Low-Carbon Housing Project

ENGR 333 Section B

Calvin University

8 December 2021

Table of Contents

Technical Memo

Problem Statement

In 2020, residences used 16.5% of all final energy in the United States, and residences were responsible for 19.3% of all U.S. CO_2 emissions. Calvin ENGR 333 students partnered with Habitat for Humanity to tackle the issue of carbon emissions when designing their homes. Habitat for Humanity for Kent County is endeavoring to design homes that reduce energy consumption, energy expenditures, and carbon emissions. They are embarking upon a "carbon footprint build" that will minimize energy consumption and carbon emissions, both during construction and across the lifetime of their new Habitat for Humanity homes.

This semester, the senior mechanical engineering students at Calvin have addressed the question, "What is the expected carbon emissions savings of the carbon footprint build houses?". After preliminary results, it was deemed that the house was not carbon-neutral and therefore a second question was asked, "how can carbon emissions be reduced by a further 20%?". The ENGR 333 Section B class examined two different Habitat for Humanity Houses (located at 726 London St SW and 930 Woolsey St SW) and analyzed the carbon emissions throughout the entire life cycle of the house. This section was split up into four teams: embodied carbon, onsite activity, utilities, and design.

Methods

The embodied carbon group examined how much carbon is emitted that comes from manufacturing the materials that go into construction. This encompasses any carbon that is emitted from extracting the material from the Earth all the way through the manufacturing process until the materials are ready to be shipped to the construction site. The onsite group then looked at the carbon footprint that comes from transporting the materials to the construction site as well as the emissions from the construction activities at the site itself. The utilities group analyzed the last step of the process by looking at the carbon emissions from when the house is connected to the grid through the 30-year lifespan of the house. The last group was the design group. They were tasked with creating design models that would reduce the carbon emitted by 20%. By analyzing the house located on Woolsey and the house currently being built on London, six models were created.

Results

As seen in *Figure 1*, preliminary results were run on the two base case houses located at London and Woolsey Street. This analysis showed the importance of electricity and natural gas usage in terms of carbon emissions. This established a need to account for the changing factor of these emissions as utilities companies move towards more renewable energy. The utility technical memo found in *Appendix C* discusses in further detail how the final design options change when implementing the Consumer Clean Energy Plan. Once the design group saw that utilities were the leading contributor of carbon emissions, they created six designs that would try and reduce the amount of emitted carbon. These designs are outlined in more detail in *Appendix D*. After the six models were analyzed, the final design had a 44% reduction in carbon emissions. This house included an attachment of solar panels which increased the amount of embodied carbon, but significantly decreased the amount of carbon coming from the utilities section (*Figure 2*). A best-case house was selected by combining aspects of different design options and resulted in more than the projected 20% decrease in carbon emissions. However, no matter what option Habitat for Humanity chooses none of them are carbon neutral. Habitat for Humanity must continue to focus on optimizing efficiency of the heating/cooling system and appliances in addition to investing in environmentally friendly construction processes.

