Low-Carbon Housing Project

ENGR 333 – Section A

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8 December 2021

Abstract

Habitat for Humanity (HFH) requested a carbon footprint analysis of their most recent home build. Mark Ogland-Hand, a representative of HFH, connected with Professor Heun's ENGR 333 students to perform the carbon footprint analysis on their new low carbon house. Assuming Consumer's Energy will incorporate their predicted percentage of renewables into their electric grid, the London home reduces projected carbon emissions by 18% when compared to a "To Code" house over a 25 year lifespan. For the *current* Consumer's Energy grid, the "Improved" London house is shown to reduce projected carbon emissions by 30% when compared to the current London House.

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Introduction

Habitat for Humanity (HFH) recently built a low carbon house at 726 London Street SW. Mark Ogland-hand, a representative of HFH, connected with Professor Heun's ENGR 333 class to begin a carbon study of this new home with the goals of understanding the carbon footprints of a traditional HFH home (located at 536 Stolpe), the low carbon house, and future improvements feasible for HFH to make in reducing the carbon emissions of their houses.

Method

The ENGR 333 class split into 5 groups to study each major sector of carbon emissions from the homes:

1. The Embodied team evaluated carbon emissions from the manufacturing and fabrication of materials used in the houses (i.e. cement production, lumber milling, insulation fabrication).
2. The Onsite and Transportation team evaluated carbon emissions from transporting materials to the build site (i.e. lumber, insulation) as well as emissions related to labor processes (i.e. running generators, using electric saws).
3. The Heating team analyzed the energy required to heat the home during the winter season for 25 years and converted this heating load to a carbon emissions number for both natural gas heating (Stolpe) and an electric heat pump (London).
4. The Utilities team analyzed the electricity used to power appliances in the home such as stoves, refrigerators, TVs, water heaters, etc.
5. The Design team used estimations from the other 4 teams to generate alternatives for the home builds to reduce home lifetime carbon emissions by at least 20%.

Each team created carbon calculators associated with their assigned sector of carbon emissions and used them to find the projected carbon emissions of the London house and a possible "improved" London house. These calculations were also compared to the Stolpe house, to a theoretical "To Code" house, which are the minimum building requirements as defined by the city of Grand Rapids building code, and to a "clean grid" case in which Consumer's Energy follows through with their plan to generate more of their electricity from clean and renewable energy in the coming years.

Results

Total estimated carbon emissions over a 25-year lifespan are indicated below in Figure I. The percentage emissions reduction relative to a “To Code” house can be found in Figure II.

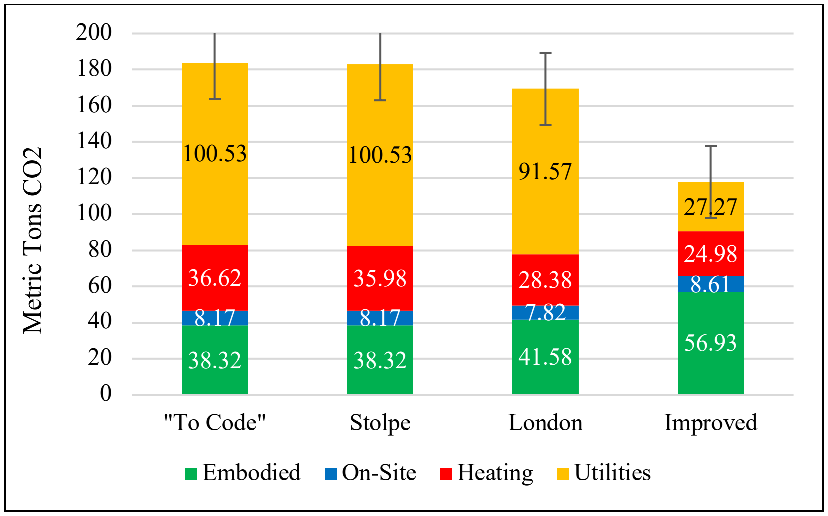

Figure I. Total Carbon Emissions for Each Case

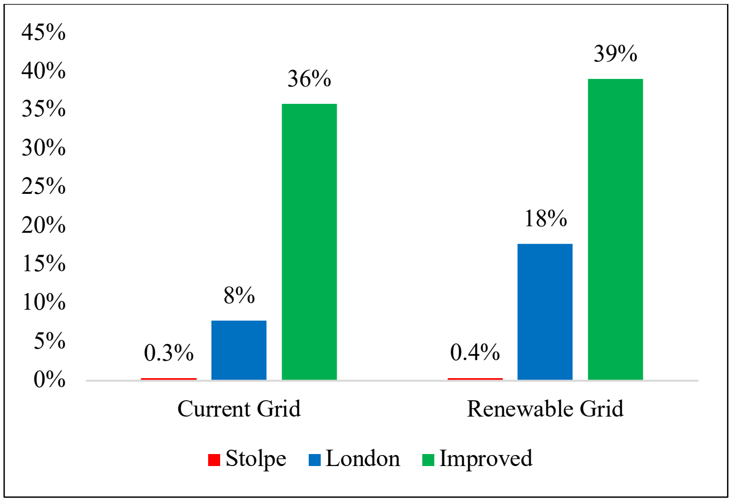

Figure II. Carbon Emission Percent Reduction Relative to “To Code” House.

Conclusion

Assuming a more renewable grid, the London home reduces projected carbon emissions by 18% when compared to a “To Code” house over a 25 year lifespan. For the current Consumer’s Energy grid, the “Improved” London house is shown to reduce projected carbon emissions by 30% when compared to the current London House.

Group A: Embodied Carbon

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Introduction

Embodied carbon is the CO_2 emissions into the atmosphere associated with the manufacturing and processing of materials. For the Low-Carbon Housing Project, embodied carbon details all carbon emissions in the production of the house's materials before they are transported to the job site. The scope for the embodied group is to calculate an estimate for total embodied carbon of the Stolpe and London homes and analyze the sources of carbon emissions.

Method

Embodied carbon is determined in several separate parts that are combined to obtain the final number as seen Equation A1. Example of this process can be seen in Appendix A2

$$\#\ of\ material \cdot \frac{embodied\ carbon}{material} = embodied\ carbon \qquad Equation\ A1$$

The first step in this process was to create a list of every material and component that is a part of the home. This was accomplished by analyzing the Grant Plan Specifications provided by Habitat as well as email communications with Mark Ogland-Hand. In order to find the specific amount of material, estimation was necessary. Some materials like the wood or the foundation have specific documents from Habitat that detail the amount that is used. Other materials like the HVAC system or insulation required were estimations from internet research and common building practices.

The next step in this process is to find the carbon coefficients for the materials. This was accomplished in three different ways. First, carbon databases such as the Inventory of Carbon and Energy (ICE) were used to find carbon coefficients for generic materials such as wood or concrete. Second, Environmental Product Declarations (EPDs) were used to find most carbon coefficients for more niche or specific materials and products. Lastly, published research was used to fill gaps in areas that were not covered in other ways. More information can be found in Appendix A1.

Results

Table A.I. Total Embodied Carbon in each House

House	Embodied Carbon [tonnes]
Stolpe	38.3
London	41.8

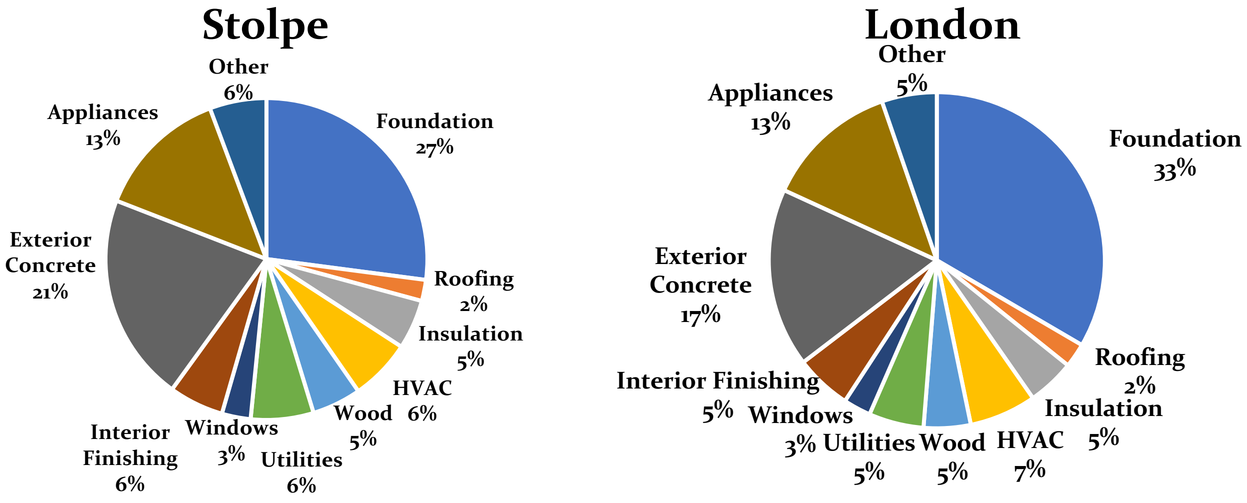

Figure A.I. Percent breakdown of total embodied CO_2 in each house by component

Further breakdown of the results can be found in Appendix A3.

Conclusion

Despite the London house supposedly being a low carbon house, it had more embodied carbon than a similar house from HFH. The differences that bring London above Stolpe are the foundation type and use of electrical appliances. Stolpe uses prefabricated concrete slabs that are placed using a crane, but London Street could not fit a crane due to space constraints; so concrete was poured to lay down the foundation. The electrical appliances were another source of increased embodied carbon. The all-electrical appliances of London had about 12% more embodied carbon than the gas appliances of Stolpe. Although the electrical appliances may save the tenants money and contribute less carbon through the lifetime of the house, they contribute more carbon upfront and were represented as such.

Several design options were considered to reduce the embodied carbon of the London house. These future design choices were using a prefabricated concrete foundation (including solar panels), using triple pane windows, and switching to a solar water heater. The data for embodied carbon design options can be found in Appendix A4. Figure A4.I depicts the total embodied carbon for each design option and Table A4.II shows their numerical values. Precast concrete decreased the embodied carbon by 3.6 tonnes of CO_2, the most of all the design options, while the solar panels added 12 tonnes of CO_2 to decrease the carbon contribution from electricity across its lifespan.

Appendix A1 – Carbon Coefficients

The Inventory of Carbon and Energy was the main database that was used to find carbon coefficients for generic building materials. Dr. Craig Jones and Geoffrey Hammond from the University of Bath developed the database including information on materials such as concrete, timber, aluminum, steel, glass and more. The values are an average of collected data points from various sources such as World Steel, the Kupferinstitut, and many EPDs. Approximately 20% of all carbon coefficients were pulled from this database.

Environmental Product Declarations (EPDs) are reports produced by companies that report on the environmental impact of a product over its lifecycle. These are verified by third party companies so that the published information is accurate, and the company cannot lie to make themselves look better. EPDs were used for about 60% of all carbon coefficients because they cover a wide range of abstract materials and systems that could not be found in something like a carbon database. A disadvantage of using EPDs is that they are produced by companies that choose to publish their environmental impact, so it is hard to obtain data on products that are specifically dangerous. Carbon coefficients were pulled from the Global Warming Potential (GWP) for sections A1-A3 of the product which includes raw resource extraction, transportation to facilities, and manufacturing.

The final 20% of carbon coefficients were found from case studies in published reports for things like appliances. These studies could often be found through Google Scholar and were specifically helpful in analyzing the HVAC system and the all-electric appliances.

Appendix A2 – Example Calculations – House Roofing

This section goes in-depth in how the embodied carbon was determined for the roof of the homes. This is to be used as an example for the process that was used to determine the embodied carbon of the whole home. The embodied carbon in the roofing was calculated for both houses by focusing on two main parts of the roof. The shingles and a water barrier. Wood was excluded in this calculation because it has been considered for in the carpentry section which accounts for all wood purchased for the house. Since the OSB layer of the roof is made from wood, this part of the roof was ignored during the roofing calculations. The total embodied carbon of a part (E.C.) is a function of the area of the roof (A), thickness of the section (T), density of the material (ρ), and the conversion factor from kilograms of material to kilograms of CO_2 the material embodies.

$$E.C. = A * T * \rho * K_{EC} \qquad \textit{(Equation A2.I)}$$

The total embodied carbon of Stolpe's roof was calculated to be about 620 kg CO_2 (0.62 tonnes) and the total embodied carbon of London's roof was calculated to be 790 kg CO_2 (0.79 tonnes).

Area of Roof

Since the houses have the same design and are different by 1 in in length and width, both houses were considered to have the same roofing area. The roof was calculated based on the housing plan's dimensions. It was formed of three parts. The main roof and two smaller roofs. The area breakdown is as follows with an error margin of +/- 0.1 ft.

