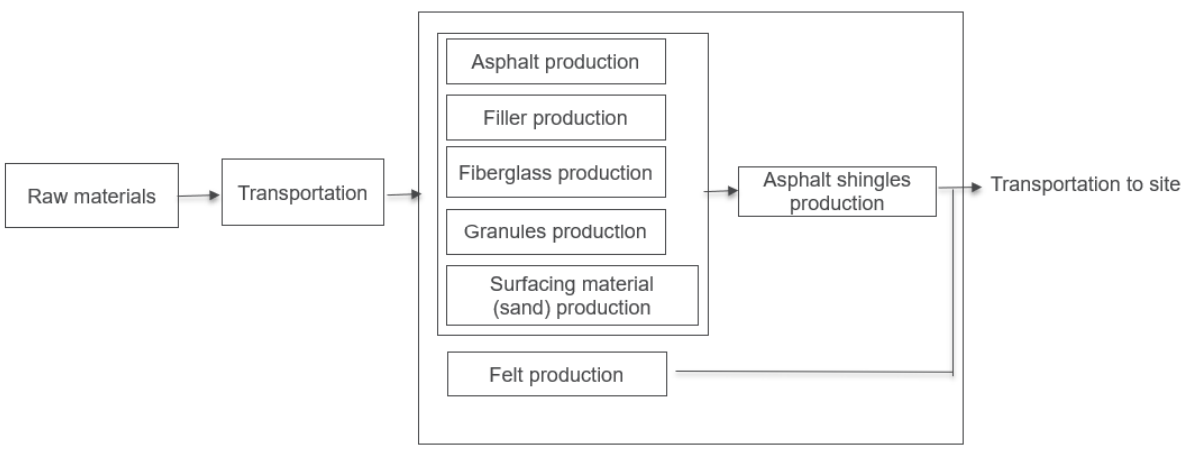


FIGURE A15. Cradle-to-Gate system boundary and manufacturing process of asphalt shingles as described in literature.

Life cycle inventory: We reviewed EPDs and literature to collect and cross check the LCI data for asphalt shingles. Not all EPDs report the key material inputs in mass units, rather the EPDs provide a percentage of raw material compositions. Out of reviewed EPDs released by several manufacturers, the Owens Corning's EPD provides the mass input. Similarly, BEES LCA model also reports the key material inputs in mass units. We validated the raw material inputs data between the Owens Corning and other EPDs utilizing the information available. For example, the share of raw material fiberglass mat is 2% in all reviewed studies. Similarly, limestone that contributes the highest in the composition is reported 35% in the Owens Corning EPD and asphalt shingles industry average, whereas its share is 43% in BEES. Granules share is reported about 25% in Owens Corning, whereas the industry average for its share is reported to be 37%. The use of sand is reported about 7-9% among review studies. Table A23 shows the LCI data based on Owens Corning and Asphalt Shingles Manufacturers Association (ARMA) and validated based on the information available in other EPDs (ARMA 2016).

TABLE A23. Life cycle inventory data to produce one square meter area of asphalt shingles

Raw materials	Unit	Strip (3-Tab)	Laminated
Fiberglass mat	Kg	0.21	0.27
Asphalt	Kg	1.84	2.20
Limestone	Kg	3.35	4.16
Granules (rock mining and grinding)	Kg	2.02	2.99
Coal slag	Kg	1.67	0.35
Sand	Kg	0.35	0.93
Dolomite	Kg	0.12	0.13
Energy inputs			
Electricity	mmBtu	0.00084	0.00084
Natural gas	mmBtu	0.00217	0.00217

According to ARMA (2016), the Cradle-to-Grave life cycle GHG emissions to produce 1 square meter of asphalt shingle roofing system is 6.5 kg CO_2 equivalent.
Limitations: No manufacturing data for felt underlayment were available, so its contribution to the life cycle may be underestimated. The energy data was not readily available in EPDs. We relied on BEES data applicable for generic asphalt shingles for energy requirement.