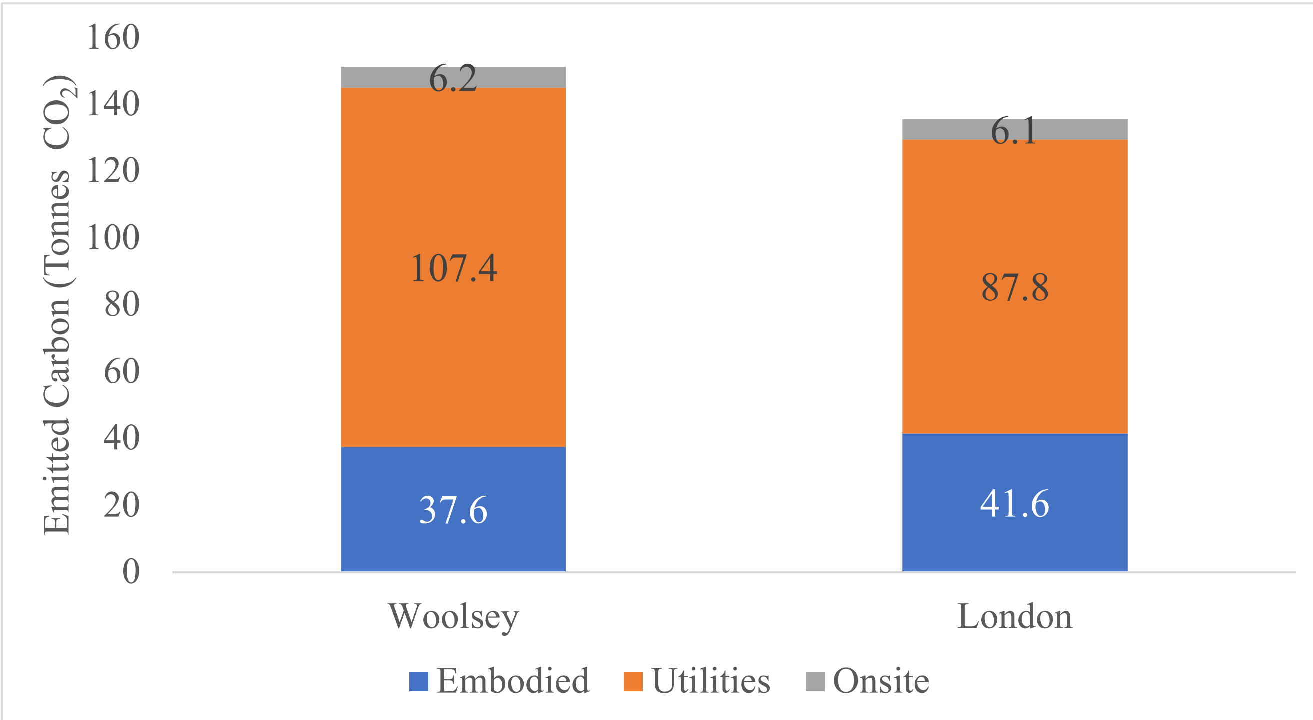

Figure 1 Preliminary results of emitted carbon from the two base case houses

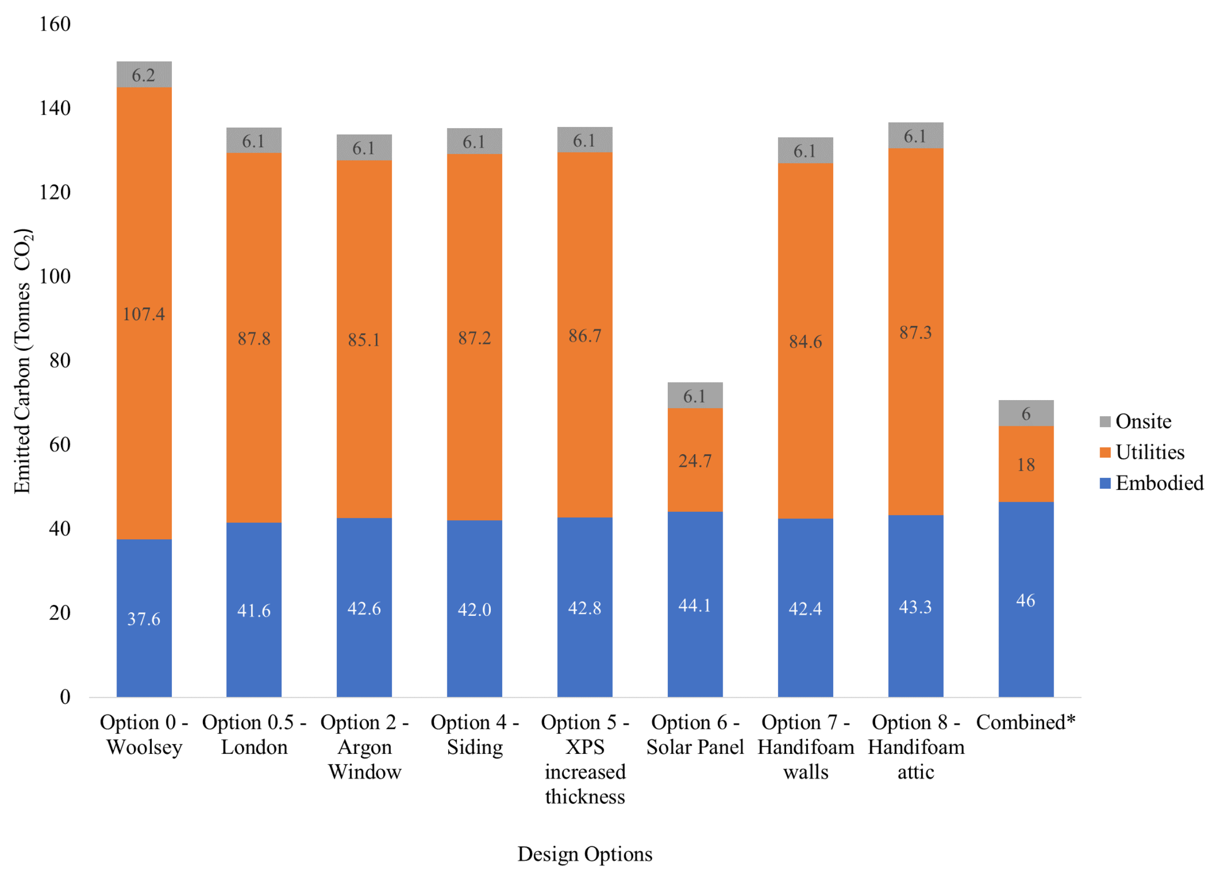

Figure 2 Emitted Carbon of six different design options as well as the two base case houses
**Includes aspects of design options 2, 4, 6, and 7*

Appendices

Appendix A: Group A—Embodied

Technical Memo

Introduction

The embodied carbon group's objective was to determine the amount of carbon in the materials used for constructing a house for Habitat for Humanity. The base for the research was the Woolsey house and analysis was done on the London house. Materials that were used for the construction of each of these houses were similar but had a few minor differences in what materials were used.

Methods

Materials were cataloged through receipts and grant specification plans. The individual documents and cataloged lists can be viewed in Appendix E. Receipts were gathered from Habitat for Humanity for the materials used in building the Woolsey house. These documents were also used to estimate the material that was used to build the London house as they have similar materials that were going to be used to build London. Next, carbon coefficients for each material were found using Environmental Product Declarations (EPDs). The Embodied Carbon in Construction Calculator (EC3) Software was used extensively as it has a large catalog of EPDs for building materials. The information gathered was compiled in excel for carbon calculations as seen in *Appendix A1*.

Results

Figure A1 below shows the results of our calculations for the base house of Woolsey and London as well as the design options chosen by the design team to improve the overall carbon emissions of the house. Although the embodied carbon of the design options is increased, this was done to make the house more carbon neutral by increasing insulation or other things that reduce the carbon emissions from utilities and heating.

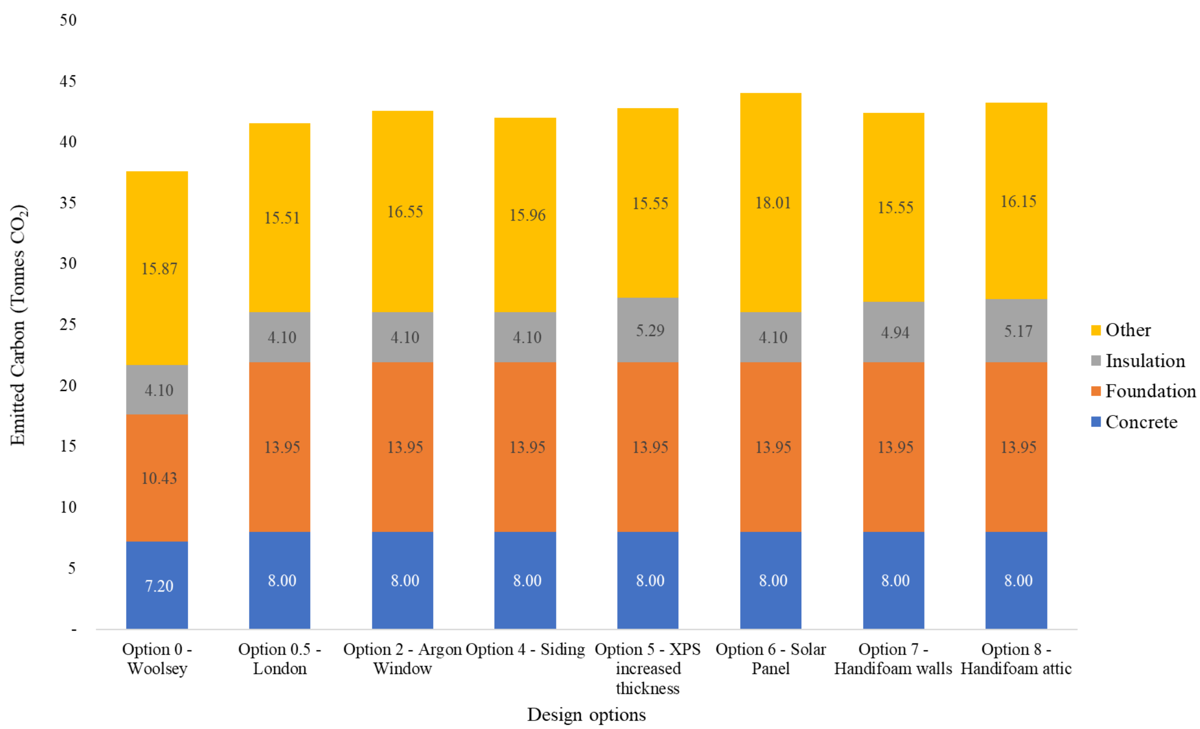

Figure A1. Graph showing the total embodied carbon as well as the biggest contributors for each design option.

