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Addressing Embodied Carbon in High Performance Design

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Abstract: Design professionals are focusing on driving down building operational energy consumption as a way to address climate change and the built environment. Passive house is one approach to high performance design using super insulation, airtight construction, and high performance windows. Operational energy savings in passive houses are anticipated to be 70% better than code. We wondered how the embodied energy (energy used in material manufacturing and construction) of passive houses compares to the carbon emissions from operating these high performance buildings. This paper compares the embodied energy and carbon emissions of a multifamily, affordable passive house building and a similar building of standard construction – the Stellar Apartments (first certified, affordable multi-family passive house in the US, completed in August 2013). The passive house (PH) building has undergone continuous energy monitoring alongside a building of identical layout but built to an optional Oregon state energy standard, Earth Advantage (EA) which is estimated to be 10-15% better than code. Revit, Zero Tool, and Tally® will be used to calculate and compare the environmental impacts of the materials and operation in these buildings. Alternative wall assemblies will also be examined to evaluate the feasibility of achieving truly zero carbon buildings.

Keywords: embodied carbon, passive house, Stellar Apartments, Tally®, Zero Tool

Introduction

The Paris Climate Agreement commits the international community to keeping "global average temperature increase well below 2°C above pre-industrial levels" while pursuing efforts to limit the temperature increase to 1.5°C. The Intergovernmental Panel on Climate Change (IPCC) estimates that in order to achieve this goal, the world must phase out fossil fuel CO_2 emissions by 2050 (IPCC, 2013) (Hare et al., 2014). Global companies, foundations, and leaders in all sectors are responding to this call and establishing practical steps and commitments to reach this goal. According to Architecture 2030, between 2015 and 2050 more than two trillion ft^2 (192 billion m^2) of building stock will be constructed, retrofitted, or torn-down and reconstructed worldwide – equivalent to building an entire New York City (all five boroughs) every 35 days for 35 years (IEA, 2016). It is crucial that we design and construct this building stock to Zero Net Carbon standards by 2050 if we hope to meet the global goal set by the Paris Climate Agreement. This goal can only be reached if building design addresses both operational and embodied carbon emissions.

Examining the lifespan (assumed 60-years) of a building built to current code standards, embodied energy represents about 45% of the building's total energy footprint, while operational energy represents the remaining 55% (Architecture 2030). However, as buildings become more efficient and operational energy consumption is reduced, the relative impact of the embodied carbon of materials increases. Furthermore, to reach Zero Net Carbon by 2050, there are only 33 years left to eliminate building sector carbon emissions. For the approximately two billion ft^2 (192 billion m^2) that we'll construct globally in that time, Architecture 2030 estimates that as much as 90% of the energy footprint of that building stock (when energy footprint estimates are cut off at 2050) will be embodied energy, emphasizing the crucial role that embodied carbon reductions must play in achieving global climate goals (Architecture 2030).

This study focuses on the relationship between the embodied carbon of materials and the operational carbon emissions of buildings designed to passive house standards. Passive house buildings are estimated to reduce operational energy consumption by 70%, using super insulation, airtight construction, constant fresh air ventilation, and high performance windows. However, we see multiple examples of very high-embodied carbon materials used to insulate these very low energy consumption buildings. Given our global carbon deadline, material choices play a much more significant role. If the embodied carbon of building materials exceed the operational energy savings, the effort to achieve a high performance building becomes futile.

Research Objectives

This study offers a quantitate analysis of both the embodied carbon of materials and the carbon emissions from operational energy consumption in the Stellar Apartments: comparing a passive house (PH) building with an identical in layout building built to an optional State energy code, Earth Advantage (EA) (estimated to be approximately 10-15% better than code). The Stellar Apartments passive house building was the first affordable, multi-family apartment complex to achieve PHIUS certification in the United States, built in 2013 in Eugene, Oregon by the Saint Vincent de Paul Society of Lane County. The following objectives will test assumptions about material choices when designing high-performance buildings:

- Calculate the embodied carbon of the materials of the PH and EA buildings to determine if the PH building is more carbon intensive than the EA building, and if so, by how much;
- Compare the embodied carbon results of the PH and EA buildings to their operational energy use intensity (EUI) to see if the operational energy performance is worth the embodied carbon investment;
- Using those results, identify and analyse alternative wall assemblies to explore the feasibility of designing zero-carbon buildings.