A.3.4 Glass and window

Introduction and applications: Glass products are widely used in modern residential and commercial buildings. It is typically used as glazing materials in external walls and windows. It is electric and chemical resistant and flexible in molding, which are outstanding properties for construction use. In 2019, global revenue of construction glass market reached $45 billion worldwide (Brandessence Market Research And Consulting, 2021).
System boundary and manufacturing process: Multiple glass products are studied for GREET building module. Flat glass is the basic material used for architectural glazing in building envelope, which is formulated from soda-lime silicates and metal-oxide materials. It is manufactured by mixing raw materials at high temperature and floating them onto the surface of a molten tin bath, which smooths the glass by gravity and surface tension. The flat glass ribbon is

guided on rollers through an annealing lehr where it is cooled under controlled conditions to avoid buildup of internal stress until it emerges at essentially room temperature. The resulting flat glass is cut to desired sizes and is available in a range of thicknesses and surface treatment options (National Glass Association, 2019). Optically transparent nanoscopic layers can then be sputtered onto glass via magnetron sputtering in vacuum sputtering chambers to produce coated glass. Also, tempered glass can be produced by controlled thermal treatments to increase strength (Cardinal Glass Industries, 2020). Furthermore, double-pane insulating glass units have an improved energy efficiency compared to single glasses. With the glass coating and argon gas filled between window panes, windows and doors will have enhanced glazing performance (Cardinal Glass Industries, 2020).

Functional unit: The functional unit of flat glass is 1 tonne. The functional units of coated and tempered glass and double pane insulating glass unit are both 1 m^2 of glass product.

Literature review: National Glass Association (2020) conducted the most recent industry-wide study, which reported a Cradle-to-Gate GHG emissions of 1.43×10^3 $kgCO_2eq$ per metric tonne of flat glass. Manufacturers also reported life cycle GHG intensities for specialty glass products. For example, the Cradle-to-Gate GHG emissions of Cardinal Glass Industries' facilities (Cardinal Glass Industries, 2020) are summarized in Table A24.

TABLE A24. Life cycle GHG emissions of glass and window products from Cardinal Glass Industries' EPDs.

Product	GHG emissions (kg CO_2eq per m^2 of glasses)
Coated glass	13.7
Tempered glass	17.1
Coated and tempered glass	22.3
Laminated glass	49.0
Double pane tempered glass	54.3
Triple pane tempered glass	93.9

As for window system, research papers, reports and EPDs for a range of products have been published. For example, Carlisle & Friedlander (2016) compared the Cradle-to-Grave impacts of different frame materials and found that despite the high embodied impacts of aluminum manufacturing, when material recycling and durability are taken into consideration, total environmental impacts of aluminum window frames were consistently lower than wood or PVC window frames.

Life cycle inventory: Cradle-to-Gate inventory data for flat glass is collected from 36 manufacturing facilities in the United States (National Glass Association, 2019), which is summarized in Table A25. Cradle-to-Gate inventories for processed glass and insulating glass unit are collected from EPDs (Cardinal Glass Industries, 2020), which are summarized in Table A26 and Table A27.

TABLE A25. Life cycle inventory for flat glass (functional unit: 1 tonne of flat glass)

Input	Flat glass	Unit
Material		
Silica sand	550	kg
Limestone	50	kg
Soda ash	210	kg
Dolomite	140	kg
Sodium sulphate	<10	kg
Sodium nitrate	<1	kg
Iron oxide	<1	kg
Carbon	<1	kg
Other	43	kg
Energy		
Fossil fuels	1.34×104	MJ
Nuclear	539	MJ
Solar	142	MJ
Wind	143	MJ
Hydropower	58.8	MJ
Biomass	5.15	MJ
Water		
Water consumption	2.64×10^3	m3

TABLE A26. Life cycle inventory for coated and tempered glass (functional unit: 1 m^2 of glass product)

Input	Coated & tempered glass	Unit
Material		
Flat glass	99.95%	
Nickel	<0.1%	
Silicon	<0.1%	
Silver	<0.1%	
Tin	<0.1%	
Titanium	<0.1%	
Zinc	0.04%	
Energy		
Renewable primary energy	26.9	MJ
Non-renewable primary energy	325	MJ
Water		
Water consumption	65.9	m^3

TABLE A27. Life cycle inventory for double-pane insulating glass unit (functional unit: 1 m^2 of glass product)

Input	Double, annealed	Double, tempered	Unit
Material			
Glass	44%	27%	
Coated glass	49%	36%	
Tempered glass		19%	
Coated tempered glass		12%	
Aluminum	0.3%	0.2%	
Argon	1%	1%	
Desiccant	1%	0.9%	
Masking film	2%	2%	
PIB	0.10%	0.1%	
Silicone	0.70%	0.6%	
Plastic spacer	0.03%	0.02%	
Stainless steel	1%	1%	
Energy			
Renewable primary energy		70.7	MJ
Non-renewable primary energy		802	MJ
Water			
Water consumption		186	m^3

According to National Glass Association (2019), the Cradle-to-Gate life cycle GHG emissions per 1 metric tonne of flat glass is 1.43×10^3 kg CO_2 equivalent. The GHG emissions for coated and tempered glass, and double-pane insulating glass unit are summarized in Table A24.