Appendix A1—Excel Spreadsheet Link

Embodied Carbon Excel File

File linked above shows the calculations and exact numbers for each house and design options analyzed.

Appendix B: Group B—Onsite

Technical Memo

Executive Summary

The onsite group examined the carbon emissions that came from transporting materials to the construction site as well as the construction activities that occurred onsite during the building process of the Woolsey house. The analysis of the Woolsey house was used as a base case that would later help make assumptions and comparisons for the London house.

Methods

The main software used to calculate the carbon emissions for onsite activity was Microsoft Excel. One Microsoft Excel file with several spreadsheets was created to track both the transportation and construction activities. Furthermore, each spreadsheet not only had the onsite activity calculations for the Woolsey and London houses, but also entailed all design options that were developed by the design team.

Transportation

Within the transportation analysis, there were many factors that had to be accounted for. First, the type of vehicle and the number of trips each vehicle took to transport materials were analyzed. Knowing the type of vehicle used helped to determine the fuel mileage of the vehicle, and the distance traveled was used to determine the total amount of fuel used. Second, the CO_2 emission rate for each machine had to be determined. Using the U.S. Energy Information Administration (EIA), the CO_2 emission rates for both gasoline and diesel were found to be 8.50 and 10.19 $kgCO_2$ per gallon of fuel, respectively. With the total amount of fuel used for each vehicle and the values of the CO_2 emission rates for gasoline and diesel, the total amount of CO_2 emissions for all transportation during construction could be calculated. The total CO_2 emissions for each machine can be found in the Excel spreadsheet provided on the USB drive. Similarly, the greatest contributors to the carbon emissions for transportation can be found in *Figure B1* outlined by the black boxes.

Construction Activity

The second part of tracking the carbon emissions for onsite activity was analyzing the construction activity at the construction site. One of the factors taken into consideration was the amount of time that the machine was running during the construction project. The second factor taken into consideration was finding the rate of fuel consumption for each machine, like what was done for the transportation analysis. Knowing the running time for each machine and the rate at which it consumed fuel meant that the total amount of fuel used for each machine could be calculated. With this information and using the CO_2 emission rate for gasoline and diesel (as seen in the transportation analysis), the total amount of CO_2 emissions for all construction activities could be calculated. The preliminary results were run on the London household since it was being built in tandem with this project. It was assumed that the construction activities for the Woolsey house, which was already completed, were the same as the LCHP for the London household, except for the use of a crane. A crane could not be used at the London house due to the restrictive location of the house. The total CO_2 emissions for each machine used for construction can be found in the Excel spreadsheet provided on the USB drive. Similarly, the greatest contributors to the carbon emissions for construction activity can be found in *Figure B1* outlined by the red boxes.

Results

As seen in *Figure B1*, the total carbon emissions for all design options, including the general onsite activity for Woolsey and London, for onsite activity was about six tonnes of CO_2.

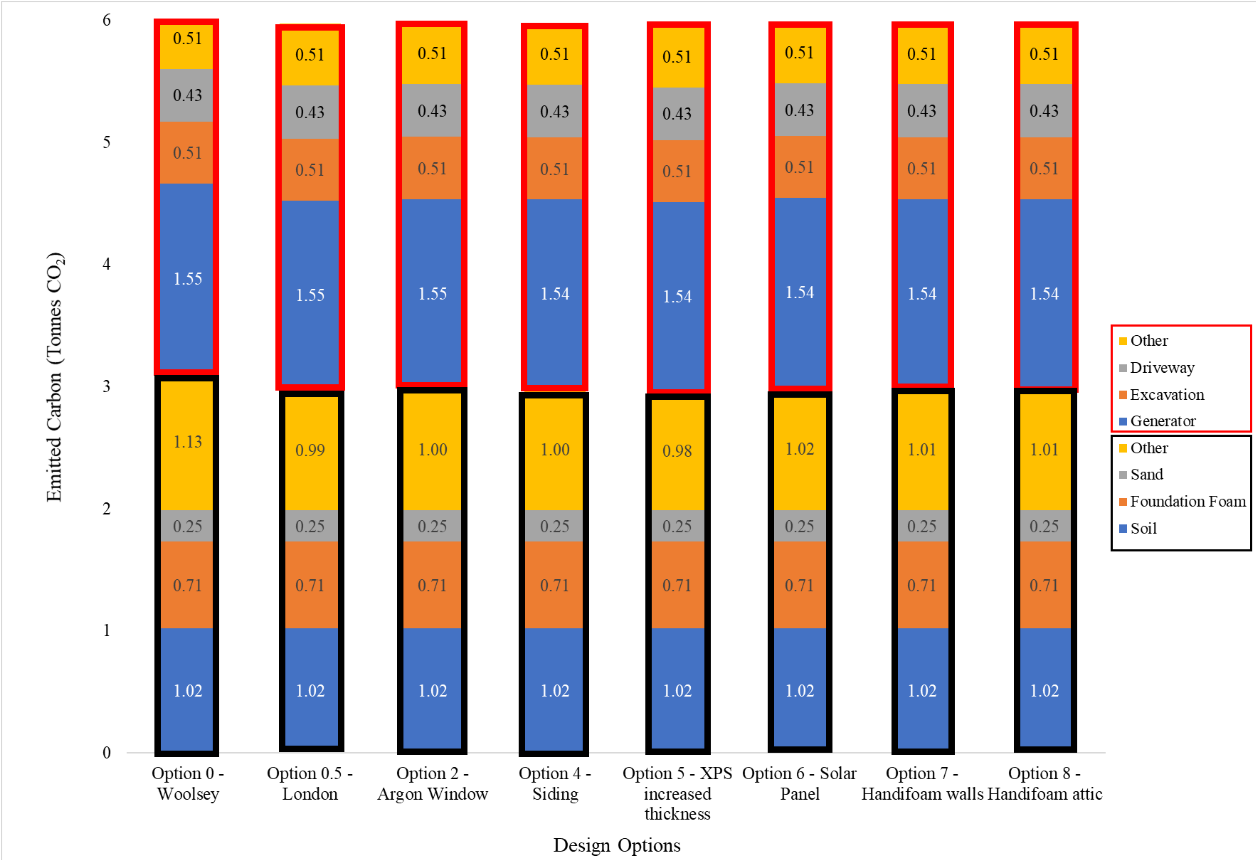

Figure B1. Total carbon emissions for transportation and construction activity.

