242 Kehl Street | Kitchener

Embodied Carbon vs. Operating Emissions

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Introduction

The Kehl Street project is a Habitat for Humanity development in the Waterloo Region consisting of a group of townhomes built with volunteer labour. This project was adopted by the Warrior Home Student Design at the University of Waterloo for the Race to Zero student competition in 2018 [1]. The Warrior Home design team adjusted the original home to fit “net-zero” requirements and was successful in winning first place in the semi-detached housing category while achieving net-positive energy efficiency.

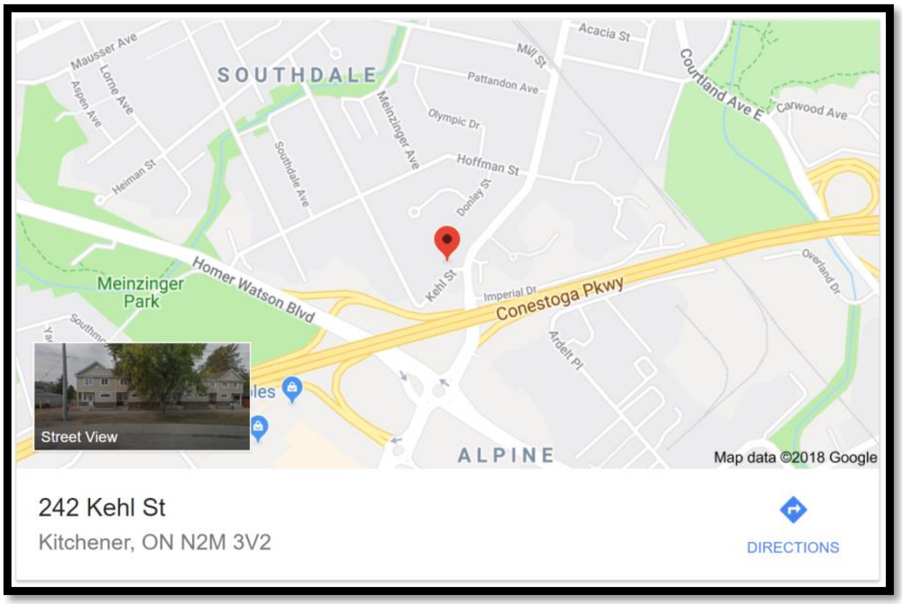


Figure 1: Habitat for Humanity Development, located at 242 Kehl St, Kitchener

Background Material

Net-Zero

The American National Institute of Building Sciences (NIBS) defines net-zero buildings as buildings where the total energy consumed is less than or equal to the energy produced on a site [2]. Efforts to move towards net zero buildings are growing internationally and in Canada, where the Canada Green Building Council (CaGBC) states that we need to effectively eliminate greenhouse gas emissions from all building operations by 2050 in order to avoid the worst effects of climate change [3]. The CaGBC has developed a Zero Carbon Building Standard, which is the only standard in North America that uses carbon as the key performance metric (normally net-zero refers to energy, not carbon). The goal is to enforce the importance of energy efficiency, while encouraging renewable energy generation on and off the building site.

The Warrior Home design team analyzed multiple components of the Kehl Street development to achieve “net-zero” status. These components included the building enclosure, mechanical and electrical systems, and interior finish materials. The final energy of the townhomes was measured using the HERS Index, which evaluates the energy performance on a relative basis (see 242 Kehl St report or http://www.hersindex.com/ for a definition). Analysis was conducted after each design iteration in REM/Rate (an energy analysis program), to give a decreasing HERS Index Score from 81 (Baseline Design), down to 48. A HERS Index Score of 48 means that the building was 52% more energy efficient than the HERS reference home. The final step to achieving net-zero energy status included using a 31 kW solar solution (see Figure 2).

