UNIVERSITY OF CALIFORNIA

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ENVIRONMENTAL PERFORMANCE OF ALTERNATIVE BUILDING MATERIALS IN THE CONTEXT OF RESIDENTIAL CONSTRUCTION

A thesis submitted in partial satisfaction of the
requirements for the degree of

MASTER OF SCIENCE

in

PHYSICS

by

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June 2024

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Abstract

Environmental Performance of Alternative Building Materials in the Context of Residential Construction

by

Mana Iwata

The rise of global temperatures and greenhouse gas emissions establish the critical importance of sustainable development strategies, particularly in material efficiency. The Building sector is a large contributor of global CO_2 emissions. The growing global population drives demand for residential construction, amplifying the need for alternative building materials and methods to mitigate carbon emissions while meeting housing needs. One potential solution lies in repurposing shipping containers, with millions circulating globally each year, making it an ideal resource for structural construction material. This thesis aims to quantify and compare the environmental impact of framing materials used in residential construction, specifically standard wood framing and Intermodal Steel Building Unit (ISBU) framing. ISBUs are the term for ISO shipping containers repurposed for building construction. We model our dimensions from an off-grid shipping container home designed and built by Team UCSC, EcoHus, to conduct an Eco Audit of manufacturing stages of the building lifecycle using Ansys®Granta EduPack 2021 software. We found that the materials used for the standard wood frame home require 2.67 times more energy and emit 2.31 times more CO_2 than the ISBU framing. Additionally, we examine the sustainable attributes of EcoHus, including its

integration of renewable energy and water systems. While acknowledging the considerable work ahead, this research contributes to the exploration of advancing sustainable practices in residential building construction and aims to guide future endeavors in decarbonizing the building sector through sustainable design strategies.

To the women in my life who have illuminated paths, shattered barriers, and inspired girls like me. Your enduring strength and unyielding conviction drive my journey.

Kokoroyori kansha to sonkei o shite orimasu.

Acknowledgments

I would like to acknowledge and extend my deepest gratitude to my advisor, Sue Carter, for her compassionate mentorship and guidance. She has provided me with many opportunities that I would not have pursued without her example, and I am forever grateful to her dedication and kindness. I also want to express my appreciation to my committee members, Sandra Faber and David Smith, for their support during this chapter of my academic career. I am deeply honored for their presence and guidance throughout this process.

I also must thank UC Santa Cruz and the physics department for providing a nurturing environment for my academic pursuits. I sincerely appreciate all that I have learned and the people that I have been fortunate enough to meet along the way. I'd like to thank my lab mates, Eli and Carey, for their patience and generosity as graduate mentors. I would also like to include Katie Hellier for introducing me to Carter Labs, and for being my first and most influential role model as a physicist. I could not have gotten through graduate school without my cohort and peers that I am lucky enough to call great friends. Phillip, Aidan, Sam, and most of all, my partner Chris. Thank you for always having my back.

Finally, I would like to acknowledge my family, who have put up with my irregular responses and check ins during my time in school. To my family in Japan, Miho Tanaka, Kumiko, Yasuhisa, and Yuma Sebe on my mother's side, and to Kozo Iwata on my father's side for his support throughout my education, and for his encouragement to pursue my dreams. I would like to make a special thanks to Toyoko Yoshimoto, or as I knew her, Chachan. May she rest in peace, for her contagious joy and laughter that filled my childhood continues to ring in my heart. My gratitude for you all is more than I can express in words, thank you for cheering me on and for showing me that love persists, no matter how great the distance. My siblings, Hinano and Soichiro, who inspire me everyday. I love you both dearly and I am honored to be your sister. And finally, I would like to thank my parents, Kanako and Yasuhiro Iwata, for their unwavering support and belief in me. Your strength in the face of hardship and your sacrifice in the name of love is the reason I am able to be here today. As I reflect on my achievements, I recognize that they are ours to share.

Chapter 1

Introduction

In the recent decades, the need for sustainable development has become imperative, with growing urgency to address environmental degradation and mitigate the effects of climate change. As reported by the Intergovernmental Panel on Climate Change (IPCC), human-induced greenhouse gas emissions between 1970 and 2019, as depicted in Figure 1.1, exhibit a clear correlation with the average global temperatures [1]. The average global surface temperature has increased by 1.1^{o}C in 2011 to 2020 since the pre-industrial era, 1850 to 1900 [1]. Notably, the Global Climate Report from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information identified 2023 as the warmest year on record for land and ocean areas individually [2]. In order to reduce the severe impacts and risks associated with climate change, the Paris Agreement was established in pursuit of maintaining the global temperature below 2^{o}C above pre-industrial records, while striving to limit the increase to 1.5^{o}C [3].

The major greenhouse gases emitted as a result of human activity include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and fluorinated gases (F-gases), shown in Figure 1.2 [4]. Carbon dioxide is the primary greenhouse gas produced by humans, released through the burning of fossil fuels and industrial processes [1]. These processes have raised the atmospheric carbon dioxide concentrations by 50% since 1750 [5]. The extent of future warming is contingent on greenhouse gases emitted within this century, necessitating significant changes and developments to steer temperature increases well below 2^{o}C.

The global building sector is the largest emitter of greenhouse gases, represent-

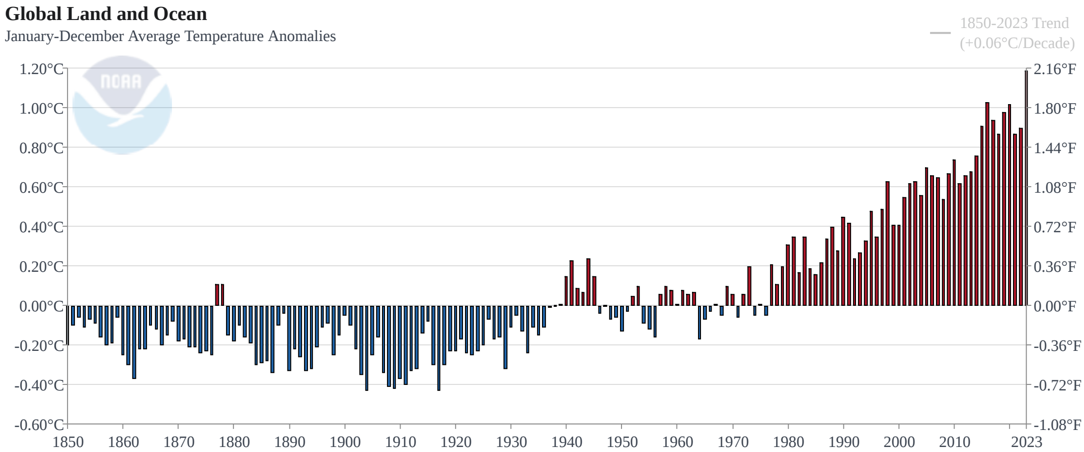

Figure 1.1: Annual land and ocean temperature averages from 1850-2023. Sourced from [2]

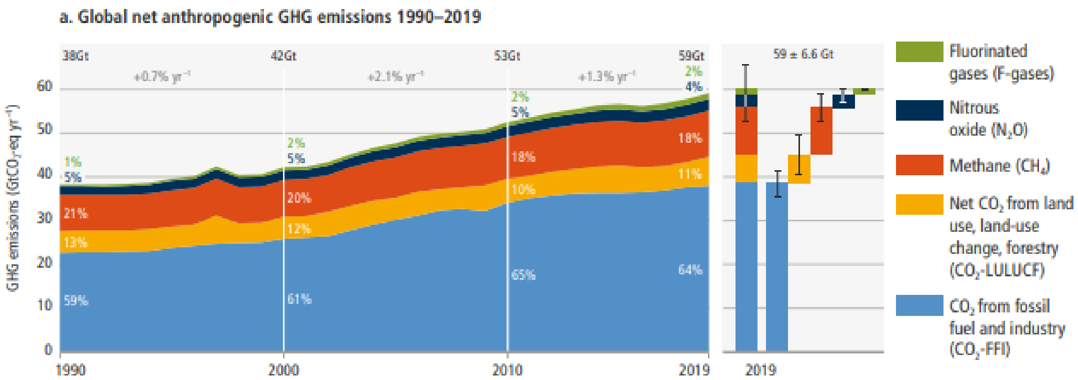

Figure 1.2: Total yearly emissions in Gt CO_2 equivalent from 1990 to 2019. The greenhouse emissions are distinctly shown by the specific type of gas: fluorinated gases (F-gases), nitrous oxide (N_2O), methane (CH_4), CO_2 from land use, and CO_2 from burning fossil fuels. Sourced from [4].

ing 37% of CO_2 emissions and 34% of energy consumption [6], with growing population and urbanization raising demands [7]. The building sector encompasses the direct and indirect energy and processing emissions from residential and non-residential sources worldwide, as well as the energy and emissions associated with materials utilized in construction [6], as illustrated in Figure 1.3. Figure 1.4 depicts the distribution of global energy-related CO_2 emissions across different economic sectors. Despite recent indications of emission reductions within the building sector, these trends primarily reflect pandemic-related disruptions rather than systematic efforts to lower emissions or energy consumption, as observed by the United Nations Environment Programme (UNEP) in their 2022 Buildings Global Status Report [8]. In order to adhere to the Paris Agreement's objectives for decarbonizing the building sector, a 77% reduction in greenhouse gas emissions must be achieved by 2050 [9].

While methodologies for assessing operational energy in residential buildings are well established and continually improving, evaluating the embodied carbon presents a more nuanced challenge. Operational carbon refers to the greenhouse gas emissions attributed to the energy consumption of buildings in use [11], whereas embodied carbon encompasses the greenhouse gases released across the entire life cycle of a product or a service. Operational and embodied carbon are mutually exclusive, preventing the double-counting of emissions and energy use. In the context of the building sector, embodied carbon attributes to the emissions stemming from the extraction, manufacture, transportation, installation, maintenance, and disposal of building products and materials [12]. Embodied carbon is assessed using Life Cycle Assessments (LCAs), a

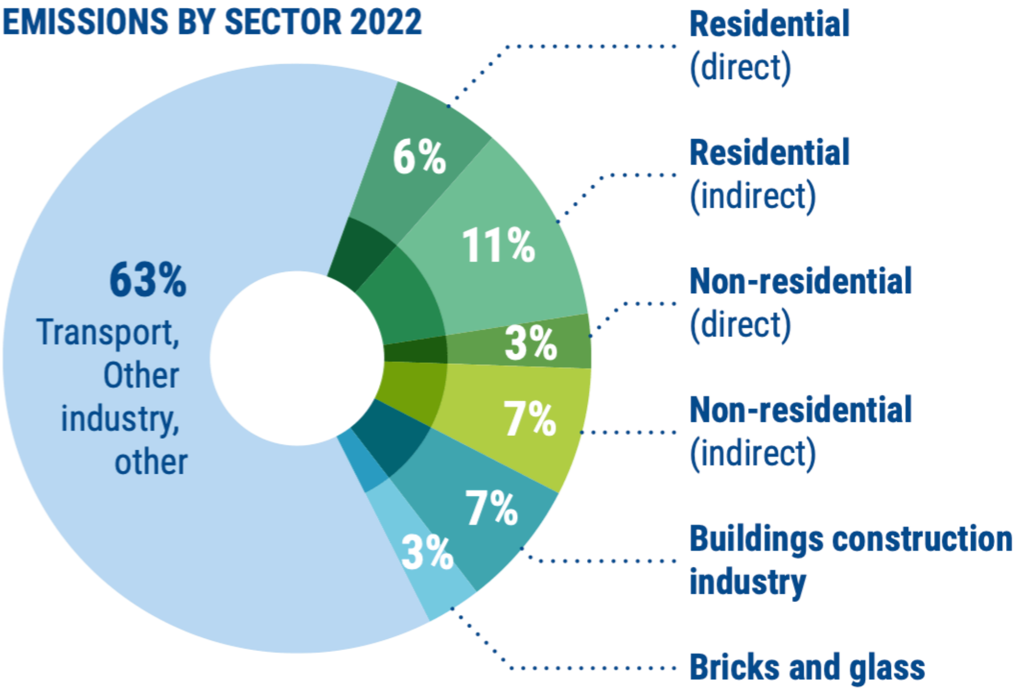

Figure 1.3: The building sector encompasses both direct and indirect energy and processing emissions from residential and non-residential sources worldwide, as well as the energy and emissions associated with materials utilized in construction, denoted as "Buildings construction industry" and "Bricks and glass" here. Sourced from [6].