The reason for such equivalent results for Woolsey and London is because both houses were built in unison. Furthermore, the design options provided by the design team took into consideration the distance from where the materials will be acquired. Since HFH mainly gets its materials in Grand Rapids, the total carbon emissions for transportation had little variations. As seen in *Figure B1* above, the largest carbon emitters for transportation include soil, other transportation, foundation foam, and sand. Construction activity also had similar results for all design options as Woolsey and London were assumed to be built alike with exception of the crane since the crane was too big to operate at the construction site for the London house. As seen in *Figure B1* above, the largest carbon emitters for construction activity included the generator, excavation, other construction, and the driveway.

Although there is a total of about six tonnes of CO_2 being emitted into the atmosphere just for onsite activity, onsite activity has negligible impact during the construction process when compared to the results founded by the embodied team and utilities team. This is one of the main reasons why the design team did not create any design options for onsite activity as it would not make any significant changes.

Appendix B1—Excel Spreadsheet

Onsite Carbon Excel File

File linked above shows the calculations and exact numbers for each house and design options analyzed.

Appendix C: Group C—Utilities

Technical Memo

Executive Summary

Heating and utilities are high contributors to carbon emissions in a house, specifically over a lifespan of 25 years for a family of four. A kilowatt-hour of electricity has 4.99 x 10^{-4} tonnes of carbon emissions associated with it while natural gas has even higher carbon emissions associated with it at 5.48 X 10^{-4} metric tonnes per hundred cubic feet. Because of this, it is important to increase insulation and reduce utility use in order to decrease the emitted carbon of a house during its lifespan.

The objective of the Low Carbon Housing project was to develop a model that calculated and compared the energy consumption and carbon emissions of a baseline home at 930 Woolsey St SW (the "Woolsey house") and a "carbon footprint build" home at 726 London St SW (the "London house"). The model also found ways of reducing the carbon emissions in the London house by 20%.

Methods

he analysis and reduction of the carbon emissions associated with the use of utilities in both houses were divided into two main subcategories: "Heating" and "Appliances".

Before analyzing these two subcategories for the homes, a generic model of the utilities use of an average home of similar size and region was created using data from the United States Energy Information Administration. This was done to create a baseline of reasonable carbon output

The "heating" subcategory involved analyzing all the carbon emissions associated with warming the house. In order to accomplish this, a heating resistance network model was created for both homes. For the Woolsey house, the materials used in the house were found in the LEED summary. For the London house, the materials used were found in the grant plan document. Both documents were provided by Habitat for Humanity. The R values for each material were found in these documents and the "Heat and Mass Transfer" textbook by Cengal. The heating model accounted for months the months of October through April - in Grand Rapids in which atmospheric temperatures are cold enough to require home heating by the average home and made use of research heating degree days.

The "appliances" subcategory involved analyzing all the appliances and lighting that were not involved in heating the home. This included the dishwasher, range, refrigerator, washer, dryer, and all the lighting in the house. This approach only accounted for appliances supplied by Habitat for Humanity, not appliances that homeowners add to the house as that fell outside of the project scope. In order to calculate the energy use of appliances, the Energy Star Rating by the United States Environmental Protection Agency and Department of Energy were used. With regards to calculating the energy used by lighting, the wattage rating from the manufacturer's website was used to calculate the amount of power used during an assumed cycle time that took account of the typical duty cycle of lighting in Grand Rapids.

The first step to creating the total carbon emissions model from both heating and utilities in 726 London St SW was to create a rough carbon emissions model for the baseline Woolsey house. The energy consumption and the carbon emissions tied into that energy were broken down into both gas and electricity consumption categories as total amounts in a year. The energy consumption values were taken from the Woolsey GR fuel summary report and placed in the model via Excel.

The next step was to formulate two carbon emission models for both heating and utilities. The goal of these two models was to use bottom-up calculations to achieve the exact energy consumption results given by the generic Woolsey model. This ensured that the calculations in the models were accurate and could be applied to the London house to achieve exact carbon emissions. From there, these Woolsey models were changed to account for London's different insulation and appliance values, such as changes in the R values, different energy consumptions and cycles of use for appliances, and the use of an electric heat pump/ water heater instead of the Woolsey furnace and water heating boiler.

Results

The results from the rough baseline Woolsey model can be seen in *Table C1*, found in the Appendix. These results show that the tonnes of carbon emissions per year for Woolsey were lower than the US average total.

The heating model for Woolsey resulted in a low 2.83 % difference between the energy consumption results from the bottoms up approach heating model and the results from the Woolsey GR fuel summary report. The total carbon emissions from the gas furnace for the Woolsey house in a lifetime of 25 years was 37.9 tonnes of CO2. A pie chart listing the respective percent of heat loss from the roof, windows, walls, and basement of Woolsey can be found in Figure C5 in the Appendix. As seen in Figure A-1, the largest cause of heat escape came from the windows.

The heating model for London required 14.53% less heating energy than the Woolsey house, due to increased insulation in the roofing and basement walls in the London house and the increased efficiency of the heat pump in comparison to the traditional furnace. The electricity usage by the heat pump resulted in 1.32 metric tons of CO2 per year, as compared to Woolsey which was 1.52 metric tons of CO2 per year. The lifetime CO2 emissions of the London house was 33.09 tonnes of carbon dioxide. When following Consumer's Energy Sustainability Plan (SPE) the lifetime CO2 emissions for London are 24.43 tonnes of CO2. A pie chart listing the respective percent of heat loss from the roof, windows, walls, and basement of London can be found in Figure C6 in Appendix C1. As seen in Figure C6, the largest cause of heat escape came from the windows.

The utilities model for Woolsey, including appliances, lighting, and boiler water heating, resulted in 105.87 metric tons of carbon in the house life cycle. Under the SPE, the total carbon emissions in the given lifetime of 25 years were 88.48 metric tons. The total carbon emissions per year for each utility can be seen in the pie chart in Figure C7, in Appendix C1.

The utilities model for London resulted in 54.74 tonnes of carbon emissions over the lifetime of the house. With the SPE in place, 40.41 tonnes of carbon emissions were emitted into the life cycle of the house. The major cause for the difference in utility carbon emissions for London and Woolsey was the Bradford water heater system in the London house. The total carbon emissions per year for each utility can be seen in the pie chart in Figure C8, in the Appendix.

Table C2, shown in the Appendix, shows the final carbon emission results for both heating and appliances for both London and Woolsey houses. In addition, Table C2 also shows the carbon emissions if the SPE becomes effective. Figure C3 shows the carbon emissions for each of the design options in terms of heating and utilities for the life cycle of the London house. Figure C4 shows the carbon emissions for all the design options if the SPE was applied. Figure C1, in the appendix, compares the total tonnes of carbon emissions from heating and utilities in the 25-year life cycle from London and Woolsey. Figure C2, in the appendix, shows the comparison of London's total lifetime CO2 emissions following the current electricity emissions and the sustainability plan emissions.