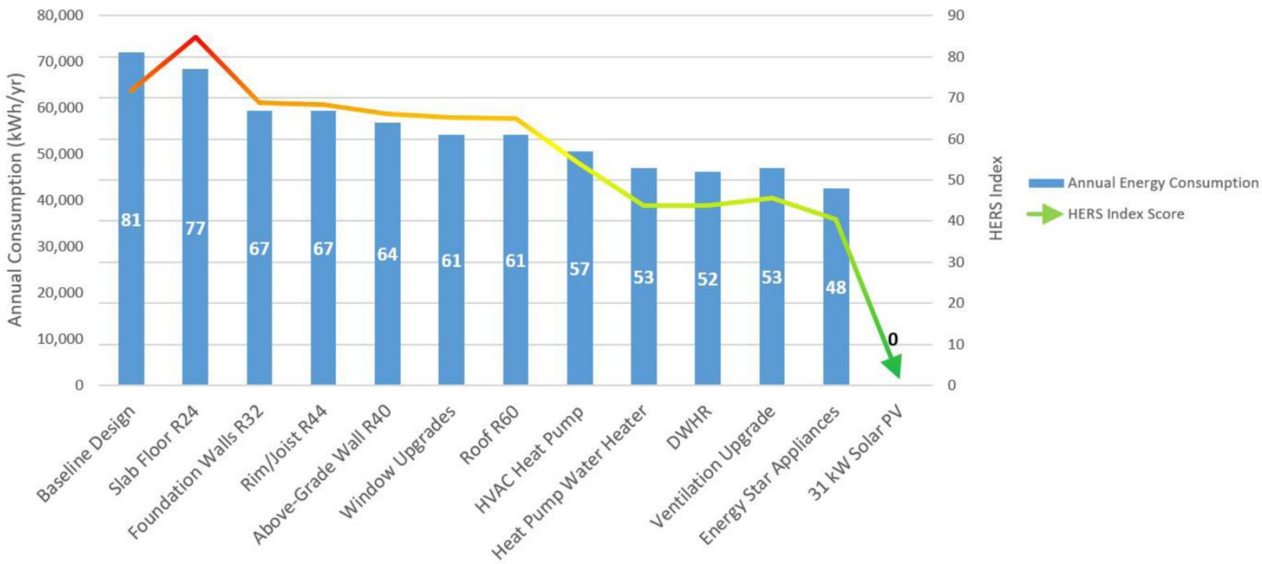


Figure 2: Progression of Design Iterations and HERS Index Score for Kehl St. Warrior Home [1]

This is a typical procedure when attempting "net-zero" on a building site; step 1 is to increase energy efficiency through efficient building procedures and systems, and step 2 is to address the remaining energy needs with onside renewable energy, as shown in Figure 3.

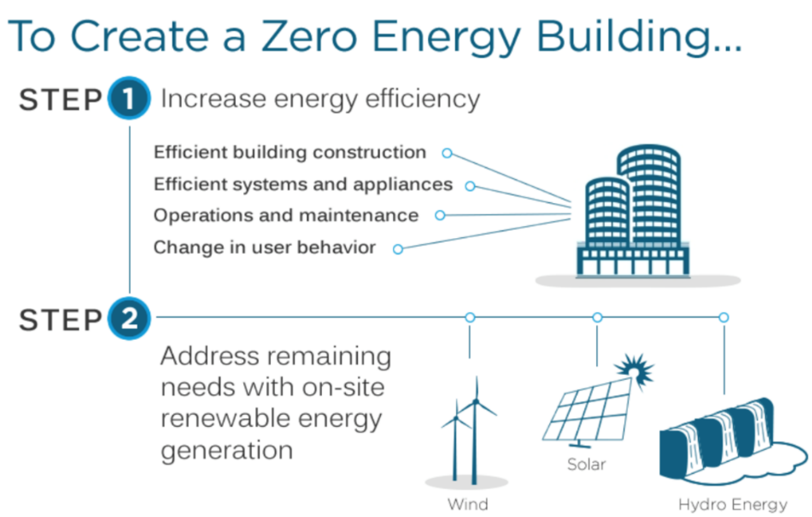


Figure 3: How to Create a Net-Zero Building [2]