Table A2.I. Area of roof sections

	Main Part	Front Section	Back Section
Width (ft)	32	17	10
Length (ft)	42	7	7
Height (ft)	9.3	5	2.9
Total Area (ft^2)	1556.0	78.7	69.5

The width of the roof was the width of the building with an additional 2 ft overhand added to both sides. Length was the building length with an additional 1 ft on both sides for the long part. The small part's length did not increase overall due to losing as much length from overlap with the main part as gain from 1 foot of overhang. The height (H) and total area ($A_{section}$) were calculated as functions of the roof's width (W) and length (L).

$$H = \frac{7}{12}(0.5 * W) \qquad \textit{(Equation A2.II)}$$

$$A_{section} = L * 2 * \sqrt{(0.5 * W)^2 + H^2} \qquad \textit{(Equation A2.III)}$$

The total area of roofing was then added up to be 1704.2 ft^2

Thickness

Table A2.II. Thickness of layers of roof

Water barrier	Stolpe's shingles	London's shingles
0.0037 ft	0.0208 ft	0.0167 ft

A set thickness was used for both houses for the water barrier. As it was not given, the estimate thickness was 1.14 mm which is 0.0037 ft (AC, 1). The shingles thickness is different for the two houses. London's shingles are 0.2 in (0.0167 ft) thick (Architectural, 8). Stolpe's shingles are 3/16 in thick initially (Right, 1). Theses shingles then have a 1/3 area of overlap. As such the thickness was increased by a factor of 1.333 resulting in Stolpe's shingles being 0.0208 ft thick. The overlap was calculated from area covered of 144 in^2 (Helpful, 7) and dividing it by the area of the shingle which is 432 in^2 (IKO, 1).

Density

Table A2.III: Density of layers of roof

Water barrier	Stolpe's shingles	London's shingles
16.2 kg / ft^3	65.8 kg / ft^3	53.5 kg / ft^3

The density of the water barrier was calculated to be 16.2 kg/ft^3 by taking the mass and dividing it by the volume which are both found in the AC Granular ICE and Storm seal data sheet (Data sheet – AC, 1). The density asphalt was used for the shingles for Stolpe and was found to be 65.8 kg/ft^3 (Asphalt, 1). The density for the London house's shingles was calculated based off the material being recycled for the shingles and the rest being asphalt. The shingles' recycled material can be calculated using information given based on panel units which are equivalent to 100 ft^2 of shingles with 2 in thickness. Every 30 panels are equivalent to 4 tires treads and 2900 plastic bags (Architectural, 2). Tire's mass is 15 kg and 35% of that mass is the tread (How, 3-5). Thus 1 tread is 5.25 kg and the 4 treads add up to 21 kg. The mass a plastic bag is 0.0053 kg (Plastic, 1) and having 2900 bags the total mass is 15.37 kg. The remaining material, asphalt is calculated by comparing the volume of the rubber treads and plastic bags relative to the volume of the shingles. The mass is converted to volume for a single panel using rubber density of 34.8 kg/ft^3 and plastic density of 37.8 kg/ft^3 (Density, 1). This results in rubber having a volume of 0.56 ft^3 and plastic being 0.11 ft^3. The area of a panel (100 ft^2) is 1.67 ft^3. Thus 1.00 ft^3 of the panel is asphalt.

Table A2.IV. Dimensions of a single panel of London roof.

	Volume (ft^3)	Mass (kg)
Rubber	0.56	19.488
Plastic	0.11	4.158
Asphalt	1	65.7517

Using the data in Table A2.IV the total mass was divided by the total volume to get a density of 53.5 kg/ft^3 for the shingles of London's house.

Conversion Factor

Table A2.V. Conversion factors (K_{EC}) of layers of roof

Water barrier	Stolpe's shingles	London's shingles
1.4064 kg CO2 / kg	0.204 kg CO2 / kg	0.4219 kg CO2 / kg

The water barrier is made from AC Granular Ice and Storm seal. It is made from fiberglass, tar, and asphalt. As there is no data on the exact compound of the water barrier, as such a compound breakdown was made. Both fiberglass and asphalt's embodied carbon were found in ICE database. The embodied carbon ratio for tar was unknown, so it was assumed to be the same as fiberglass. The combined embodied carbon is shown in Table A2.VI.

Table A2.VI. Embodied carbon of water barrier

Material	Compound ratio	EC (CO2 kg/kg)
Fiberglass	0.45	1.54
Tar	0.45	1.54
Asphalt	0.1	0.204
Total Embodied Carbon: 1.4064 kg CO2 / kg		

The roof of Stolpe is made from asphalt roofing, which was found to be asphalt at 40% bitumen content as it is the cheapest option (Recycled, 2). A linear equation was made for the conversion factor relative to percent Bitumen in the asphalt. Data points were grabbed from ICE data base (ICE, 10). Then using the bitumen content of the roofing, the conversion factor was calculated to be 0.204 $kg\ CO2/kg$.

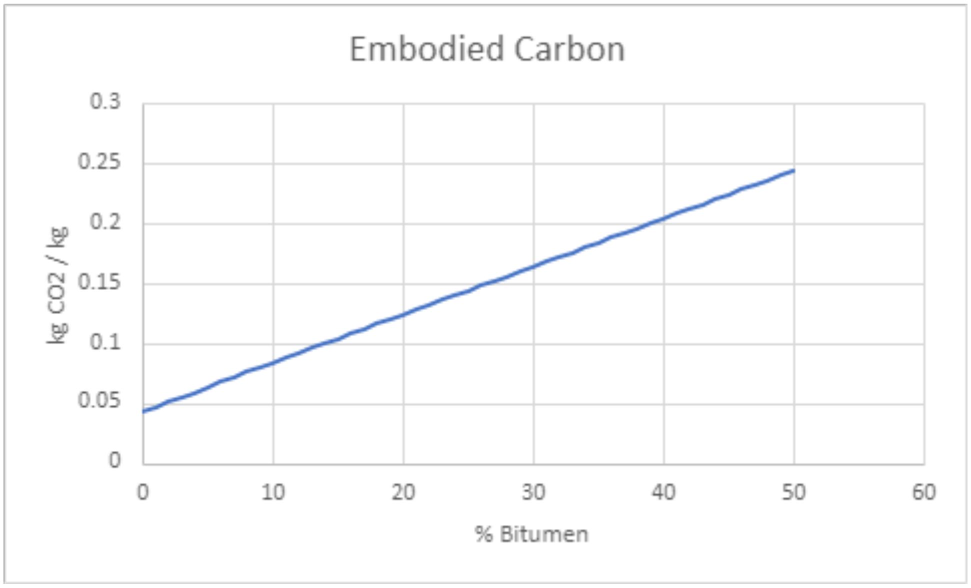

Figure A2.I. Calculation of roofing carbon based on bitumen content

(Initial numbers from ICE Database)

The roofing of London was made with the compound shown in Table A2.II. The embodied carbon ratio was found for rubber and plastic in their raw form in ICE data base (ICE, 12 + 19). The raw version embodied carbon is significantly more than the recycled material, and so the ratio was multiplied by a factor of 0.147 to consider the recycle process. The factor was calculated by comparing the ratio of general aluminum made from raw material compared to the recycled version in the ICE data base. (ICE, 10). The total embodied carbon ratio for London's roof was then calculated in Table A2.VII.

Table A2.VI. Embodied carbon of London's roof

Material	Compound ratio	EC (CO2 kg/kg)
Rubber (recycled)	0.334	0.815
Plastic (recycled)	0.067	0.41
Asphalt	0.599	.204
Total Embodied Carbon: 0.4219 kg CO2 / kg		

Appendix A3 – Results

Table A3.I. Embodied Carbon Breakdown of London

Section of House	Embodied Carbon [tonnes CO_2]
Foundation	14
Roofing	0.97
Insulation	1.9
HVAC	2.7
Wood	1.9
Utilities	2.2
Windows	1.1
Interior Finishing	2.0
Exterior Concrete	7.2
Appliances	5.4
Other	2.2

Table A3.II. Embodied Carbon Breakdown of Stolpe

Section of House	Embodied Carbon [tonnes CO_2]
Foundation	10.4
Roofing	0.8
Insulation	1.9
HVAC	2.4
Wood	1.9
Utilities	2.4
Windows	1.1
Interior Finishing	2.1
Exterior Concrete	8
Appliances	5.1
Other	2.2

Concrete has a very high embodied carbon because clinker must be formed and for it to be formed it must be heated to a temperature of approximately 1200 °C. Clinker is limestone and a mixture of minerals that gives concrete a lot of its structure.

The appliances in the London house are all electric compared to Stolpe which uses natural gas boiler, dryer, and stove. The electric appliances have more embodied carbon since they have more electrical components which complicates the manufacturing processes.

Wood has a much lower carbon coefficient per kg than almost any other material. This is due to wood being naturally grown and does not need to be mined or heavily processed in order to be produced into wood planks.

Appendix A4 – Design Options

Four design options were looked at for the London house. Precast foundation, solar panels, triple pane windows, and solar water heater. The effect on embodied carbon is shown in Table A4.I.

Table A4.I. Total Embodied Carbon of the London House with each Design Option

	CO_2 (Tonnes)	ΔCO_2 (Tonnes)
London (base model)	41.78	0
London (precast foundation)	38.17	-3.61
London (solar panels)	54.12	12.34
London (triple pane windows)	42.28	0.5
London (solar water heater)	42.06	0.28

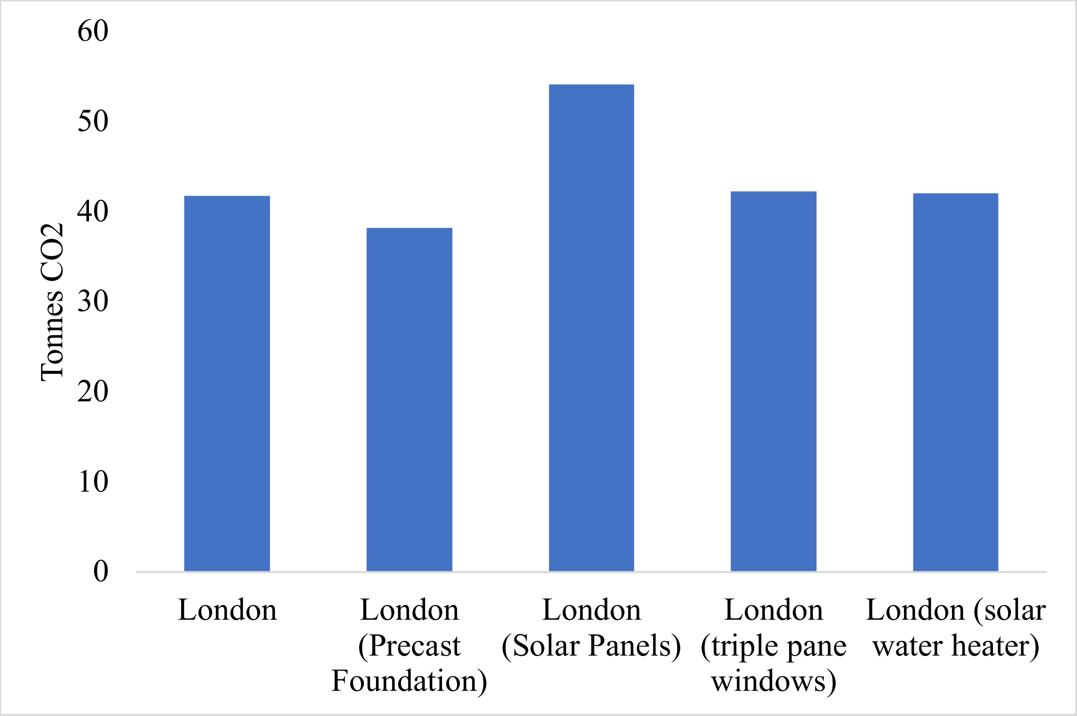

Figure A4.I. Total Embodied Carbon of the London House with each Design Option

Precast foundation

For both foundations the floor and the footings were identical, but the difference comes in the walls of the differing foundations. Precast foundation has about half of the embodied carbon as the poured ICF’s because of one main factor, it has half the amount of material. From the dimensions given in the catalogs for both foundation types, the ICF's have twice as much insulation and twice as much concrete needs to be poured to fill the area between the insulation. This leads to the embodied carbon of the ICF's to be twice as high as the precast foundation.

Solar panels

Solar panels embodied carbon comes from three main sources. The panels, inverter, and power wall. The panels were calculated with a conversion factor of 2560 kg/ max kwp from circular ecology (Embodied, 2). The max kwp for the 10 solar panels is 4.25 kwp Solar panels (Solar, 8) resulting in about 10,900 kg of embodied carbon or 10.9 tons. The power wall was calculated based off a embodied carbon calculation, 85 kg CO2/ kWh max storage, from Forbes (Estimating, 4). The power wall has 13.5 kWh of max storage (Powerwall, 1). This puts the power storage at about 1200 kg or 1.2 tonnes CO2. The inverter has no embodied carbon calculation. To calculate the inverter, the size of the inverter was compared to the powerwall, which was about 21% the size and the inverter was assumed to have similar complexity to the power wall. The calculated CO2 was calculated to be about 240 kg or 0.24 tonnes. The life span of the solar panels are 25 to 30 years (Service, 1). Since this is the life span of the house, no additional components would be needed for replacements. The components needed were all then added up to be 12.34 tonnes.