A.3.5 Exterior Stucco Finishes

Introduction and applications: Exterior stuccos are typically cement-based coating and finishing to the outside of buildings. It is typically a mix of cement, lime, sand, and water. It is usually applied as a three-coat system with scratch, brown, and finish coats over metal lath (Athena Institute, 2001).

System boundary and manufacturing process: Mixing of the dry stucco components (cement, lime, and sand) is typically conducted on job site (Athena Institute, 2001).

Functional unit: The functional unit of 3-coat Portland-cement-based stucco is 1 cubic meter (m^3).

Literature review: No EPD or report has been found on the life cycle impacts of exterior stucco finishes with a scope of studying the United States. Some EPDs, such as Portland Cement Association (2016), covered stucco together with other concrete products and only reported a consolidated result. As for research studies, Dodge & Liu (2018) compared the life cycle impacts

of several exterior wall finishes by studying a residential house in Ohio, and found that the GHG emissions of stucco is higher than wood and vinyl siding, but lower than aluminum, fiber cement and brick.
Life cycle inventory: The life cycle inventory for exterior stucco finishes is summarized in Table A28 (Athena Institute, 2001).

TABLE A28. Life cycle inventory for exterior stucco finishes

Inputs	Data	Unit
Materials		
Portland cement	495.8	kg
lime	186.4	kg
sand	2426.7	kg
water	483.4	kg
Energy		
Energy consumption in stucco mixing	3.95	MJ

Limitations: The inventory data is collected from facilities in Canada, which may not be representative of the material and energy inputs to produce stucco in the United States. However, life cycle impacts of raw materials including Portland cement, lime, and sand, which are modeled by GREET based on data representative of the U.S. average manufacturing processes.

A.3.6 Wood Products

Introduction and applications: Wood is a renewable resource and considered 'environmentally friendly' material and is widely used in building construction. Lumber is a primary wood product which produces other derived wood products. The common use of wood products includes framing, flooring, glulam and plywood, etc. Lumber is used in construction for both structural and non-structural purposes and has been produced into a wide variety of products from many different species. The softwood in PNW includes Douglas-fir and hemlock. The softwood species in NE-NC region include white pine, red and jack pine, spruce, and balsam fir. The hardwood species include maple, oak, beech, birch, and hickory among others. The hardwood species generally spread out across the country. Typically, dimension lumber can be either green or dry but most lumber produced in the U.S. is dried. So, we consider dry planed lumber as a final product regardless of region and species.
Functional unit: Due to its unique properties and its market nomenclature, dimension lumbers are sold in different sizes and terminologies. Typical dimension lumber sizes as sold in the market ranges from 2×*4 to 2×*12. These sizes represent the nominal size of the lumber. The actual size of the lumber can vary depending on the stage of processing. Typically, a 2×*4 dimension lumber becomes 1.55" ×* 3.55" after drying and it is further reduced to 1.5" ×* 3.5" after planed drying as a final product (Milota 2015). We present the energy and emissions based on the functional unit of 1cubic meter of dry, planed lumber produced.

System boundary and manufacturing process: In this study, we consider the wood products system boundary starting from forest management and log production, to lumber product production. Figure A16 shows the lumber manufacturing process and system boundary.