Energy Use Intensity

In general, most buildings are not net-zero from an energy perspective. However, with enough renewable energy generated on-site, even a very poorly designed and energy inefficient building may technically be "net-zero". As a result, this classification doesn't tell the whole picture. In order to get a good idea of the efficiency of a building, the energy use intensity (EUI), measured in energy per unit of floor space (GJ/m^2 or kWe/ft^2, for example), is a better metric. Even so, different types of buildings will have different energy demands, so the EUI of a building should be compared to the EUIs of other similar use buildings in similar environments. The simple equation for calculating EUI is given below:

$$\text{EUI} = Yearly\ Energy\ Consumed\ /\ Building\ Area$$

Table 1 shows the average EUI for different building types in Canada. The numbers reported here are *source* EUI and not *site* EUI. The difference is that source EUI measures the energy at the source, and accounts for the losses between the source and the site. Site EUI is easier to obtain (since it can be obtained from building meters). The Canadian median *site* EUI for 2017 was 1 GJ/m^2 compared to 1.6 GJ/m^2 for *source* EUI (see final row in Table 1). Therefore, a rough conversion may be taken as 1.6.

Table 1: Average EUI for Building Types in Canada [4]

BUILDING TYPE	MEDIAN SOURCE EUI (GJ/m^2)
Office	1.8
Hospital	3.6
Food Service	5.8
Multi-unit Residential	1.1
K-12 School	0.9
Canadian Median	1.6

Embodied Carbon vs. Operating Emissions

Most efforts into reducing the carbon impact of buildings today focus on a reduction in operating emissions. This could be for two main reasons: first, these operating emissions have historically been the primary source of carbon impact, and second, these emissions have an obvious incentive to reduce (using less fuel, for example, saves a building operator money). However, a second source of carbon emissions in buildings comes from "embodied carbon". Embodied carbon refers to carbon emissions that have taken place (or will take place), for the acquisition or manufacturing of materials, as well as the transportation, installation, and demolition (or recycling) of those materials [5].

Embodied carbon is a general term, but it should generally be used in conjunction with a more specific term indicating which parts of the material life cycle are being taken into account. The steps in the full life cycle of a material, shown in Figure 4, can be broken down into:

- Extraction,
- Manufacturing,
- Transportation,
- Construction/Installation,
- Demolition,
- and Recycling.

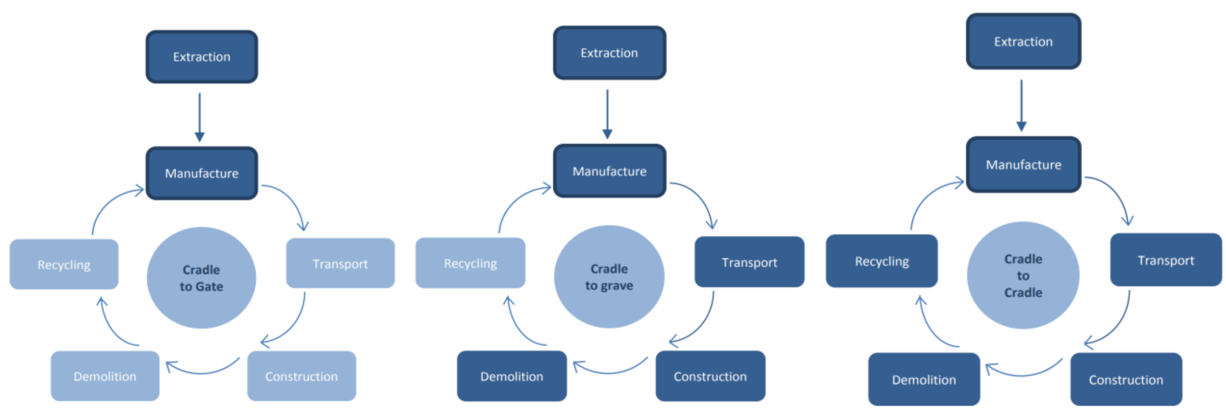


Figure 4: Material Life Cycles [6]

As Figure 4 suggests, the term “Cradle to Gate” embodied carbon covers the carbon produced from the extraction and manufacturing of the material. In contrast, “Cradle to Grave” covers all the way until the demolition of the material, and “Cradle to Cradle” includes the last step of recycling the material for future use.