Triple pane windows

The triple pane windows provide a greater thermal resistance compared to the double pane windows but at the cost of increasing the embodied carbon. Triple pane windows have a more carbon intensive process compared to the double pane windows because of the extra pane of glass used.

Solar water heater

The solar water heater is more carbon intensive than a regular water heater for similar reasons to the solar panels. The solar panels are what attribute the increase in embodied carbon.

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Group B: Onsite and Transportation Team

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Introduction

The onsite and transportation team for the ENGR 333-A class project focused on quantifying the carbon emissions associated with the transportation of all materials, equipment, and labor during construction, the carbon emissions associated with the use of equipment during construction, and those associated with electricity use in the houses during construction. The transportation that was considered for the material deliveries began with where the materials were purchased by Habitat and ended with either the vehicle arriving at the Habitat site if the vehicle would carry items for another consumer to a new location or the vehicle returning to the supplier if the vehicle would return to the supplier empty. Transportation carbon costs associated with production of the materials are accounted for by the embodied group. The electricity carbon costs while the house is occupied are accounted for by the utilities group.

Method

Excel spreadsheets were created to track carbon emission events, perform calculations to determine the amount of carbon emissions associated with each event, and organize the data meaningfully. Over 100 unique carbon emission events were analyzed. The contents of the spreadsheets are described in Appendix B1 and the differences between the spreadsheets for various design options are described in Appendix B2.

Transportation

All transportation events associated with the construction of the house were described in detail by Mark Ogland-hand. To calculate the embodied carbon of transportation, the fuel expended during transportation was found and multiplied by a carbon coefficient (for each respective fuel). A fuel efficiency in miles per gallon was found from averages taken from each respective vehicle's manufacturer's specifications. The distance traveled for each trip was found using Google Maps, by typing in the start and end location of each trip. The fuel expended was accounted for both vehicles driving to the jobsite from their starting location and from the jobsite back to their starting location if applicable. For items that were stored in the Habitat warehouse, the transportation embodied carbon was included for both transportation to the warehouse from the supplier and from the warehouse to the jobsite. Volunteer and contractor transportation emissions were also considered and calculated for this report.

Construction Equipment

In order to find the embodied carbon of construction equipment, the amount of fuel expended during operation was calculated using known fuel consumption rates and known fuel efficiencies. The amount of fuel used was multiplied by a carbon coefficient for the type of fuel used. In some cases, the amount of fuel consumed was known from information provided by Mark Ogland-Hand, in others the amount of time it ran was known and the rate of consumption was either researched or given by Mark Ogland-Hand. For the purposes of this analysis, construction equipment is any equipment that is used on site, without travelling, for example a generator or a crane.

Electricity

The onsite and transportation group accounted for the carbon emissions associated with electricity use while constructing the house, while the utilities group accounted for that while the house is occupied. The amount of electricity used was based on the electricity bill for the Stolpe house and then estimated for the other houses based on the average electricity bill for the Stolpe house and expected build time. The carbon emissions were then calculated based on the electricity use using the same carbon coefficient used by the electricity group. Note: electricity carbon costs associated with the onsite and transportation group are unaffected by the renewable grid carbon coefficient projections because the builds are considered to occur in the present and the grid improvements are modeled to occur gradually over the next 25 years.

Results

For the London and Stolpe build, complete numbers for onsite and transportation emissions were calculated and broken down by category. Overall, these numbers have an expected margin of error of -20% to +50% due to the potential of missed steps in delivery or factory origination locations other than the places where the materials were delivered from. However, in the grand scale of the total carbon emissions, even a +50% addition of carbon emissions for onsite and transportation does not significantly impact the results across all the carbon emissions associated with the house.

Figure B.I compares the onsite and transportation emissions associated with the London and Stolpe homes. It is evident that the construction machinery and labor transport were the most significant contributors to onsite and transportation carbon emissions. Looking at the "Generator" and "Electricity" categories, the comparison between London and Stolpe demonstrate the tradeoff between electricity provided by an onsite generator versus the grid, since generator power production occurred for longer for the London build and the electricity connection with the grid which was connected longer for the Stolpe build. The Stolpe electricity consumption was much higher due to the heating of the home using electric heaters during the winter months. For the "Material Delivery" category, emissions were higher for the London home due to the delivery of the insulated concrete forms (ICFs) delivered from Indianapolis. Otherwise, the carbon emission data are similar between the London and Stolpe homes.

Figure B.I. Onsite and transportation carbon emission comparison for London and Stolpe.

Overall, the results for London and Stolpe show that construction machinery and labor transport were the most significant contributors to onsite and transportation carbon emissions. Looking at the "Generator" and "Electricity" categories, the comparison between London and Stolpe demonstrate the tradeoff between generator electricity produced, since generator power production occurred for longer for the London build, and the electricity connection with the grid which was connected longer for the Stolpe build. The Stolpe electricity consumption was much higher due to the heating of the home using electric heaters during the winter months. For the "Material Delivery" category, emissions were higher for the London home due to the delivery of the insulated concrete forms (ICFs) delivered from Indianapolis. Otherwise, the carbon emission data are similar between the London and Stolpe homes.

Design options were also considered for the London build and the carbon emissions associated with each were calculated as shown in Figure B.II below. Overall, most of the design options had a small effect on the overall carbon emissions associated with onsite and transportation. The most significant carbon contribution design option was the addition of solar panels delivered from Buffalo, New York. The solar panel delivery alone accounted for 0.93 tonnes of CO_2 and, if included in the London build, would account for 11% of the total onsite and transportation emissions.

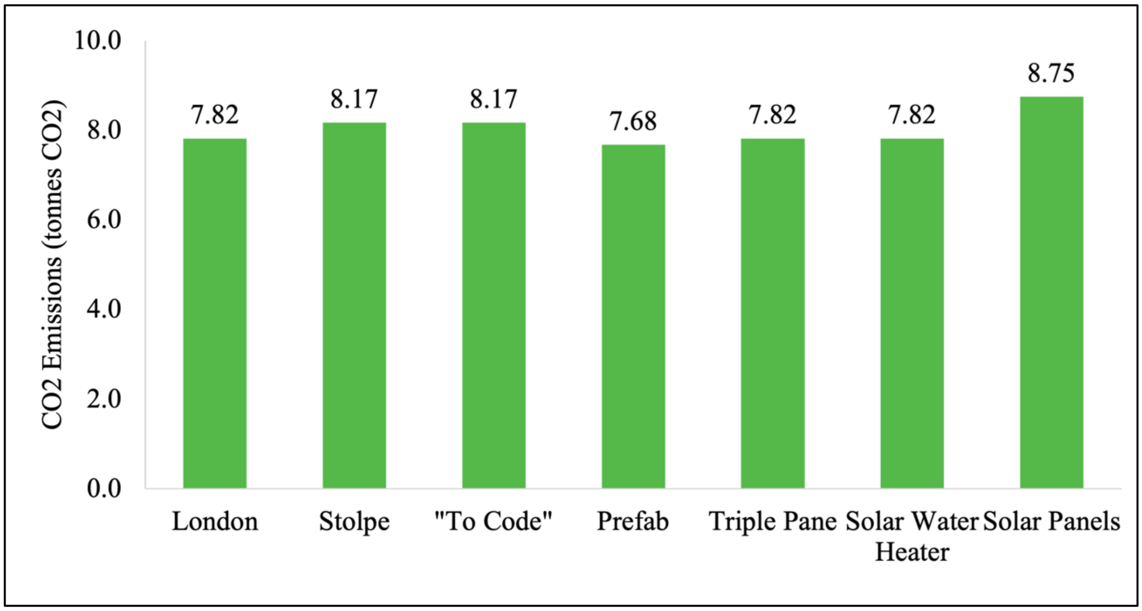


Figure B.II. Carbon emissions associated with various design options.

Conclusion

The results of our analysis show that the total carbon emissions from onsite and transportation are 7.82 tonnes of CO_2 for the London home, and 8.17 tonnes of CO_2 for the Stolpe house. These numbers are fairly insignificant compared to the total carbon emissions from the other teams and these results indicate that the onsite and transportation emissions are not of high concern for reducing the overall carbon footprint of the low-carbon Habitat build. Thus, design tradeoffs that reduce carbon emissions in another category but increase onsite and transportation emissions are likely to reduce the total carbon emissions associated with the house.

Appendix B1: Spreadsheet Tab Descriptions

A carbon emissions calculator was developed to take into account all onsite and transportation carbon emissions using an excel spreadsheet. The general format of this calculator is described below with descriptions of each individual sheet used in the calculator.

Accounting

The accounting sheet was used to keep track of the different possible sources of carbon emissions for the associated site, whether they had already been accounted for, where they had or would be accounted for, and what the next action that should be taken for each item was. Because the design options are relatively simple modifications of the London and Stolpe calculations, this sheet is only included in the London and Stolpe spreadsheets.

Data Communication

The data communication sheet summed the amount of carbon used for each category designated in the carbon calculators.

Carbon Calculator

This sheet took the amounts of fuel and electricity used from each of the sources and converted them to metric tonnes of carbon using the carbon coefficients found through research.

Electricity

In the case of the Stolpe address, the electricity bills are known, and electricity consumption was tracked from when the house was hooked up to the grid until it was occupied by the homeowners.

Fuel (Known Amount)

For some equipment, the amount of fuel used was already known. This sheet also served as a catchall for fuel use that did not fit into one of the other calculators.

Fuel (Known Operating Time)

In other cases, the operating time and the fuel efficiency were used to calculate the amount of fuel consumed.

Fuel (Known Locations)

This tab includes the transportation carbon emissions by using the known driving distance and the known fuel efficiency to get an amount of fuel used.

Fuel (Volunteers)

Mark Ogland-hand provided the average number of volunteers working on the jobsite on a given day and the percentage of volunteers that went out to lunch brought a lunch. The average driving distance of the volunteers to and from the job site was added to the average distance driven to lunch. A fuel efficiency was used to get the amount of fuel consumed. The resulting fuel consumption from this sheet was plugged into the Fuel (Known Amounts) sheet.

Appendix B2: Spreadsheet File Names and Descriptions

Following is a description of each of the attached spreadsheets associated with the onsite and transportation carbon emissions calculations.

Onsite_A_London

This spreadsheet contains the nominal values for 726 London St. SW. This spreadsheet was the base from which other onsite spreadsheets were created. For instance, the design options either added or replaced a single line of transportation and onsite installation.

Onsite_A_Prefab

This spreadsheet was a copy of London with the only change being the inclusion of the "prefab" design option replacing the existing foundations.

Onsite_A_Solar_Panels

This spreadsheet was a copy of London with the only change being the inclusion of solar panels added to the roof. The transportation cost was the main source of carbon.

Onsite_A_Solar_Water_Heater

This spreadsheet was a copy of London with the only change being the inclusion of a solar water heater, which comes from the same location as the preexisting water heater and therefore does not change the onsite costs.

Onsite_A_Stolpe

This spreadsheet was partially copied from London because most of the transportation and onsite expenditures were near as made no difference. The electricity expenditures from Stolpe were used to infer the electricity expenditure for London.

Onsite_A_To_Code

This spreadsheet is a copy of Stolpe. The main difference between a To Code house and the Stolpe house is the amount/quality of the insulation. We assumed the insulation came from the same source, so there is no onsite and transportation carbon cost difference between a To Code house and the Stolpe house.

Onsite_A_Triple_Pane

This spreadsheet was copied from London because the base house is the same. Additionally, the only change (triple pane windows up from double pane) comes form the same location as the original London windows. There is no onsite carbon cost for installation.

Onsite_A_Wool_Insulation

This spreadsheet was copied from London but the value of insulation transportation was changed to be sourced from Reno, Nevada. This was modelled as a one-way trip because it was assumed that such a long trip would be used for other materials going back to Reno, so Habitat would not be responsible for that carbon. This design option was later dismissed by the design team.

Group C: Heating Team

Group Members

Derrick Bittner

William Terpstra

Matthew Winkle

Kelsey Yen (Executive)

Table of Contents

Introduction

The houses at 536 Stolpe St and 726 London St were to be analyzed for total carbon emissions of their heating. The Stolpe house used a natural gas furnace and was analyzed as a base case. The London house utilized an electric, Mitsubishi heat pump and was analyzed to determine whether its heating system could be labeled a "low-carbon alternative." Additionally, a "to-code" house, with Michigan's minimum insulation requirements, was modelled similarly to the Stolpe house and building design changes were analyzed for the London house.

