Life Cycle Assessment of Carbon Condo vs US Average Condo in Seattle, WA

Final Project Report

CEE 226 Life Cycle Assessment of Complex Systems

Advisor: Prof. Michael Lepech

Project Sponsor: Tess Hegarty

Group Members:

Hemanth Hariharan

Jayce Martinez

Ruby Tian

Andrea Yau-Chan

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Stanford University

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1 Abstract

The construction industry has remained static for years, and different options must be explored to revolutionize building construction by enhancing efficiency and elevating sustainability. The industry is pivoting towards the development of buildings that promote energy efficiency and reduce building greenhouse impacts, but the financial implications have burdened the execution of innovative ideas. Within a capitalistic society, most constructors are driven by financial incentives—the ability to produce a low-cost product. On the other hand, there is a movement geared towards gaining environmental consciousness and in addition to people, many companies are also driven by the motivation to develop sustainable products.

In Seattle, the building sector contributes to a third of the city's greenhouse gas emissions, accelerating climate change and pollution. The city aims to develop more efficient buildings that prioritize clean energy and human health. This Life Cycle Assessment (LCA) compares the environmental impact and cost feasibility of two buildings in Seattle: Carbon Condo — a structural system composed of Carbon Nanotubes (CNT) developed by MIT researcher M. Goulthorpe — and a US average building, which constitutes as a typical wood frame construction building.

The goal of the LCA is to provide the city and building professionals with quantitative decision-making tools on the implementation of adopting CNT as a building material to make efficient use of energy resources, eliminate pollution, and reduce climate change. The functional unit is a 21,119-square-foot residential building with 20 condominiums for 50 years in Seattle, Washington. The life cycle of a building is divided into three phases: the pre-use phase, use phase, and end-of-life phase. The system boundary of this study includes material production, manufacture and transportation in the pre-use phase, and use-phase.

The inventory analysis is centered around the material production and operational use, where the highest degree of difference was observed between the two buildings. Equivalency assessment method is used to evaluate and calculate environmental impact with data from SimaPro software and CNT research. The comparison of these impacts reveals that the Carbon Condo has less lifecycle environmental impact than the US average condo. The total global warming potential for the Carbon Condo is 2,672,306 kg CO2e in comparison to the US Average condo with a value of 3,487,471 kg CO2e. The results for the Carbon Condo also indicate that the use phase has the largest contribution to the Global Warming Potential with a percentage greater than 70%, whereas building material and transportation are only valued at 24.7%, and 2.69% respectively.

Our study found that the Carbon Condo design is a sustainable model that optimizes building efficiency and reduces building greenhouse impacts; however, the greatest challenge in implementing this option is the excessive cost. For the Carbon Condo model to be considered, the city and developers must be informed of the benefits of choosing such model to close the knowledge gap—it is forecasted that if CNT is utilized as a building material more often, the material price will decrease as demand increases.

2 Introduction

2.1 Construction Industry

Construction in today's world has truly become synonymous with a nation's prosperity. The construction industry contributes significantly to many countries' gross domestic products (GDP) and expenditure on the construction industry exceeds $11 trillion a year, which is equivalent to about 13 percent of global GDP (Data Based Analysis, 2022). Residential and commercial buildings contributed to around 28% of all end-use energy consumption (EIA, n.d.), as seen in Figure 1.

With a rapid rise in awareness of climate change and its repercussions, there is an even bigger need to invest time and resources in understanding how buildings can be made more efficient. In such a scenario, it becomes crucial to do a Life-Cycle Assessment (LCA) to assess sustainability of buildings.

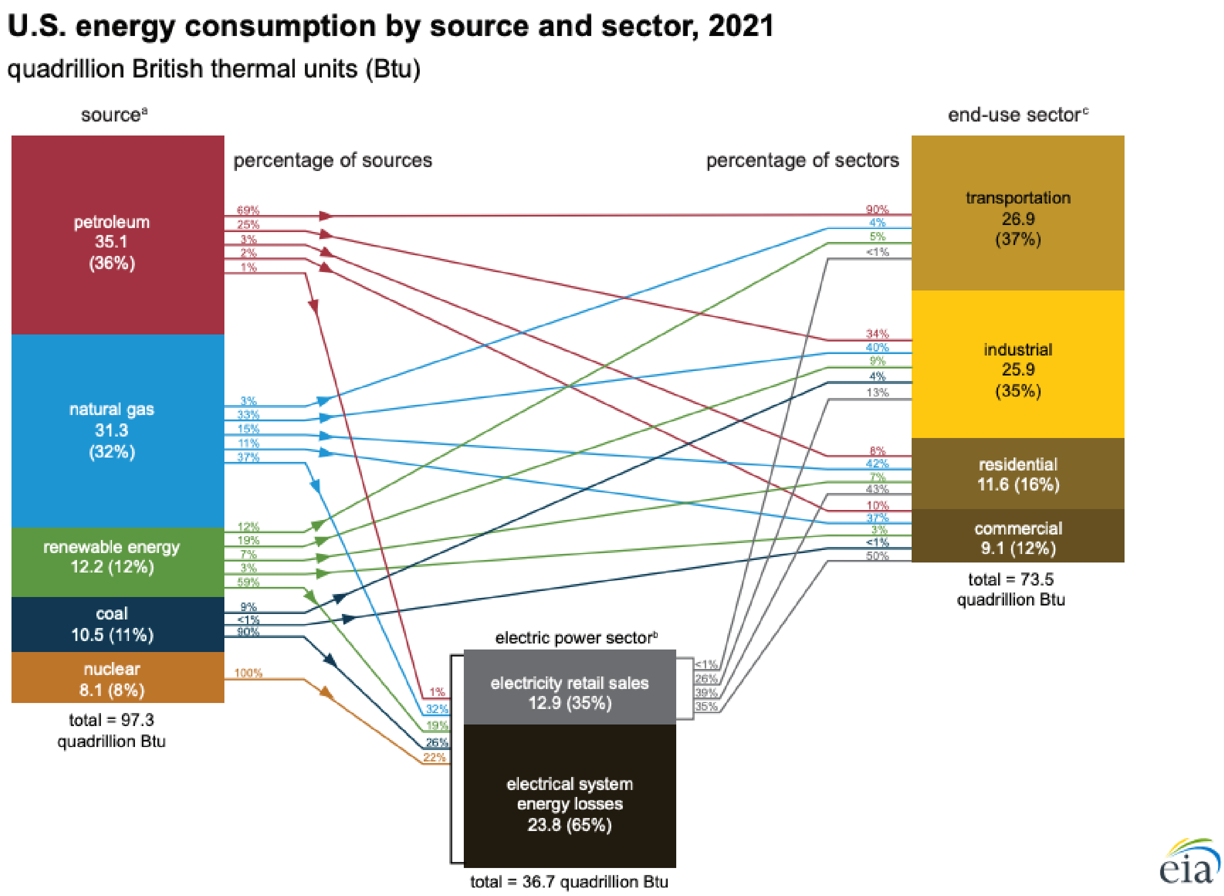


Figure 1. US Energy Consumption by Source and Sector (EIA, n.d.)

