

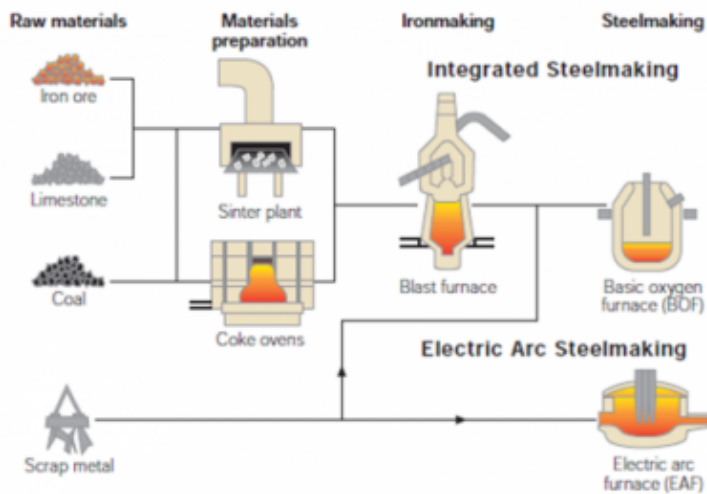
Stanford Embodied Carbon Outlook

By Alex Evers, Stanford University

Embodied Carbon can be defined as all of the greenhouse gas (GHG) emissions associated with using a particular manufactured material. In the construction industry, the term embodied carbon primarily refers to the total greenhouse gas emissions from extracting, transporting, manufacturing, and installing building materials on-site, as well as from the end-of-life emissions when the building is deconstructed. Embodied carbon constitutes 11% of global GHG emissions and 28% of the building sector GHG emissions (Architecture 2030). To reduce embodied carbon there needs to be a consistent effort by the contractor in the early stages of the project as embodied carbon is held within the actual materials being used for construction. There are multiple materials with high carbon intensity that are used frequently in the construction sector. The carbon intense materials include steel, concrete, wood, insulation, carpet, and gypsum board, while the low-impact materials include bamboo, hempcrete, sheep's wool, straw bale, and wood. Wood appears in both lists because of the various ways wood can be sourced and manufactured. Highlighting the various materials and their interaction with carbon emissions will be key in understanding areas of improvement and further reducing the campus carbon footprint.

Steel

Steel is a key commodity in the construction sector, with more than 50% of worldwide steel demand coming from construction alone (WorldSteel Association). As the human population grows and urbanization spreads, the demand for more buildings will also rise, further increasing the demand for steel. Steel has many uses within the building industry. Some examples of its use include structural sections, reinforcing bars, roofing, ceilings, HVAC, and fixtures. A large, often overlooked use of steel within buildings is the reinforcing steel used in concrete. Steel adds tensile strength and stiffness to concrete. Tensile strength is the maximum load that a material can withstand without fracturing when being stretched and is a key component in seismic active locations. Steel is also the optimal material due to its ability to bond well with concrete as well as having similar thermal expansion coefficients.



The main determinant of the embodied carbon of steel is how the steel is manufactured. Large steel mills typically employ basic oxygen furnaces (BOFs), which primarily smelt raw materials gathered through mining. These large mills typically utilize lower amounts of recycled steel (25-37%) than smaller factories do, which reuse scrap metal almost

entirely, with the recycled content of around 93% of the total material used. Smaller factories also normally use electric arc furnaces (EAF) to melt the scrap metal, which further reduces the energy needed, in turn, mitigating the amount of embodied carbon. The average requirement of energy for EAF is 2.25×10^9 joules per metric ton while a basic oxygen furnace has an energy demand typically of 11×10^9 joules per metric ton (Martelaro). The embodied carbon could be reduced even further within these small factories by powering the electric arc furnaces through clean renewable energy sources further limiting the carbon intensity of the steel. Recycled steel has no impact on structure or quality when compared to virgin steel, which would allow buildings to maintain rigid safety standards.