Method

A thermal heating resistance model was based on *Heat and Mass Transfer: Fundamentals and Applications*, Ch. 16, by Yunus A. Cengal and Afshin J. Ghajar. The models were initially created using EES, the Engineering Equation Solver software. Modeling was also attempted in Revit but was abandoned in favor of the simpler model in EES. The EES output was the total number of BTU necessary per month. Eventually, the modelling in EES was transferred entirely to Excel for ease of calculations to carbon emissions and visualization of data. The BTU values from the heat loss calculations were converted into a carbon emission equivalent in Microsoft Excel using a calculated caron coefficient. The heating calculations and analysis can be found in Appendix C1 and the carbon emission calculations can be found in Appendix C2. All houses were analyzed under a 25-year lifetime.

The Stolpe house was analyzed under the condition of the current grid since Consumers Energy's promised renewable grid would not affect the natural gas heating to the house. The Stolpe results were compared to the house's furnace heating bill provided by Habitat for Humanity (see Appendix C3). The London house was analyzed three times: according to current plans, with triple-pane windows instead of current windows, and following Consumers Energy's forecast of clean energy on the electrical grid. The London house also used information calculated from the Mitsubishi electric heat pump specifications (see Appendix C4). All Excel files used to calculate the heating breakdowns, carbon factors, and CO_2 emissions can be found in the Appendices.

Results

The model for the Stolpe was within 8% of the house's furnace heating bill. The heat loss breakdown from both Stolpe and London under typical conditions can be seen in Figure C.I below.

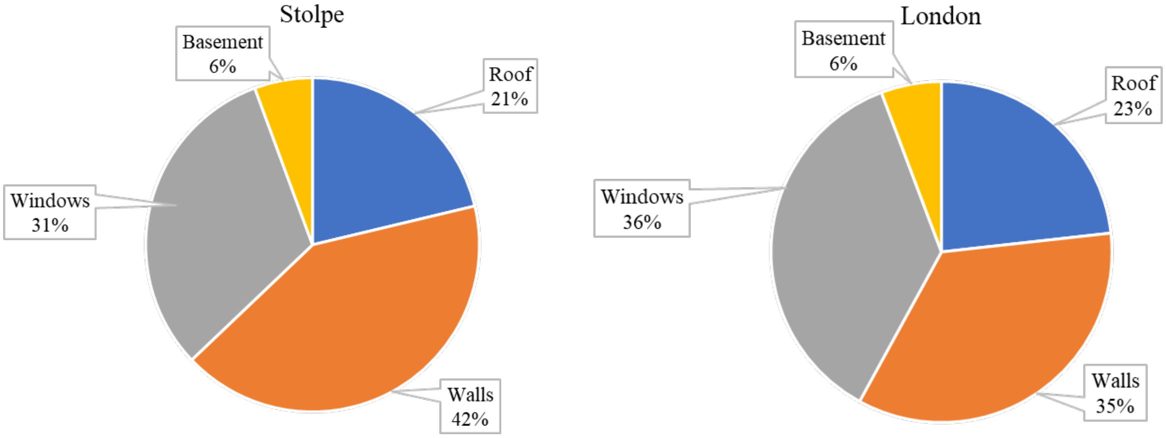


Figure C.I. Percentage breakdown of heat loss of 536 Stolpe St. and 726 London St.

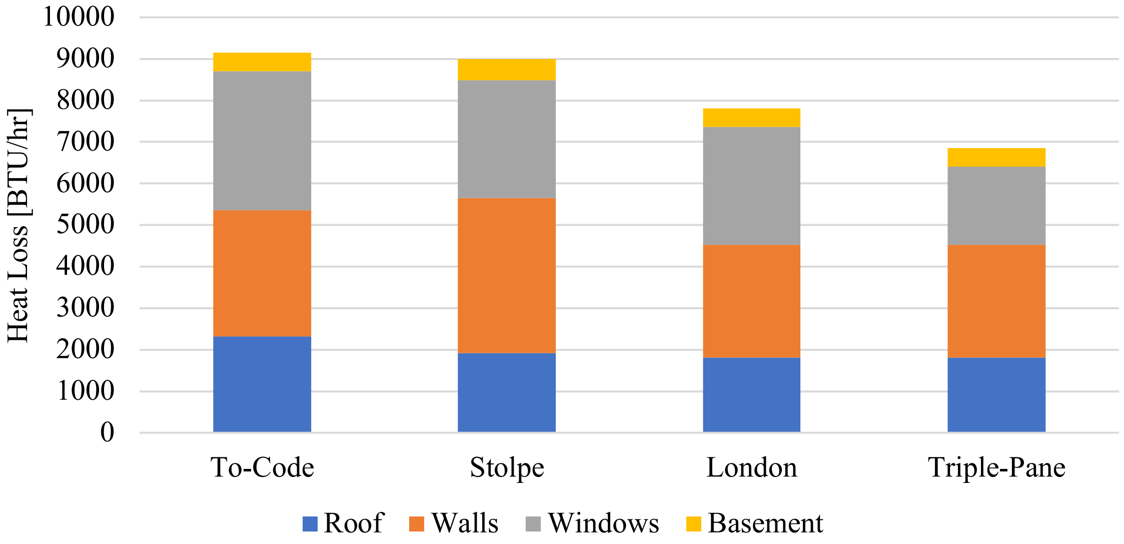


Figure C.II. Heat loss from every house considered per section of the house.

A comparison of the total heat breakdown in $\frac{BTU}{hr}$ for every house can be seen in Figure C.II above. The "To-Code" house refers to the house based on Michigan's minimum insulation requirements and the "Triple-Pane" house refers to the 726 London St. design with triple-pane windows substituted for the current windows. The lifetime carbon emissions under both the current electrical grid and Consumers Energy's forecast for a renewable grid can be seen in Figure C.III below.

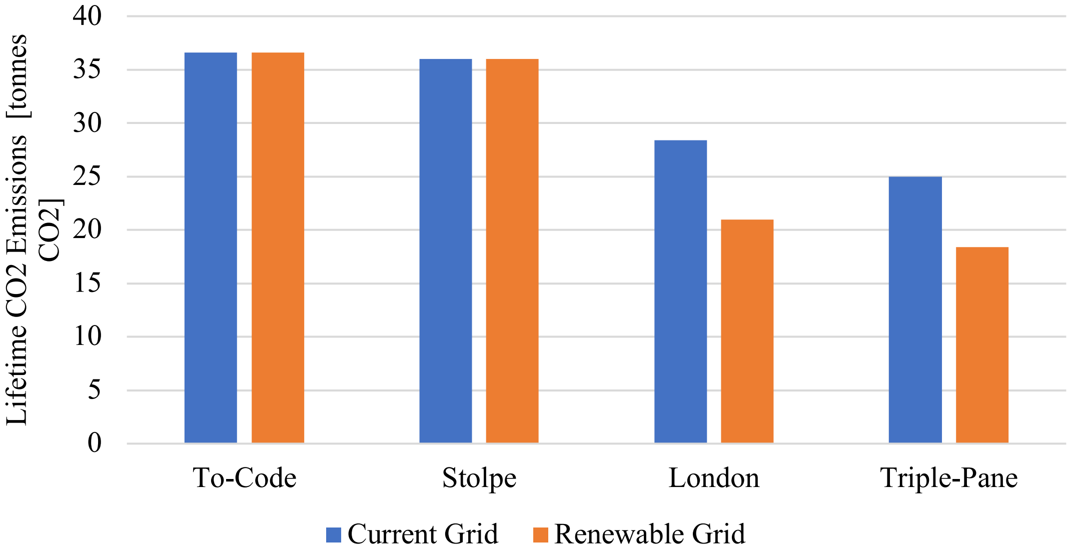


Figure C.III. Lifetime carbon emissions from heating under both the current grid and the renewable grid.

Conclusion

The "To-Code" house emitted 36.62 tonnes of CO_2 was found to emit the most carbon due to heating, followed by the Stolpe house emitting 35.98 tonnes of CO_2 and finally the London house emitting 28.38 tonnes of CO_2. With the triple-pane windows design, the London house emitted 24.95 tonnes of CO_2 and with the renewable grid, the house would theoretically emit 20.95 tonnes of CO_2. With both the triple-pane windows design and a renewable grid, the London house could emit as low as 18.42 tonnes of CO_2 from heating. Analysis assuming the renewable grid lowered the carbon usage of both 726 London St. and the Triple-Pane house, as those houses utilized heat pumps, but did not affect the To-Code house or 536 Stolpe St. as they utilized natural gas furnaces that have no connection to the electrical grid. The heat pump was found to be the better option in terms of carbon emissions; however, estimates into the yearly heating costs were not performed and therefore it cannot be concluded that using a heat pump is financially better.

Appendix C1: Heat Load Calculations

To complete the calculations the group decided to use the software Engineering Equation Solver (EES) because of its robustness and ability to solve quickly and efficiently. It was also selected because of its internal library of various thermodynamic values. To model the heat flow out of the house the resistive model was used, allowing us to change between the different variations of the house with relative ease by simply changing the R-values for the building materials. As mentioned above the team started by modeling the house at 536 Stolpe St. To do this it was decided to split the heat flow of the overall house into four main categories. Heat flow through the basement, windows, roof, and walls. The following equation shows how heat flow through the windows were calculated:

$$\dot{Q}_{Window} = U_{Window} * A_{window} * (T_{inside} - T_{outside}) \qquad \text{[Equation 1]}$$

where U_{Window} was given by Habitat for Humanity as 0.27 $\frac{BTU}{h*F*ft^2}$ for the windows they use.

A_{window} was found to be 178 ft^2 using the approved building plans that were also supplied by Habitat for Humanity. T_{inside} was set to 65 degrees Fahrenheit and $T_{outside}$ was set to 6.1 degrees Fahrenheit and will be discussed in more detail later in this appendix. Heat flow through the walls were calculated similarly and is shown in the following equation:

$$\dot{Q}_{Wall} = U_{Wall} * A_{wall} * (T_{inside} - T_{outside}) \qquad \text{[Equation 2]}$$

where T_{inside} and $T_{outside}$ are the same as before, A_{wall} was found using the approved building plans again. U_{wall} was calculated using the following equations:

$$U_{wall} = \frac{1}{R_{total}} \qquad \text{[Equation 3]}$$

$$R_{total} = \left(\frac{1}{R_{stud}} + \frac{1}{R_{blown\ insulation}}\right)^{-1} + \sum R_{other\ wall} \qquad \text{[Equation 4]}$$

where R_{stud} is the R-value of the studs depending on their size, $R_{blown\ insulation}$ is the R-value of the blow insulation put in between the studs, and $R_{other\ wall}$ is the R-values of the other wall components like siding, OSB, Gypsum board, etc…

Heat flow through the basement was calculated using Equation 5.

$$\dot{Q}_{basement} = U_{basement} * A_{basement} * \left(T_{inside\ basement} - T_{ground}\right) \quad \text{[Equation 5]}$$

T_{ground} was set as 55 degrees Fahrenheit as a recommendation from Professor Heun, and $T_{inside\ basement}$ was set to 60 degress Fahrenheit to reflect lower basement temperatures. $U_{basement}$ was found using given R-values from the manufacture of the prefabricated slabs used. Heat flow through the roof was calculated using the following equation:

$$\dot{Q}_{Roof} = U_{Roof} * A_{Roof} * (T_{inside} - T_{outside}) \quad \text{[Equation 6]}$$

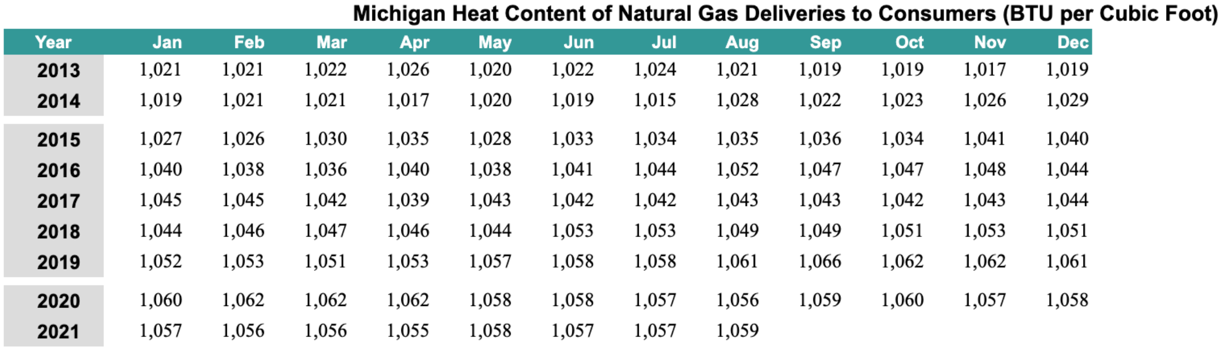
where U_{Roof} was given to be $0.018\frac{BTU}{h*F*ft^2}$ from materials info given by Habitat for Humanity.