Traditionally, construction has made use of manual labor such as tradesmen and subcontractors with most tasks being performed on-site. However, productivity in the construction industry has been far behind that of manufacturing, due to the increased automation in manufacturing and construction's continued reliance on field labor.

Residential buildings in the US typically have a wood frame with a reinforced cement concrete (RCC) slab-on-grade foundation, along with wood framing for the floors and the roof above. Other materials typically include stucco, insulation, drywall, asphalt shingles, plywood, windows, doors, tiles, and the mechanical systems. Materials are generally locally sourced, transported to site and constructed. Construction on-site generally appears to be the more economical option during the project costing phase but presents its own set of challenges such as labor shortage, lack of coordination leading to low productivity on site, site space constraints etc. often leading to cost and time overruns.

2.2 CNT as a Building Material

Industrialization of construction is the process through which construction aims to improve productivity through increased mechanization and automation. The process commonly involves modularization, prefabrication, preassembly, and mass production.

The CNT in Figure 2 is one of the most promising nanomaterials, which has remarkable mechanical, electrical, thermal properties and chemical stability.

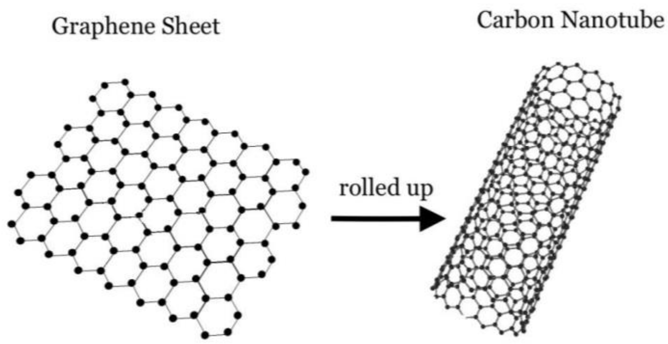


Figure 2. Carbon Nanotube Structural Organization

Given the massive scale of the construction industry, Carbon Condo whose principal materials include CNT, CFoam, Polyethylene Terethalate (PET resin) and epoxy adhesive, presents a unique opportunity to sequester huge amounts of carbon.

Each Carbon Condo panel is a composite material composed of fiber reinforcement within an epoxy matrix which gives them a unique property of being strong, yet lightweight. Since the integration of the panels with the mechanical, electrical, and other equipment is done in the prefabrication facility, we expect the Carbon Condo projects to be more efficient in terms of material usage and to keep cost and time overruns in check.

3 Goal and Scope Definition

3.1 Goal

The LCA assessment is a tool intended to help understand how the industrialization of construction affects the building life-cycle impact. The results of the LCA are to provide the city and building professionals with quantitative decision-making tools on the implementation of adopting CNT as a building material to make efficient use of energy resources, eliminate pollution, and reduce climate change. The results from the study are not intended to be used in comparative assertions intended to be disclosed to the public. The results from this study will also allow city developers and construction planners in Seattle to decide if the Carbon Condo design is worth implementing on a large scale in the city.

This study investigates the carbon emissions and cost impacts for a Carbon Condo versus an average Seattle condo. Ultimately, an LCA is conducted to weigh the benefits and drawbacks of building future condos in Seattle using the Carbon Condo design rather than keeping the current average condo design, given that the Carbon Condo is much more expensive but can reduce building greenhouse impacts.

The goals of this project are to 1) understand how the industrialization of construction affects the building life-cycle impact and 2) investigate the carbon emissions and cost impacts for a Carbon Condo versus a US average condo.

3.2 Scope

Our study compares the environmental impacts of a Carbon Condo and the US average condo. The function of systems is to provide individual units of residential spaces in a building complex. The functional unit is a 21,119-square-foot residential building with 20 condominiums for 50 years in Seattle, Washington. The US average condo is assumed to have three stories, while the Carbon Condo is assumed to have five stories. The whole life cycle of a building is divided into three phases: the pre-use phase, the use phase, and the end-of-life phase. The system boundary of this study includes material production, manufacture, and transportation in the pre-use phase, and use phase. The allocation of flows and releases is based on the linearity of raw material inputs and outputs. The process used in the analysis does not recycle materials. Refer to Figure 3 for the flow diagram.

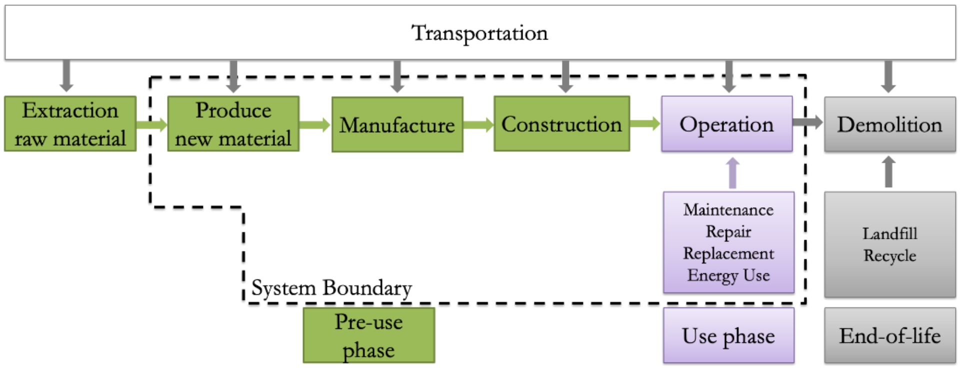


Figure 3. Process Flow Diagram with Demarcated System Boundary

The study shows the life cycle impact of global warming, acidification, eutrophication, carcinogens and heavy metals, and fossil fuel. Equivalence assessment and normalized data are used for impact assessment and interpretation.

Data used in the study is sourced from previous studies conducted by the project sponsor, Tess Hegarty, and SimaPro software. Part of the cost analysis data is collected from reliable online resources. The data collected are all reviewed by team members for quality.