Appendix C1—Figures

As seen in Figure C1 below, the London house was lower in carbon emissions than Woolsey by close to 20 tonnes. The main reason for this difference was the increased insulation in the London house and the use of a heat pump instead of a furnace.

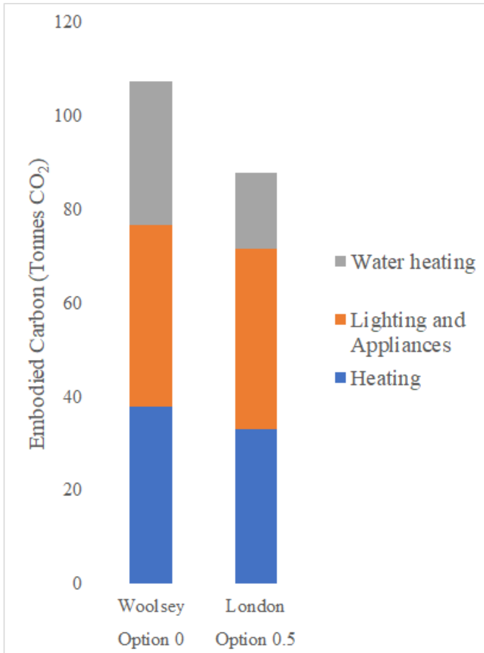

Figure C1: Total lifetime carbon emissions breakdown for utilities of Woolsey and London.

As shown in Figure C2 below, when following the SPE, the total carbon emissions from London decrease by about 23 tonnes from the current carbon cost of producing electricity.

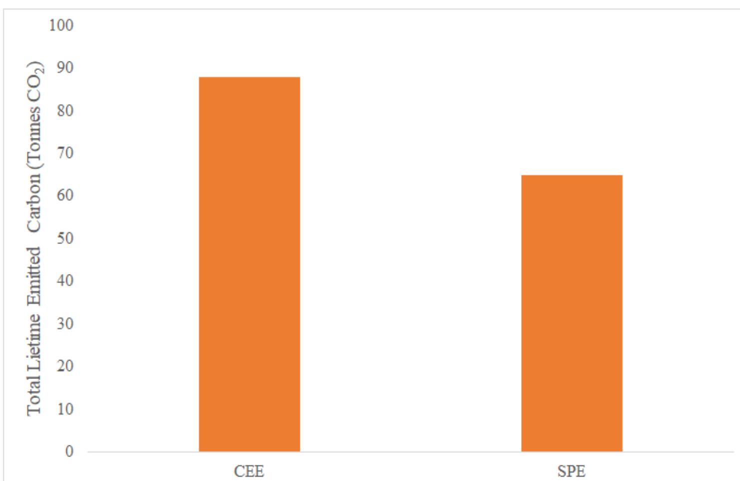

Figure C2: CEE and SPE comparison for Total Lifetime Emitted Carbon of the London house.

As shown in Figure C3, solar panels were the obvious and most optimum choice when reducing carbon emissions. In terms of design optimizations for insulation in the London house, the three panned argon windows decreased the carbon emissions the most.

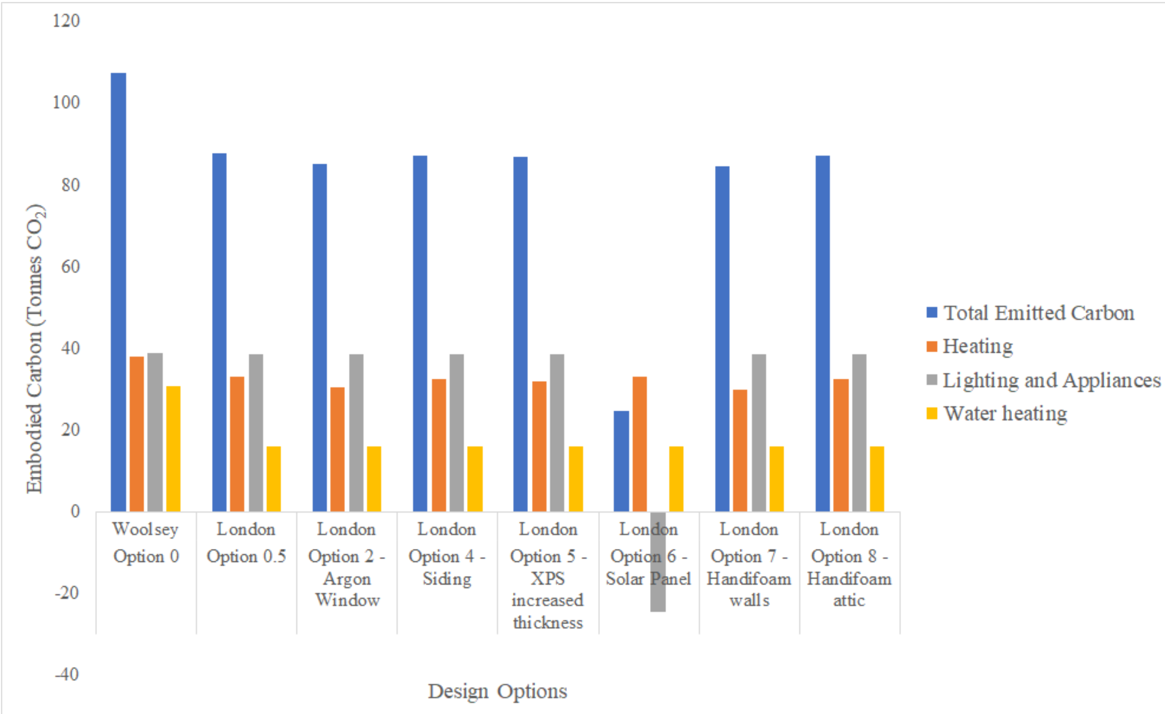

Figure C3: Embodied Carbon for Current Electricity Emissions (CEE). This is using a conversion factor of 0.000499 T/kW-hr