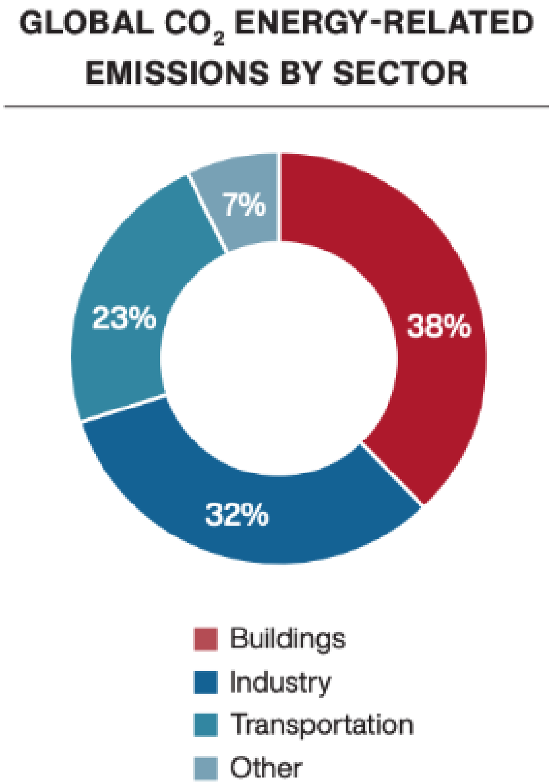

Figure 1.4: The global CO_2 energy- related emissions by economic sector. The building sector is responsible for nearly 40% of global greenhouse gas emissions, while the industry sector is responsible for a third of the emissions. Transportation and other sectors represent the last third of the global emissions. Sourced from [10].

methodology used to quantify the "carbon footprint" of systems in kilograms of carbon dioxide equivalent (kg CO_2 eq) [13]. LCAs consist of four phases, as defined by the International Standard ISO 14040: defining the goal and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation [14]. The first phase defines the level of detail and the system boundaries, the second phase involves inventory of data for the system's inputs and outputs, the third phase evaluates environmental impact and significance, and the final phase synthesizes and discusses LCI and LCIA findings to draw conclusions aligned with the assessment's objectives [14]. According to the Carbon Leadership Forum, the primary stages of a product's life cycle includes the product, construction, use, and end of life [11], as depicted in Figure 1.5.

A significant portion of the overall life cycle embodied carbon is taken up by the product stage, or the extraction and manufacturing stages of materials utilized in residential building construction [15]. The Resource Efficiency and Climate Change report by the International Resource Panel's (IRP) indicates that approximately 80% of emissions stemming from material production are associated with their use in manufactured goods and construction [17], as seen in Figure 1.6. As construction materials are projected to continue dominating global raw material consumption, and associated emissions are predicted to double by 2060 [18], the building sector emerges as a major target for transformative interventions and decarbonization strategies. One such strategy involves the adoption of recycled building materials, yielding a 15% to 20% reduction in emissions for the material cycle of residential structures in 2016 [17]. Minimizing the environmental impact of this stage can be achieved by utilizing less energy-intensive ma-

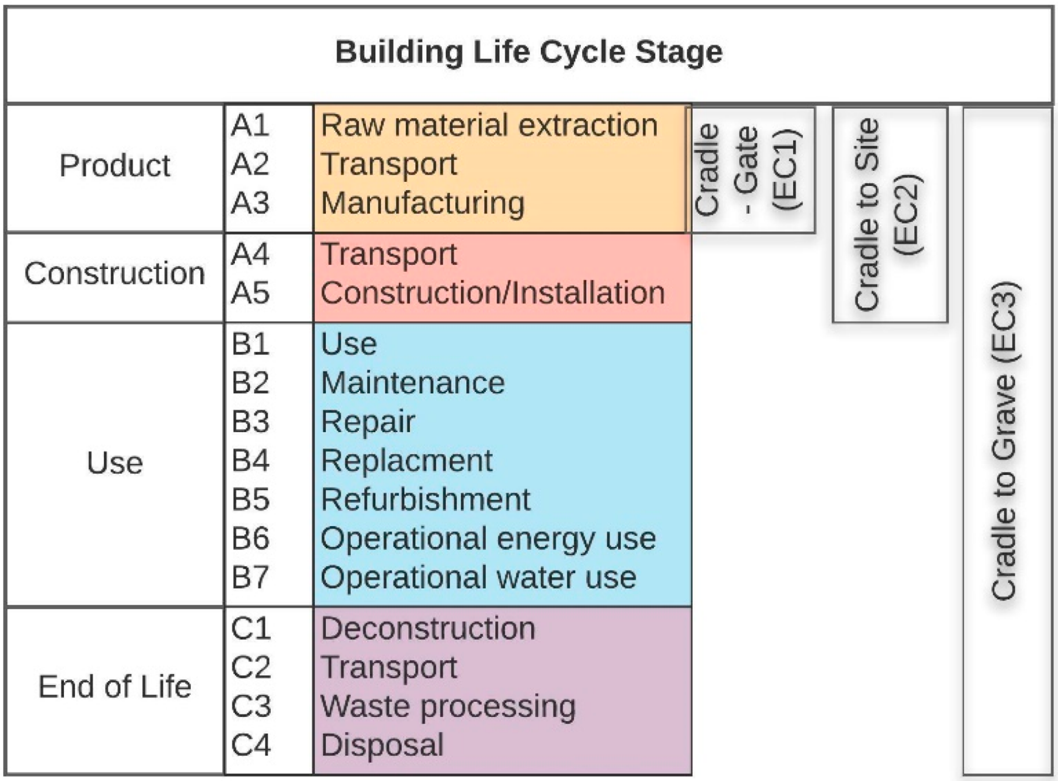

Figure 1.5: The key life stages of a building, represented by the product, construction, use, and end of life. Each of these key stages can be separated into more specific sub-stages (A1-C4). On the very right, the Cradle to Grave encompasses the entire life-cycle, serving as an expression for all stages of the product's life. Sourced from [15].

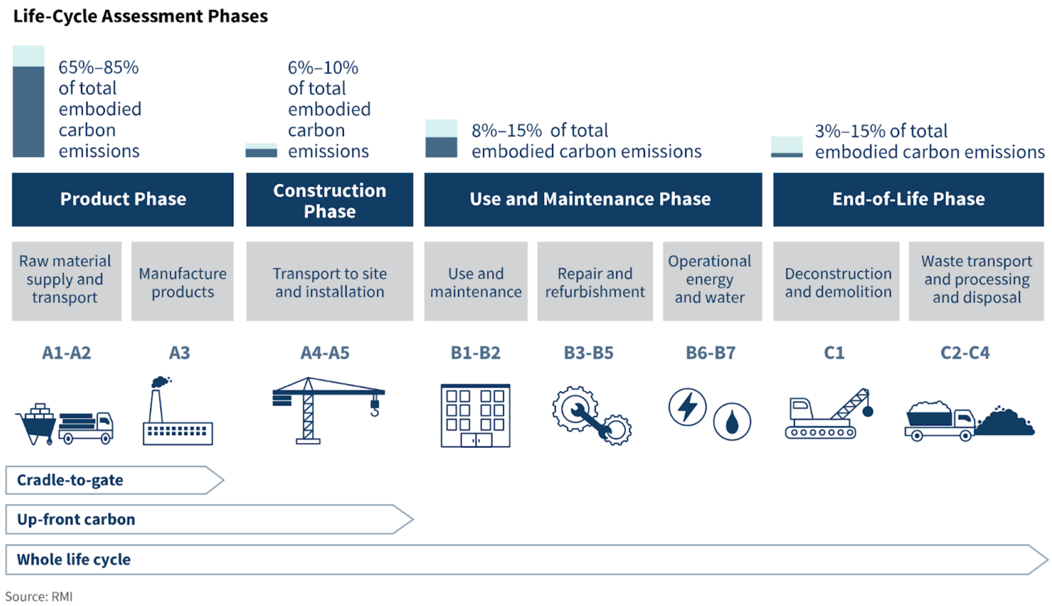

Figure 1.6: The Life-Cycle Assesment Phases of building construction. This figure breaks down the life of a building in to the product, construction, use, and end-of-life phases, and the corresponding percentage of embodied emissions represented by each phase. The product stage, or the extraction and manufacturing stages of materials utilized in residential building construction, represent up to 85% of the entire life cycle. Sourced from [16].

terials, presenting the need for alternative building resources and methodologies moving forward.

In the following chapters, we delve into the environmental implications of utilizing repurposed freight transport shipping containers, referred to as Intermodal Steel Building Units (ISBUs), as the primary framing material for residential home construction. Additionally, we introduce EcoHus, a model home representing a sustainable housing approach. However, we must first establish a foundational understanding of the model under investigation and the system boundaries of this study.

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Chapter 2

The Use of Intermodal Steel Building Units (ISBU) in Residential Construction

The research presented in this thesis uses an understanding of environmental impact assessments and modern standards of residential framing construction within the building sector. Assessing the environmental implications of building materials necessitates an examination of both factors. This thesis examines a strategy to mitigate material emissions within the building sector by utilizing recycled shipping containers, ISBUs, as an alternative material for residential construction. To understand the rationale behind this approach, we must first discuss the qualities that make ISBUs a practical candidate for sustainable building.

2.1 Introduction

Chapter 1 highlights the importance of not only reducing the greenhouse gases emissions moving forward, but also minimizing the use of energy-intensive products within the building sector. The UNEP advocates for the use of recycled materials to mitigate environmental impact by repurposing materials with high embodied energies, thereby preventing waste [1].

According to the World Shipping Council (WSC), approximately 250 million shipping containers were transported in 2022 [2], reflecting the demands of globalization and international trade. It is estimated that over 17 million structurally sound shipping containers worldwide remain available for reuse after retirement from their original freight transportation role [3]. Trade imbalances and relocation costs contribute to the accumulation of containers in ports [4]. 40 foot (ft) High Cube (HC) steel containers typically have an average life-span of 25 years and require 107 GJ of energy and 9.8 metric tons of CO_2 equivalent to produce [5][6]. Given the surplus of unused shipping containers and significant energy used during their production, repurposing containers emerges as a compelling resource for housing construction.

This chapter employs a case study model home, EcoHus, to assess the embodied environmental impact of a standard wood framed home and compare it to an ISBU framed home. To conduct an energy and carbon footprint analysis of these materials, the Eco Audit module within the Ansys®Granta EduPack 2021 software is utilized.

2.1.1 Background

The building sector, according to the UNEP, accounts for approximately 38% of global wood product consumption. One-third of timber trade involves illegal harvesting, with 90% of this activity linked to tropical hard and soft woods. The rate of deforestation and timber harvesting worldwide surpasses the rate of forest regeneration, exacerbating environmental concerns [7]. Wood frame construction dominates residential buildings in North America, constituting around 90% of structures [8]. Wood, sourced from trees, possesses inherent structural qualities that enable it to withstand wind forces and bend to accommodate torque and shear stress. However, as an anisotropic and nonhomogeneous material, the structural properties of lumber are determined by the orientation of stress relative to the wood grain [9]. In the United States, wood framing consumes 60% of softwood lumber and constitutes 85% of lumber used in home construction, including joists, studs, sheathing, and siding [10].

2.1.2 Standard Wood Frame Design and Construction

The construction of a typical wood framed home entails several sequential steps, including site preparation, foundation construction, floor framing, wall framing, roof framing, exterior finishes, and installation of windows and doors [9]. We now focus on floor, wall, and roof framing, along with the materials associated with their construction.