The following assumptions were made in the development of this study:

- The lifetime operation of each condo is 50 years
- Factory assembly of US average condo materials is negligible
- Carbon Condo's prefabricated system results in a minimal requirement for heating and cooling
- For cost analysis only: All building materials will be landfilled at the end-of-life stage, and no building materials are recyclable
- Construction costs and other building component costs (services) are the same for both buildings

The study is intended to be reviewed by the project sponsor, Tess Hegarty, and Prof. Michael Lepech. The review format includes a poster, an abstract, and a final LCA report. The final report is intended to be peer-reviewed in course CEE 226.

4 Life Cycle Inventory

Life cycle inventory analysis (LCI) involves data collection and calculation to quantify inputs and outputs of materials and energy associated with the buildings under study. Operational procedures for LCI (ISO 14041, 1998) were used for the data collection and calculation.

4.1 Data Collection and Calculations

The three life cycle stages considered are material production, transportation, and operation. In addition to the four main LCA stages, Carbon Condo considers prefabrication stage due to the additional assembly requirements of the special material. For the US average condo, raw materials are assumed to be transported to construction site directly due to the relative simplicity of materials used. Figure 4 shows an additional transportation route to a prefabrication site prior to transporting materials to construction site for Carbon Condo. This is due to Carbon Condo's assembly requirements from raw materials to creating the final carbon nanotube composites.

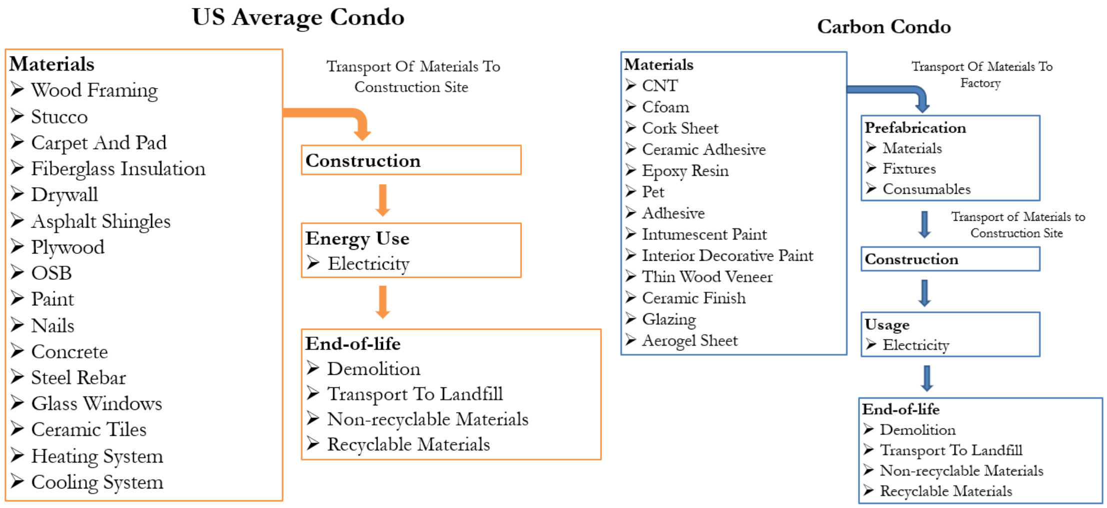


Figure 4. US Average Condo and Carbon Condo Process Flow Diagrams

Once the process flow diagrams were finalized, input and output data of unit processes in the process diagram were collected. Inventory data of the materials were prepared from the Life Cycle Inventory Database (LCI DB) SimaPro. The system boundary of the LCI DB usually spans from raw material acquisition to manufacturing of the materials. All unit processes and activities associated with the material in consideration just before exiting the gate of the manufacturing plant are included in the system boundary (cradle to gate).

As shown in Table 1, the transportation for the US average condo was calculated based on the assumed distance of 250 km from factory to site, with a total transportation distance of 155 miles per material.

Table 1. Material Quantities, Origin, and Transportation Distance (Courtesy of Tess Hegarty)

Carbon Condo

Material	Quantity	Origin	Transportation Distance
Carbon Nano Tube (CNT)	65,617 kg	New Hampshire	3,124 miles
CFoam	115,804 kg	New Hampshire	2,613 miles
Epoxy Resin	40,887 kg	BC, Canada	77 miles
PET	53,570 kg	Washington	229 miles
Adhesive	8,675 kg	Minnesota	1,821 miles
Intumescent Paint	1,367 kg	Washington	88 miles
Ceramic Finish	31,772 kg	North Carolina	2,947 miles
Glazing	474 m^2	Washington	155 miles

US Average

Material	Quantity	Origin	Transportation Distance
Wood Framing	84,162 m^3	Washington	Specific distances are not available for US average condo materials. Therefore, default average transport distances of 250km/155.3 miles are assumed for all building products. Most building products, such as aggregates and ready-mixed concrete, are likely to travel shorter distances.
Stucco	57,651 kg	Local US Suppliers	
Carpet& Carpet Pad	4,379 kg		
Fiberglass Insulation	7.633 kg		
Drywall	58,552 kg		
Asphalt Shingles	1,367 kg		
Plywood	60 m^3		
OSB	474 m^3		
Paint	1,367 kg		
Nails	4,202 kg		
Concrete	474 m^3		
Steel Rebar	22,716 kg		
Glass Window	228 m^2		
Door	3.3 m^2		
Ceramic Tiles	34,433 USD		
Heating System	178,646 USD		
Cooling System	188,676 USD		

The transportation distance was then multiplied by the weight of each material to obtain ton-mile values to calculate the estimated amount of diesel required. The transportation vehicle was assumed to be a combination truck that consumes 9.4 gallons of diesel per 1000 ton-miles (see Appendix Table A1). Based on the material weights and travel distances, it would require 6,217 gallons of diesel for Carbon Condo and 750 gallons of diesel for the US average condo. Emissions for diesel-powered trucks was used to find the total transportation-related emissions (Appendix Table A2).

The operational energy use was calculated based on the EUI data shown in Table 2, assuming a period of 50 years and converting the energy use to kWh from kBtu.

Table 2. Energy Use for the Carbon Condo and US Average (Courtesy of Tess Hegarty)

Quantity	US Average	Carbon Condo	Units
EUI (site)	31.6	19.2	kBtu/ft^2-year
Area	21,119	21,119	ft^2
Time Period	50	50	Years
Energy Use	9,777,300	5,940,700	kWh

4.2 Allocation of Flows and Releases

Allocation is a process of partitioning the input and output flows to the product system under study by distributing the environmental load created by unit processes. Allocation is applied to two cases: a multi-output process and a multi-input process. Multi-input processes have more than one input into a process. In such case, allocation deals with the distribution of output from the process to an input material into the process under study. Multi-output processes have more than one output in the form of co-products or by-products. Co-products and by-products must possess economic value to be allocated as inputs and outputs. In our study, we were able to avoid the complications around allocation by avoiding it altogether as all multi-input and multi-output processes had one main input/output for consideration.