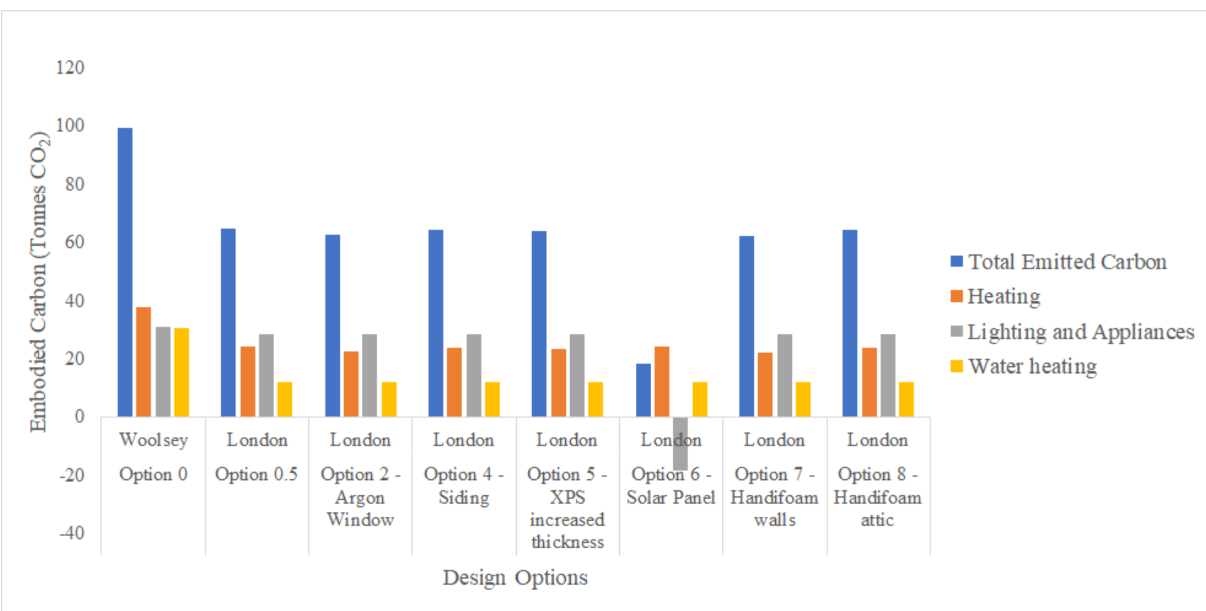

Figure C4: Embodied Carbon for Sustainability Plan Emissions (SPE). This is using a conversion factor of 0.000368 T/kW-hr

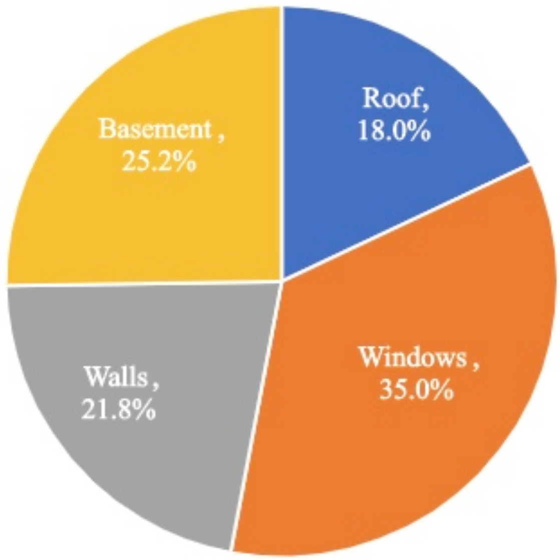

Figure C5: Heat Loss for Woolsey house

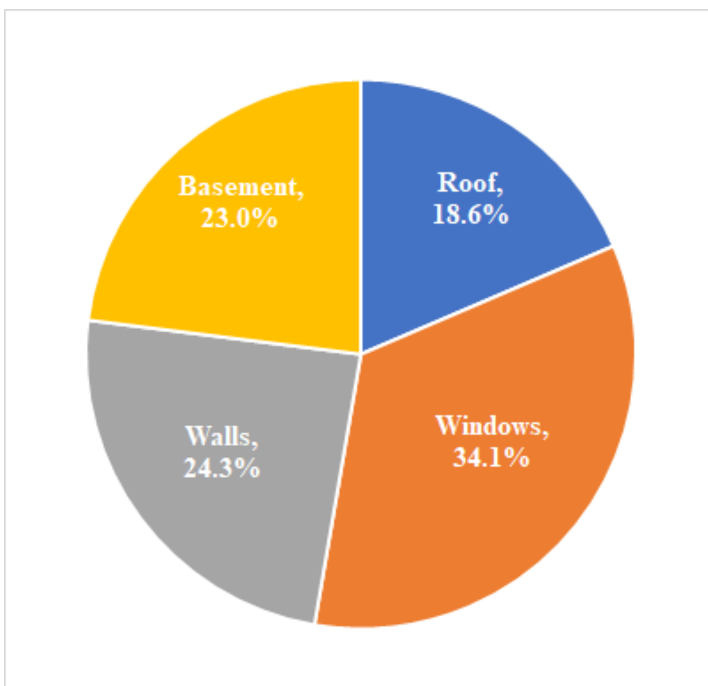

Figure C6: Heat Loss for London

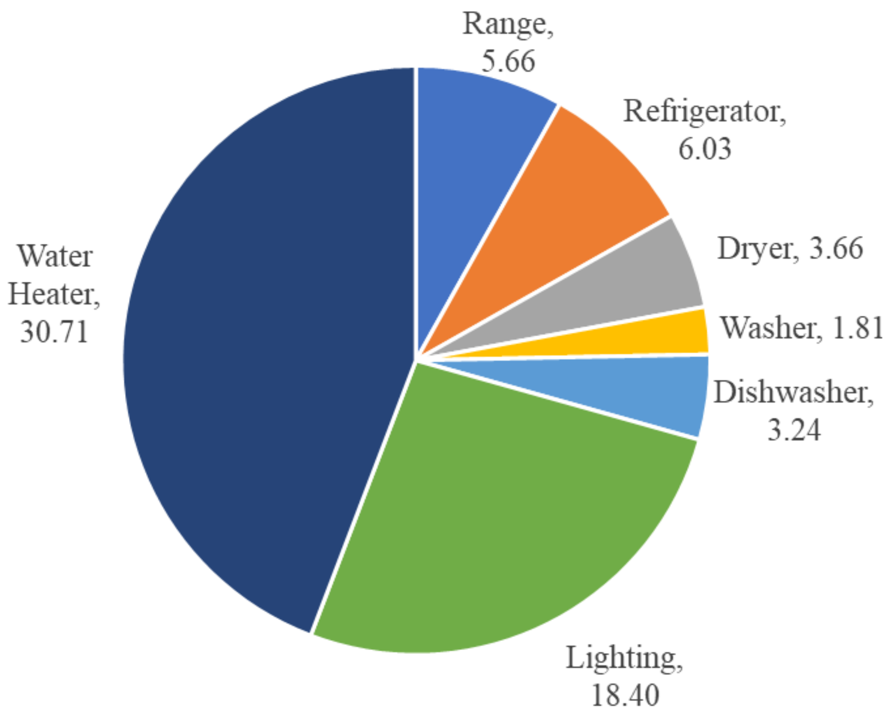

Figure C7: Carbon emission totals by appliance in the Woolsey house measured in Tonnes CO_2 per year