Beyond specific material production, optimizing steel's use is also an area to reduce embodied carbon. When designing buildings, using braced frames in 3 story buildings reduces the embodied carbon of the building by 12% due to brace frames needing less material than moment resisting frames, which are commonly used (WorldSteel Association). Braced and

Assumptions

EVGR-A	~ 6,167 m ²
EVGR-A	1879.7 m ³
Typical Multistory Office Building	12 lbs per sqft of steel
EVGR-A	9 floors
EVGR-A	333.018 tons of steel

Processes	Carbon Intensity (United States)	Total CO2 emissions (kg CO2)	Percent Decrease in Embodied Carbon EAF vs BOF
Electric Arc Furnance	600 kg CO2 per ton	199810.8	67% less emissions than Basic Oxygen Furnance
Basic Oxygen Furnance	1800 kg CO2 per ton	599432.4	

moment resisting frames are both used in buildings subjected to lateral loads and help stabilize

buildings in the lateral direction. Braced frames are joined through the use of pinned connections, which do not transfer moments, while moment resisting frames are joined through rigid joints that transfer moment. In this description moment is defined as the measure of the tendency to cause a body to rotate about a specific axis. Another method of reducing embodied carbon from steel is designing buildings at the beginning for adaptability and deconstruction. This could take various forms whether that be utilizing steel that can be easily recycled or designing a more modular building that could be easily disassembled. A framework that can be used to guarantee the recyclability of a building is the Design for Disassembly (DfD) framework, a strategy discussed by Professor Bradley Guy (Architect). Reusing building spaces or the steel used within the construction will vastly reduce the embodied carbon due to the recycling of existing building space or materials.¹

Concrete

Concrete, like steel, is a very commonly used material in building construction. Concrete is used for basic foundations, floor construction, exterior surfaces, etc. Concrete is also one of the most difficult materials and industries to decarbonize due to the inherent production of greenhouse gases throughout the concrete-making process. Concrete is composed of roughly 10% cement, 20% air/water, 30% sand, and 40% gravel. The important ingredient in concrete is Portland cement, which is a generic cement used in the vast majority of concrete and accounts for the majority of the carbon emissions. Carbon dioxide is released at two different parts of the cement production process. The first, constituting 40% of total CO₂ emissions is the burning of fossil fuels during the manufacturing process, which is needed to heat the cement mixture up to 1400 degrees Celsius (Land Ametek). The second release of carbon dioxide is the naturally occurring chemical reaction that is needed for cement to form, which constitutes 60% of total CO₂ emissions from concrete production. However, the actual proportion of ingredients used within the concrete mixture can influence its carbon impact. For example, shifting to Portland Limestone Cement, which has a higher percentage of limestone reduces the amount of cement in

¹ Using a rough estimate of the weight of steel per sqft of building applied to EVGR-A, which has an estimated floor area of 6,167 m² from rough calculations using google maps, EVGR-A uses 333.018 tons of steel. From there looking at the carbon intensity of steel from electric arc furnaces vs. basic oxygen furnaces results in the ~67% reduction in CO₂ emissions.

the mix, in turn reducing carbon emissions. Changing the kiln type is also a method of reducing carbon emissions, with preheater/precalciner kilns using on average 85% less energy than wet kilns. However, the most effective way to mitigate the embodied carbon within buildings when focusing on cement usage is to reduce the actual amount of cement needed.

Substituting cement with supplementary cementitious materials (SCMs) is an effective method of reducing cement usage within a building. Evaluating the minimum amount of cement required to meet certain standards and then filling the rest of the mixture with non-fossil fuel-based SCMs is a proven method of reducing the embodied carbon of concrete. The use of SCMs can be seen in IIT Madras campus renovation and construction where SCMs were used to reduce GHG emissions from the building of various structures on the campus (Pillai et al.). Some examples of non-fossil fuel-based SCMs include glass pozzolan and rice husk ash concrete. Glass Pozzolan is recycled post-consumer glass that is ground up and when combined with water reacts with calcium hydroxide at ordinary temperatures to create a material with cementitious properties. Depending on the needs of the project, concrete can be completely substituted with Pozzolan, a combination of Pozzolan and cement, or even a combination of Pozzolan and cement with the sequestering of CO₂ from the cement process. Rice Husk Ash Concrete is another SCM that can be used to reduce the total amount of concrete needed. Rice Husk Ash Concrete is derived from rice husks which are primarily composed of amorphous silica, which when manipulated can become and support cementitious material.