Using Equations 1-6, a design heat load for each house was calculated which reflects a design that will be comfortable for 99% of the days in the year Grand Rapids, Michigan. Using this design heating load and heating degree days, a heat flow for the house over a year was calculated.

Appendix C2: Carbon Emission Calculations

Using constant conversion coefficients, the monthly heat loss in BTU could be converted into a carbon emission equivalent in tonnes of CO_2 per year. This was done independently for the houses containing furnaces (To-Code and 536 Stolpe St.) and the houses containing heat pumps (726 London St. and the Triple-Pane House).

For the houses containing furnaces, the heat loss value in BTU for every month was converted to a heat supplied value from the furnace, also in BTU. This was done using an AFUE of 0.95, as given by the Furnace Specs Sheet (*Appendix D*). The heat supplied was then converted into a CO_2 equivalent in kg of CO_2. This was done using a conversion factor of 54.6 million kg of CO_2 per million BTU. This value is given by the U.S. Energy Information Administration (EIA) specific to the state of Michigan (*https://www.eia.gov/environment/emissions/co2_vol_mass.php*). The weights were then converted from kg to tonnes and summed together to find the annual CO_2 emissions and multiplied by the assumed lifetime of the house to determine the total CO_2 emissions. Additionally, using the EIA's data for heat content of natural gas (*Figure C2.I*), the CCF of natural gas for a year could be determined from the BTU supplied by the furnace. This was compared to heating bills from 536 Stolpe St. to validate the thermal model.



Michigan Heat Content of Natural Gas Deliveries to Consumers (BTU per Cubic Foot)

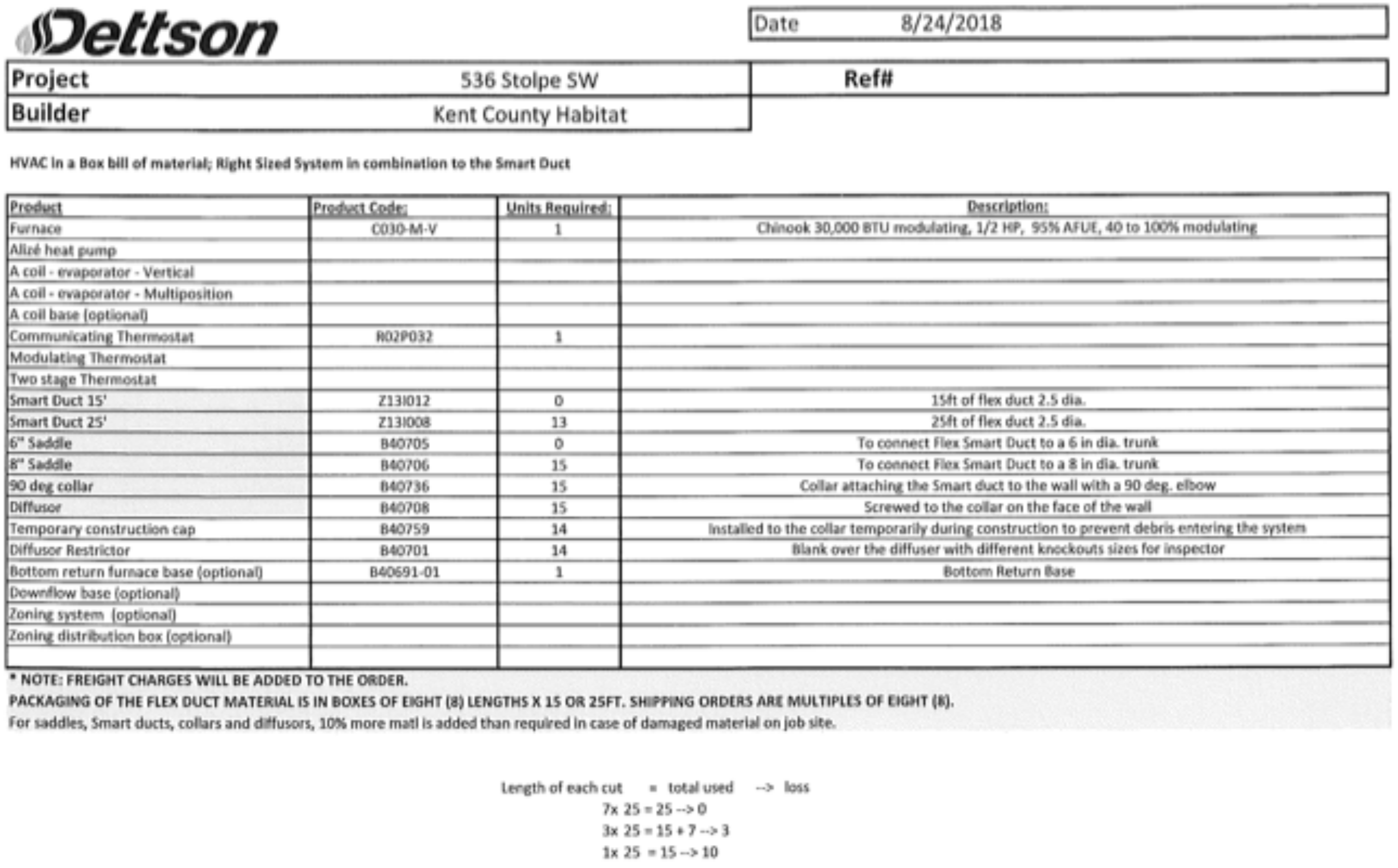
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	1,021	1,021	1,022	1,026	1,020	1,022	1,024	1,021	1,019	1,019	1,017	1,019
2014	1,019	1,021	1,021	1,017	1,020	1,019	1,015	1,028	1,022	1,023	1,026	1,029
2015	1,027	1,026	1,030	1,035	1,028	1,033	1,034	1,035	1,036	1,034	1,041	1,040
2016	1,040	1,038	1,036	1,040	1,038	1,041	1,044	1,052	1,047	1,047	1,048	1,044
2017	1,045	1,045	1,042	1,039	1,043	1,042	1,042	1,043	1,043	1,042	1,043	1,044
2018	1,044	1,046	1,047	1,046	1,044	1,053	1,053	1,049	1,049	1,051	1,053	1,051
2019	1,052	1,053	1,051	1,053	1,057	1,058	1,058	1,061	1,066	1,062	1,062	1,061
2020	1,060	1,062	1,062	1,062	1,058	1,058	1,057	1,056	1,059	1,060	1,057	1,058
2021	1,057	1,056	1,056	1,055	1,058	1,057	1,057	1,059				

Figure C2.I. Heat content of natural gas for the state of Michigan according to EIA data. https://www.eia.gov/dnav/ng/hist/nga_epg0_vgth_smi_btucfM.htm

For the houses containing heat pumps, a similar process was followed with different conversion factors. The heat loss value in BTU for every month was converted to a heat loss in kWh using unit conversions. The average COP for each month was interpolated from data on the Mitsubishi Heat Pump Specs Sheet (*Appendix C4*) corresponding to temperature data from data from Gerald R. Ford International Airport in Grand Rapids, MI (*https://weatherspark.com/y/15379/Average-*

Weather-in-Grand-Rapids-Michigan-United-States-Year-Round). Each month's heat loss was then divided by the average COP at that month to determine the electricity input to the heat pump. Using a conversion factor of 0.000499 tonnes of CO_2 per kWh of electricity, a factor given by the appliances team, the total emissions at each month could be computed and summed. The annual emissions were then multiplied by the lifetime to determine the total lifetime emissions of CO_2. This method was also used for the utilities team, shown in the main body Appendix D.

Appendix C3: Stolpe Furnace Document



Dettson

Project	536 Stolpe SW	**Ref#**	
Builder	Kent County Habitat	Date	8/24/2018

HVAC in a Box bill of material; Right Sized System in combination to the Smart Duct

Product	Product Code:	Units Required:	Description:
Furnace	C030-M-V	1	Chinook 30,000 BTU modulating, 1/2 HP, 95% AFUE, 40 to 100% modulating
Alizé heat pump			
A coil - evaporator - Vertical			
A coil - evaporator - Multiposition			
A coil base (optional)			
Communicating Thermostat	R02P032	1	
Modulating Thermostat			
Two stage Thermostat			
Smart Duct 15'	Z131012	0	15ft of flex duct 2.5 dia.
Smart Duct 25'	Z131008	13	25ft of flex duct 2.5 dia.
6" Saddle	B40705	0	To connect Flex Smart Duct to a 6 in dia. trunk
8" Saddle	B40706	15	To connect Flex Smart Duct to a 8 in dia. trunk
90 deg collar	B40736	15	Collar attaching the Smart duct to the wall with a 90 deg. elbow
Diffusor	B40708	15	Screwed to the collar on the face of the wall
Temporary construction cap	B40759	14	Installed to the collar temporarily during construction to prevent debris entering the system
Diffusor Restrictor	B40701	14	Blank over the diffuser with different knockouts sizes for inspector
Bottom return furnace base (optional)	B40691-01	1	Bottom Return Base
Downflow base (optional)			
Zoning system (optional)			
Zoning distribution box (optional)			

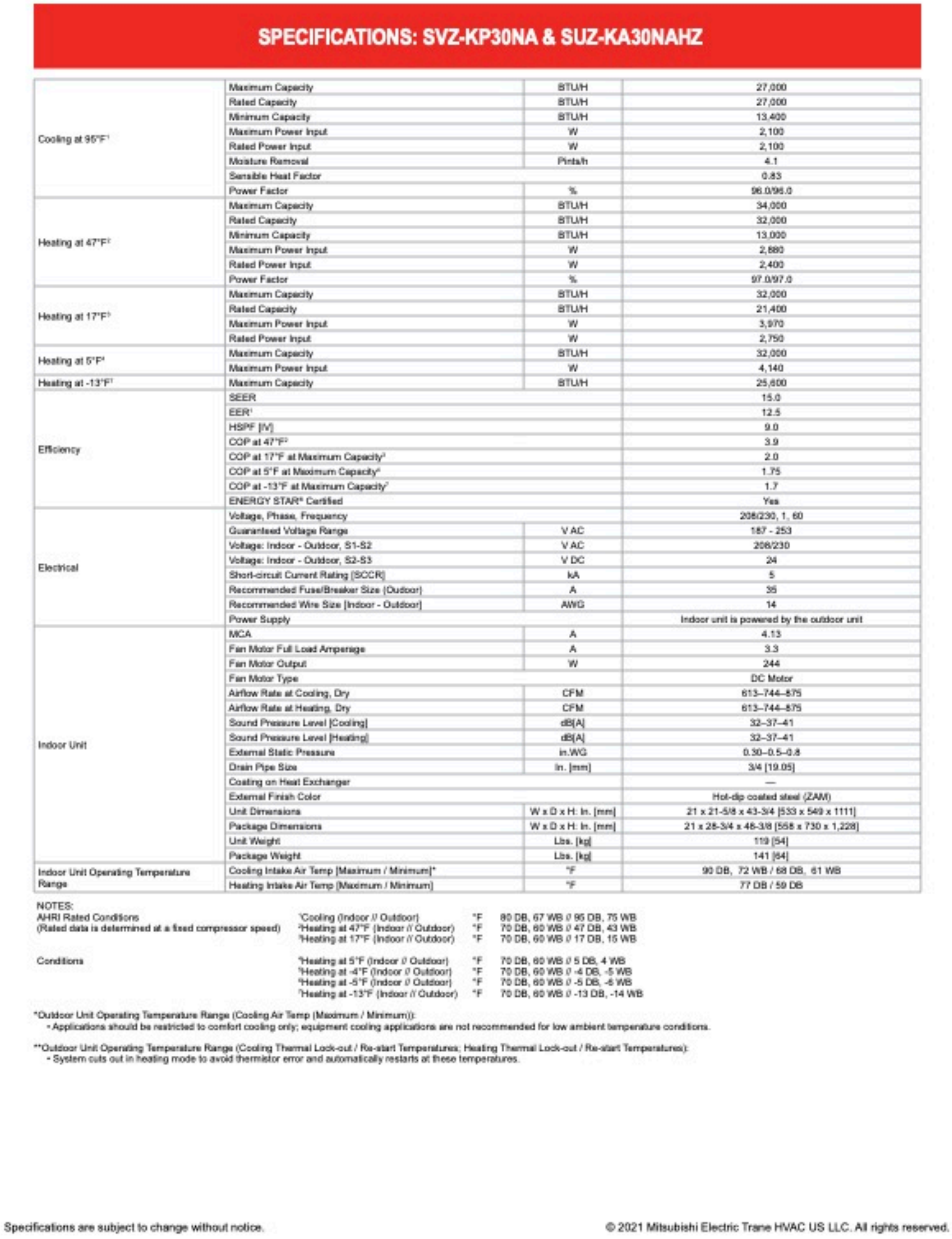
*** NOTE: FREIGHT CHARGES WILL BE ADDED TO THE ORDER.**

PACKAGING OF THE FLEX DUCT MATERIAL IS IN BOXES OF EIGHT (8) LENGTHS X 15 OR 25FT. SHIPPING ORDERS ARE MULTIPLES OF EIGHT (8).