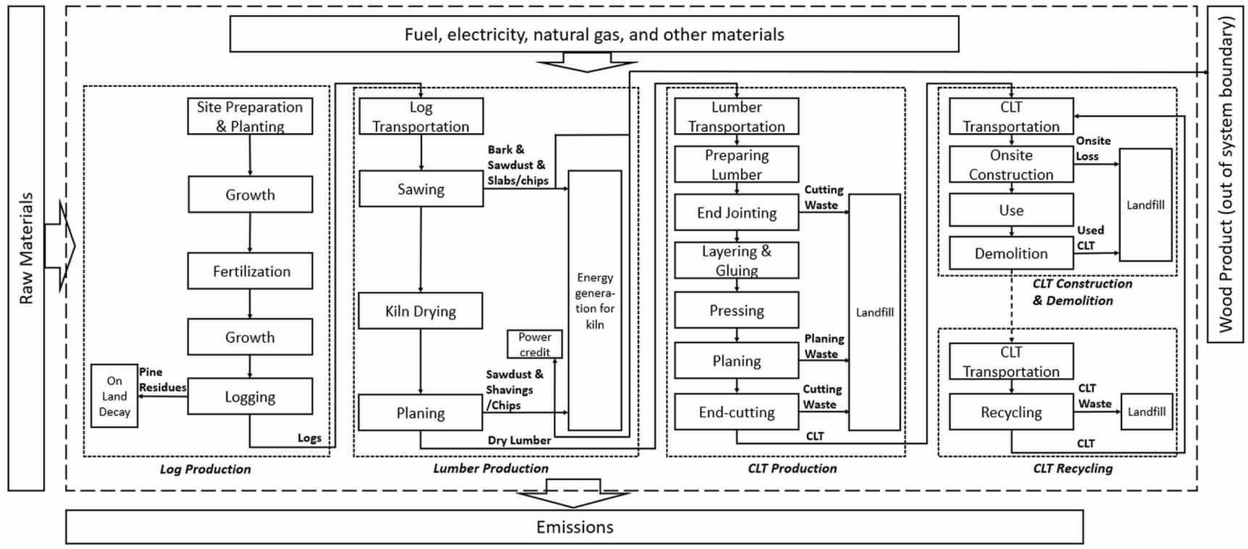


FIGURE A16. System boundary and lumber production processes (Lan et al., 2020)

Life cycle inventory: Original life cycle inventory data is presented in the unit of 1 ha, or 10,000 square meters. For consistency and convenience of comparison, inventory data in the functional unit of 1 m^3 of dry planed lumber product is summarized in Table A29.

TABLE A29. Life cycle inventory for lumber (functional unit: 1 m^3 of dry planed lumber product)

Input	Planed lumber	Unit
Material		
Nitrogen fertilizer	0.0541	kg
Phosphorus fertilizer	0.00671	kg
Herbicide (glyphosate)	0.000713	kg
Energy		
Diesel consumption in fertilization and herbicide application	0.168	MJ
Diesel consumption in planting	0.525	MJ
Diesel consumption of site preparation	1.62	MJ
Diesel consumption of logging	190	MJ
Electricity consumption of sawing	235	MJ
Electricity consumption of kiln drying and kiln heat generation	130	MJ
Electricity consumption of planing	79.6	MJ

According to Lan et al. (2020), the Cradle-to-Gate GHG emissions of 1 m^3 cross-laminated lumber product produced is 113.1 – -236.3 kg CO_2 equivalent when using mill residues for energy recovery, and the that is 260.3 – 375.4 kg CO_2 equivalent when selling mill residues to produce wood products.

A.3.7 Oriented Strand Board Panel

Introduction and applications: Oriented Strand Board (OSB) is an engineered wood-based structural panel. It is made of wood strands that are oriented along long axis, which provides optimal product properties. The outer layers of strands are aligned in the long direction of the panel, while smaller strands in the middle layer are vertical to the outers. Strands are bonded with thermosetting resins, and wax is added to increase water resistance. OSB is commonly used as wall, roof, or floor sheathing. It is typically used for new construction and remodeling of residential buildings (American Wood Council and Canadian Wood Council, 2020).

System boundary and manufacturing process: The production of OSB panels involves de-barking, stranding, drying, blending, forming and pressing, finishing and packaging (American Wood Council and Canadian Wood Council, 2020).

Functional unit: The functional unit of OSB panel is 1 cubic meter (m^3).

Life cycle inventory: The life cycle inventory data shown in Table A30 is based on the manufacturing processes of facilities in the United States and Canada.

TABLE A30. Life cycle inventory of OSB panel

Input	Data	Unit
Material		
Softwood	96%	kg
Resins	4%	kg
Primary Energy (A3)		
Renewable (LHV)	3478.12	MJ
Non-renewable (LHV)	2007.5	MJ

According to American Wood Council and Canadian Wood Council (2020), the Cradle-to-Gate GHG emissions of producing 1 m^3 of OSB panel in North America is 242.58 10^3 $kgCO_2eq$.