Beyond reducing the amount of cement, sequestering the CO₂ produced in the heating and chemical reaction of the cement process back into the concrete would mitigate the carbon intensity associated with creating concrete, while also improving strength. This is a new method that some companies have begun to adopt. An example of one company is CarbonCure, which actively injects carbon dioxide into their concrete mixture which is then sent to various construction sites around the United States.²

² Using a rough estimate of the area of EVGR-A foundation which has an estimated floor area of 6,167 m² from rough calculations using google maps. Also assuming a 1 foot depth of this foundation then results in 1,879.7 cubic meters of concrete, as shown in the top chart. Then using the base line carbon intensity for traditional concrete, when compared with various concrete mixtures from CarbonCure we can see the expected reduction in the embodied carbon of the concrete.

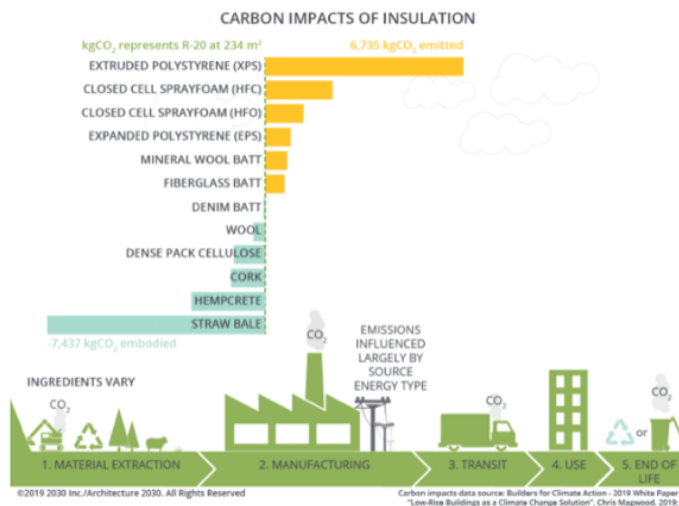
Assumptions

EVGR-A	~ 6,167 m ²
EVGR-A	1879.7 m ³
EVGR-A	0.3048 m thickness
Traditional Concrete	279.5 kg CO ₂ e per cubic meter
Baseline CO ₂ e	525376.5972 kg

Materials	Carbon Sequestered	Total kg of CO ₂ sequestered	Net kg of Embodied Carbon	Percent Decrease in Embodied Carbon (vs. Baseline)
Carbon Cure Ready Mix	15 kg per cubic meter	28195.524	497181.0732	5%
CarbonCure Precast	20 kg per cubic meter	37594.032	487782.5652	7%
Hempcrete	140 kg per cubic meter (net)	263158.224	-263158.224	(upwards of 100%)
Traditional Concrete (Baseline)	0 kg per cubic meter	0	525376.5972	

Insulation

Insulation plays a large role in building both thermally and cost-efficient buildings, especially when situated in colder climates. There are various forms of insulation, with some of the most common being Fiberglass, Mineral Wool, Cellulose, Polystyrene, Polyurethane, Natural Fibers, Polyisocyanurate, Cementitious Foam, and Phenolic Foam. The types of insulation chosen is guided by a variety of factors, including R-value, which is the thermal conductivity of a material, with higher R-values indicating better insulation. Cost, environmental friendliness, fire resistance, sound insulation, and R-value are all the main factors that are considered when choosing optimal insulation (NY-Engineers). The largest problem with the embodied carbon of insulation is that many of the high R-value insulations are synthetic and carbon-intensive, which really impacts the embodied carbon reduction that we can expect from insulation in colder climates where these higher R-values are needed. The carbon-intensive insulation material



includes expanded polystyrene (EPS), extruded polystyrene (XPS), polyisocyanurate (Polyiso), structurally insulated panel systems (SIPS), and spray foam insulation. These materials’ embodied carbon is largely attributed to the amount of energy needed to produce it, as well as the type of fuel used to generate this energy.