The last two steps of demolition/recycling could be view as the “end of life scenario”, where the decision is made as to what to do with a product after its useful life is over. Each material has a different set of feasible options; in the following sub-section, we take a look at end of life scenarios for the three most common building materials in North America.

Material End of Life Scenarios

Concrete, timber, and steel are the three most common structural building materials in North America. Each of these materials has advantages and disadvantages in terms of overall sustainability. Steel, for example, takes a great deal of energy and resources to create, but it is highly recyclable (about 93%!). In contrast, the bulk of concrete is comprised of readily available and inexpensive materials (sand, gravel, and water), but it is less recyclable, and instead is often “downcycled” (about 75% of the time). For concrete, downcycling means being ground up and used as gravel or aggregate in a new application. Of the three materials, wood is the only naturally occurring and renewable material, but it has low rates of recycling and re-use, with about 58% of all wood products heading for the landfill eventually [6]. Figure 5 illustrates this comparison.

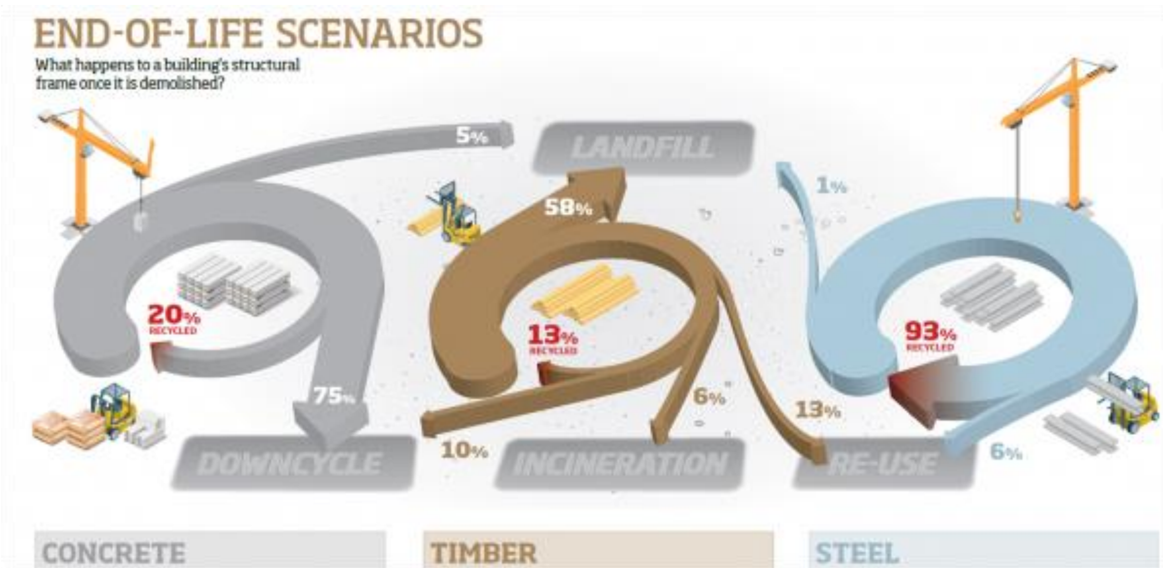


Figure 5: Material End-of-Life Scenarios [6]

Embodied Carbon of Common Building Materials

In Table 2, the embodied carbon of various structural building materials is shown. Line items are broken down into “Production”, which consists of extraction and manufacturing of material (Cradle to Gate), followed by demolition and recycling. The final column is a total; transportation and construction values are not given, because they are hard to quantify and depend on many variables (some having little to do with the material itself). Totals may still be used as an overall estimate for Cradle to Cradle carbon emissions. Note that embodied carbon is generally reported in units of the weight (or mass) of $C0_2e$ per weight (or mass) of material. A conversion will often have to be made for comparison to yearly carbon emissions from operation, which are often reported in tonnes $C0_2e$ per year.

In Table 3, embodied carbon values are given for several other materials. Here the values are only from material production (Cradle to Gate).