Methods and Approach

Buildings: The Stellar PH and EA buildings are identical in their layout and orientation but differ in their wall assembly, windows, ventilation, and shading. Both buildings have a 2x6" (51x152 mm) stud wall with blown in cellulose insulation, use cement-fiber board siding, asphalt shingled roofs, and the same interior finishes. However, the PH building has an additional 4 inches (102 mm) of polyisocyanurate (polyiso) insulation outboard of the studs, and has high-performance windows. The PH building uses triple pane, argon-filled casement windows and the EA has double pane double-hung windows. Beginning in 2013 the two buildings underwent a two-year energy-monitoring case study. The operational energy consumption data from that case study will be used in the following calculations and comparisons.

Carbon emissions from operational energy: The operational energy consumption of the PH and EA buildings were calculated. This data will be run through Architecture 2030's Zero Tool to estimate and compare the operational greenhouse gas (GHG) emissions of the PH and EA buildings. This step converts energy consumption into carbon emissions. The Zero Tool uses EPA Target Finder data and methodology to calculate energy baselines normalized by climate, weather, space type, building size, occupancy, and schedule, and estimates operational GHG emissions.

Embodied carbon from building materials: Tally®, a software plug-in for Revit, will be used to quantify the embodied carbon impacts of the building materials. The analysis will be run for both the PH and EA buildings and will be compared to their operational carbon emissions. Though Tally® provides a robust number of environmental impact measurements, this analysis will focus primarily on Global Warming Potential (GWP). Note that the Tally-provided averages were used to estimate transportation and construction emissions for two reasons: First, to make the results of this study more universally applicable instead of site-specific, and second, it was not possible to track down the exact material manufacturer for every material used in the apartment buildings. However, when used in architectural design projects, specifying project-specific data instead of using Tally® averages will result in more accurate calculations, allowing for better decision-making.

Embodied carbon of alternative building materials: This study will also examine alternative material choices, comparing four wall assemblies to see how lower embodied carbon materials impact the total GHG emissions (embodied and operational) of the PH building and analyzing the balance of embodied and operational carbon on the path towards zero-carbon construction.

Results

The Stellar Apartments PH building has an average site EUI of 16.3 kBtu/ft^2/year (49.6 kWh/m^2/yr). The Stellar EA building's EUI was 25.6 kBtu/ft^2/year (77.7 kWh/m^2/yr). Throughout the two-year energy monitoring case study, it was found that the PH building performed 38% better than the EA building (NetZED Laboratory, 2016). These values were used in the Zero Tool to estimate the correlating GHG emissions from operational energy consumption.

Table 1. Emissions impacts of Stellar PH and EA; GSF = 6,156 ft^2 (571.9 m^2)

	Annual Operational GHG emissions (metric tons CO_2e)	Total Operational GHG emissions assuming 60 year lifespan (metric tons CO_2e)	Estimated Total GWP (metric tons CO_2e)	Operational Payback for Embodied (years)	Total E+O emissions, assuming 37 years, or 2013 to 2050 (metric tons Co_2e)	Total E+O emission, assuming 60 years (metric tons Co_2e)
Stellar PH	12	720	245.5	2.9	605.5	965.5
Stellar EA	18	1080	208.1	5.2	748.1	1288.1

Payback Time Analysis:

Tally® results show that the Stellar passive house building has an estimated GWP of 245,532 $kgCO_2e$, or 245.5 metric tons CO_2e. The Earth Advantage building has a GWP of 208,077 $kgC0_2e$, or 208.1 metric tons CO_2e [Table 1]. This means that the added four inches (102 mm) of polyiso insulation and the high-performance windows added 37,455 $kgCO_2e$ (37.5 metric tons CO_2e).