2.1.2.1 Framing

Once proper site preparations are complete and the foundation is laid, wood framing begins with the attachment of the sill plate on top of a concrete foundation. The sill plate is the first layer of the frame, outlining the perimeter of the house. Floor joists are horizontal lumber components that are laid in rows of equal spacing, where the ends are fastened to the sill plate, spanning the gap between the sill plate and any beams [11]. In order to provide more lateral stability, blocking, or smaller wood components embedded perpendicularly between the joists are placed every 4 ft to 6 ft [12]. The subfloor, frequently made of oriented strand board (OSB) or plywood, is then secured onto the joists to act as a horizontal diaphragm to resist lateral building loads. The floor framing consists of the structural components of the home that distribute dead and live loads of the house within the frame and foundation. Dead loads consider the loads caused by the weight of all the materials used in the structure, while live loads describe loads imposed by occupancy and use of the building [13].

Wall framing is then placed on top of the subfloor, often constructed out of 2x4 or 2x6 nominal lumber. A simple wall frame consists of top and bottom plates, studs, and blocking. The top and bottom plates describe the horizontal pieces of wood that are fastened perpendicularly to the end of studs, which are vertical pieces with equal on-center spacing [12]. On-center spacing describes the distance between the center of two pieces of lumber, and is commonly 16 inches (in) on-center for studs. In order to distribute lateral loads to the wall framing, structural sheathing is added to the frame. For external walls, structural sheathing is attached to the outside edges of wall studs in order to resist lateral loads like seismic and wind loads. Interior walls or room partition framing use interior finishing, referred to as drywall or gypsum board, to serve the same structural purpose. There are two types of interior partitions, non-bearing partitions and bearing partitions. Non-bearing partitions carry only the weight of the materials within their framing and are permitted to have a single top plate. Bearing partitions support other aspects of the structure like floors, ceilings, or roofs and require two top plates [13]. Alternatively, beams made of laminated veneer lumber (LVL), an engineered wood product, can be employed as a structural alternative to bearing walls. Integrating LVL beams aids in expanding interior spaces by replacing intermittent load bearing walls and minimizing the materials required for their framing.

Roof framing typically comprises a sloped structural system supporting lateral and gravity loads. Ceiling joists are placed 24 in on-center, and are secured to the exterior wall plates. Maximum spans for joists are determined by the species of wood and are laid out in the Span Tables for Joists and Rafters standardized by the American Wood Council [14]. The joists transfer the ceiling and roof loads to the underlying walls and beams, but require intermediate bearing walls to support the span between exterior walls. For flat roof construction, the roof joists serve as the ceiling joists for the space below. Sheathing is then nailed onto the framing, serving as the roofing of the structure [13].

2.1.3 Intermodal Steel Building Units

ISBUs are the term used to describe any ISO shipping containers that are repurposed for building, making it a more appropriate term for this study [15].

It should be noted that the reuse of ISBUs does not entail the melting down of the material. Converting a 3.63 metric ton (approximately 8000 lbs) steel shipping container into steel beams necessitates the consumption of 8000 kWh of energy to melt the material, whereas repurposing the same container into a residential unit consumes 400 kWh, only accounting for 5% of the energy required for the former process [16]. Additionally, when COR-TEN A steel, comprising 78% of the structural assembly, undergoes recycling through melting, it emits 5.7 metric tons of CO_2 equivalent greenhouse gases [6]. Within the context of this study, the reuse of ISBUs denotes their comprehensive integration into construction projects, thereby preventing material waste and offering an avenue for mitigating the environmental footprint associated with future residential construction.

Shown in Figure 2.3, the container analyzed in this study is a steel structured container, designated by ISO as 1AAA, more commonly referred to as a 40 ft High Cube container [18]. This container represents a standard shipping unit widely utilized

ISO 1AAA Dimensions			
External	Length	12192 mm	40’
	Width	2438 mm	8’
	Height	2896 mm	9’ 6”
Internal	Length	12032 mm	39’ 5 45/64”
	Width	2352 mm	7’ 8 19/32”
	Height	2698 mm	8’ 10 7/32”
Door Opening	Width	2340 mm	7’ 8 1/8”
	Height	2585 mm	8’ 5 49/64”
Internal Cubic Capacity		76.4 m^3	2700 ft^3

Table 2.1: Dimensions of a 1AAA or 40 ft High cube container given by ISO 668. Sourced from [17].

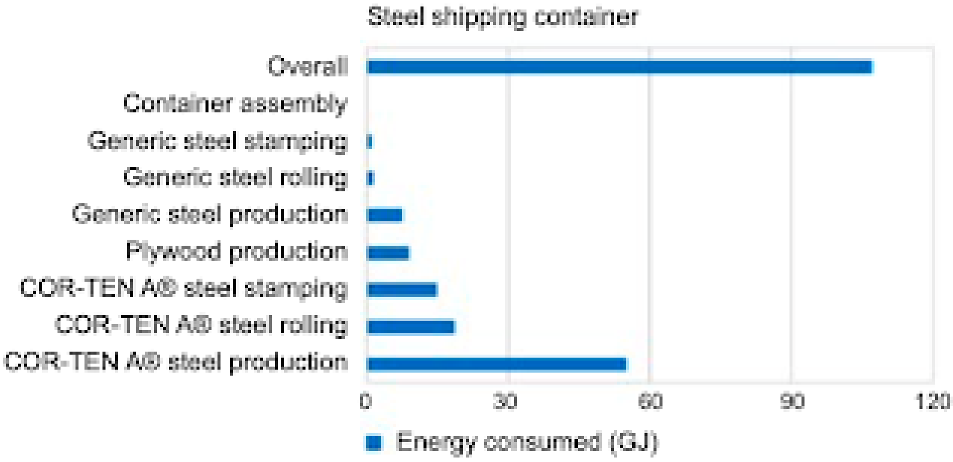

Figure 2.1: The energy consumption of the production and manufacturing of a 40 ft steel shipping container. Image sourced from [6].

in global freight trade and transportation.

2.1.3.1 Components and Materials: The Impact of Shipping Containers

The process of producing a steel container consists of materials production, materials processing, and container assembly. ISBUs are mostly manufactured with Weathering Structural Steel, specifically COR-TEN A steel [6]. The material is also recognized as S355J2 Steel, categorized as a high-quality grade of non-alloy structural steels [19], also referred to as ASTM A572 [20]. The fabrication of a steel container entails several sequential stages: the manufacture of COR-TEN and generic steel, rolling and stamping of COR-TEN and generic steel, plywood production, and finally, container assembly [6]. The corresponding energies required for these processes are shown in Figure 2.1.

For the production of a 40 ft steel container, the total emission of greenhouse

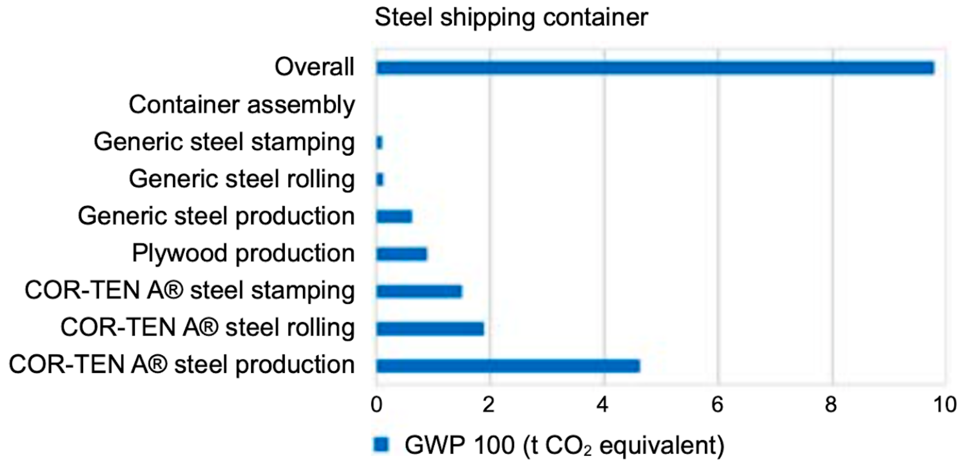

Figure 2.2: The environmental burden of a 40 ft steel shipping container in GWP. The overall emissions during production are 9.8 t of CO_2 equivalent. 47% is emitted through the production of COR-TEN A steel, while the rolling and stamping account for 19% and 16% of total emissions, respectively. Image sourced from [6].

gases amounts to 9.8 metric tons of CO_2 equivalent, with the manufacture and processing of COR-TEN A steel identified as the primary source of emissions, as illustrated in Figure 2.2 [6].

The standardized dimensions and specifications of ISBUs make them highly advantageous as modular construction materials, enabling structural integrity, expedited construction processes, and cost reduction [15]. The dimensions of the container utilized in this study are detailed in Table 2.1, with 40 ft in length, 9 ft and 6 in in height, and 8 ft in width [17]. The container weighs 8,290 lbs, with COR-TEN A steel comprising the majority of its material composition. COR-TEN A steel is corrosion resistant and has a high yield strength of 50,000 psi and a tensile strength of 70,000 psi [22]. The 40 ft high cube container is constructed by welding together its top and bottom

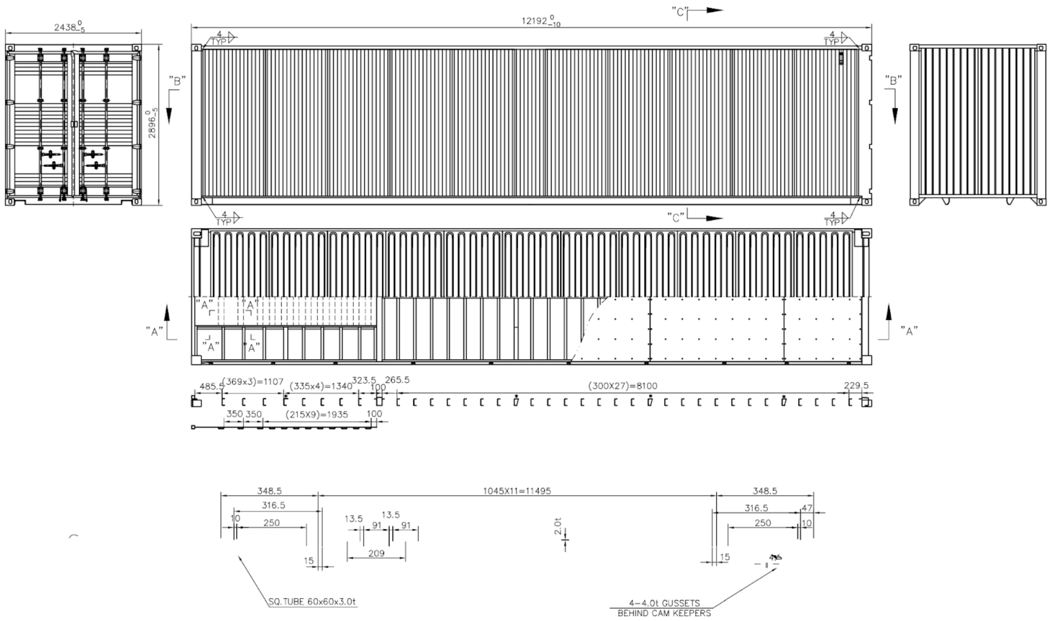

Figure 2.3: A computer aided design drawing of the side walls, end walls, and base of the ISO 1AAA container. Sourced from [21].

walls, sidewalls, and endwalls at their edges during assembly. Corner posts facilitate the connection of the side and end walls to withstand both live and dead loads. The base structure consists of two side rails linked by perpendicular steel floor joists welded every 12 in. A 1 inch marine plywood sheathing is screwed into the floor joists. This flooring system can accommodate a maximum weight of 67,000 lbs, reducing to 55,000 lbs after considering the weight of the container itself [21]. Durability is ensured in adherence to ISO 1496 standards, including rigorous tests that validate stacking strength, as well as transverse and longitudinal rigidity, incorporating wind and seismic regulations outlined in Section 3115.8.4.2 of the 2021 International Building Code [23].