Table 2: Embodied Carbon of Structural Materials [6]

Product	Production (kg CO_2e/kg)	Demolition (kg CO_2e/kg)	Recycling (kg CO_2e/kg)	Total (kg CO_2e/kg)
Conventional Brick	0.16	0.0100	-0.021	0.15
Concrete Block	0.09	0.0103	-0.005	0.10
Plain Concrete	0.17	0.0037	-0.005	0.17
Hollowcore Slab	0.20	0.0006	-0.010	0.19
50 MPa Reinforced Concrete	0.25	0.0063	-0.031	0.22
Reinforced Concrete w/ Fly Ash	0.20	0.0057	-0.031	0.17
Galvanized Steel	2.49	0.0600	-1.450	1.10
Hot Rolled Steel	2.49	0.0600	-1.380	1.17
Reinforcing Steel	1.27	0.0610	-0.426	0.91
Steel Decking	2.52	0.0600	-1.450	1.13
Glued Laminated Timber	-1.00	1.768	-0.46	0.31
Plywood	-1.20	1.850	-0.49	0.16

Table 3: Embodied Carbon of Other Products (Cradle to Gate) [5]

Product	Embodied Carbon (kg $C0_2$e/kg)
Rammed Earth	0.023
Rockwool	1.05
Expanded Polystyrene	2.55
Polyurethane Foam Insulation	3.48
Aluminum	8.24
Glass	0.85
PVC Pipe	24.4

Problem Statement

Estimates for energy use on an operational basis for the 242 Kehl Street development can be found from the BEopt analysis completed as part of that tutorial. A comparison needs to be made between the energy use intensity (EUI) between the current development, and the 20 Mill St. location. A proper comparison should consider the type of homes (semi-detached vs. detached) being compared. Following this, the drawings for 242 Kehl Street should be used for quantity take-offs of the main structural materials, and a life cycle analysis (LCA) should be completed, considering the embodied carbon of those materials. This LCA should be compared to the operating carbon emissions, so that decisions can be made for future projects in terms of what type and how much material should be used during construction.

Lesson Objectives

After the lesson, students should be able to:

- Compute the energy use intensity for a building with energy and size data,
- Compare the embodied carbon in a building to the operating emissions,
- Make decisions on where to focus on carbon reduction based on that comparison,
- Comment on the most beneficial end of life scenarios for various building materials, and
- Size on-site renewable energy required to attain net-zero energy or carbon.

Readings

**needed to complete assignment*

- *Background Material
- *Kehl St. Project Drawings
- Warrior Home Kehl St Report
- Life Cycle Assessment and Embodied Carbon [6]
- Tackling Embodied Carbon in Buildings (paper)
- The Carbon Impacts of Wood Products (paper)

References

[1] Kehl-0 Race to Zero Volume 1, April 3, 2018, University of Waterloo Warrior Home Report

[2] Zero Energy Buildings. U.S. Department of Energy, 2018. Obtained from: https://www.energy.gov/eere/buildings/zero-energy-buildings

[3] Canada Green Building Council (www.cagbc.org), Zero Carbon Building Standard (May 2017)

[4] Survey of Canadian Household Energy Use (2011), Natural Resources Canada. Obtained from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=SH&sector=aaa&juris=ca&rn=6&page=1

[5] http://www.greenspec.co.uk/building-design/embodied-energy/

[6] Life Cycle Assessment and Embodied Carbon, 2018. Obtained from: https://www.steelconstruction.info/Life_cycle_assessment_and_embodied_carbon#Resources

242 Kehl Street | Assignment

Notes:	- Complete the following calculation and discussion questions. - Always show units, and cite sources, where appropriate. - Clearly indicate final answers. - Minimum standards of neatness are expected.