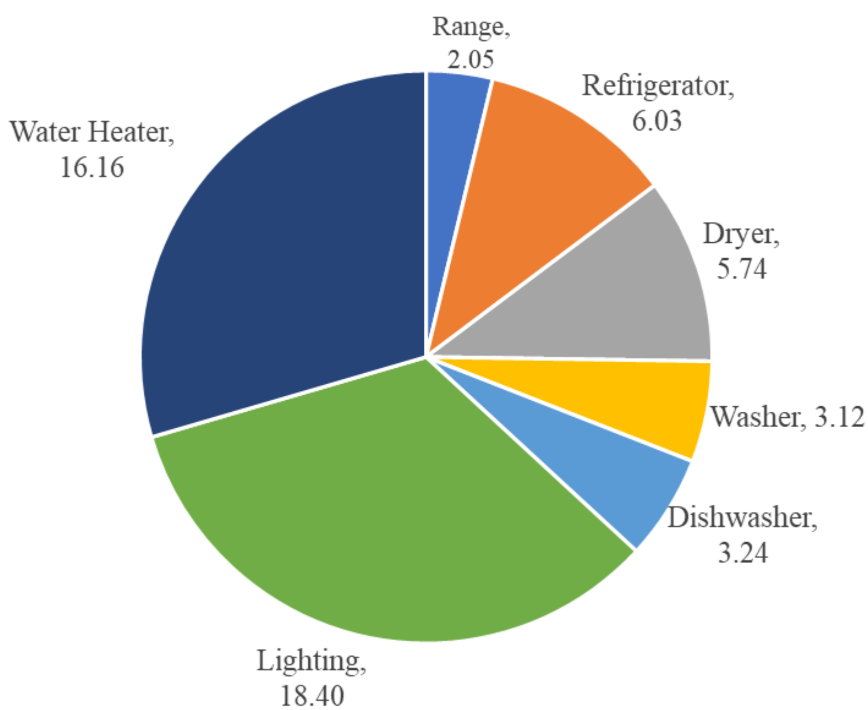

Figure C8. Carbon emission totals by appliance in the London house measured in Tonnes of CO_2 per year

Table C1: Results from Generic Woolsey model.

		Woolsey [CCF]	Woolsey [$]	Woolsey [MTCO2]
Gas	Heating	269	$ 272.77	1.47
	Water Heating	182	$ 184.55	1.00
	Lights & Appliances	48	$ 48.67	0.26
	Gas Total	499	$ 506.00	2.73
Elect		Woolsey [kWh]	Woolsey [$]	Woolsey [MTCO2]
	Heating	78	$ 8.27	0.06
	Cooling	638	$ 67.62	0.45
	Lights & Appliances	4511	$ 478.11	3.20
	Elect. Total	5227	$ 554.00	3.71
	Service Charge		$ 185.00	
		Woolsey Totals	$ 1,245.00	6.44
		US Avg Totals	$ 1,953.86	8.94

Table C2. Final carbon emission results for the heating and appliances.

	Heating			Appliances			Total
	Yearly Heat Loss	Yearly CO2	Lifetime CO2	Yearly Usage	Yearly CO2	Lifetime CO2	Lifetime CO2
Woolsey CEE	2.6E+07	1.52	37.90	8,282	2.78	69.51	107,403
London CEE	2.4E+07	1.32	33.09	4,388	2.19	54.74	87,823
Difference	-2.2E+06	-0.19	-4.81	-3,894	-0.59	-14.77	-19,580
Woolsey SPE	2.6E+07	1.52	37.90	8,282	2.47	61.63	99,525
London SPE	2.4E+07	0.98	24.43	4,388	1.62	40.41	64,846
Difference	-2.2E+06	-0.54	-13.47	-3,894	-0.85	-21.21	-34,679
Units	BTU/yr	Ton/yr	Ton	kWhr/yr	Ton/yr	Ton	kg

Appendix C2—Excel Spreadsheet

Section B Heating and Appliances Worksheet

File linked above shows the calculations and exact numbers for each house and design options analyzed.

Appendix D: Group D—Design

Technical Memo

Objective

The main goal of the design team was to research viable design changes for future Habitat for Humanity builds that will reduce the total amount of carbon emissions in their current low carbon-footprint build at 726 London St SW by 20%. Additional goals were developed during the semester through communication with Mark Ogland-Hand. These include:

- What impact in carbon emissions does the Heat-pump installed at London have compared a gas furnace in the same house?
- Is the electrification of a house a "win"?

Methods

To achieve these goals, each member of the team focused on researching materials and building techniques that reduce the carbon emissions of a house. A material that is deemed to be a viable replacement or addition to the current London house would be identified as a design option. After selecting an initial design option set from the research, the relevant information for each option was sent to the analysis teams. The analysis teams applied each design option to their models and returned the total carbon emissions and largest contributors via an interface form. The initial analysis returned info identifying the utilities of the house over its 25-year time span to be the largest contributor of carbon. This led the design team to focus solely on design options that would decrease utilities despite an increase in embodied or onsite carbon. A final set of design options was sent again to the analysis teams and the carbon emission totals for each design option was returned. The utilities model was manipulated to compare a heat-pump to a gas-furnace in the London home.

Initial Design options

The team's initial analyses were done under the assumption that embodied carbon and heat loss would be the two largest contributors to affect the overall embodied carbon in the London house. Since the London house used 2 x 4 Blown Cellulose Insulation on the interior of the walls and a 2 in thick DOW foam (worst influence on GHG emissions) on the exterior, the team focused on improving the embodied carbon by going for options with the lower embodied carbon. This led to the team considering Polyiso and EPS insulations. Polyiso was overlooked because it performs badly in cold temperatures, which won't be logical to use in Michigan. EPS on the other hand, has a lower R-value of 4/in compared to Polyiso, but it performs better in the winter. Another option was recommended by Habitat for Humanity, Rockwool insulation. The last consideration was aimed at the foundation and the driveway of the house. For this, a design option with lower embodied carbon was chosen, PLC to replace Portland cement. The team proceeded to use Rockwool insulation (Design Option 1) and Portland Limestone Cement (Design option 3) as the first options to begin the analysis.

To reduce heat loss in the house, the team focused on getting design options with higher R-values. EPS was eliminated as an option here because it has a lower R-value than XPS with not as much influence on the overall embodied carbon emissions. Two other options were generated to tackle the heat loss from the house. Double Insulated Vinyl Siding (Design Option 2) and 3-pane Argon Windows (Design Option 4). Adding an extra layer of a much better siding and adding another pane to the argon windows was decided to be viable to provide more resistance to heat loss in the house.