From the Zero Tool, we calculated that the annual operational GHG emissions for the PH building were 12 metric tons CO_2e and 18 metric tons CO_2e for the EA building. To calculate total embodied and operational carbon emissions, we multiply annual GHG emissions by the assumed life span (assumed 60 years) for total operational GHG emissions and add that to embodied carbon value. For the PH and EA buildings, the total emissions are 965.5 and 1288.1 metric tons CO_2e, respectively. However, taking into account the goal of Zero by 2050, we would be looking at the time span between construction and 2050; in this case, that is 37 years. Therefore, the total emissions would be 605.5 and 748.1 metric tons CO_2e, respectively.

These results show that even though the embodied carbon in the PH building is higher due to the additional insulation, the payback time was actually lower than the EA building due to the operational energy performance. Additionally, for both the time span to 2050 and the life of the building, PH has a lower total combined emissions than the EA building. The results from this research shows one great approach to designing zero carbon buildings is to follow passive house standards for operational energy performance (higher insulation values, airtightness, fresh air ventilation, and high performance windows) and then to greatly reduce embodied carbon of the materials chosen through comparative analysis. The following attempts to do just that.

Key GWP contributors:

The Tally® results show that the six highest GWP contributors for the Stellar PH building were: polyiso insulation (17%); asphalt singles (13%); gypsum board (13%); wood framing with insulation (13%) [blown-in cellulose with kiln-dried softwood framing]; plywood (7%); and carpet (5%) [Figure 1]. These seven categories alone contributed 68% of the overall GWP, or roughly 166,961 $kgCO_2e$.