Calculation Questions:

1. Calculate the site EUI and the carbon emissions intensity of the 20 Mill Street residence if the total energy used in 1 year is 54 GJ, the total carbon emissions are 6.55 tonnes $C0_2e$, and the total livable square footage is 1,200 ft^2. Compare that to a typical Canadian building, and to one unit at 242 Kehl Street, where 33350 kWh per year are estimated, along with 4.52 tonnes $C0_2e$, for an average unit size of 1,116 ft^2? *Hint: Compare to the Canadian average on page 4.*

   Solution:

   20 Mill Street

$$\text{EUI} = \textit{Yearly Energy Consumed} \;/\; \textit{Building Area} = \frac{54\text{GJ}}{111.5\text{m}^2} = 0.48\ \text{GJ/m}^2$$

$$\text{CEI} = \textit{Yearly Emissions} \;/\; \textit{Building Area} = \frac{6.55\ \text{tonnes C0}_2\text{e}}{111.5\text{m}^2} = 58.7\ \text{kg C0}_2\text{e/m}^2$$

   242 Kehl Street

$$\text{EUI} = \textit{Yearly Energy Consumed} \;/\; \textit{Building Area} = \frac{30\text{GJ}}{103.7\text{m}^2} = 0.29\ \text{GJ/m}^2$$

$$\text{CEI} = \textit{Yearly Emissions} \;/\; \textit{Unit Area} = \frac{4.52\ \text{tonnes C0}_2\text{e}}{103.7\text{m}^2} = 43.6\ \text{kg C0}_2\text{e/m}^2$$

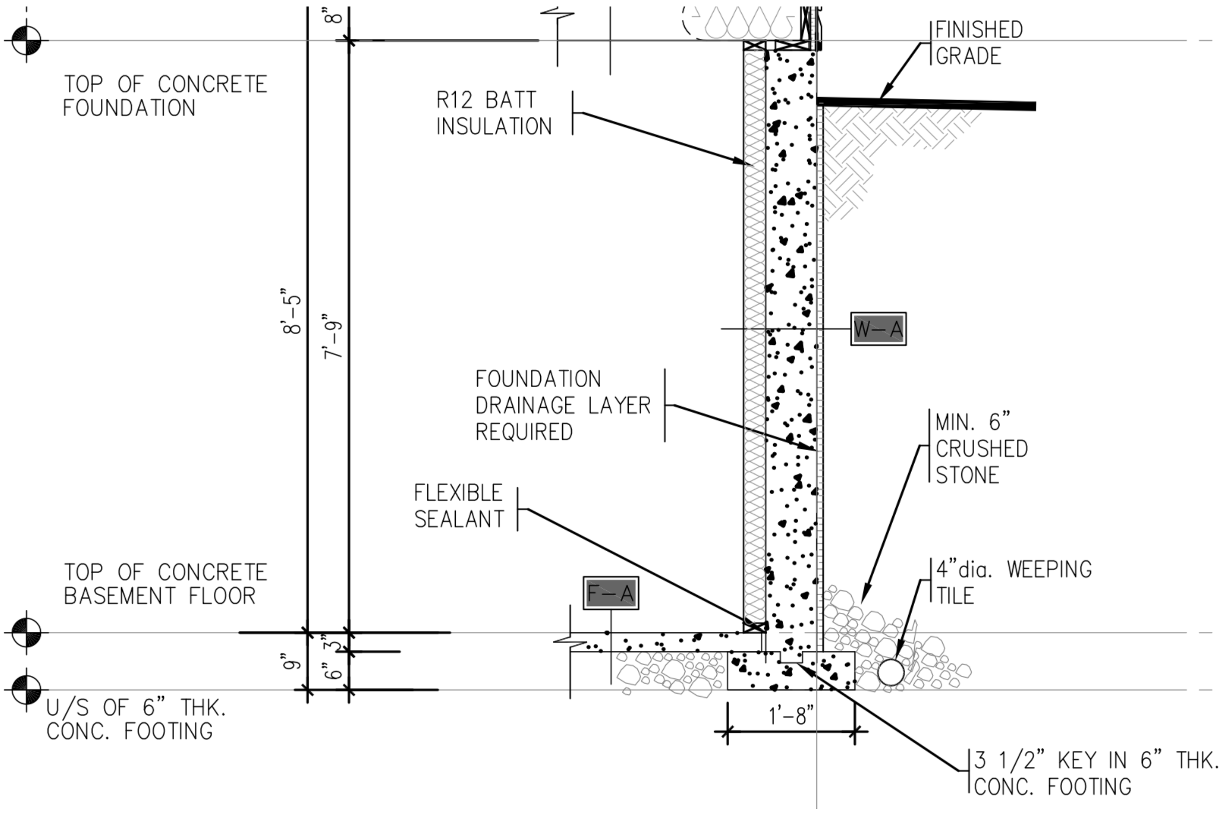
   These numbers fall well below the Canadian average of 1.0 GJ/m^2 (site EUI), however, they are for residences, and should be below. That said, they are still below the multi-unit residential figure (1.1), even after scaling up to source EUI with a factor of 1.6.