For saddles, Smart ducts, collars and diffusors, 10% more matl is added than required in case of damaged material on job site.

Length of each cut = total used --> loss
7x 25 = 25 --> 0
3x 25 = 15 + 7 --> 3
1x 25 = 15 --> 10

Appendix C4: Mitsubishi Heat Pump Specs Sheet



SPECIFICATIONS: SVZ-KP30NA & SUZ-KA30NAHZ

Cooling at 95°F[1]	Maximum Capacity	BTU/H	27,000
	Rated Capacity	BTU/H	27,000
	Minimum Capacity	BTU/H	13,400
	Maximum Power Input	W	2,100
	Rated Power Input	W	2,100
	Moisture Removal	Pints/h	4.1
	Sensible Heat Factor		0.83
	Power Factor	%	96.0/96.0
Heating at 47°F[2]	Maximum Capacity	BTU/H	34,000
	Rated Capacity	BTU/H	32,000
	Minimum Capacity	BTU/H	13,000
	Maximum Power Input	W	2,880
	Rated Power Input	W	2,400
	Power Factor	%	97.0/97.0
Heating at 17°F[3]	Maximum Capacity	BTU/H	32,000
	Rated Capacity	BTU/H	21,400
	Maximum Power Input	W	3,970
	Rated Power Input	W	2,750
Heating at 5°F[4]	Maximum Capacity	BTU/H	32,000
	Maximum Power Input	W	4,140
Heating at -13°F[7]	Maximum Capacity	BTU/H	25,600
Efficiency	SEER		15.0
	EER[1]		12.5
	HSPF [IV]		9.0
	COP at 47°F[2]		3.9
	COP at 17°F at Maximum Capacity[3]		2.0
	COP at 5°F at Maximum Capacity[4]		1.75
	COP at -13°F at Maximum Capacity[7]		1.7
	ENERGY STAR® Certified		Yes
Electrical	Voltage, Phase, Frequency		208/230, 1, 60
	Guaranteed Voltage Range	V AC	187 - 253
	Voltage: Indoor - Outdoor, S1-S2	V AC	208/230
	Voltage: Indoor - Outdoor, S2-S3	V DC	24
	Short-circuit Current Rating [SCCR]	kA	5
	Recommended Fuse/Breaker Size (Outdoor)	A	35
	Recommended Wire Size [Indoor - Outdoor]	AWG	14
	Power Supply		Indoor unit is powered by the outdoor unit
Indoor Unit	MCA	A	4.13
	Fan Motor Full Load Amperage	A	3.3
	Fan Motor Output	W	244
	Fan Motor Type		DC Motor
	Airflow Rate at Cooling, Dry	CFM	613–744–875
	Airflow Rate at Heating, Dry	CFM	613–744–875
	Sound Pressure Level [Cooling]	dB[A]	32–37–41
	Sound Pressure Level [Heating]	dB[A]	32–37–41
	External Static Pressure	in.WG	0.30–0.5–0.8
	Drain Pipe Size	In. [mm]	3/4 [19.05]
	Coating on Heat Exchanger		—
	External Finish Color		Hot-dip coated steel (ZAM)
	Unit Dimensions	W x D x H: In. [mm]	21 x 21-5/8 x 43-3/4 [533 x 549 x 1111]
	Package Dimensions	W x D x H: In. [mm]	21 x 28-3/4 x 48-3/8 [558 x 730 x 1,228]
	Unit Weight	Lbs. [kg]	119 [54]
	Package Weight	Lbs. [kg]	141 [64]
Indoor Unit Operating Temperature Range	Cooling Intake Air Temp [Maximum / Minimum]*	°F	90 DB, 72 WB / 68 DB, 61 WB
	Heating Intake Air Temp [Maximum / Minimum]	°F	77 DB / 59 DB

NOTES:

AHRI Rated Conditions (Rated data is determined at a fixed compressor speed)	[1]Cooling (Indoor // Outdoor)	°F	80 DB, 67 WB // 95 DB, 75 WB
	[2]Heating at 47°F (Indoor // Outdoor)	°F	70 DB, 60 WB // 47 DB, 43 WB
	[3]Heating at 17°F (Indoor // Outdoor)	°F	70 DB, 60 WB // 17 DB, 15 WB
Conditions	[4]Heating at 5°F (Indoor // Outdoor)	°F	70 DB, 60 WB // 5 DB, 4 WB
	[5]Heating at -4°F (Indoor // Outdoor)	°F	70 DB, 60 WB // -4 DB, -5 WB
	[6]Heating at -5°F (Indoor // Outdoor)	°F	70 DB, 60 WB // -5 DB, -6 WB
	[7]Heating at -13°F (Indoor // Outdoor)	°F	70 DB, 60 WB // -13 DB, -14 WB

*Outdoor Unit Operating Temperature Range (Cooling Air Temp (Maximum / Minimum)):
- Applications should be restricted to comfort cooling only; equipment cooling applications are not recommended for low ambient temperature conditions.

**Outdoor Unit Operating Temperature Range (Cooling Thermal Lock-out / Re-start Temperatures; Heating Thermal Lock-out / Re-start Temperatures):
- System cuts out in heating mode to avoid thermistor error and automatically restarts at these temperatures.

Specifications are subject to change without notice.

Appendix C5: Values for Design Considerations

Table C3.I. Total CO_2 emissions for each house considered under the current electrical grid and the renewable grid.

House Design Consideration	Lifetime CO_2 Emissions [tonnes CO_2]	
	Current Grid	Renewable Grid
To-Code	36.62	36.62
Stolpe	35.98	35.98
London	28.38	20.95
Triple-Pane	24.95	18.42

Table C3.II. Total heat loss and heat loss per subcomponent of the house in BTU/hr for each house analyzed.

Heat Loss [BTU/hr]				
	Stolpe	To-Code	London	Triple-Pane
Roof	1913	2319	1813	1813
Walls	3744	3030	2712	2712
Windows	2831	3355	2831	1887
Basement	506	448	448	448
Total	8994	9152	7804	6860

Appendix C6: Heating Team Excel Files

The two Excel files used to perform the heating calculations, carbon factor calculations, and carbon emission calculations can be found in Appendix X (the zip file of Excel madness?).

The first file is “Heating Models and Carbon Emissions – Heating”. The first sheet shows the heating breakdowns of all the houses and considerations analyzed, each embedded with numbers calculated by the other sheets in the file. The four houses, To-Code, Stolpe, London, and London with Triple-Pane Windows, each have a sheet with their individual heat model calculations, with their specific building specifications and R-Values. The houses then have sheets with their individual carbon emissions based on their source of energy (natural gas or electricity). These Excel sheets were created and formatted so that R-values for different materials (i.e. insulation or windows) could easily be replaced and generate new heat loss and carbon emission results.

The second file is “Carbon for Renewable Grid – Heating” which shows the process for calculating a carbon coefficient based on Consumers Energy’s promised renewable grid information. This information can be found here:

https://www.consumersenergy.com/-/media/CE/Documents/company/IRP-2021.ashx?la=en&hash=A345F333F84DE174D59A6BA8D5A23B2C

Group D: Utilities Team

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Introduction

The utilities team was tasked with determining the electricity consumption rate of the two houses after occupation. This was done by evaluating the appliances, lights, water heater and created “TV/Media” and “Other” categories for both the baseline home, Stolpe, and the “carbon footprint build” which was the London house. Design options, given by the design team, were also implemented into the analysis to determine the effects on carbon emissions in both cases.

Method

Information on the baseline home, Stolpe, was provided by Habitat for Humanity, which included the annual natural gas and electricity usage. This data was used to calculate a yearly tonnes of CO_2 emitted, which was done by using a conversion factor for electricity (kWh) and natural gas (CCF); these factors were found from the EIA government website. The annual Stolpe usage was used as a base to estimate the yearly usage of the London home. Due to the London home being all electric, the gas usage of the Stolpe home was converted to an electrical equivalent. The lighting schedule was the same for both homes and was calculated so the electrical usage of the Stolpe home could be separated into appliances and lighting, as it appears on the fuel summary. Some of the appliances in the London home are newer and more powerful, so their power draw is higher; this was accounted for by adding the difference between the manufacturer’s estimated yearly usage. The gas usage of the Stolpe water heater was also provided separately on the fuel summary and could be directly compared to the expected usage of the electric water heater in the London home by using the manufacturer’s specifications. The estimated yearly electrical usage of London was then converted to tonnes of CO_2 emitted and could be compared to the Stolpe home. This CO_2 factor is explained in *Appendix C2*.

With the baseline home and the new home analyzed and compared, the options of solar panels and a solar water heater were considered as ways of offsetting the CO_2 emission of the home. For solar panels, the average hours of peak sun were found per year and then, using Tesla solar panels, the amount of electricity generated per year could be estimated; this was used to ultimately estimate the yearly CO_2 reduction. For the solar water heater, the electrical usage reduction was predicted by the manufacturer, and that was used as an estimate to calculate the yearly CO_2 reduction.

Results

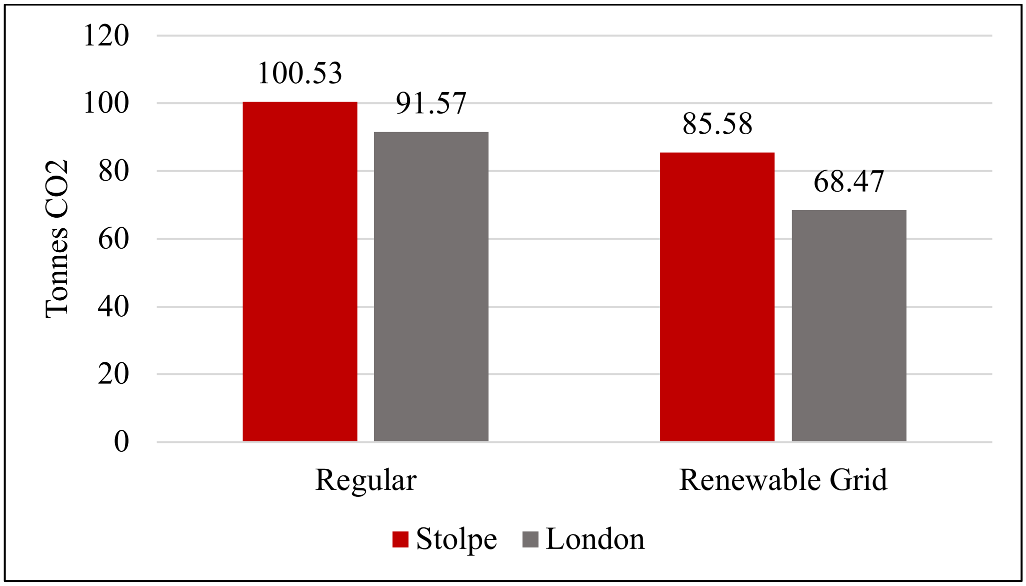

Figure D.I. Carbon emissions for London compared to Stolpe for current and future grids.

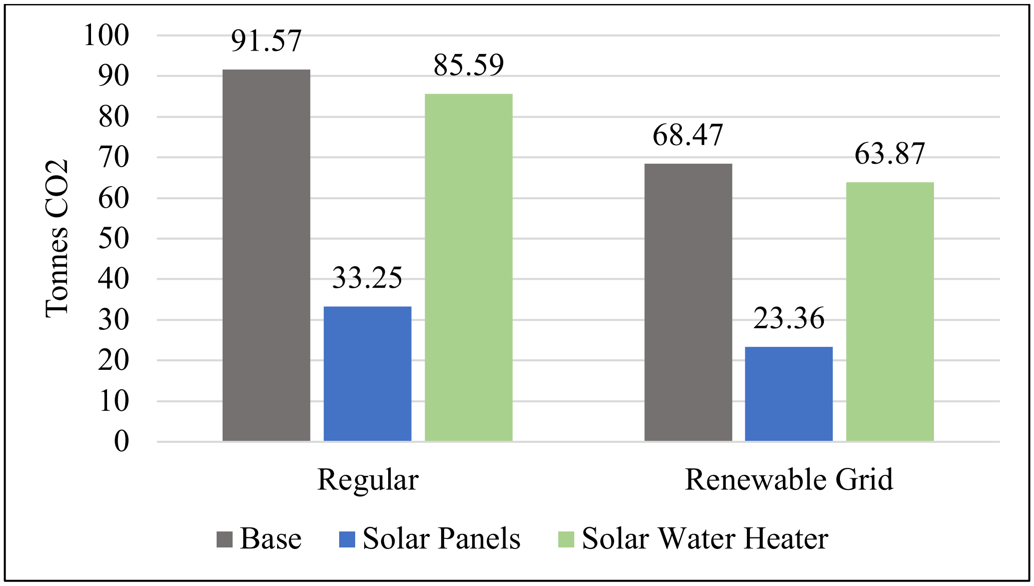

Figure D.II. London design options for the current vs. renewable grid

Conclusions

As demonstrated by the results in the above section, the London house reduces carbon emissions in comparison to the base home by about 9%, and this reduction increases to about 20% using DTE's planned renewable grid. Although the use of all electric appliances increases the carbon emission in the London home, the new, all-electric water heater alone, with an increased heat capacity (bigger tank), used in the London house emits 65% less carbon than the natural gas water heater used in Stolpe. The implementation of solar panels could also reduce the carbon emissions in the London house by about 64% with the base grid and the inclusion of a solar water heater would further reduce emissions about another 6.5%.