2.1.4 Our Model: EcoHus

To serve as a model structure, EcoHus was selected for this study. Crafted under the guidance of our faculty advisor, Sue Carter, alongside three graduate student leaders and ten undergraduate students, EcoHus is a sustainable dwelling encased within a greenhouse framework, designed for the Orange County Sustainability Decathlon. Although this design is atypical for residential housing, EcoHus was developed as an approach to reducing the amount of materials and energy used to construct and live in a home, as an innovative solution for sustainable building. The greenhouse is constructed out of recycled steel, and the main house utilizes two recycled ISBUs that are laid parallel to one another, shown in Figure 2.4.

The framing material for interior room dividers and the center modular section that spans the two shipping containers is Douglas fir #2 lumber. The inner part of the home, or the conditioned structure, is equipped with plumbing and electrical systems akin to a modular home. In this chapter, we will exclusively consider the conditioned structure, excluding the greenhouse, as we analyze the framing materials. We consider the same dimensions, depicted in Figure 2.5, for both ISBU and wood frame cases to determine the embodied energy and carbon of each approach with the Eco Audit tool from Ansys®Granta EduPack 2021 software. More details about the model home are discussed in Chapter 3.

EcoHus' use of recycled materials and minimized resource consumption is expected to diminish both energy consumption and carbon emissions during the product

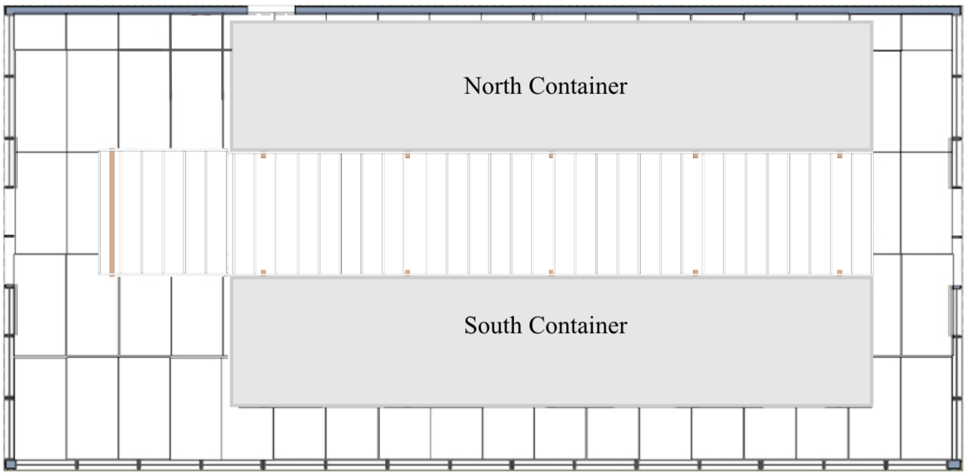

Figure 2.4: Simple schematic of EcoHus and the bordering greenhouse structure, shown in grey. This is the model home from a bird's eye view. The positioning of the north and south container is illustrated, with floor joists spanning the distance between each ISBU. This design creates more space than typically possible for a single ISBU construction.

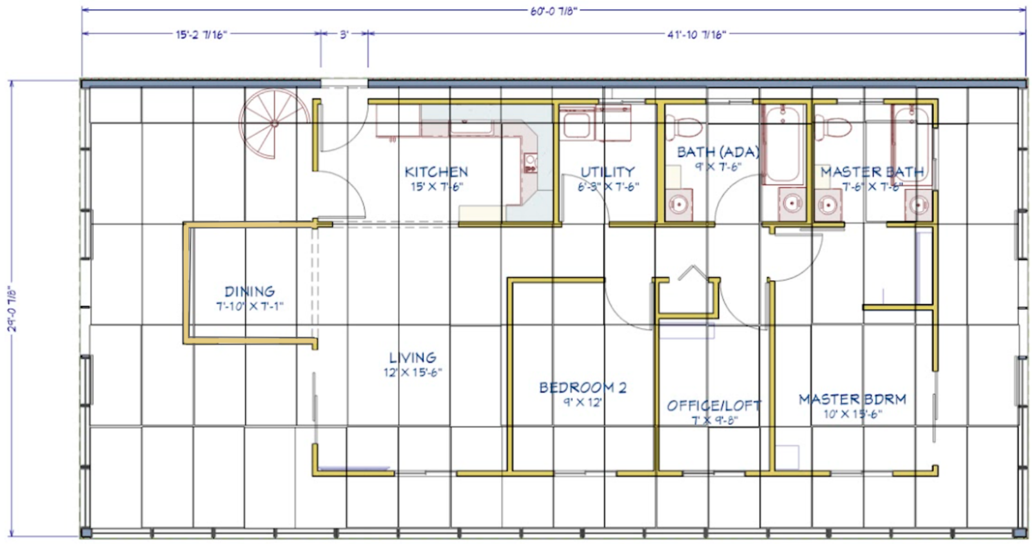

Figure 2.5: Schematic of model home, EcoHus, displays the dimensions of the house and greenhouse structure. In Chapter 2, we exclusively consider the dimensions of the conditioned structure within the greenhouse, indicated here by the yellow walls.

phase of the building life cycle. The subsequent sections of this chapter will focus solely on the framing materials of each home.

2.2 Comparison of Materials

The goal of this study is to evaluate the environmental impacts of framing materials for residential building. It should be noted that the impact of the container itself was not included in the analysis, as it was considered a non-virgin, recycled material. We take a cradle-to-gate approach in this Life Cycle Impact Assessment, focusing on the impact of the product stage. The ISBU and wood frame homes are assessed to have identical square footage and dimensions, modeled after the EcoHus floor plan.

2.2.1 LCIA System Boundary and Eco Audit

The energy and carbon analysis were calculated using the Eco Audit module within Ansys®Granta EduPack 2021 software [24]. The goal and scope of this assessment is to compare construction materials for residential buildings, to evaluate whether the use of ISBUs are a viable approach to sustainable building construction. The system boundaries considered extraction and processing of raw materials, as well as the manufacture of the building materials for a building with a 20-year life span. The Eco Audit tool makes an assessment of the distribution of energy demand and carbon emissions over a product's life. The Ansys®Granta EduPack 2021 software heavily relies on Ecoinvent Data v3.9 for environmental data.

Ecoinvent Data, maintained by the Swiss Center for Life Cycle Inventories, is a life cycle inventory database that provides data on the environmental impacts spanning the entire lifetime of diverse products and processes [25]. The Eco Audit tool first requires a bill of materials, as seen in Figure 2.6, to begin the audit. Data on embodied energies and process energies is sourced from the Ansys material properties database, with outputs presented in both graphical and tabular formats, showcasing the energy or carbon footprint of each life cycle phase. The Eco Audit is divided into four steps, beginning with the material and manufacturing input, details on transport, the use phase, and concluding with the generation of a report [24]. We exclusively consider the initial step, where mass, material, and primary shaping process data for each component are inputted. We compare the footprint of wood and ISBU materials at

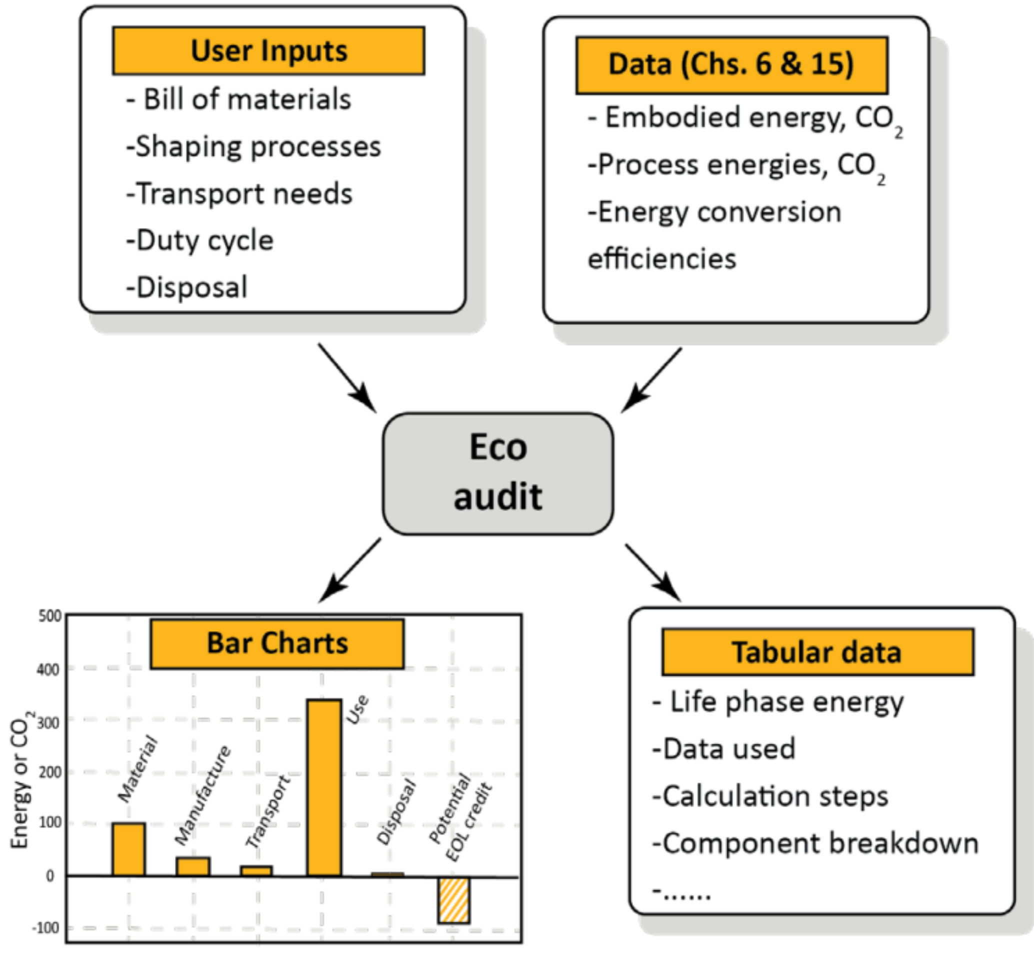

Figure 2.6: A schematic of the Eco Audit Tool, describing the inputs from the user and the Materials Database within Ansys®Granta EduPack 2021, which heavily relies on life cycle database, Ecoinvent for environmental data. The outputs from the tool generate results in bar chart and tabular forms. Schematic sourced from [24].

the onset of their life cycle, focusing on stages A1-A3, as illustrated in Figure 1.4. These stages represent the "initial embodied carbon" which significantly influences the total embodied impact [26]. Thus, efforts to reduce emissions at these stages hold greater significance compared to subsequent stages with lower impact [27]. Embodied energy, as defined by Ansys®Granta EduPack 2021, pertains to the energy required in producing 1 kilogram of a material from its raw feedstock. This encompasses the energy input from the primary feedstock, transportation, and consuming energy of the material. The embodied energy per unit weight, denoted as H_e , is described by Equation 2.1.

$$H_e = \frac{\Sigma \text{ Energy Entering Plant per Year}}{\text{Mass of Material Shipped per Year}} \tag{2.1}$$

For embodied energy within primary production, values vary with material grades. The term 'virgin grade' denotes material devoid of any recycled content, while 'typical grade' integrates energy considerations for both virgin production and recycling, factoring in the portion of recycled content R_f within the current supply chain, as shown in Equation 2.2.

$$\text{Typical Grade Energy} = \frac{100 - R_f}{100} \times \text{Virgin Grade Energy} + \frac{R_f}{100} \times \text{Recycling Energy} \tag{2.2}$$

The shipping containers considered in the construction of the structure are reused parts, and therefore have no contribution to the total embodied energy and carbon footprint. The totals are determined by summing the product of each component's mass (lbs) and its corresponding impact value (BTU/lb for energy or lbs/lbs for CO_2), as outlined in Equations 2.3 and 2.4.

$$\text{Total Embodied Energy} = \Sigma(\text{mass of part} \times \text{quantity}) \times \text{embodied energy} \tag{2.3}$$

$$\text{Total Carbon Footprint} = \Sigma(\text{mass of part} \times \text{quantity}) \times CO_2 \text{ footprint} \tag{2.4}$$

The components and masses included are summarized in the bill of materials in Figure 2.9 and Figure 2.10. The embodied energy and CO_2 footprint values are represented in the program in each material datasheet, the primary production and processing for coated steel shown in Figure 2.7.