To reduce the embodied carbon of insulation, utilizing natural materials and blown-in applications, when possible, can reduce the embodied carbon of the building. Some examples of natural insulating materials include straw, wood, clay-Straw, hemp, cork, sheep wool, and

cellulose (Carbon Smart Materials Palette). As I mentioned before these materials typically have lower R-values than some of the carbon-intensive insulation materials but in Stanford’s climate, these natural alternatives are feasible. Hempcrete, which is insulation/cementitious material made through the use of hemp is a promising new source of insulation, which consists of hemp hurds, lime, and hydraulic additive. Hempcrete utilizes the waste of the hemp plant which is the woody core. Hemp is a very efficient and fast-growing plant, which would allow for optimal hempcrete production. It requires minimal energy investment when compared to other crops, which allows for the efficient production of hemp products. Another benefit of hemp-based composites is that it not only eliminates the use of carbon dioxide but actually sequesters/stores ~ 325 kg of carbon per metric ton. Hempcrete however cannot be used in foundations and load-bearing walls as it has a compressive strength that is 1/20 the strength of concrete (Roberts). Hempcrete and HempWool are resistant to pests, mold, and can last for centuries. This incredibly long lifetime is due to the interaction between plant-based materials and mineral binders, which give the material a high pH and good capillarity/vapor permeability creating the perfect environment to preserve the hemp. Some examples of hempcrete usage include The Triangle low-energy townhomes by Glenn Howells Architects and the Highland Hemp house built in Bellingham, Washington (Carbon Smart Materials Palette).

Assumption
 200 m3 of insulation (Hempcrete)
 1000 sqft of Walls

Material	Embodied carbon by weight*	Embodied carbon for 4x8 foot wall R-28**	Carbon footprint after sequestration	Assume 1000 sqft of Wall
Straw bales	0.063 kgCO2e/kg5	8 kgCO2e	-42.8 kg per panel	-1337.5 kg of CO2
Mineral wool batt	1.28 kgCO2e/kg	21.75 kgCO2e	21.75 kg per panel	679.6875 kg of CO2
Fiberglass batt	135 kgCO2e/kg	17.6 kgCO2e	17.6 kg per panel	550 kg of CO2
Denim batt	1.5 kgCO2e/kg	22.45 kgCO2e	15.45 kg per panel	482.8125 kg of CO2
Dense packed cellulose	0.63 kgCO2e/kg	41.3 kgCO2e	-10.3 kg per panel	-321.875 kg of CO2
Extruded polystyrene foam	3.42 kgCO2e/kg	38.5 kg CO2e	38.5 kg per panel	1203.125 kg of CO2
Expanded polystyrene foam	3.29 kgCO2e/kg	37.25 kgCO2e	37.25 kg per panel	1164.0625 kg of CO2
Hempcrete		-140 kg per m3	-140 kg per m^3	-28000 kg of CO2

<https://www.greenbuildermedia.com/buildingscience/carbon-smart-straw-bale-structural-insulated-panels>³

Wood

³ Majority of these embodied carbon values comes from referenced source. Hempcrete was added to show the benefits of utilizing a material that can sequester substantial amounts of CO2