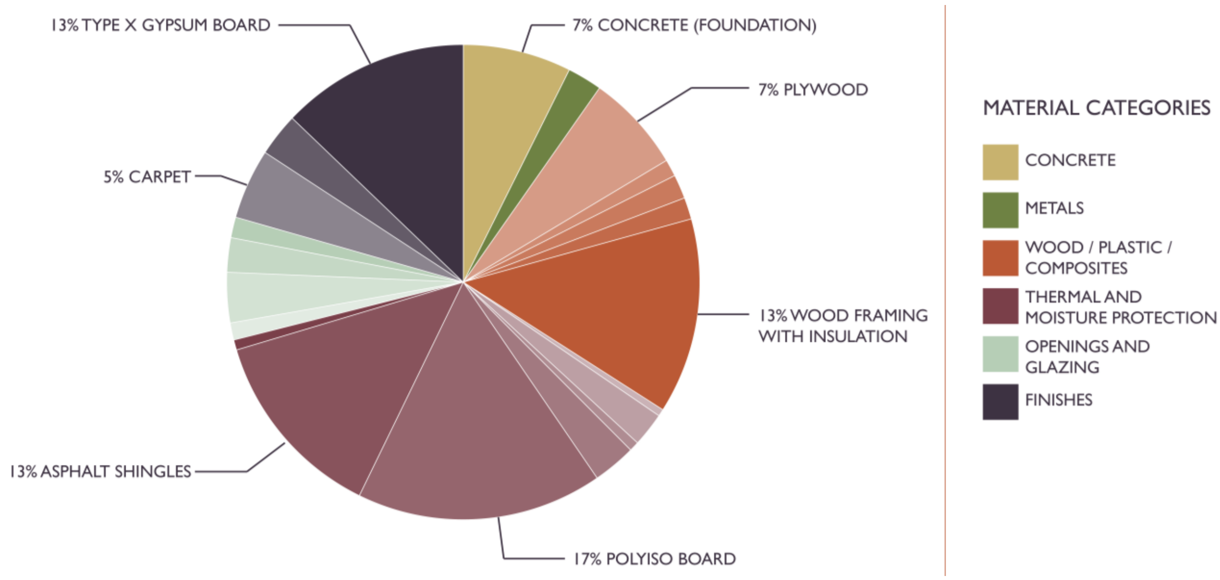


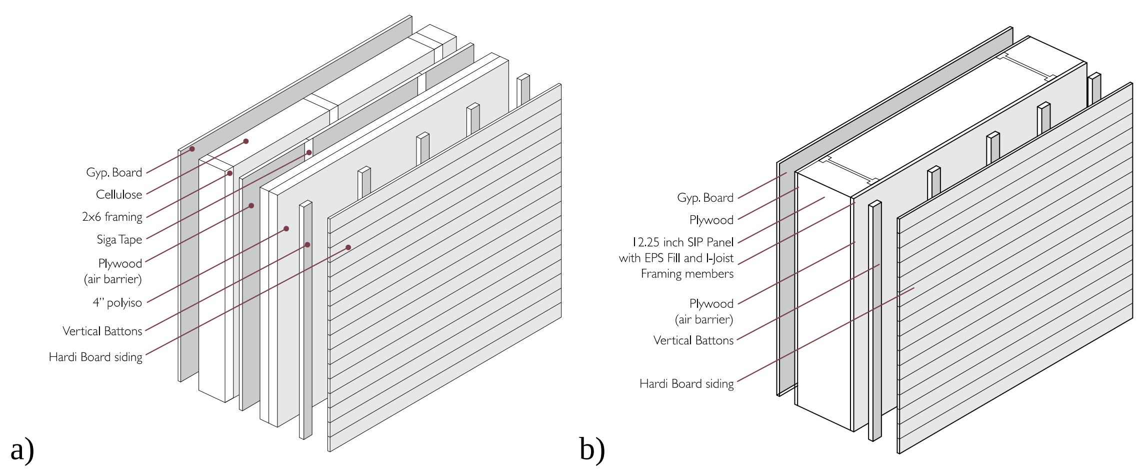
Figure 1: Embodied Carbon break-down of the as-built Stellar PH building

Polyiso has the highest R-value per inch of any insulative material resulting in the greatest operational energy savings, but was also the largest contributor of embodied carbon to the Stellar PH. This highlights the importance of understanding the embodied carbon impacts of material choices and balancing that with their relative operational savings.

Alternative Wall Assembly Comparison:

This analysis compares four wall assemblies of equal R-value to quantify and understand the opportunities for lower embodied carbon in buildings. Each wall assembly was designed to have the same R-value as the as-built PH wall, R-48, so that operational performance would remain relatively constant. The Stellar PH wall assembly was compared with a SIPS panel wall assembly with EPS, a double stud wall assembly, and a ModCell® straw panel system [Figure 2].

These wall assemblies were chosen to represent the (assumed) extremes of embodied carbon. It was predicted that even with EPS instead of XPS, SIPS panels would have the most embodied carbon, followed by the Stellar PH wall assembly, the doubled stud wall assembly, and then Straw Panels with the lowest embodied carbon.