5 Life Cycle Impact Assessment

5.1 Impact Category, Category Indicator, Characterization Models

Impact categories selected fall under three general groups: ecosystem impacts, human health, and resource depletion. Those impact categories are caused by mid-point indicators through damage pathways. Ecosystem impacts include global warming, acidification, and eutrophication as indicators. Human health uses carcinogens and heavy metals as indicators. Resources depletion has a single indicator of fossil fuel.

The characterization factors of the impact assessment are based on the Eco-Indicator of SimaPro and the prefabrication data of CNT. It uses equivalency assessment and applies equivalency factors to inventory data as aggregated results. For example, Global Warming Potential (GWP) is measured in CO_2 equivalent. By using the indicator, we converted the inventories in the project into the emissions of CO_2, SO_2, BaP, PO_4, NO_2, Pb, and energy resources.

5.2 Classification

LCI inventories are assigned to specific point indicators based on their emissions and their corresponding environmental impacts. In the material production phase, raw material is extracted and used to manufacture new materials and building systems. The process creates an environmental burden by producing CO_2, SO_2, BaP, and energy resources. The transportation uses diesel fuel trucks and creates emissions of CO_2, SO_2, BaP, NO_2, and energy resources. The use phase, which is measured using electricity from the grid, contributes to CO_2, SO_2, NO_2, Pb, and energy resources.

5.3 Characterization

Calculation of the lifecycle impact. Equivalence assessment and normalized data are used. Equivalence assessment methods quantify the impacts when different substances contribute to the same mid-point indicator. In the material production phase, the impact calculation is based on emission factors collected from SimaPro using the Eco-indicator 95 V2.06/Europe method. The emission factor considers the respective unit that quantifies each material, varying from the mass, volume, to cost. Then, the total emission of the specific material or process is calculated by multiplying the emission factor and the inventory.

The emission factor of CNT and CFoam is based on the emission of the full-scale prototype, 1.27 kg CO_2e and 0.24 kg CO_2e per kg material produced (see Appendix Table A5).

The impact of transportation is based on the amount of diesel required from the LCI. Based on the assumed fossil CO_2 emissions for a tractor-trailer of 25,427 lb CO_2 per 1000 gallons of diesel, the total kg of CO_2e was estimated for each material's transportation requirements to find the total transportation-related CO_2 emissions. The total CO_2 emissions are summarized in Table 3.

The indicator results of the use phase are calculated based on EcoBalance US Energy Grid Energy Inputs and Emission (see Appendix Table A3).

5.4 LCIA Results

The Life Cycle Impact Assessment (LCIA) step calculated the significance of the mid-point indicator to analyze the impact. The LCIA results are shown in Table 3. Each life cycle stage has a different percentage of the indicator impact on the whole category impact, displayed in Figure 5. The total impact of each indicator category was compared by moralizing the US average to identify the deviation of the impact from Carbon Condo in Figure 6.

Table 3. LCIA Calculation Results

Impact Group:		Ecosystem Impacts				Human Health		Resources Depletion
Mid-point Indicators:		Greenhouse	Acidification	Eutrophication		Carcinogens	Heavy Metals	Energy Resources
Substances:		CO2e(kg)	SO2(kg)	POx(kg)	NO2(kg)	BaP(mg)	Pb(kg)	MJ LHV
Carbon Condo	Building Material	660,650	3,138	503	-	22,949	16	12,076,700
	Material Transportation	71,856	350	-	1,232	119	0	2,072,623
	Use Phase	1,939,800	25,663	-	14,115	-	2	74,423,868
	Total Life Cycle	2,672,306	29,152	503	15,347	23,068	18	88,573,191
US Average	Building Material	286,257	1,679	338	-	45,736	10	5,311,266
	Material Transportation	8,664	21	-	74	7	0	124,960
	Use Phse	3,192,550	42,238	-	23,231	-	4	122,489,034
	Total Life Cycle	3,487,471	43,938	338	23,305	45,743	14	127,925,260