The inputs for the masses included in the Eco Audit were derived from the EcoHus floor plan. The masses of lumber were obtained from the Approximate Weight Chart provided by the Osborne Lumber Company (see Appendix A)[29]. Natural materials such as wood are an example of several material classes within the Ansys®Granta database that include the energies associated with the primary shaping process in the value for raw material production.

2.3 Results and Discussion: Embodied Impact

The Ansys®Granta EduPack 2021 Eco Audit module's analysis offers a detailed breakdown of energy consumption and CO_2 emissions for each component of the

Coated steel, steel, galvanized

Datasheet view: All attributes | Show/Hide | Find Similar

Primary production energy, CO2 and water

Embodied energy, primary production (virgin grade)	1.64e4	-	1.81e4	BTU/lb
Sources 40 MJ/kg (Hammond and Jones, 2008)				
Embodied energy, primary production (typical grade)	* 9.67e3	-	1.14e4	BTU/lb
CO2 footprint, primary production (virgin grade)	2.87	-	3.16	lb/lb
Sources 3.01 kg/kg (Hammond and Jones, 2008)				
CO2 footprint, primary production (typical grade)	* 1.71	-	2.01	lb/lb
Water usage	* 1.56e3	-	1.72e3	in^3/lb

Processing energy, CO2 footprint & water

Casting energy	* 5.16e3	-	5.7e3	BTU/lb
Casting CO2	* 0.9	-	0.994	lb/lb
Casting water	* 628	-	943	in^3/lb
Roll forming, forging energy	* 1.21e3	-	1.34e3	BTU/lb
Roll forming, forging CO2	* 0.212	-	0.234	lb/lb
Roll forming, forging water	* 76.4	-	115	in^3/lb
Extrusion, foil rolling energy	* 2.3e3	-	2.54e3	BTU/lb
Extrusion, foil rolling CO2	* 0.402	-	0.444	lb/lb
Extrusion, foil rolling water	* 106	-	159	in^3/lb

Figure 2.7: An example of material data available on the Ansys®Granta EduPack 2021 software under the material selection, "Coated steel, steel, galvanized". The data is showcased in tabular form, here showing the tables showcasing the primary processing energy and carbon footprint for processing galvanized steel per unit mass. Sourced from [28].

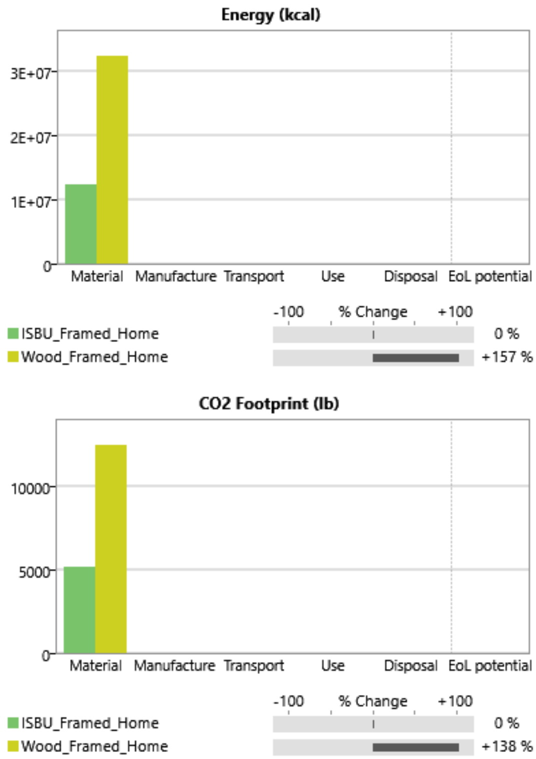

Figure 2.8: An Eco Audit Summary Chart comparing the Energy (kcal) and CO_2 Footprint (lbs) of the material and manufacturing stages of an ISBU frame and a wood frame home [28].

structure, emphasizing the pivotal role of material selection in environmental management. We specifically use the module to analyze the energy and CO_2 footprint associated with material processing and manufacturing stages.

In the case of the wood frame home, constructed entirely from natural materials, the product manufacturing values were integrated into the material phase analysis. However, for the ISBU frame home, where metal parts are included in the structure, the manufacturing process was separately shown in the Eco Audit report (see Appendix B). Notably, while the manufacturing process impacts were considered, the primary en-

ISBU Frame

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	Energy (kcal)	%	CO2 footprint (lb)	%
ISBU	Structural steel, S355J	Reused part	8.3e+03	2	1.7e+04	0	0.0	0	0.0
Brackets (interior framing)	Coated steel, steel, galvanized	Virgin (0%)	0.075	220	17	7.2e+04	0.6	50	1.0
ISBU wall framing horizontal (2x2x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	5.3	55	2.9e+02	3.5e+05	2.8	1.1e+02	2.1
Room separating walls (2x4x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	13	84	1.1e+03	1.3e+06	10.8	4.1e+02	7.9
Floor joists (2x6x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	20	37	7.4e+02	8.8e+05	7.1	2.7e+02	5.2
Joist hangers (floor)	Coated steel, steel, galvanized	Virgin (0%)	0.27	30	8.1	3.5e+04	0.3	24	0.5
Blocking (Floor) (2x4x14.5")	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	2	54	1.1e+02	1.3e+05	1.0	40	0.8
Subfloor (4x8 sheet)	Oriented strand board, type F1, parallel to board	Virgin (0%)	68	12	8.2e+02	1.7e+06	13.7	7.2e+02	13.9
Ceiling Joists and Framing (2x8x10)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	33	35	1.2e+03	1.4e+06	11.2	4.3e+02	8.2
Sheathing (ceiling) (4x8 sheet)	Plywood (5 ply, beech), parallel to face layer	Virgin (0%)	70	15	1.1e+03	2.9e+06	23.6	1.5e+03	28.6
Beam hanger (kitchen)	Structural steel, ASTM A36	Virgin (0%)	88	1	88	3.1e+05	2.5	2.6e+02	5.1
Container Ceiling Joists North (2x6x8) + blocking	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	20	30	6e+02	7.2e+05	5.7	2.2e+02	4.2
Exterior Siding (wall) (4x8)	Oriented strand board, type F1, parallel to board	Virgin (0%)	68	9	6.1e+02	1.3e+06	10.3	5.4e+02	10.5
Joist Hangers (kitchen)	Coated steel, steel, galvanized	Virgin (0%)	0.27	10	2.7	1.2e+04	0.1	8.1	0.2
Steel Posts (south container support)	Structural steel, ASTM A500 Grade A	Virgin (0%)	38	3	1.1e+02	4e+05	3.2	3.4e+02	6.6
Container Ceiling Joists South (2x4x8) + blocking	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	13	30	4e+02	4.8e+05	3.8	1.5e+02	2.8
ISBU wall framing vertical (2x2x6)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	4	55	2.2e+02	2.6e+05	2.1	80	1.6
Room separating wall blocking (2x4x14.5")	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	2	64	1.3e+02	1.5e+05	1.2	47	0.9
Total				746	2.4e+04	1.2e+07	100	5.2e+03	100

Figure 2.9: A detailed breakdown of the bill of materials inputted into the Eco Audit Tool by Ansys®Granta EduPack 2021 for the ISBU frame home. The table shows the materials used in the framing of the ISBU home, the corresponding mass of each component, and the total energy and CO_2 footprint of each material at the given mass and quanitity [28].

Wood Frame

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	Energy (kcal)	%	CO2 footprint (lb)	%
Sill Plate (2x6x10)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	25	15	3.8e+02	4.5e+05	1.4	1.4e+02	1.1
Exterior Wall Framing (2x6x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	20	165	3.3e+03	3.9e+06	12.2	1.2e+03	9.7
Room Separating Walls (2x4x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	13	116	1.5e+03	1.9e+06	5.7	5.7e+02	4.5
Beam (Flooring) (4x8x20)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	1.5e+02	3	4.4e+02	5.2e+05	1.6	1.6e+02	1.3
Floor Joists (2x8x12)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	40	69	2.8e+03	3.3e+06	10.2	1e+03	8.1
Blocking (Floor) (2x4x14.5")	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	2	117	2.4e+02	2.8e+05	0.9	86	0.7
Subfloor (4x8)	Oriented strand board, type F1, parallel to board	Virgin (0%)	68	36	2.4e+03	5.1e+06	15.8	2.2e+03	17.4
Kitchen Beam (2x8x12'10")	Glulam	Virgin (0%)	37	2	75	1.6e+05	0.5	63	0.5
Trim for Kitchen Beam (2x4x8)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	13	4	53	6.4e+04	0.2	20	0.2
Ceiling Joists + Frame (2x8x16)	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	67	49	3.3e+03	3.9e+06	12.1	1.2e+03	9.6
Sheathing (Ceiling) (4x8)	Plywood (5 ply, beech), parallel to face layer	Virgin (0%)	70	32	2.2e+03	6.3e+06	19.4	3.2e+03	25.4
Room Separaing Wall Blocking (2x4x14.5")	Douglas fir (pseudotsuga menziesii (coastal)) (l)	Virgin (0%)	2	82	1.7e+02	2e+05	0.6	61	0.5
Exterior Wall Sheathing (4x8)	Oriented strand board, type F1, parallel to board	Virgin (0%)	68	44	3e+03	6.3e+06	19.4	2.7e+03	21.2
Total				734	2e+04	3.2e+07	100	1.2e+04	100

Figure 2.10: The bill of materials inputted into the Eco Audit Tool by Ansys®Granta EduPack 2021. This table shows the materials necessary to build the model home, EcoHus, entirely out of wood materials. The 'Material' input is chosen from the database of material properties, specifically "Sustainability Level 3". The table also includes the energy and CO_2 footprint associated with each material at the mass and quantity given [28].

vironmental burden was attributed to the raw material extraction during the product stage.

Both homes were assessed over a 20-year product life time, an average length for residential structures. Beginning with the ISBU frame home, the total amount of energy used for the material and manufacturing life phase is 1.2 x10^7 kcal or 1.39 x10^4 kWh, while the CO_2 emitted is 5.2 x 10^3 lbs CO_2 equivalent or 2,358 kg of CO_2 equivalent. Due to the product life being set at 20 years, the equivalent annual environmental burden, averaged over a 20-year product life, amounts to 6.28 x 10^5 kcal/year or 730 kWh/year, alongside 262 CO_2 lbs/year or 118 kg of CO_2 eq/year.

In contrast, the wood frame home exhibits significantly higher carbon emissions and energy consumption, more than doubling those of the ISBU frame home. The total amount of energy required for the raw material extraction, transportation, and manufacture of the materials needed to build the wood frame home uses 3.2 x 10^7 kcal or 3.7 x 10^4 kWh of energy and emits a total of 1.2 x 10^4 lbs CO_2 equivalent or 5,431 kg CO_2 equivalent. Over a 20-year lifespan, it necessitates 1.62 x 10^6 kcal/year or 1,882 kWh/year, accompanied by 625 CO_2 lbs/year or 283 kg CO_2 eq/year of carbon emissions.

The wood frame home's material and manufacturing stages require nearly 2.67 times more energy and emits 2.31 times more CO_2 than the ISBU home. This underscores the substantial environmental advantage of the ISBU frame home in terms of energy efficiency and carbon footprint management during construction and material processing phases.

The ISBU design uses 7,320 lbs of wood, representing only 36.6% of the 20,000 lbs required for wood frame construction. This reduction in raw material usage demonstrates the efficacy of integrating recycled materials in construction to decrease initial embodied carbon emissions and embodied energy.

These findings do not imply that steel, as a construction material, inherently carries a lesser environmental impact compared to lumber. On the contrary, constructing with sustainably sourced lumber constitutes a viable strategy for carbon emission reduction [30]. Incorporating low-embodied carbon, biobased materials such as wood, bamboo, and clay contributes to the decrease of carbon emissions within the building sector. Moreover, utilizing materials like wood, which removes carbon from the atmosphere through photosynthesis prior to processing, further diminishes the embodied carbon of the material, especially when it is locally sourced [30].