After the initial analysis of the base case houses, the largest contributor to embodied carbon was found to be from utilities. This changed the scope of the design team to solely focus on utilities reduction and options 1 and 3, Rockwool insulation and Portland Limestone Cement, were eliminated.

Final Design Option

The final design options were aimed solely at reducing utilities. The design team focused on increasing the R-value of multiple types of insulation in the home as well as sourcing electricity from photovoltaic panels, better known as solar panels (Design Option 6). In the case of the insulation, the design team sacrificed using lower embodied carbon insulations and instead used the insulation with the highest R-value per inch possible. This led to a one for one replacement of the blown in cellulose insulation used in the house's walls (Design Option 7) and attic (Design Option 8) with spray in closed cell Handifoam™. A solar panel calculator was used to find the amount of energy the London house could produce. All energy was assumed to go into the appliances of the house despite excess power supplied during the day and no storage capabilities. The grid's capability to store excess energy allowed the design team to assume excess clean energy produced by the panels and used by the rest of the grid to be counted as an offset to unclean energy used by the house.

Results

Design options 2,4,6,7 decreased total carbon emissions by roughly 44% with 40% of the reduction due to the solar panels (*Figure D1*). The heat-pump causes a 5% reduction in emissions compared to a gas-furnace in the same home at the current carbon emissions per kW-hr (*Figure D2*). In the case of a cleaner grid, this reduction could be far greater.

Conclusions

After all design options were analyzed the carbon emissions were theoretically reduced by 44% far surpassing the 20% benchmark. The solar panel design option contributed close to 40% of that reduction while the rest of the options only contributed a few percentages with some even increasing carbon despite reducing utilities. The heat-pump's addition to the London house decreased the amount of carbon emitted with the opportunity of greater reduction due to grid cleanliness. Overall, the electrification of the house is a "win". It reduces the current emissions as well as increases the opportunity for far greater reductions in the future.

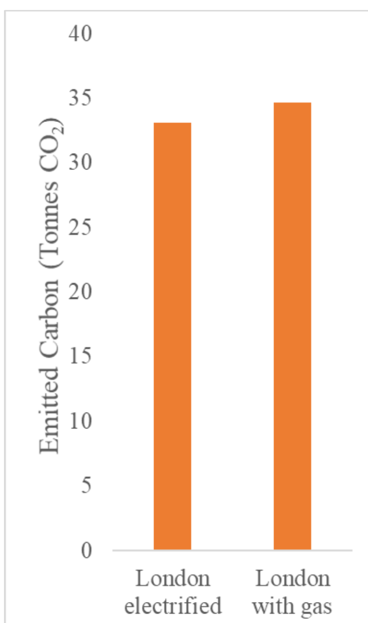

Figure D1. Carbon emission totals by appliance in the London house measured in Tonnes of CO_2 per year

Appendix D1—Figures

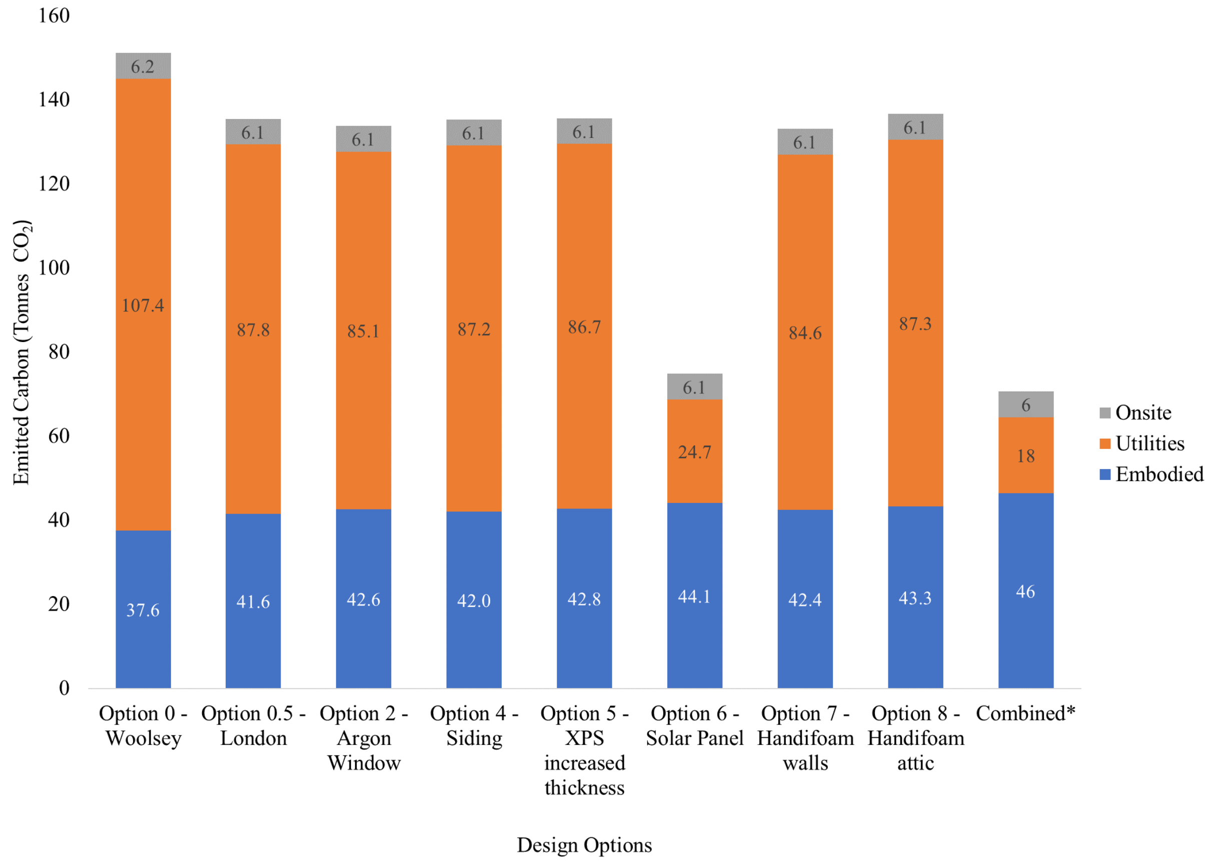

*Figure D2. Emitted Carbon of six different design options as well as the two base case houses. *Includes aspects of design options 2, 4, 6, and 7*

Appendix D2—Excel Spreadsheets

[Design Option Interface]()

Appendix E—Habitat for Humanity Documents

Woolsey Lumber Package

Woolsey Siding Package

Woolsey Roofing Materials

Woolsey Grand Plan Specifications

Woolsey Approved Stamped Plans

Woolsey LEED Summary

Woolsey GR Fuel Summary

London Grant Plan Specifications

London Approved Plans