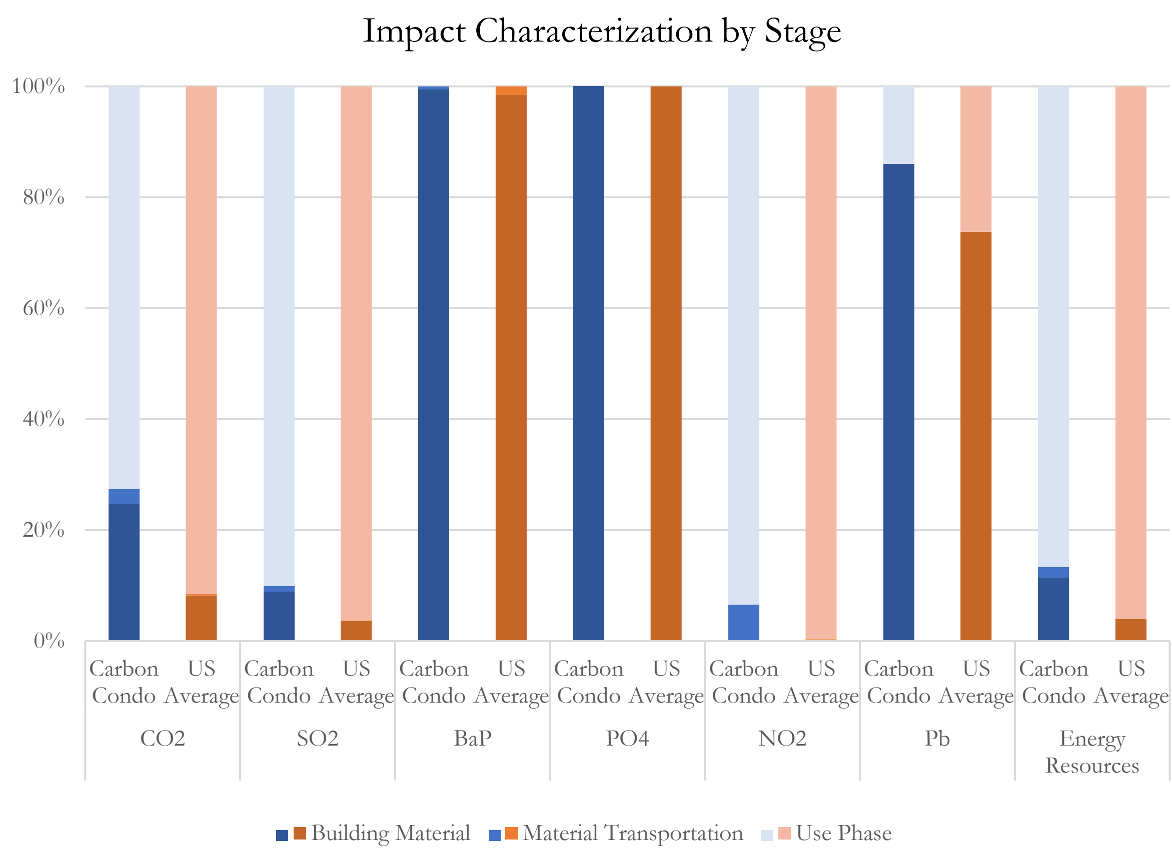


Figure 5. Impact Characterization by Life Stage Comparison

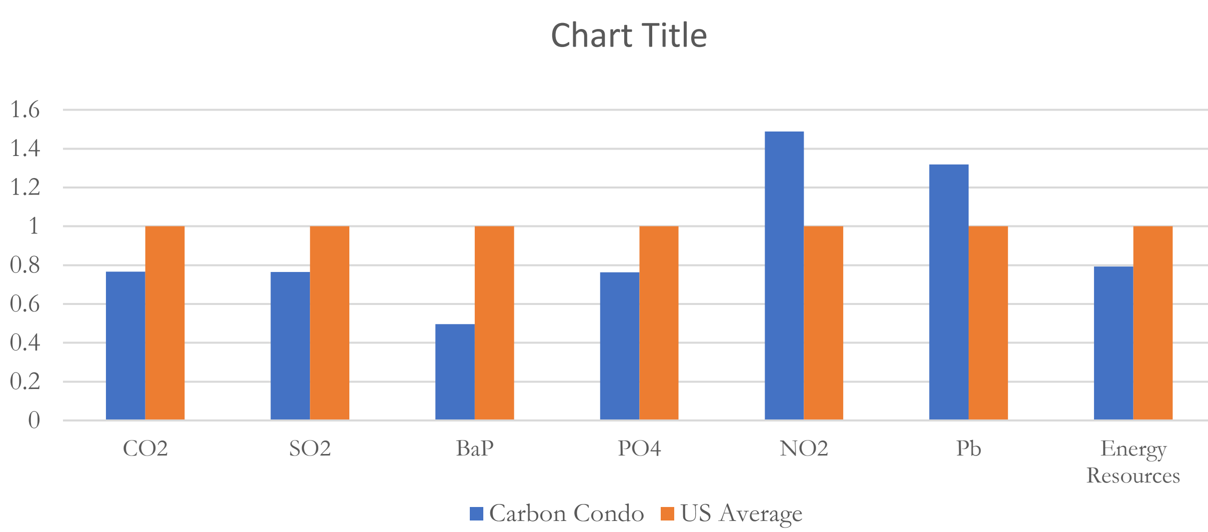


Figure 6. Normalized Impact Assessment Comparison

6 Interpretation

Impact assessment results from both the use phases produce the largest impact on greenhouse gas emissions, acidification, eutrophication, and energy resources. In comparison to the US average condo, Carbon Condo has a carbon payback period of 17 years. This supports the goal of the study which tries to understand the positive environmental impact of using Carbon Condo. Recently, EPA proposed to increase the social cost of carbon from $51 per metric ton of CO2 to $190 (Farah et al., 2022), which favors the interest of the current generation over the future generation. In the climate change context, Carbon Condo is favored to release more greenhouse gas initially and less during the 50 years of use.

Building materials impacts have the largest impact on human health and a moderate impact on damage to the ecosystem. There is a huge quantity of carcinogens are released from heavy metals from the US average condo and Carbon Condo materials. Carcinogens increase in various types of cancer and diseases, while heavy metals have toxic effects on body organs. The CNT's aggregation of materials and large demand for resin adhesives make it a potential risk to human health. Eutrophication caused by the building material also brings a burden to freshwater species.

Transportation has the least percentage of impacts. Since the impact of transportation is based on the weight and distance, transportation of Carbon Condo materials results in larger emissions than the US average condo does because of the further locations of supplies and larger material weight.

In comparison to the US average condo, Carbon Condo has positive life cycle environmental impact categories such as global warming, acidification, eutrophication, carcinogen, and energy source. Additional conclusions and recommendations are provided in Section 9.

7 Life Cycle Costing (LCC)

7.1 Cost Estimation

The cost of most materials for the US average condo are based on RS Means estimated costs of materials included in the Average Wood Framed Quantities list created by the project sponsor. Certain materials such as stucco, plywood, OSB, nails, and steel rebar were not included in the list of Average Wood Framed Quantities and rather were estimated based on current market price rates and cost guides. Although market price rates are generally more expensive than wholesale rates of materials used for mass production such as construction, the difference in market and wholesale cost rates is assumed to be negligible in this study. Building material costs is a summation of the cost of all materials unique to each condo type (see Appendix Table A4). In addition to raw materials used for building construction, other building components such as elevators, electrical utilities, and water utilities are assumed to add another $1.17 million to the overall total material cost for both condo types.

For the US average condo, construction costs were assumed to be equivalent to only the installation cost requirements, which include contractor and architectural fees. Factory construction costs were assumed negligible for the US average condo since the materials are rather simple as opposed to Carbon Condo. For Carbon Condo, construction costs include installation costs as well as prefabrication costs. Prefabrication equipment costs for Carbon Condo were estimated by mouldCAM Limited; other prefabrication costs include fixed costs, wages, and consumables used in the process at the prefabrication facility (see Appendix Table A6, Table A7).

Building usage costs were based only on energy derived from electricity use, which was assumed to be the largest contributor to a typical building's energy requirements. For the US average condo, the total price of building energy use was found from the average price per kWh of electricity paid by Seattle residents and multiplied by the energy requirements per building square footage. The average price per kWh of electricity was obtained from the US Bureau of Labor Statistics, which provided the average energy prices in Seattle (U.S.

Bureau of Labor Statistics, 2022). The energy requirements per building square footage were provided by the project sponsor. The energy requirement values (kWh) represent on-site electricity consumption at each building with the assumption that all electricity would be drawn from a local grid only.

The end-of-life costs were assumed to be the same for both Carbon Condo and the US average condo. The cost of deconstruction was estimated based on Seattle's average cost of deconstructing building materials by weight, which is $130 per ton of material (Seattle DPD, n.d., p. 3). If building materials are found to be recyclable in the future, the end-of-life cost is predicted to be greater. However, the benefits of greater investment in recyclables are predicted to reduce greenhouse impacts.