Nevertheless, the present discourse primarily focuses on the strategy of mitigating the environmental impact of the building sector through the repurposing of materials as alternative construction components.

2.4 Conclusion: Reuse of ISBUs as a building material

To manage greenhouse gas emissions within the building sector, the integration of alternative construction materials emerges as both necessary and feasible for enhancing material efficiency in construction. While advancements in renewable energy systems and energy efficiency measures offer opportunities for improving operational carbon and energy, the embodied carbon and energy associated with material production remain fixed once a building is constructed. Embodied carbon is projected to account for nearly half of the total new construction emissions by 2050 [31], stressing the importance of tactics such as material efficiency and the reuse of recycled materials in shaping future emission trajectories. Leveraging ISBU containers for residential framing exemplifies a pragmatic approach to construction, streamlining building processes while minimizing material usage and environmental footprint. ISBUs have great potential as a viable resource in sustainable building material applications.

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Chapter 3

EcoHus: An Approach to Sustainable Residential Housing

3.1 Introduction

The Orange County Sustainability Decathlon (OCSD) is a collegiate competition consisting of 10 contests aimed at inspiring student teams to design and construct innovative residential structures powered by renewable energy. This competition not only serves as a platform for fostering architectural solutions but also addresses pressing issues such as California's housing crisis and the imperative to combat climate change.

As Team UCSC, we participated in the conception, fabrication, and deconstruction of an off-grid home as part of our involvement in OCSD. Our team and design secured first place in both innovation and water use conservation categories, second place in market potential, and third place in lighting and appliances.

The design of EcoHus evolved through the collaborative efforts of faculty advisor Sue Carter, graduate student leaders Eli Nygren, Carey Williams, and myself, along with input from 10 undergraduate students. Eli Nygren spearheaded the construction of EcoHus, while Carey Williams designed the water remediation system. My primary focus encompassed interior design, outreach, and assisting in the building's construction. Under the guidance of our faculty advisor, our team cultivated a collaborative environment where each member contributed to and influenced each other's areas of focus.

EcoHus is a concept that envisions a home within a greenhouse framework. The EcoHus proposes a hybrid modular approach, mirroring contemporary trends prevalent in today's real estate landscapes [1]. Leveraging the inherent modularity of ISBUs, our design maximizes spatial flexibility, allowing containers to be strategically positioned and sidewalls to be removed to form expansive living areas.

3.1.1 Background

EcoHus is inspired by the work of Swedish architect, Bengt Warne, who proposed a space that integrated garden areas and a home within a greenhouse structure. In 1976, Warne termed his concept NaturHus or Nature House [2], and constructed an enclosed timber structure within a glasshouse in Saltsjobaden, Sweden. Building upon this idea, EcoHus was designed to be a sustainable and affordable adaptation of the original concept.

Diverging from the traditional wooden construction, we employ repurposed steel shipping containers as the primary building material. This choice not only enhances affordability but also promotes sustainability through the reuse of globally abundant materials. The greenhouse structure serves multiple purposes, providing shade during summer months, providing power through the incorporation of photovoltaic panels, and capturing rainwater to supply clean water for our home. EcoHus represents a modern interpretation of Warne's vision, combining sustainability, affordability, and innovative design to create a self-sustaining home.

Description of House Design

The internal structure is 1024 square feet (sq ft) and is constructed from two 40 ft x 8 ft high cube shipping containers interconnected by 8 ft beams of Douglas fir #2 lumber. High cube ISBUs, with a height of 9 ft 6 in, were utilized to optimize ceiling heights, resulting in an interior ceiling height exceeding 8 ft upon incorporation of flooring and roof insulation. Additionally, a 40 sq ft dining nook extends outward from the shipping containers, supported by their doors, thereby expanding the available living area.

The central section of the dwelling spanned by nominal lumber serves to minimize material consumption while creating more rooms than what is typically achievable with shipping containers alone. EcoHus accommodates a three-bedroom, two-bathroom configuration, with integration of natural lighting and direct access to 1000 sq ft of garden space within the greenhouse. The design also includes a roof-top deck, on top of the shipping containers, where plant beds and passive solar tanks can be placed for food production as well as water heating.

3.1.2 Greenhouse

The greenhouse frame has a 6 ft by 29 ft mono-slope pitch design that integrates solid photovoltaic (PV) panels and Luminescent Solar Concentrator Panels to harness solar energy to power the household, as seen in Figure 3.1. The PV panels are sealed to create a waterproof roof, which serves as the rainwater capture system. The greenhouse frame is able to withstand structural loads with wind, roof, and seismic loads engineered to code. With the typical length of solar panels being 85 in, the 29 ft span can accommodate four rows of solar panels on its south-facing roof. Each row has the capacity to accomodate 18 standard 40 in wide PV panels. The roof pitch was set at 12 degrees to comply with a height restriction of 18 ft, set by OCSD.

In the absence of a height restriction, modifying the pitch of the greenhouse offers customization potential aligned with the resident's optimization objectives. Pitch adjustments could influence power generation, floor area, and the capacity for rainwater collection. For instance, aligning the pitch to approximately 29°, specified for the Los Angeles area, would maximize energy generation for the solar system [3]. However, this adjustment would raise the overall height by an additional 10 ft, bringing the total to 28 ft. The increased height presents opportunities for expansion, particularly by incorporating a second story on the northern half of the building. By stacking an ISBU atop the northern container and welding at the corner posts, an additional 300 sq ft of living space may be accommodated. Utilizing an ISBU minimizes raw material costs since it inherently provides external, internal, and floor framing for the additional space. The structural integrity of this design choice is upheld by ISO 1496 standards, ensuring that the maximum stacking strength of containers is sufficient, with a capacity of 470,378 lbs. This confirms the feasibility of adding an ISBU atop the northern container to increase the living space for a greenhouse with a higher pitch. Additionally, adjusting the pitch to 29° would also expand the rainwater capture area to 1980 sq ft, resulting in a 10% increase in total rainwater capture, discussed in section 3.1.3, amounting to 16,632 gallons of collected rainwater.

3.1.3 Off-grid capabilities

Power Production

First, we provide a brief overview of Luminescent Solar Concentrator (LSC)

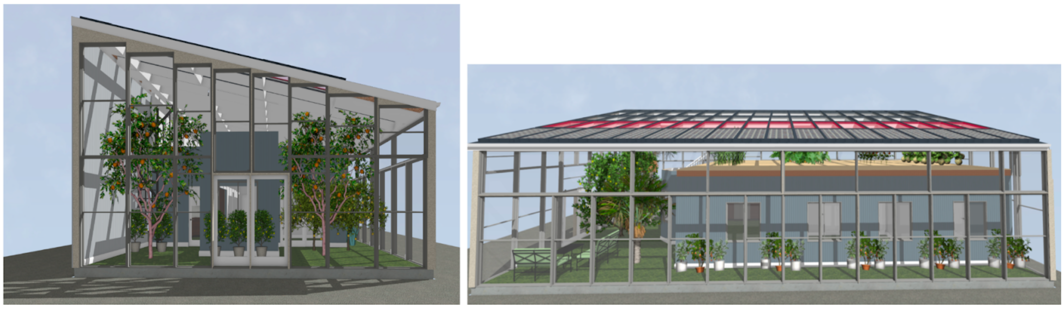

Figure 3.1: 3D rendering of EcoHus from the West side of the house and the South.

technology employed within our off-grid structure for power and food production purposes.

LSCs are designed to concentrate light onto photovoltaic (PV) cells while allowing partial light transmission. These devices typically comprise a flat plate of transparent material embedded with fluorescent dye, termed a host matrix, with PV cells positioned at the edge, shown in Figure 3.2 [4]. The LSCs used in our greenhouse structure differ through the use of bifacial cells that improve module efficiency by capturing light from both sides of the cell [5][6].

Incident light enters the LSC, inducing photoluminescence, where the photons within the absorption band are absorbed by the dye molecules. Subsequently, absorbed photons are re-emitted isotropically and undergo internal reflection towards the edge of the matrix, where PV panels are located, thus converting into energy [4]. Photons emitted at or exceeding the critical angle, θ_c , can be described using Snell's law in

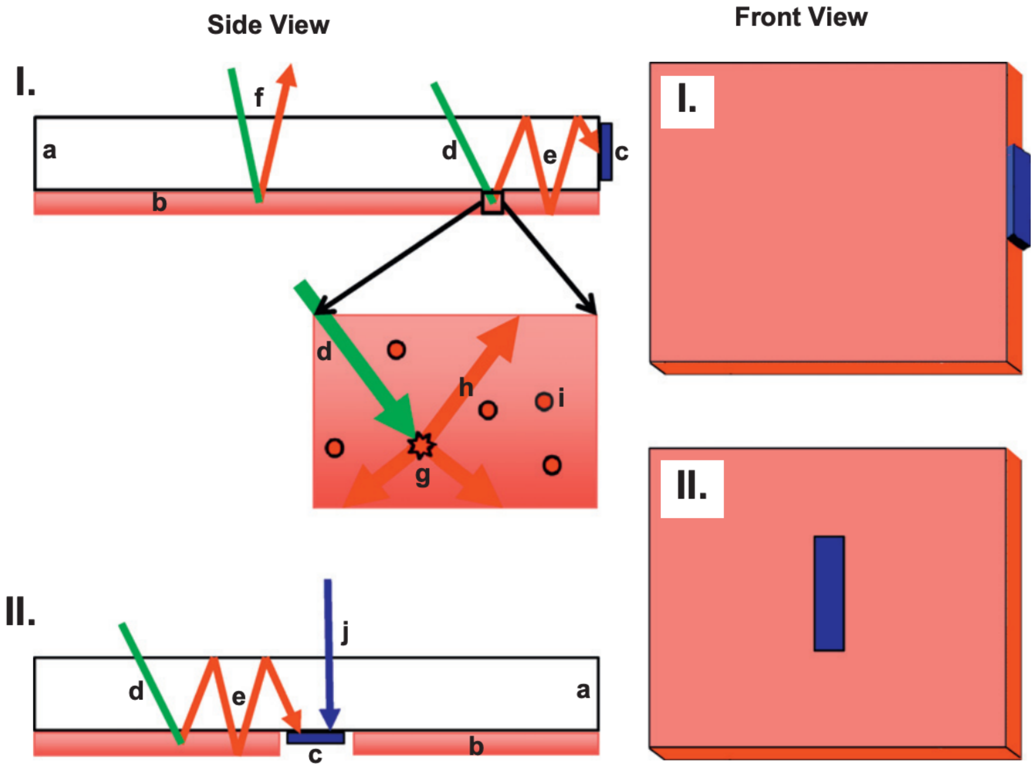

Figure 3.2: A simplified schematic of a conventional LSC (I) and a front facing greenhouse LSC (II) is depicted. Within the diagram, various components are labeled: 'i' denotes the dye molecules, 'f' represents the incident photon absorbed and subsequently re-emitted by the dye due to the angle, 'd' signifies the incident photon absorbed by the fluorescent molecule, 'g' indicates the excited molecule that is downshifted and emits light isotropically, and 'h' depicts the photon re-emitted to the waveguide. The 'j' component describes light that is directly absorbed by the front-facing photovoltaic cell 'c' , while 'a' and 'b' represent the acrylic panel, and luminescent sheet respectively. Sourced from [7].

Equation 3.1.

$$\theta_c = \sin^{-1}\frac{1}{n_{LSC}} \qquad \text{or} \qquad n_{LSC}\ \sin\theta_c = (1)\ \sin(90°) \tag{3.1}$$

Here n_{LSC} denotes the refractive index of the LSC. Photons emitted below the critical angle escape the system [4].

In practical application, the Soliculture panels integrated into the EcoHus greenhouse structure are engineered to optimize plant growth by selectively transmitting and enhancing wavelengths that optimize photosynthesis, as well as absorbing the wavelengths of the solar spectrum unused by plants to generate electricity, as illustrated in Figure 3.3.

This represents a pivotal aspect of our design, enabling our versatile greenhouse structure to concurrently foster plant growth and generate energy for residential use.