A.3.8 ZIP Sheathing

Introduction and applications: ZIP sheathing products can be used in both roof and wall applications for moisture protection and energy efficiency. It is made of combined wood strands, polymer and resin. Out of the two key materials, wood strands represent the largest component in sheathings. Commonly used ZIP sheathing types include roof and wall sheathing and insulated R-sheathing. The standard dimensions of sheathing include 8 ft length, 4 ft width and about 3 ft of height. The total weight ranges between 1,720 kg to 1746 kg per cubic meter for roof and wall sheathing whereas 520 kg to 830 kg in the case of insulated R-sheathing (Huber Corporation 2020).

Functional unit: The functional unit is one cubic meter of zip sheathing.

System boundary and manufacturing process: First, the logs are debarked and fed into a strander, which slices the material into small pieces (strands). The strands are then dried. The strands are then sent through a cyclone for screening process. The screened strands are then blended with resins, waxes, and other binders to hold them together. Forming of strands into mats are carried out using forming machine where the strands are converted to structurally consistent panels. The mats are then trimmed into the desired lengths, and heat and pressure are applied to activate the resin and bond the strands into a solid panel. The panels are sanded and coated (Huber Corporation 2020). Figure A17 shows the system boundary and manufacturing process of zip sheathings.

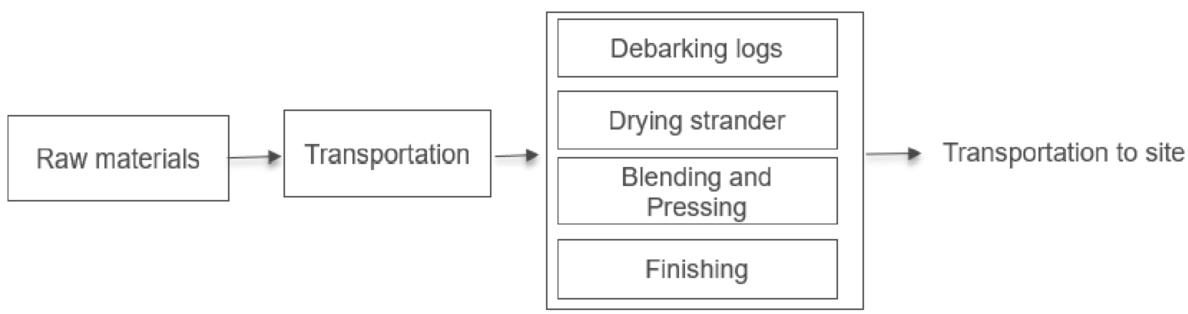


FIGURE A17. Cradle-to-Gate system boundary and manufacturing process of zip sheathing as described in literature.

Life cycle inventory: No detailed life cycle studies were found on zip sheathing. We collected data from the EPD produced by Huber Corporation. Table A31 shows the life cycle inventory data for zip sheathing based on Huber Corporation (Huber Corporation 2020).

TABLE A31. Life cycle inventory data to produce one cubic feet of zip sheathings

Input	Roof and Wall Sheathing	Insulated R-Sheathing
Material		
Wood	90-95%	70-90%
Core Resin	0.5-5%	0-5%
Surface Resin	0.5-1%	0-1%
Wax	0.25-2%	0-2%
Release Agent	<0.5%	<0.5%
Ink	<0.1%	<0.1%
Overlay (polymer-modified sheet material)	2-4%	0-2%
Insulation Foam	-	5-30%
Edge Seal	<0.1%	<0.1%

According to Huber Corporation (2020), the Cradle-to-Grave life cycle GHG emissions of 1 cubic meter of ZIP system roof and wall sheathing is 5.5×10^5 kg CO_2 equivalent, while the values for ZIP system insulated R-3, R-6, R-9, R-12 sheathing are 3.9×10^2, 3.3×10^2, 3.1×10^2, 3.1×10^2 kg CO_2 equivalent, respectively. The roof and wall sheathing product has much higher thickness and mass per declared unit than insulated sheathings, which makes it more GHG intensive.

Limitations: Zip sheathing LCI data is based on a single manufacture data. This needs further validation.

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