7.2 Cost Analysis Interpretation

The total life cycle costs for each building were determined by summing the costs required for all four life cycle stages defined in this study (i.e. material need, construction, usage, end-of-life). The total life cycle cost of the US average condo and Carbon Condo are $5.52 million and $8.53 million, respectively. As shown in Figure 7, building material costs made up the largest percentage of the total life cycle cost for both Carbon Condo and the US average condo.

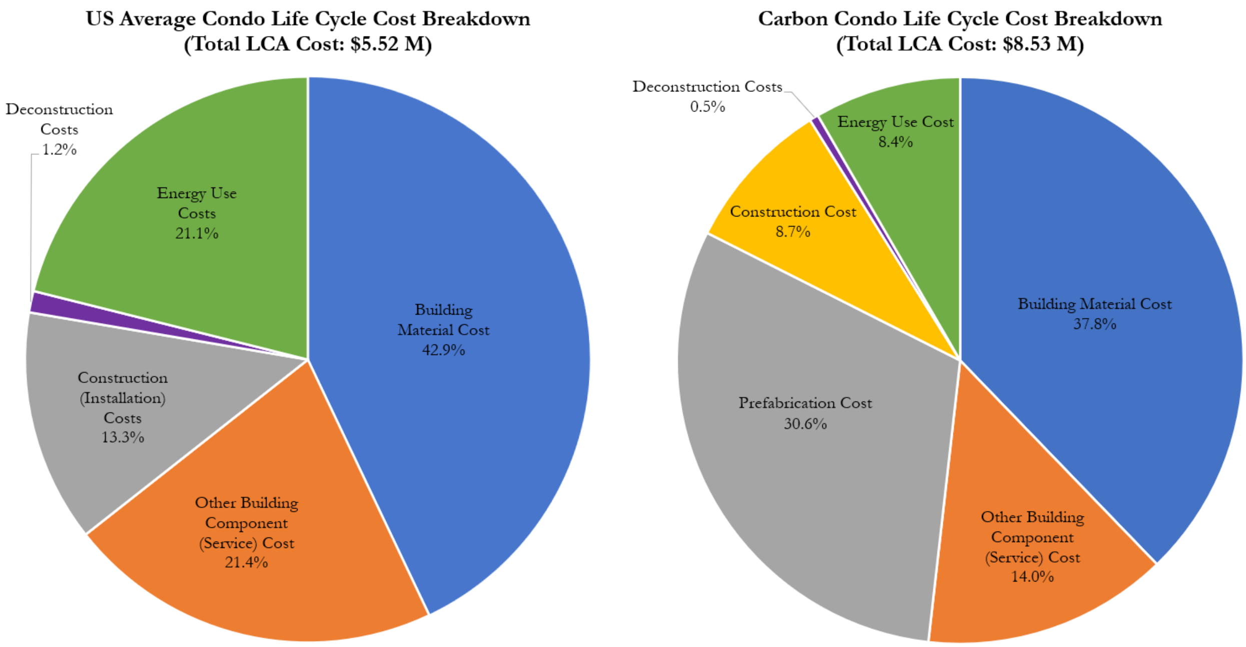
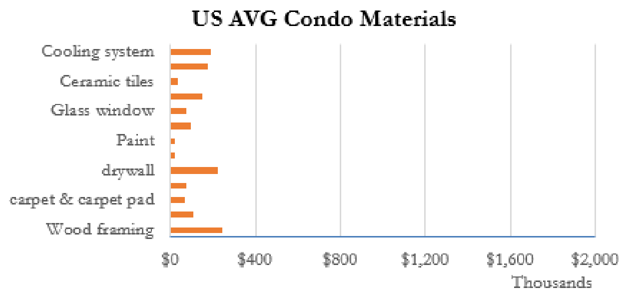


Figure 7. Life Cycle Cost Breakdown by Percentage of Total for US Average and Carbon Condo

The total material building cost for Carbon Condo is about $3.16 million and the total material building cost for the US average condo is about $2.35 million (see Appendix Table A8, Table A9). Carbon Condo's construction phase cost considers both installation costs and prefabrication costs, while the US average condo's construction phase only includes construction installation costs. Prefabrication costs $2.56 million, which comprises greater than 30% of Carbon Condo's total life cycle cost. As a result, the main sources of pricing for Carbon Condo are building material costs and prefabrication costs. On a per year basis, Carbon Condo consumes 40% less energy than the energy that the US average condo consumes. The annual energy consumption of Carbon Condo and the US average condo was assumed as 119,000 kWh and 196,000 kWh, respectively, based on a use phase projection calculation in Table 2. The deconstruction phase costs the least since all materials will just be landfilled and no additional processing is required for recyclables.

The materials considered are essential components in the development of each building type. As shown in Figure 8, in terms of the Carbon Condo, CFoam and CNT are the most cost-intensive materials and are the most solicited in the development of this building model.



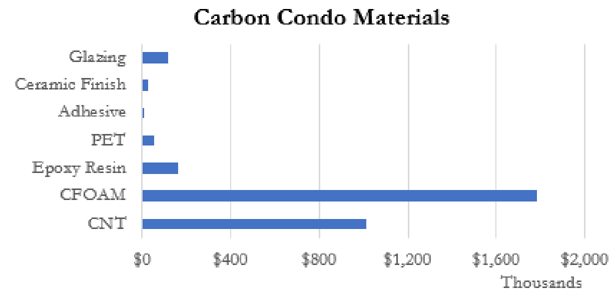


Figure 8. Material Costs for US Average Condo and Carbon Condo

The construction of the Carbon Condo primarily revolves around the utilization of CNT. Considering CNT is one of the most cost-intensive materials, we performed a break-even analysis to determine how much CNT would need to cost for the entire project to break even in terms of material costs. The breakeven price for CNT would need to be $12.5 per kg, as demonstrated in Figure 9.

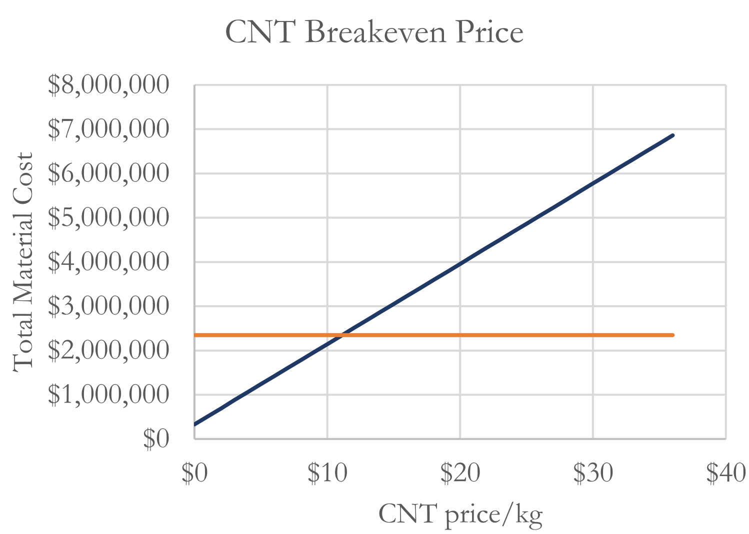


Figure 9. CNT Breakeven Price to Allow Project to Breakeven for Total Material Costs

Other materials required within the construction process are also developed from CNT, which explains why there are fewer materials listed for the Carbon Condo rather than the US average condo. When considering the key elements of the construction process, the factory assembly of the US average condo materials was assumed to be negligible.