The greenhouse structure integrates both solid PV panels and Soliculture panels on the south-facing side. We implement a configuration of 18 QCELL Q.PEAK DUO XL-G10/BFG 480 Watt bifacial panels on the first row (south edge) to offer summer shading for the south-facing windows [8]. Concurrently, 18 Soluculture LUMO 180 Watt bifacial panels are positioned on the second row, catering to optimal light conditions for plant growth on plant beds installed on the roof of the conditioned home, as shown in Figure 3.1 [9]. Access to the roof in the completed structure is provided by a staircase attached to the exterior of the conditioned home, located within the greenhouse. The integration of bifacial cells, coupled with reflective paint application on the ISBU roof facilitates the reflection of unabsorbed light back to the solar panels, increasing power

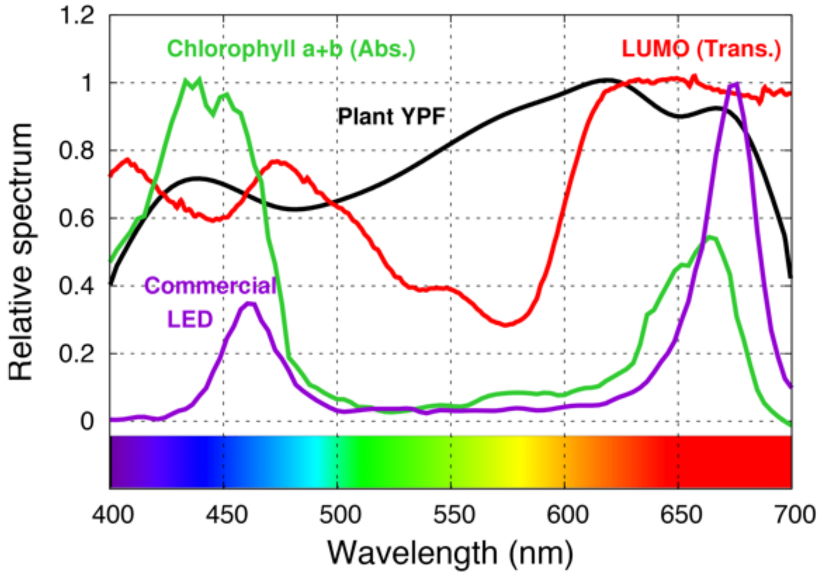

Figure 3.3: Relative spectrum and wavelengths (nm) of the spectral responses of plants compared to Soliculture PV panels and LED grow lights. The absorption and spectral responses of plant growth, in green, peak at Photosynthetically-Active Regions (PAR), which describes the portion of the solar spectrum used by plants. LUMO panels, shown in red, transmit light in these regions far better than the Commercial LED, represented here in purple [6]. Image sourced from Soliculture website.

generation. Under standard conditions, meaning absence of reflection, the combined output of these two panel rows amounts to 11,880 Watts.

A 30 kWh 48 V lithium phosphate battery tank is installed, along with a 200 A solar battery charger, an 8 kWh inverter, and associated breaker boxes. These components are housed in the utility room to ensure temperature control and optimal functioning. Additionally, a dedicated DC line of 12 volts is established from the solar battery charger to power a smart LED lighting system and portable device chargers, maximizing overall efficiency.

Greywater System

Utilizing the rainwater capture system installed on the greenhouse roof, our objective is to optimize the environmental water resources within the household to minimize losses. This strategy involves employing high-efficiency faucets, shower heads, toilets, and kitchen appliances to maximize water consumption within the home.

Considering the greenhouse collection area spanning 60 ft by 29 ft or 1,740 sq ft, and based on the average rainfall in Orange County, where our competition was held, we estimated the potential water collection of our system. With an average annual rainfall of 14 in, approximately 15,000 gallons of water can be collected [10]. This value was found by multiplying the annual rainfall (inches) by the collection area (sq ft) and 0.6, which is found from 1 inch of rain yielding 600 gallons of water per 1000 sq ft [11]. This translates to approximately 40 gallons of fresh water per day, which should support potable water use in all sinks.

Anticipating usage during the rainy season, EcoHus includes a storage tank with a capacity of 10,000 gallons. To ensure water quality, the collected rainwater will undergo filtration to eliminate microbial contaminants. For interior drinking water, including sinks and dishwashers, a multi-step filtration process will be implemented. Initially, the rainwater passes through a first-pass filter to remove particulate matter, followed by filtration through activated carbon and UV to eliminate microbial life and smaller particulates. UV filtration will be employed to treat any water source, ensuring it meets safety standards for various applications, including drinking. Given the high energy demands of water heating, two 40 gallon Sunbank systems are equipped on the roof of the house, with additional 2400 kW or 240 volt heaters, as a passive-solar water heating system for the showers, sinks, dishwasher, and washing machine.

These systems contribute to our water conservation efforts by reusing the majority of the 40 gallons used daily, excluding water used for washing machine and toilet flushing. The recycled water undergoes filtration, utilizing a natural plant bioremediation system in tandem with another UV filter. This greywater mechanism is founded on the principles of biomimetics and integrated water resource management. By implementing elements of nature's hydrological cycle, particularly the natural purification processes observed as water flows through root systems of macrophytic plants, the system effectively filters out organic compounds and various dissolved solids. Our constructed wetlands, a term for smaller-scale applications, mimics the natural cleansing process of water in nature [12].

To ensure the survival of our natural filtration system, the use of biocompatible soap, Oasis, will be used in the house. The soapy water decomposes into nutrients that can be absorbed by the plants, fostering a symbiotic relationship between the occupants and the plants within the greenhouse.

3.2 Construction and Building

3.2.1 Simplified building method of structure

OCSD presented a challenge to student teams: construct a home within a 10-day timeframe at the Orange County Fairgrounds. To expedite on-site assembly, plumbing and electrical systems were self-contained within each shipping container, which was prepared off-site. The northern container houses the kitchen, baths, and utility rooms, consolidating plumbing and a majority of the electrical components within a single 320 sq ft unit that is easily transportable. Meanwhile, the south-facing container accommodates a subpanel for electrical requirements in the bedrooms, office, living rooms, as well as HVAC and fire alarm systems. The design makes electrical installations within the central unit unnecessary, except for solar-powered lights that were fitted on-site. A signal wire connects the subpanel in the south container to the main in the north, ensuring seamless electrical connectivity. The greenhouse, spanning the entire structure, was constructed on-site. PV panels were installed once the structure was in place.

The off-site construction began with the 40 ft HC containers, their walls removed to expand the house footprint. Plasma cutters were used to remove the inner face of the south container, with steel posts welded in place to replace the structural support provided by the corrugated walls of the ISBU. Steel brackets were welded to the inner surface of the container to create a framework for insulation and interior finishing. Given that these frames were non-bearing and had ample support, 2x2 lumber was used as backing for the interior walls lining the container, as shown in Figure 3.4. The containers' exteriors served as the bearing walls, eliminating the need for additional sheathing, siding, or weather-proofing layers, as these were already integrated into the COR-TEN steel exterior. As illustrated in Figure 3.5, joist hangers were welded onto the bottom rails of the ISBUs on the sides facing towards the center of the house. 2x6 Douglas fir lumber was placed into the hangers, spanning the gap between the north and south sections of the house.

Following the installation of floor joists, reinforced with proper blocking using 2x4 lumber, Oriented Strand Board (OSB) was secured on top to establish a subfloor. The interior of each ISBU was already equipped with a subfloor, with standardized 1AAA containers requiring plywood flooring, utilized as subflooring in our construction. Partition walls were framed and anchored within the containers, and intermediate modular section. With the exception of the kitchen, there were minimal cutouts in the sidewall of the north container, which functions as the foundation for a walkable deck above. A 6x2 steel beam was introduced to the kitchen area to provide ceiling support. Joist hangers were then welded onto the beam, allowing for ceiling joist installation. Using 2x8 lumber, roof framing spanned across the top of each ISBU, providing a slightly taller ceiling for the middle section. To conclude the framing stage, plywood sheathing was fastened to seal the roof. It is noted that this roofing structure lacks in-

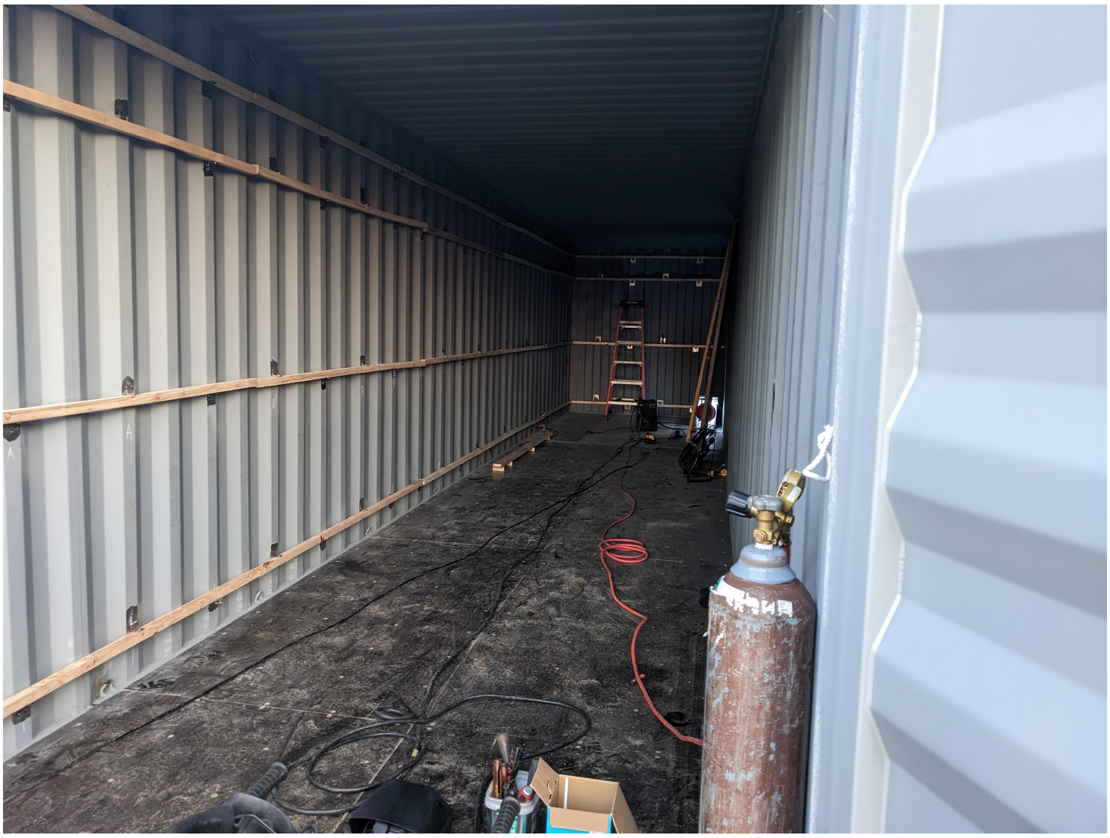

Figure 3.4: Image of interior of ISBU container for EcoHus construction. Steel brackets were welded on to the walls, and 2x2 lumber was secured as framing and backing for insulation and interior finishes.