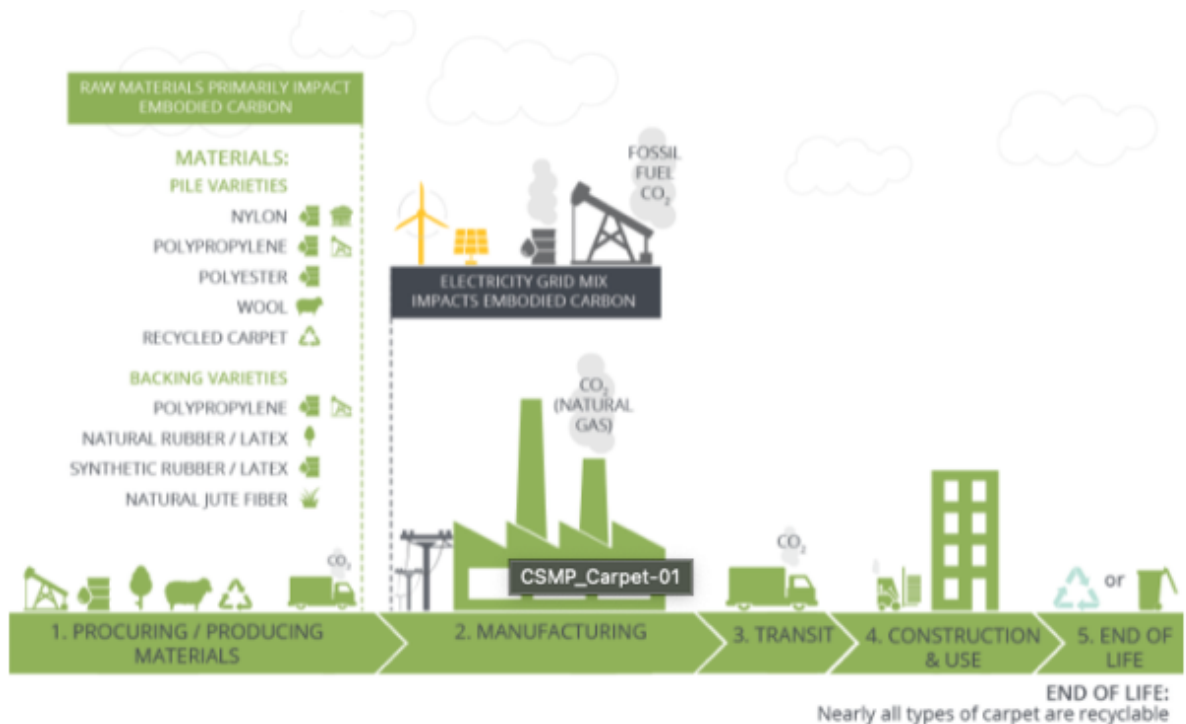
Wood has historically played and continues to play a key role in construction. Wood is different from other major construction materials in that it can either have low or high embodied carbon values depending on the extracting and processing methods of the wood. A key aspect to mitigate carbon emissions from wood is through using reclaimed wood as well as sourcing wood from “climate smart-forests,” where the wood is also not processed using fossil fuels.

Climate-smart forests have responsible forest stewardship as well as conservation efforts put in place. These might include longer rotation periods on deforestation, protection of water quality, and the restricted use of chemicals. Another best practice is avoiding sourcing wood from primary forests. Primary forests, also named old growth forests, are forests that are in the final process of succession where forest maturity has reached its peak. Harvesting from primary forests results in greater emissions of carbon because of the sequestering ability of these forests. Primary forests sequester 30 to 70 percent more carbon than degraded forests, which means preserving these primary forests is of utmost importance (INTACT). On another note, extracting from primary forests undermines the biodiversity present as primary forests typically have the highest levels of biodiversity when compared to less mature forests. Climate smart forests are not actively regulated but there are many voluntary organizations that provide certifications for climate-smart forests like the Forest Stewardship Council (FSC) certification (Ecotrust). The key takeaways from the analysis of embodied carbon in wood are to use reclaimed wood or source wood from climate-smart forests.