An error assumption of +/- 15% was added to the results; due to assumptions about usage rates for certain appliances the occupants would use and using a fuel summary that supports a suggested use of the homes' energy consumption rates. Note that these errors were not calculated but added from various decisions made.

The team decided to leave out the "TV/Media" and "Other" categories that were created based off U.S. averages. The main purpose of this project was to analyze the difference in carbon emissions between the two homes and these two created categories are the same for both homes and simply add on more carbon to the final number. It is of more importance to analyze the two homes in their most basic sense, including the lighting, water heater, and appliances. The breakdown, including the two created categories, can be found in Appendix D1.

Future work and upgrades to the new habitat homes should include a solar panel system to understand the exact effects it would have on carbon emissions. Partnering with a local solar panel manufacturer could be an effective way to obtain solar panels at a lower cost. Growing community relationships is a main goal of Habitat for Humanity, and this would only increase that.

Future analysis with this project would include looking deeper into the individual appliances and their consumption rates as well as a cost analysis to determine the tradeoff between the cost of utilities and the carbon emitted; optimizing this tradeoff would be the main objective

<u>**Appendix D1 – Specific Results & Other Figures**</u>

Table D1.I. London House results for habitat and occupant boundaries for a 25-year lifetime.

Source	**Usage (kWh/yr)**	**Carbon Emission (Tonnes/yr)**	**Lifetime (Tonnes)**
Lighting	1269	0.633231	15.830775
Main Appliances	5113.2	2.5514868	63.78717
Water Heater	958	0.478042	11.95105
TV Media	274.49	0.25872651	6.46816275
Other	622.58	0.49549702	12.3874255
Total	8237.27	4.41698333	110.4245833

Table D1.I. Stolpe House results for habitat and occupant boundaries for a 25-year lifetime.

Source	**Usage (CCF/yr)**	**Usage (kWh/yr)**	**Carbon Emission (Tonnes/yr)**	**Lifetime (Tonnes)**
Lighting	-	1269	0.633231	15.830775
Main Appliances	54	3460	2.03164	50.791
Water Heater	247	-	1.356277	33.906925
TV Media	-	274.49	0.25872651	6.46816275
Other	-	622.58	0.49549702	12.3874255
Total	301	5626.07	4.77537153	119.3842883

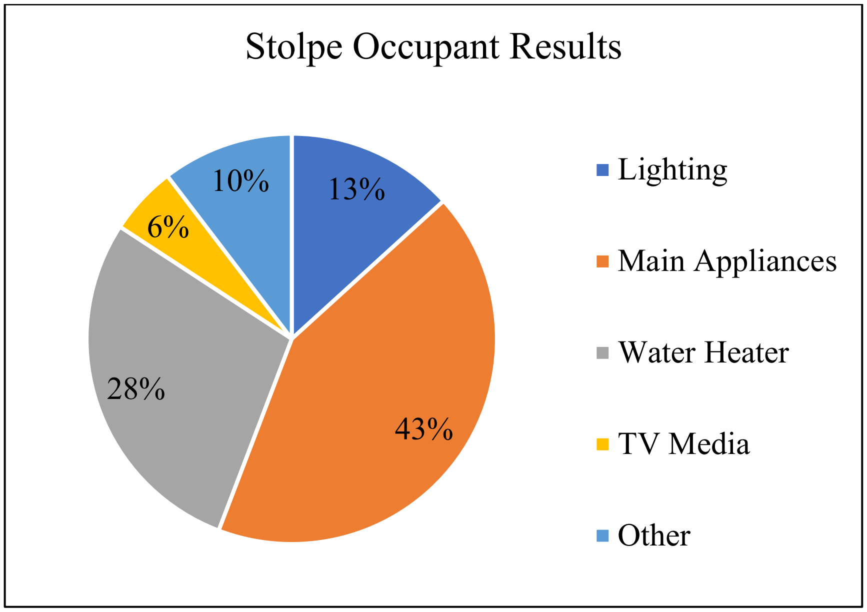

Figure D1.I. Percentage of CO2 emitted by each source for the Stolpe house

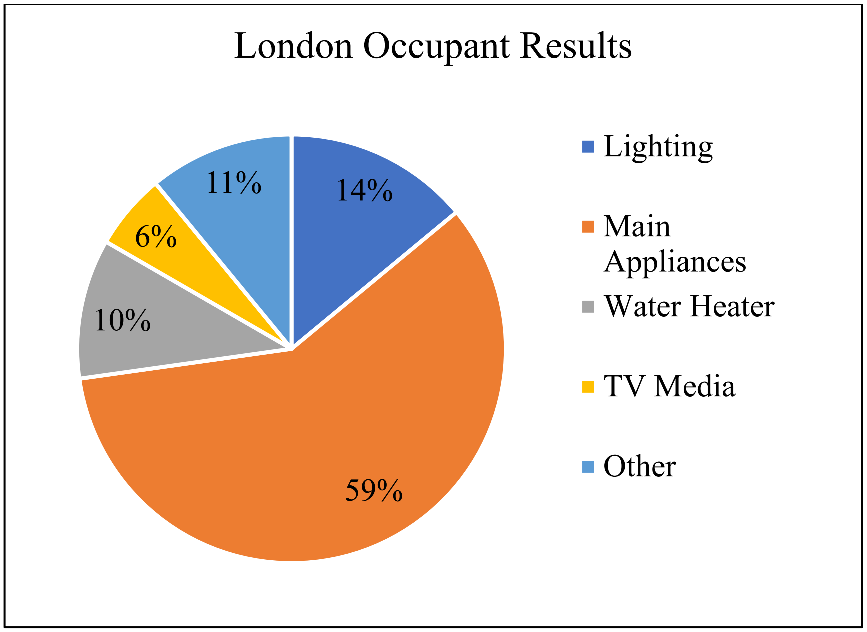

Figure D1.II. Percentage of CO2 emitted by each source for the London house

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Group E: Design Team

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Executive Summary

To reduce the carbon impact of the London house over a 25-year lifespan by an additional 20%, four design options were selected and analyzed by the analysis teams. In each case, lifetime emissions related to heating and utilities were considered under two grid scenarios: (1) current grid, which uses carbon coefficients based on the current grid carbon intensity in Grand rapids, MI, and (2) renewable grid, which integrates planned fuel switching and grid decarbonization of the local utility. Our analysis indicates that by changing the current design of the London house to incorporate a prefabricated concrete basement, triple paned windows, roof solar panels and a solar water heater the lifetime carbon emissions of the improved house could be reduced by 36% relative to a "To-Code" house with the current grid, or 39% with our renewable grid model. This translates to a 30%, 26% improvement over the London house with the current and renewable grid models.

Design Option Selection

To reduce the carbon impact of the London house over a 25-year life span by an additional 20%, thirteen design options were considered and four were selected for analysis (Table E.I). Design options were selected for analysis based on 2 criteria: potential contribution to total carbon reduction and predicted ease of analysis. Design options were generated through interviews with analysis teams and consideration of LEED best practices. Ease of analysis was estimated through conversations with analysis model developers, and the potential carbon reduction was estimated using preliminary results and internet research. Each design option was assigned a score 1-5 (5 is most desirable), and the top 4 design options were selected for further review. Restricting the selected design options in this way contributed to the feasibility of the overall analysis. No design options were proposed to reduce onsite carbon emissions due to the relatively small contribution to lifetime emissions from this source.

Table E.I. Design option decision matrix.

Design Option	Targeted Reduction Area	Potential Carbon Reduction	Ease of Analysis	Total Score
Prefab Basement	Embodied	4	5	9
Solar Panels	Utilities	5	4	9
Triple Pane Windows	Heating	4	4	8
Solar Water Heater	Utilities	4	4	8
Concrete Additives	Embodied	4	3	7
Wool Insulation	Embodied	3	4	7
Metal Roof	Heating	3	4	7
Geothermal	Heating	5	1	6
Low E Window Glazing	Heating	4	2	6
Tankless Water Heater	Utilities	3	2	5
Energy Star Appliances	Utilities	3	2	5
Green Roof	Carbon Sink	4	1	5
Trees	Carbon Sink	4	1	5

Selected Design Options Discussion

Prefabricated Concrete Foundation

The Stolpe residence was constructed with precast and cured concrete slabs that were transported to the site and dropped into place during construction. The London residence utilized cast-in-place concrete which is poured into site-specific forms and cured on site. The concrete option used for the Stolpe residence from Great Lakes Superior Walls is implemented to the London residence reducing embodied carbon in the concrete [1].

Triple Pane Windows

The London residence uses JELD-WEN double pane windows for all the windows. By switching to using JELD-WEN triple pane windows, the U-value could be decreased from 0.30 to 0.18 resulting in a better insulation of the house [2]. Because of this design option, the energy usage of the house for maintaining a constant temperature in the house decreases thus increasing the energy efficiency of the house.

Solar Panels

Since most of the London appliances rely on electricity, design options that reduce the overall electrical load from the Grand Rapids power grid would reduce a large amount of the embodied carbon emissions. For this reason, the solar panel and solar water heater design options were selected for analysis. Tesla solar panels were chosen for analysis [3]. Tesla offers four bundles of solar panels, small, medium, large, and x-large, ranging from 10-40 panels in magnitudes of 10. The small solar bundle was chosen for the London house due to its relatively minimal electrical load compared to an average residence. 10 Tesla solar panels are rated at 4.25 kW and store excess energy in the Tesla Powerwall, which serves as a backup energy storage for use during cloudy days, at night, or during an outage.

Solar Water Heater

To reduce the overall electrical load on the house, thus reducing the total carbon emissions due to electricity, a solar water heater would remove the need for an electric water heater. The solar water heater company chosen for analysis was Event Horizon Solar & Wind Inc [4]. According to Energy.gov, installing a solar water heater will drop a residence’s water heating bills by 50% [5]. Using this metric as a basis for analysis, the electrical team implemented this design option by dividing the electrical load of the electric water heater in half.

The CO_2 reduction result by applying all four design options is shown in Figure E.I as the improved option. The current grid is the base case worked on by this project where the renewable grid is a case that implements renewable energy. Other figures showing the results are shown in Appendix E1. The descriptions of design options that were not selected can be found in Appendix E2.

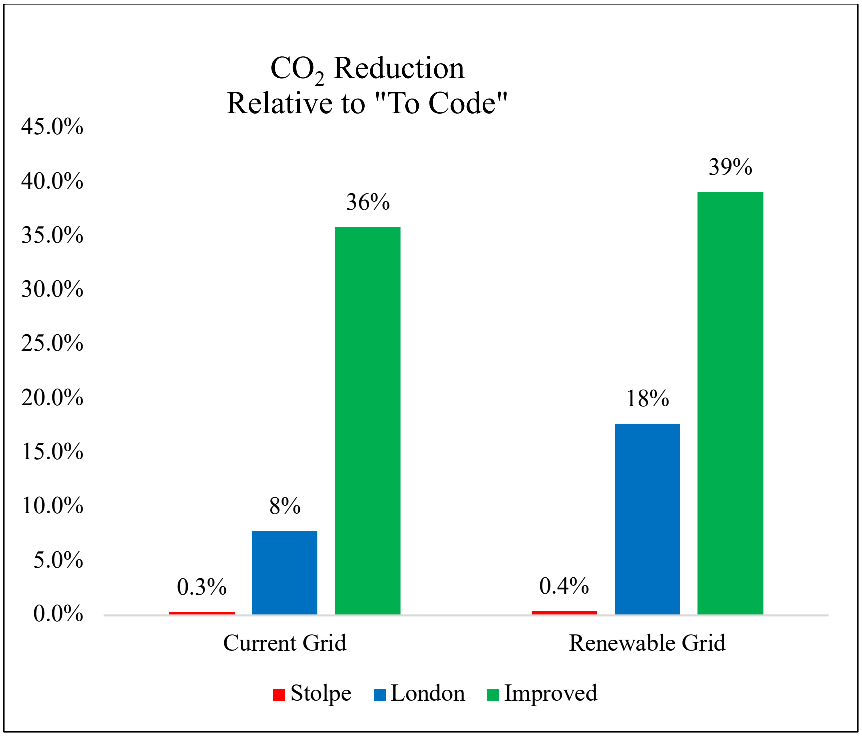

Figure E.I. CO_2 reduction from each house options to the “To Code” house for both grids.