8 Sensitivity Analysis

A sensitivity analysis is used to determine how various sources of uncertainty contribute to the model's overall uncertainty. For this project, we calculated sensitivity analysis on greenhouse impact and on life cycle cost for Carbon Condo. The scenarios developed were designed to encompass realistic uncertainties with respect to material availability and elements of the construction process.

The sensitivity analysis was conducted around the following scenarios:

- Scenario 1: Epoxy resin increases by 10% and decreases by 50%
- Scenario 2: CNT/CFoam quantity increases by 10% and reduces by 10%
- Scenario 3: Annual electricity use increases by 20% and reduces by 40%
- Scenario 4: CNT/CFoam price ($15.4/kg) drops by 50%, increases by 20%
- Scenario 5: 5% of prefabrication cost allocated vs 100%

The results from each scenario are shown in Figure 10.

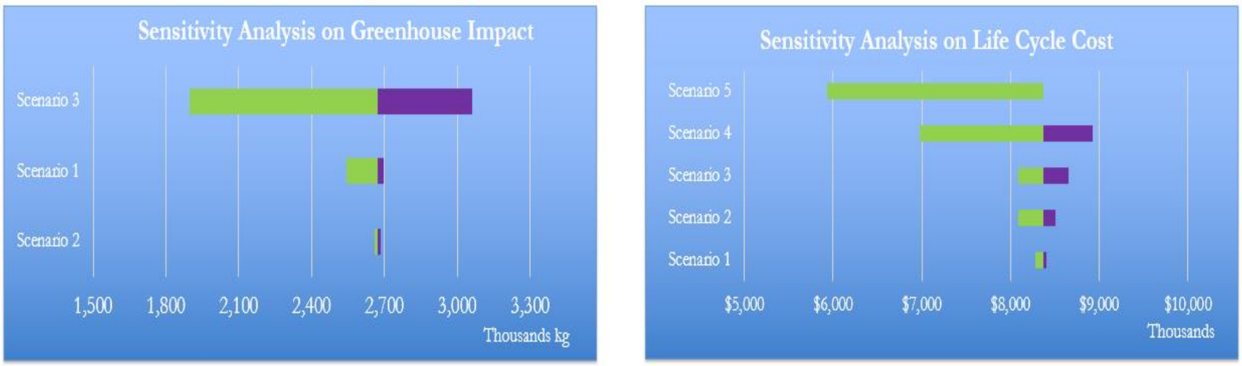


Figure 10. Sensitivity analysis results on GHG impact and Life Cycle Cost

The sensitivity analysis on greenhouse impact was performed to understand how the use phase and material quantity change the lifecycle of CO_{2e} emission. For each scenario, a new variable is introduced while all other assumptions remain unchanged. The life cycle greenhouse emission of Carbon Condo is most sensitive to Scenario 3, the annual electricity use change. Since electricity use has a high sensitivity because the prefabricated building components would minimize air infiltration and reduce the need for mechanical heating and cooling. Scenario 1, change in the epoxy resin used in CNT prefabrication also affects the life cycle greenhouse impact. Scenario 2, the change of CNT and CFoam quantity by 10% has a limited impact.

The sensitivity analysis on Carbon Condo LCC incorporates the same scenario from Greenhouse Impact and includes two additional scenarios – 4 and 5, that introduced new variables for unit price and prefabrication cost allocation. The cycle cost is most sensitive to the prefabrication cost allocation of CFoam and CNT. When the prefabrication cost is allocated 100% on a Carbon Condo project, the life cycle cost is extremely high. However, the industrial process usually yields more than one single output. As the demand for production increases, the production cost can be allocated to several products for more cost-friendly outcomes.

9 Conclusions

In terms of cost, the carbon condo is much more expensive than the US average condo for a multitude of reasons. Due to its scarcity, CNT is expensive and as of right now, it does not seem like a financially plausible option in comparison to a traditional US average condo. The most cost-intensive aspect of the CNT production process is prefabrication, which makes up 30.6% of the total Carbon Condo life cycle cost. A significant factor contributing to the high prefabrication cost is the scarcity of CNT. Since CNT is a newly explored material, it is not widely accessible and the great distances for procurement largely contribute to the significant increase in material cost.

Ultimately, the high price of CNT reduces its consideration for usage; however, supply meets demand and as demand increases, CNT will become a more financially feasible option within the construction industry. In order to increase demand and drive down costs, constructors must gain exposure to the benefits of building with CNT. CNT is not a very well-known material within the construction and by closing this knowledge gap, it will be considered more often for building construction. The price of CNT would eventually break even at $12.5 per kg due to increased production levels, which would decrease material price and increase accessibility, as well as drive down transportation distances that contribute to the high cost.

9.1 Recommendations

Fundamentally, CNT poses great benefits for the environment, and its unique qualities in strength and malleability make it a revolutionary material within the construction industry. To further explore the benefits of implementing CNT into the construction process, a list of recommendations was developed.

Recommendations to enhance the benefits of utilizing CNT:

- Invest in research & development of CNT as a building material
- Explore recycling methods for CNT
- Achieve economies of scale for CNT production and prefabrication — price falls exponentially
- Focus on energy efficiency in the use phase
- Use passive design strategies to reduce mechanical heating and cool needs
- Reduce on-site construction and prioritize prefabrication processes
- Minimize transportation distances by sourcing local materials
- Constructors should gain exposure to the benefits of building with CNT

10 References

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11 Appendix

Table A1. Transportation Fuel Requirements (Courtesy of Prof. Lepech)

Table A-5

1993 TRANSPORTATION FUEL REQUIREMENTS

		Fuel Consumed per 1,000 Ton-Miles	Energy Consumed (1) (Btu/ton-mile)	DQI
Combination truck (tractor trailer)				
Diesel	gal	9.4	1,465	B
Gasoline	gal	9.4	1,308	B
Single unit truck				
Diesel	gal	26.5	4,129	B
Gasoline	gal	26.5	3,689	B
Rail				
Diesel	gal	2.4	374	B
Barge (2)				
Diesel	gal	2.0	316	C
Residual	gal	0.8	131	C
Total			447	
Ocean freighter (2)				
Diesel	gal	0.1	23	C
Residual	gal	1.8	307	C
Total			330	C
Pipeline - natural gas				
Natural gas	cuft	2,300	2,581	C
Pipeline - petroleum products				
Electricity	kwh	22	241	C
Pipeline - coal slurry				
Electricity	kwh	235	2,578	C

(1) Includes precombustion energy for fuel acquisition.