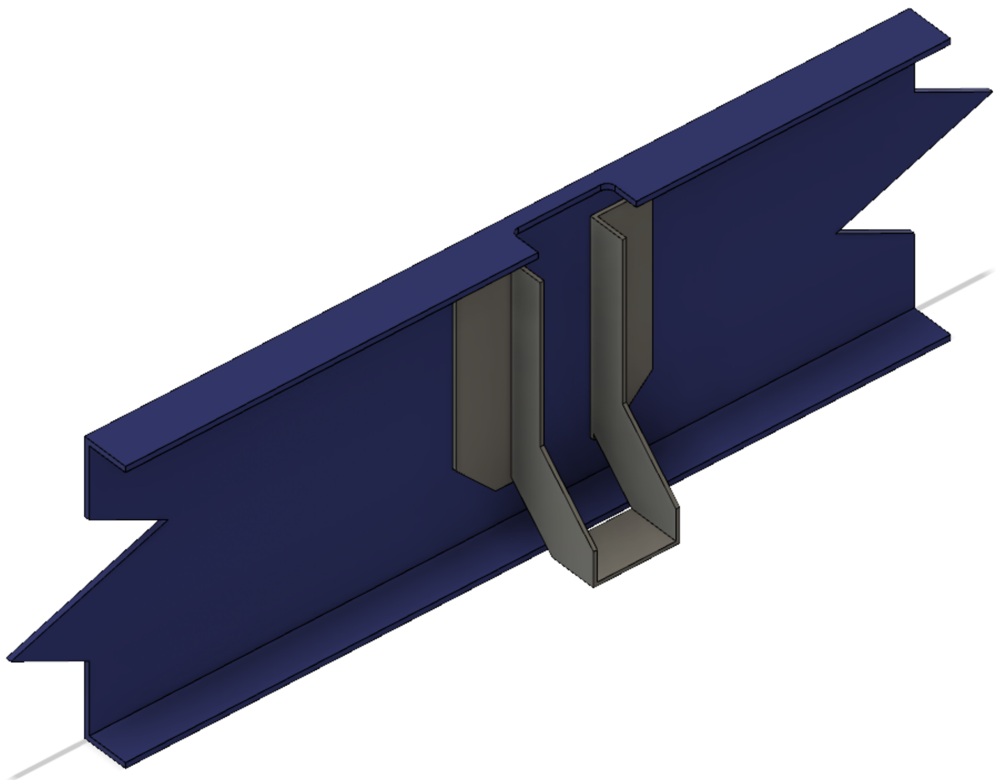

Figure 3.5: Drawing of steel joist hanger welded onto the bottom rail of the ISBU. The hangers were placed in order to span the modular section between the south and north containers.

herent weatherproofing capabilities, as the greenhouse structure is intended to function as the actual roof of EcoHus. Wood siding was applied to the exterior framing of the modular section, with doors and windows installed to complete the framing and exterior finishing.

To ensure optimal insulation and prevent thermal bridging, low Global Warming Potential (GWP) spray foam insulation was chosen for its high R-value and capacity to expand and fill the corrugated space in the ISBU walls and ceilings. Interior paneling, termed gypsum board or drywall, was fastened to reinforce the structure of partition walls while providing a surface for final interior finishing, including mudding and painting. Finally, flooring, cabinets, appliances, and furniture were put into place, completing the construction of EcoHus' conditioned unit.

3.3 Results and Discussion

EcoHus, a project undertaken by UCSC students, led by project lead Eli Nygren and faculty advisor, Sue Carter, was fully constructed and operationalized within the 10-day frame of the OCSD competition. This excludes the rain capture system due to the time frame of the build. The competition, overseen by jurors appointed by OCSD organizers, encompassed evaluation across 10 categories. The criteria include sustainability, innovation, energy efficiency, water use and conservation, health and comfort, and lighting appliances. EcoHus secured first place in both the innovation and water use conservation categories, second place in market potential, and third place in lighting

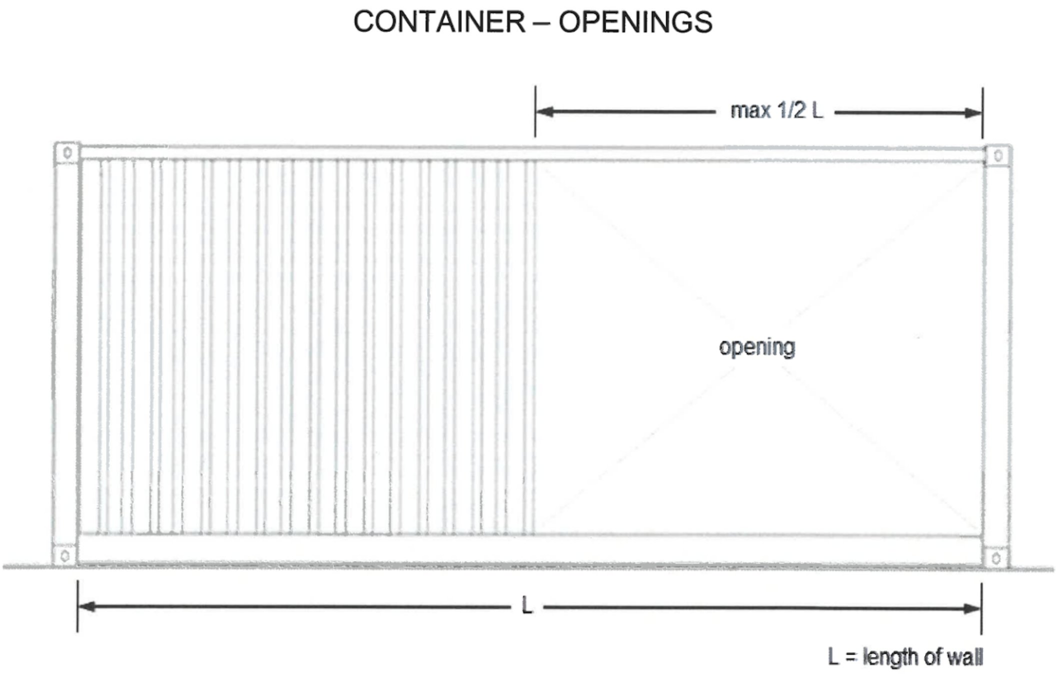

Figure 3.6: An illustration of the allowable shear value for a container side with an opening. The total opening must be less than 50 % of the total container length, Sourced from [13].

and appliances.

While our design was successfully erected at the competition site, concerns regarding the permitting of EcoHus persist. Permitting shipping container homes can pose challenges due to the lack of standardization in ISBU use and permit codes. To streamline construction and permitting processes, modifying the design of the south container may prove advantageous.

The San Bernardino County Land Use Services Building and Safety Division introduced updated building code requirements for ISBUs in 2020, specifying an allowable shear value code. According to these regulations, a container will be permitted for use if the total linear length of all openings in a container side does not exceed 50% of the length of the container, as shown in Figure 3.6 [13]. Adjusting the design of EcoHus' south container, which currently features an opening spanning the entire length of the container with welded supports, could yield several benefits. Not only could this modification conserve construction materials and time, but it could also substantially reduce the necessity for additional inspections to secure permitting for the structure.

3.4 Conclusion

Adapting the design of EcoHus to comply with building codes standards of San Bernardino County holds the potential to expedite both the construction and permitting processes, ensuring structural integrity without the need for additional material or building to meet code requirements.

The hybrid modular approach and harnessing of renewable water and energy systems position EcoHus as an alternative residential building design aimed at fostering harmonious living between the residents and the surrounding natural environment. The construction phase involved the reuse of ISBUs and renewable technologies, with the overarching goal of enabling the creation of off-grid, cost-effective residences. This design approach allows for swift reproduction, transportation, and assembly of the dwelling within a 10-day timeframe.

Building a residential structure within a condensed time frame as students with no professional contracting experience presented prominent challenges. Nonetheless, it served as a profound learning experience, offering insights into the intricacies of designing, constructing, and deconstructing a house, with a particular emphasis on sustainable construction practices.

Architectural innovations are imperative in addressing the challenges posed by climate change and the housing crisis. Initiatives in design like EcoHus, rooted in sustainable material choices and comprehensive consideration of the building life cycle, exemplify the importance and accessibility of holistic approaches in residential construction. While our attention to minimizing the house's environmental footprint was driven by the competitive nature of the project, it highlights the necessity for new residential buildings to embrace similar sustainability goals.

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Chapter 4

Conclusion and Final Thoughts

The need for material efficiency and sustainable resource management has never been more urgent. ISBUs offer a compelling option for sustainable construction materials, with the potential to significantly reduce material impact and consumption within the building sector. In this thesis, we have delved into the concepts of embodied energy and embodied carbon, and the distinctions among the life cycle stages of a product, providing insights into approaches towards decarbonizing residential building construction for future applications. First, we introduced modern wood building construction standards as a benchmark for comparison with the ISBU framed home, modeled after EcoHus. Through an impact assessment focused on the product stage of materials used in residential framing, we utilized the Eco Audit Tool to analyze the initial embodied footprint of wood and ISBUs. Despite the incorporation of steel in ISBU construction, typically associated with high embodied impact, our results revealed that constructing a wood frame house requires nearly 2.67 times more energy and emits 2.31 times more CO_2 emissions than an ISBU frame home of identical dimensions. Furthermore, we explored a sustainable design approach through EcoHus, demonstrating how ISBUs can be integrated into residential construction to promote sustainable living. The incorporation of a greenhouse structure and off-grid capabilities within the home serves as a glimpse into a potential future for residential architecture, one that facilitates balanced, net-zero living for communities and families at an affordable price point. I envision a future where architectural models akin to EcoHus are commonplace in residential construction, characterized by a commitment to material efficiency and the seamless integration of renewable energy and water systems. Optimizing material selection and leveraging abundant resources with materials featuring high embodied footprints can significantly mitigate the emissions associated with building construction, thereby playing a crucial role in advancing sustainable building practices. Research efforts centered on alternative building materials that reduce material volume, expand living space, and efficiently reuse energy-intensive resources will be paramount in the pursuit to optimize sustainable construction and align with the objectives outlined in the Paris Agreement by 2050. Although much more work is needed, our collective progress towards mindful material use and decarbonizing the building sector signifies a promising step towards a more sustainable future.

Appendix A

A.1 Approximate Weight Chart of Nominal Lumber

A.2 Manufacturing and Processing of Metal Components of ISBU Frame House Extracted from Eco Audit Report

APPROXIMATE WEIGHT CHART

	lbs per Lineal Ft.	lbs per board ft	Full Unit Qty
Green Douglas Fir			
2x3 DF S4S	1.25#/lf	2500#/MBF	256
2x4 DF S4S	1.67#/lf		208
2x6 DF S4S	2.5#/lf		128
2x8 DF S4S	3.33#/lf		96
2x10 DF S4S	4.17#/lf		80
2x12 DF S4S	5#/lf		64
3x4 DF S4S	2.6#/lf	2600#/MBF	112
3x6 DF S4S	3.9#/lf		80
3x8 DF S4S	5.2#/lf		60
3x10 DF S4S	6.5#/lf		40
3x12 DF S4S	7.8#/lf		40
4x4 DF S4S	3.6#/lf	2700#/MBF	91
4x6 DF S4S	5.4#/lf		56
4x8 DF S4S	7.2#/lf		42
4x10 DF S4S	9#/lf		35
4x12 DF S4S	10.8#/lf		28
4x14 DF S4S	13.1#/lf	2800#/MBF	21
4x16 DF S4S	14.9#/lf		
Rough Timbers		3100#/MBF	
6x6 DF S4S	9.3#/lf	3100#/MBF	32
6x8 DF S4S	12.8#/lf	3200#/MBF	24
6x10 DF S4S	16.5#/lf	3300#/MBF	20
6x12 DF S4S	20.4#/lf	3400#/MBF	16

Figure A.1: Approximate wight chart of Lumber used to find the masses of Douglas fir building components for the wood frame home analysis. Sourced from [1].

Component	Process	% Removed	Amount processed	Energy (kcal)	%	CO2 footprint (lb)	%
Brackets (interior framing)	Extrusion, foil rolling	-	17 lb	1e+04	13.3	7	13.3
Brackets (interior framing)	Cutting and trimming	-	0 lb	0	0.0	0	0.0
Joist hangers (floor)	Extrusion, foil rolling	-	8.1 lb	4.9e+03	6.5	3.4	6.5
Joist hangers (floor)	Cutting and trimming	-	0 lb	0	0.0	0	0.0
Beam hanger (kitchen)	Roll forming	-	88 lb	2.5e+04	32.6	17	32.6
Joist Hangers (kitchen)	Extrusion, foil rolling	-	2.7 lb	1.6e+03	2.2	1.1	2.2
Joist Hangers (kitchen)	Cutting and trimming	-	0 lb	0	0.0	0	0.0
Steel Posts (south container support)	Roll forming	-	1.1e+02 lb	3.4e+04	45.4	24	45.4
Total				**7.6e+04**	**100**	**52**	**100**

Figure A.2: Energy (kcal) and CO_2 footprint of processes of non wood materials inventoried for the ISBU frame home. The wood frame home includes these values within the 'Material' stage.

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