Carpet

Carpet is one of the largest carbon dioxide contributors in the interior of a building. The actual amount of embodied carbon attributed to carpet varies significantly depending on the type and brand. The type of carpet with the highest amount of carbon emissions is nylon fiber-based carpets, where the nylon is produced from crude oil. Approximately 75% of carpets today are made of nylon, making it the most used material in the carpet industry. The most impactful way to reduce the embodied carbon of carpets is to reduce installation/maintenance waste, use carbon-neutral carpet tile products, and use carpets with a high recycled content. The virgin

production of carpet has an estimated emission factor of 2.34 metric tons of carbon equivalent per ton of carpet (EPA). Carbon neutral tiles like Tarkett Floorprint can be used to drop this emission factor significantly. For example, when focusing on the Tarkett Lino 2.55 mm sheet of carpet the carbon footprint is 2.72 kg of carbon dioxide equivalent, while traditional carpet carbon footprint is 15.28 kg of carbon dioxide equivalent.



©2020 2030 Inc./Architecture 2030. All Rights Reserved

Gypsum Board

Gypsum board, also referred to as drywall, is made from a variety of materials, but is primarily known for the gypsum within the core of the board. Gypsum board is used as an interior wall, ceiling, and partition surface material that is typically painted over. Gypsum is naturally fire-resistant and is used extensively within the construction industry. It is difficult to reduce the carbon emissions generated by the gypsum board due to the synthesizing process of the material. The best way to reduce emissions is to design with the intent to eliminate waste and to utilize

lower embodied carbon panel products like compressed agricultural fibers (CAF). Compressed agricultural fibers operate similarly to gypsum board but instead are formed from compressed plant straw, which are treated and compressed to form a thick panel that is pest, fire, and water resistant.

Conclusion

Based on this research, Stanford should focus on the first two categories, steel and concrete, because of their high embodied carbon values and their importance to construction on campus. There are also various ways to reduce the embodied carbon in these materials, while also improving the safety and delivery of construction projects on campus.

The idea of designing with the intent to eliminate waste is something that should be considered for all materials. The “Green Square Complex” in Raleigh, N.C. is a prime example of the benefit of reducing and recycling materials from previous projects to greatly improve the cost and sustainability of a new project. Through the reuse and recycling of material from two older buildings on the property the project saved \$359,000 dollars and qualified for LEED platinum (Todd, Green Square).

Other than minimizing waste, potential next steps could include specifically analyzing the embodied emissions in the specific materials that Stanford contractors buy and looking into feasible alternatives. These alternatives could take the form as only using recycled steel, concrete with high percentage of SCMs (volcanic ash), blown-in insulation or hempcrete, or carbon neutral carpeting.

Bibliography

- Ecotrust. “Building the Pipeline for Climate-Smart Forestry in the Pacific Northwest.” Accessed February 5, 2022. <https://ecotrust.org/project/climate-smart-forestry/>.
- Contributor, Tobias Roberts, Rise. “Building with Hempcrete.” Rise, October 16, 2020. <https://www.buildwithrise.com/stories/building-with-hempcrete>.
- “Carbon Neutral | Tarkett.” Accessed February 5, 2022. http://commercial.tarkett.com/en_US/node/carbon-neutral-11914.
- “CARBON SMART MATERIALS PALETTE – Carbon Smart Materials Palette.” Accessed February 6, 2022. <https://materialspalette.org/palette/>.
- “Carpet How It’s Made.” Accessed February 5, 2022. <https://strathmoredesign.com/carpethowitsmade>.
- “Energy Use in US Steel Manufacturing.” Accessed February 5, 2022. <http://large.stanford.edu/courses/2016/ph240/martelaro1/>.
- “What Is Hempcrete? | American Lime Technology Website.” Accessed February 5, 2022. <http://www.americanlimetechnology.com/what-is-hempcrete/>.
- “Why The Building Sector? – Architecture 2030.” Accessed February 5, 2022. <https://architecture2030.org/why-the-building-sector/>.
- “Worldsteel | Buildings and Infrastructure.” Accessed January 7, 2022. <http://www.worldsteel.org/steel-by-topic/steel-markets/buildings-and-infrastructure.html>.
- https://19january2017snapshot.epa.gov/www3/epawaste/consERVE/tools/warm/pdfs/CarpetPCReport_11_21.pdf (EF carbon)
- <https://files.nc.gov/ncdeq/document-library/Green%20Square%20Demo%20Case%20Study.pdf>
(case study)