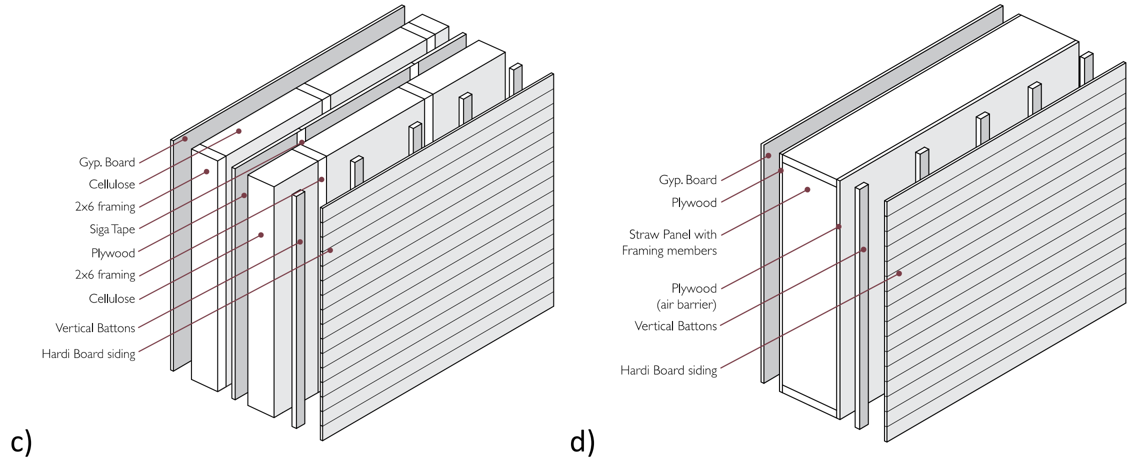


Figure 2. Four wall assemblies compared: a) Stellar PH; b) SIPS; c) double stud; and d) ModCell straw panel system.

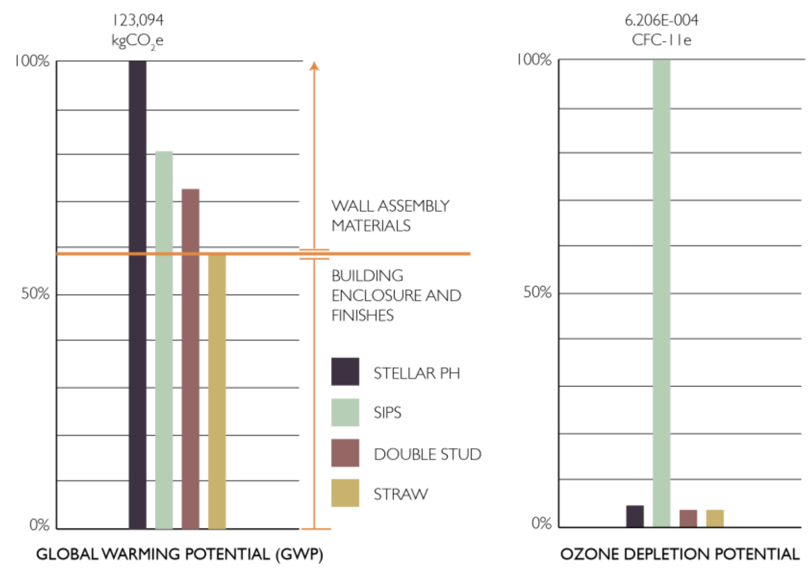


Figure 3. Wall assembly comparison: GWP (left) comparison shows the embodied carbon of the building enclosure and finish materials (interior walls, floors, and roofing) and the additional embodied carbon of the compared wall assembly materials. The ODP (right) comparison shows the impact of SIPs due to the harmful blowing agent, HCFCs.

The results both proved and disproved our assumptions. As illustrated in Figure 3, the embodied carbon of the Stellar PH wall assembly greatly exceeded the other wall assemblies, which was not predicted. Additionally, the SIPS panel was relatively close to the double stud wall assembly, also unexpected. It should be noted, though, that the Ozone Depletion Potential of the SIPS panels greatly exceeded all other wall assemblies [Figure 3, right], showing that the hydrochloroflorocarbons (HCFC's) in the blowing agent for EPS insulation has the greatest impact on the climate, though results in ozone depletion rather than global warming. The double stud wall is shown to have a relatively high GWP, which contradicts our assumptions and previous research. The GWP result for cellulose was much higher than expected. The Environmental Product Declaration (EPD) used by Tally® showed an embodied carbon of 32.19 $kgCO_2e$ per m^3 for cellulose, but was only valid until 2014. A second EPD, issued in 2014 and valid until 2019, found that when adding the production phase (which was carbon negative) to the disposal phase (more carbon intensive), the total embodied carbon ranged from 4.89 to 11.61 kgCO_2e per m^3 for cellulose for densities of 28 kg/m^3 and 65 kg/m^3, respectively (Bau EPD, 2014). This newer information might explain why the GWP for the Stellar PH wall and the double stud wall was higher than expected.