2. Comment on the algebraic sign for each embodied carbon value given (production, demolition, and recycling), for wood, as compared to brick, concrete, and steel, as shown in Table 2. Specifically, why is the production of wood associated with a negative embodied carbon value, and why is the demolition of wood products associated with such a high embodied carbon value? What is a negative embodied carbon, and why is the recycling of materials assigned a negative value?

   Solution:

   Wood has a negative EC value for production because of "carbon sequestration". By using wood in buildings, the carbon inside the wood is being stored there for many years, offsetting the carbon emissions that would occur if the tree died and decomposed. However, at the end of the products life, the wood is typically burned or decomposed in landfills, releasing that carbon (and a significant amount of it). Negative embodied carbon arises from the recycling of materials *because it saves carbon that would occur due to the extraction and manufacturing of new raw material.*

3. Add up the quantity of concrete required to make the footings, foundation walls, and basement slab of the 242 Kehl Street building. What is the total cradle to cradle embodied carbon of that concrete? How does this value compare to the carbon arising from yearly operation, if the building lasts for 50 years? 100 years?



You may assume: 3,744 linear ft. of footing/wall (shown above), and a slab area of 2,414 ft. Add a 15% allowance to the total concrete volume to account for waste from the truck, and miscellaneous other strip/spread footings. Take the unit weight of concrete to be 2,350 kg/m³.

Solution:

Concrete	W (in)	T (in)	L (in)	m^3	kg
Footing	20	6	3,744	7	17,305
Slab	34	3	71	0	279
Wall	96	8	3,744	47	110,750
					147,584
61,013	in^3/m^3		25,089	kg CO_2e	
2,350	kg/m^3		25.09	tonnes CO_2e	

We see that just the concrete material alone gives 25 tonnes of $C0_2e$ in embodied carbon (taking a factor of 0.17). This is equivalent to more than 5.5 years of operating emissions at 4.52 tonnes per year (give in Q1). Over a 50 year lifespan, this would constitute 10% of overall emissions, but over a 100 year lifespan, it would only constitute 5%. However, if operating emissions were *reduced further through better sourced electricity, the embodied carbon would be come a higher percentage of the overall emissions (and this is only considering the concrete!).*

Discussion Questions:

1. Why is the embodied carbon of aluminum so high, and what can be done to change this?

   Aluminum takes a great deal of electricity to produce. It is likely that electricity produced from greenhouse gas emitting procedures was common for the source used in Table 2 (to get a value of 8.24 kg $C0_2$e/kg Al). Better sources of electricity (hydro, wind, solar, nuclear), would change this. Case in point – Quebec Aluminum!

2. What do you think is more important to focus on between embodied carbon of materials, and operational carbon? What are the simplest strategies for reducing each?

   To reduce embodied carbon:

- Use less material!
- Make buildings that last a long time
- Find better ways to recycle material or reuse/repurpose buildings
- Use low embodied carbon materials (or substitutes, such as fly-ash)

   To reduce operational carbon:

- Create energy efficient buildings
- Minimize energy losses by producing energy on-site
- Move away from Natural Gas and Coal as a means to produce electricity

3. Where are the embodied carbon values shows in Tables 2 and 3 taken from (what source and what locale)? How important is it for every country to have their own embodied carbon estimates? What factors change from country to country that may affect the values?