Conclusion

By implementing solar panels, triple pane windows, prefabricated foundation walls, and a solar water heater our analysis predicts a net emissions reduction of 36% relative to a “To-Code” house with our current grid model. Applying a renewable grid model, this percentage reduction increases to 39% relative to a “To-Code” house (See Appendix E3 for definition of “To-Code” house). Further study could integrate additional consideration of cost and economic impact of each design option. Further analysis of tankless water heaters and energy star appliances may provide the most feasible options to integrate in the future.

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Appendix E1 – Relevant Figures and Data

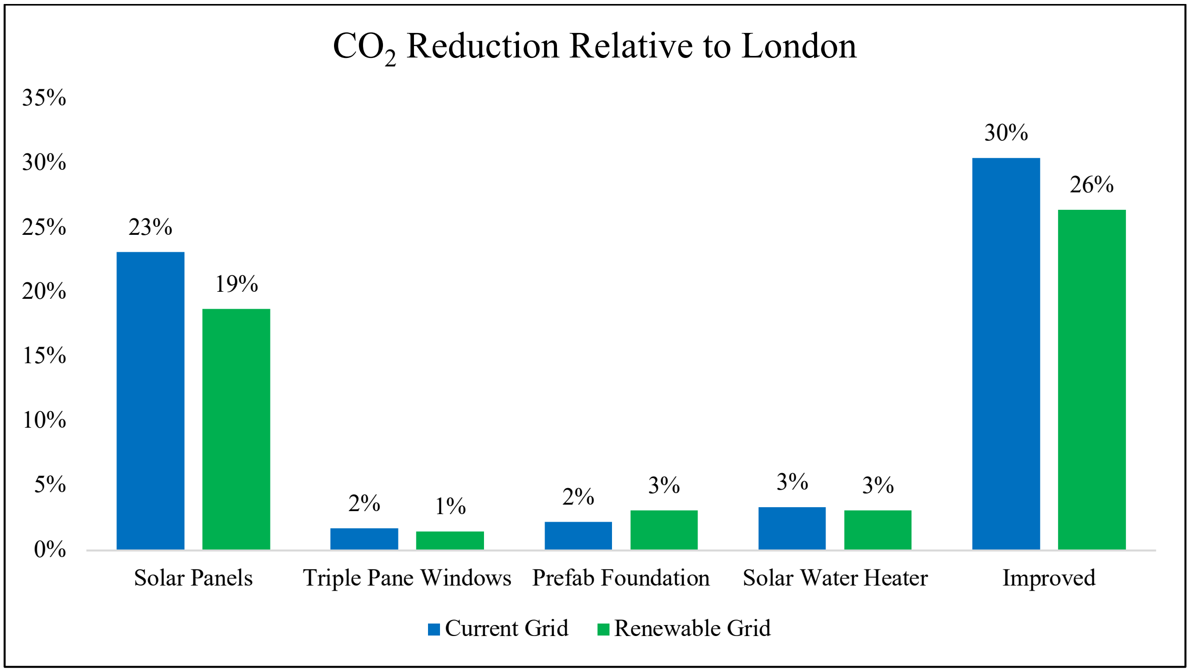

Figure E1.I. CO_2 reduction from each design option and the improved house relative to the London house.

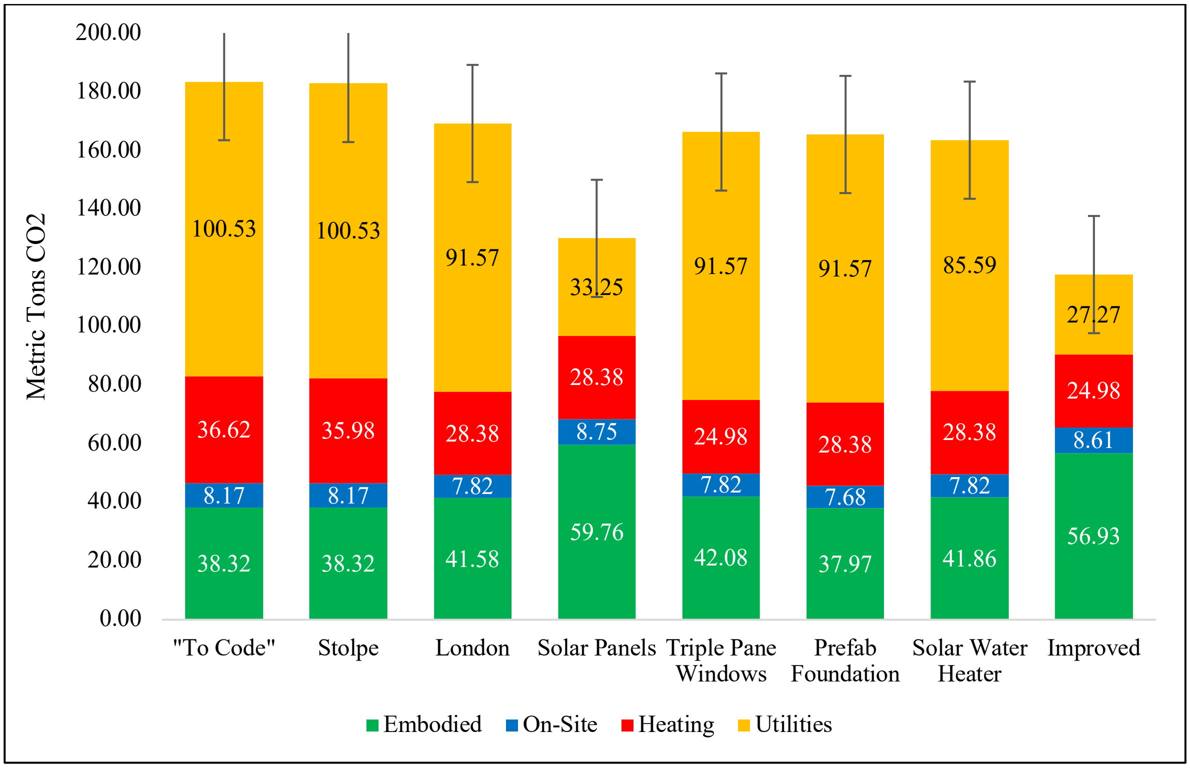

Figure E1.II. Implemented design option results for the current electrical grid model.

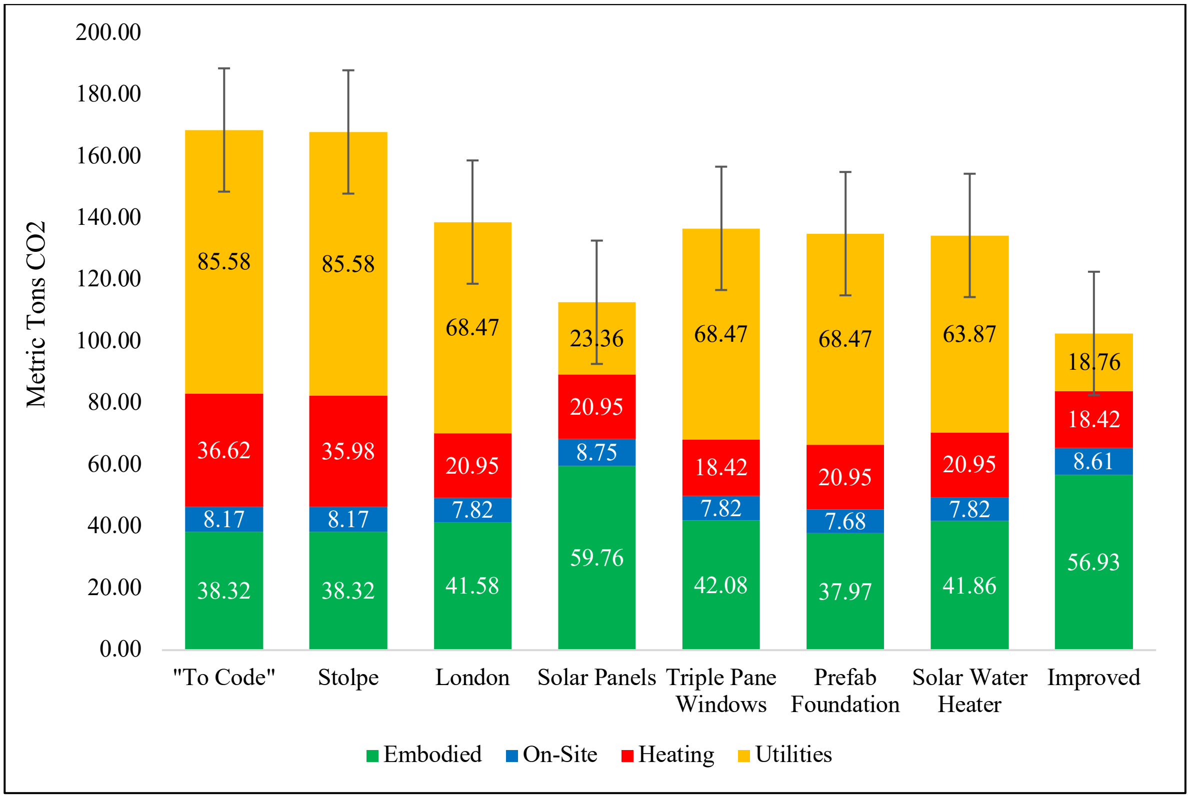

Figure E1.III. Implemented design option results for the proposed renewable electrical grid.

Appendix E2 – Descriptions of Design Options Not Selected

Concrete Additives

Several concrete additives, including recycled re-bar and recycled concrete aggregate were initially investigated. Upon further study, we determined that structural analysis necessary to ensure that a new concrete mix would still be viable in the house construction was outside of the scope.

Wool Insulation

Wool insulation was selected for consideration based on initial projections that wool may have a negative embodied carbon contribution, though its lower R value would contribute to higher emissions due to heating. After preliminary analysis, the embodied carbon analysis team determined that wool insulation was not carbon negative. In addition, the contribution of insulation to the total embodied carbon is very low (less than 5%). For these reasons, analysis of wool insulation was discontinued.

Metal Roof

Metal roofing alters the emissivity of the roof surface which influences solar heat gain and radiative heat loses. After conversations with the heating team, we determined that radiation would not be included in their heat modeling. For these reasons, metal roofing was discontinued as a design option.

Geothermal

Moving from an electric heat pump to a geothermal heat pump could significantly reduce or eliminate the electricity usage and carbon emissions due to heating. While our analysis teams have the skills to perform an analysis of a geothermal heating option, this could result in more significant structural changes and would require more dedicated time to analyze. Largely due to time constraints, this option as discontinued.

Low E Window Glazing

Low emissivity window glazings influence solar heat gain through windows. Since the heating analysis model does not incorporate heat loss or gain due to radiation, this option was discontinued.

Tankless Water Heater

Tankless water heaters conserve 27 to 50 percent more energy than traditional water heaters and heat water on-demand. Initial projections indicated this would have a lower impact than a solar water heater. To limit the number of design options targeting the water heater, a solar option was selected for analysis over the tankless model.

Energy Star Appliances

Increasing the energy efficiency of in-house appliances was projected to have a minimal impact per appliance. Due to the extensive research required for each individual appliance and the relatively high efficiency of the current appliances, this option was discontinued over feasibility concerns.

Green Roof

A green roof option was considered as a potential carbon sink. After preliminary research, we determined that more structural changes to the house would be required to support the additional weight. To limit our scope and avoid time intensive structural analysis, this option was discontinued.

Trees

Including trees and other vegetation on the property within the bounds of our analysis was discontinued after visiting the site. With not much space to plant additional trees, this option was not feasible. In addition, carbon sink analysis was determined to be outside of our current scope.

Appendix E3 – "To-Code" House Definition

Habitat for Humanity requested a comparison of the Stolpe and London homes to a "to-code" house, which would show how much better Habitat for Humanity's houses are than a house that meets the minimum requirements for a house according to the building code in Grand Rapids. The main differences between the two building codes are listed below in Figure E3a.

Table E3.I. Habitat for Humanity and City of Grand Rapids Building Code Comparisons.

	Habitat's Building Standards	**Grand Rapids Building Standards**
Insulation under slab	2" XPS	N/A
Foundation insulation	ICFs w/ 4" total insulation	N/A
Wall system	R-15 w/ R-10 continuous exterior	R-20 in wall or R-13 in wall with R-5 continuous exterior
Roof insulation	R-50 blown	R-38
Windows	U value 0.270 - Double Pane	0.32 Maximum

For simplification of the model, we decided to only observe the differences between the two building codes for the *heating* team's calculations. These changes also would have slightly affected the embodied and onsite teams, but we neglected these changes to reduce the amount of work that these teams needed to do.