Tally® does not have straw in its material database, so data for the straw panel came from ModCell (a U.K. based straw panel manufacturer). ModCell straw panels are 3 x 3.2 m (roughly 9'10" x 10'6") panels which each hold 1300 kg CO_2 of sequestered carbon. However, materials such as straw and wood that sequester carbon can actually be considered carbon neutral since they release their stored carbon at the end of their life. Manufacturing emissions are not included in this value.

Future Steps

With each variation in the materials choice, the thermal performance of the building will likely vary and therefore new operational energy assessments are necessary, using predictive modeling. Additionally when comparing wall assemblies with the goal of reducing the embodied carbon of the building design, the next step would be to determine vapor drives in each wall assembly to verify that it would perform as intended in the specific climate zone.

Conclusions

Using Tally®, we were able to quantify the embodied carbon impacts of the first affordable, multi-family passive house in the U.S., the Stellar Apartments. The results show that even though the PH building had a longer payback period when comparing embodied carbon to operational GHG emissions, the total emissions for the PH building are significantly lower than the EA building both in the lifespan of the building and to a deadline of 2050. This shows that one feasible pathway to design zero carbon buildings is using passive house standards to greatly reduce operational carbon emissions, and then focusing on using low embodied carbon materials to further drive down total carbon emissions.

When specifying low embodied carbon materials, it is important to identify the materials with the largest embodied carbon values and to consider lower-embodied carbon alternatives. This also opens the conversation about alternative material choices. Gypsum board, for example, is the predominant interior wall finish used in U.S. construction today, yet it is one of the highest contributors to total embodied carbon. In designing low embodied carbon building, alternative interior finishes should be investigated and used.

It is important to compare materials by both the embodied value and the lifespan of the material. Two materials may have similar kgCO_2e/kilogram values, but it makes a significant difference if one has a lifetime of 15 years and the other has a lifetime of 60 years. In this case, the asphalt shingles contribute considerably to the overall embodied carbon of the building partly due to their short life-span (15 years) requires multiple replacements (and thus additional embodied carbon emissions) over the lifespan of the building.

Comparing manufactured materials to natural, carbon-neutral materials is complex and it is critical to define a time span when evaluating embodied carbon impacts. For example, cellulose (recycled paper) sequesters carbon and has an initial carbon negative value, but when sequestered carbon is released at end-of-life, the material does have a significant carbon impact. That said, materials that sequester carbon can never release more than what they initially sequester (not accounting for manufacturing, transportation, and disposal emissions), and are inherently carbon-neutral. This study did a whole life cycle (cradle to grave) analysis, showing the full lifecycle of carbon emissions and not just the upfront carbon emitted or sequestered. However, when the timeframe is shortened from the life of the building (assumed 60 years) to the threshold set by the Paris Agreement of Zero by 2050, using materials that sequester carbon up-front is key to reaching the goal of Zero by 2050.

If we hope to meet the goal set by the Paris Agreement of Zero Net Carbon by 2050, the embodied carbon and material choices becomes significant. There are many factors involved in deciding which material to use in a wall assembly; and it is important to examine energy *and* an embodied carbon as in iterative process throughout all phases of design. Tools such as Tally® make this much more feasible and get us closer to reaching Zero by 2050.

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Tally® life cycle assessment software: developed by architecture firm KierenTimberlake, uses material quantities from by Revit and embodied carbon data from a life GaBi database to estimate embodied energy.