(2) An average ratio of diesel and residual fuels is used to represent barge and ocean freighter transportation energy.

References: A-4 and A-57.

Source: Franklin Associates, Ltd.

Table A2. Emissions for diesel powered trucks (Courtesy of Prof. Lepech)

Table A-28b

ENVIRONMENTAL EMISSIONS FOR 1992 TRACTOR-TRAILOR DIESEL POWERED TRUCKS (pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.66	29.8	31.5	B
Nitrogen Oxides	8.47	210	218	B
Hydrocarbons (other than methane)	50.2	37.7	87.9	C
Sulfur Oxides	25.8	36.2	62.0	B
Carbon Monoxide	6.36	209	215	B
Fossil Carbon Dioxide	2,627	22,800	25,427	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47	5.50	5.97	C
Other Organics	0.30	116	116	D
Ammonia	0.040		0.040	C
Lead	1.4E-04		1.4E-04	B
Methane	4.05		4.05	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05		7.9E-05	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.0E-05		9.0E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.2E-05		7.2E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

Table A3. EcoBalance US Energy Grid Energy Inputs and Emissions (Courtesy of Prof. Lepech)

EcoBalance US Energy Grid Energy Inputs and Emissions

LCI for Producing One MJ (= 0.27778 kWh) of Electricity for the US Grid

Environmental Flows	*Units*	*Quantity*
Inflow		
(r) Coal (in ground)	kg	0.069
(r) Limestone (CaCO3, in ground)	kg	0.013
(r) Natural Gas (in ground)	kg	0.0076
(r) Oil (in ground)	kg	0.0024
(r) Uranium (U, in ground)	kg	1.7 E-06
Water Used (total)	liter	0.0021
Outflow		
(a) Dust & Particulates	g	0.97
(a) Carbon Dioxide (CO_2, fossil)	g	213
(a) Carbon Monoxide (CO)	g	0.047
(a) Sulfur Oxides (SOx as SO_2)	g	1.2
(a) Nitrogen Oxides (NOx as NO_2)	g	0.66
(a) Non-Methane Hydrocarbons	g	0.0045
(a) Methane (CH_4)	g	0.52
(a) Hydrogen Chloride (HCl)	g	0.037
(a) Hydrogen Fluoride (HF)	g	0.0046
(a) Lead	g	1.0 E-04
(w) Dissolved Solids	g	0.11
(w) Suspended Solids	g	0.0040
(w) Heavy Metals (total)	g	5.6 E-05
(w) Oils and Greases	g	0.00051
(w) Other Organics	g	
(w) Phosphates (as P)	g	
(w) Ammonia (as N)	g	0.00022
Waste (total)	kg	0.031
Energy Reminder		
E (HHV) Total Energy	MJ	3.48
E (HHV) Fossil Energy	MJ	3.37
E (HHV) Non-Fossil Energy	MJ	0.11

Table A4. Building Material Costs for US Average Condo

Building Materials	Cost of Material Required	Source
Wood Framing	$ 242,428	Courtesy of Tess Hegarty
Carpet & Carpet Pad	$ 70,770	
Fiberglass Insulation	$ 76,706	
Drywall	$ 225,676	
Asphalt Shingles	$ 24,634	
Paint	$ 19,974	
Concrete	$ 95,581	
Glass Window	$ 76,706	
Door (and Fitting)	$ 151,464	
Ceramic Tiles	$ 34,433	
Heating System	$ 178,646	
Cooling System	$ 188,867	
Stucco	$ 112,898	[1]
Plywood	$ 753,862	[2]
OSB	$ 17,438	
Nails	$ 21,675	

Steel rebar	$	56,253	

[1] D. Weinberger & L. Pelchen. (2022). How Much Does it Cost to Stucco a House?. Forbes Home. https://www.forbes.com/home-improvement/siding/stucco-cost/.
[2] Lowe's. (2022). https://www.lowes.com/.

Table A5. LCI for CNT and CFoam (Courtesy of Tess Hegarty)

Material	**Scale**	Kg CO_2/kg
CNT	Demo scale	3.98
	Full scale	1.27
	Full scale with carbon capture	1.24
CFoam	Demo scale	9.56
	Full scale	0.24

Table A6. Prefabrication Equipment Costs for Carbon Condo (Courtesy of mouldCAM)

Prefabrication equipment costs			
Equipment	**Cost per unit (USD)**	**# of Units**	**Total Cost (USD)**
CNC router	290000	4	1160000
CNC Tools per year	28000	1	28000
Fabric cutting tools	22000	1	22000
Screw compressor	32000	1	32000
13 tables	23500	1	23500
Roller unit for each table	28000	13	364000
Skin bonding	7000	1	7000
Gantry crane fitting	110000	1	110000
Spray paint booth	120000	1	120000
Material handling forklift	12000	1	12000
2 suction cup lifters	12000	1	12000
A and B set motherboards	2800	2	5600
Adhesive pumps	4000	2	8000
Paste mvp pump	17000	2	34000
Vacuum pump	5800	1	5800
General	18000	1	18000
Factory establishment	200000	1	200000
TOTAL			2161900

Table A7. Summary of prefabrication costs for Carbon Condo (Courtesy of mouldCAM)

Summary of prefabrication costs (USD)	
Fixed cost	1243000
Wages	660000
Materials	583845
Consumables	77000
Production Cost total	**2563845**

Table A8. US Average Life Cycle Cost Breakdown

Building Material Cost	$	2,348,000
Other Building Component (Service) Cost	$	1,172,800
Construction (Installation) Costs	$	726,600
Deconstruction Costs	$	66,900
Energy Use Costs	$	1,153,700
Total Life Cycle Cost:	***$***	***5,468,000***

Table A9. Carbon Condo Life Cycle Cost Breakdown

Building Material Cost	$	3,161,700
Other Building Component (Service) Cost	$	1,172,800
Prefabrication Cost	$	2,563,800
Construction Cost	$	726,600
Deconstruction cost by weight	$	42,800
Energy Use Cost	$	701,000
Total Life Cycle Cost:	***$***	***8,368,800***