Future of Thermal Insulation, Zero Carbon Options

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ABSTRACT: *The paper is looking into the future of thermal insulation to come up with a fair assessment of traditional and innovative alternatives. The building industry is now looking into not only reducing operational energy, but also embodied energy. A general look at thermal insulation materials currently used in buildings shows an urgent need to transformative change in the market towards low-carbon materials. Since market changes typically take time and face resistance, it is time to find out which future materials are ready to replace the traditional ones. Considering thermal performance of the building envelope, thermal insulation is the layer that contributes the most to overall thermal resistance. High performance buildings call for higher levels of thermal resistance. This research project acknowledges the need to assess embodied carbon of thermal insulation. First, a review was conducted of insulation types available in the American market. A sample of materials was selected based on availability and market share. The sample includes fiberglass bass insulation, cellulose, extruded Polystyrene, and spray foam. Second, a typical wall assembly for a house in the U.S. was defined and modeled using the selected types of insulation materials. Location of the study set to Oklahoma and the baseline wall assembly was in compliance with IECC 2018. Total R-value of all tested wall assemblies were kept the same in order to limit the analysis to embodied energy, since operational energy would be equal in all cases. Then, life cycle carbon analysis was performed in Tally to assess the insulation types. Research results showed that Insulative Cork Board had the best performance (lowest carbon footprint) among the types of materials selected. Cork Board undergoes extensive testing of the final product with third-party certification and verified EPD (Environmental Product Declaration), resulting in high-quality input data for carbon analysis. The next contender among the innovative insulation materials is Mycelium. Mycelium is still a new product to the market and there has not been any certification performed to ASTM standards.*

KEYWORDS: Decarbonization, Insulation Materials, Building Envelope, Life Cycle Analysis, Building Innovations

INTRODUCTION

Building insulation plays an important role in the lifespan of a building. It improves the thermal comfort and well-being of the occupants while reducing energy consumption. However, most materials used are manufactured using mined and/or fossil fuel-based materials. These materials are by-products of oil and are being used in increasing quantities, which will eventually lead to problems associated with material depletion and its disposal during its end-of-life stages. One sustainable solution suggests the use of biodegradable materials. There have been several attempts to develop biomaterials. The comprehensive study entails the comparative documentation of these following attributes: carbon emissions, cost, protective features, production and manufacturing, market shares, durability, acoustics and energy analysis. In order to produce a well-rounded report, a handful of materials were selected to analyze against the project objective. The non-renewable products are materials that have the highest market shares for oil-based insulation and will serve as a basis of expectation for the insulative properties in the renewable materials. Along with mycelium, the highest market shared materials that will be analyzed are soy-based insulation, hempcrete, rigid cork, and cementitious foam; all of which are utilized as lateral comparison. Software was utilized for comparative analysis. Tally analyzed the life-cycle analysis performance while EC3 organized the visual of carbon flows.

1. METHOD -- MATERIAL OVERVIEW

1.1. Conventional insulation materials

- *Fiberglass Batt*: It is made primarily from silica spun into glass fibers with a binder. Most fiberglass insulation has at least 30% recycled-glass content. Low-density fiberglass may be less effective under very cold conditions due to its tendency to allow for air movement, but high-density products are available.
- *Extruded Polystyrene XPS*: XPS is thermoplastic, closed-cell foam insulation derived from petrochemicals. But XPS's excellent moisture resistance, high compressive strength, and low cost make it a popular insulation material particularly for below-grade applications.
- *Spray Foam Closed Cell*: It can be used for an exterior foundation, with proper drainage. While the blowing agent is non-ozone depleting, it is potent for greenhouse gas, with a high global warming potential (GWP).
- *Spray Foam Open Cell*: Compared to closed-cell SPF, open cell products use significantly less material, making it less expensive. However, open cell insulation achieves a much lower R-value and is not as effective at stopping moisture flow. It cannot be used below grade or in high-moisture applications.

- *Cellulose:* Cellulose Batt is made from recycled newspaper by hammer milling but also requires other fibers, binders, and borate-based and/or ammonium sulfate flame retardants.
Of the five analyzed components, closed-cell extruded polystyrene has the best R-value per inch at 7.1 per inch, however it has a high carbon footprint per square foot in comparison to the other conventional materials.

1.2 Innovative insulation materials

- *Soy-Base Spray Foam:* A high-performance, versatile spray foam insulation designed for residential construction. Its unique formula incorporates recycled plastic bottles and renewable oils to create high-performance, closed-cell spray foam insulation. It combines multiple control layers into a single application.
- *Cementitious Foam (Airkrete):* An inorganic, foamed magnesium-oxide cement insulation, and is good for people with chemical sensitivities. There is no off gassing, and it requires no flame retardants to remain noncombustible. The cured foam does not function as an air barrier.
- *Insulative Cork Board*: This versatile material is formed into a semi-rigid board as an insulative panel. It will not lose R-value over its lifetime unlike XPS. Since cork has a high vapor permeability than foam, there is a reduced risk of moisture issues in the wall assembly that can potentially extended the structure's lifespan.
- *Hempcrete:* A biocomposite material that is a mixture of hemp hurds, lime, sand, and pozzolans. It is easier to work with than traditional lime mixes and acts as an insulator and moisture regulator. It is a lightweight material that is ideal for most climates, and it combines the insulation and thermal mass into one.
- *Mycelium:* This insulation board is an R-4-per-inch rigid material made from mycelium that are grown in agricultural waste materials.

Insulative cork board is the best in terms of renewability, carbon absorption and certifications. However, the next contender for an innovative insulation is going to be the mycelium insulation. Mycelium is still a new product to the market and there has not been any certification performed to the ASTM standard making it difficult to produce a solid conclusion based on qualitative information alone.

1.3 Software utilized

- *Tally* utilizes BIM data to perform a life cycle assessment based on the quantities of materials used. For simplicity, ceilings and floors were omitted and the interior was assumed to be finished with a gypsum wall board. The emphasis was on the envelope itself so specific data points could be excluded from the analysis.
- *EC3* used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly.

2. METHOD -- ENERGY SIMULATION

2.1 General information

This section compares different insulation technologies discussed in the previous section. For this purpose, a basic wall assembly was created to produce LCA data for the conventional insulation. By utilizing the IECC 2018, the comparison baseline is created for needed to explore and compare (Table 1).

Table 1: Wall Assembly. (Author 2021).

Location	Oklahoma
Climate zone	3A
Wall dimension	4'-0" wide x 9'-0" tall
Wall thickness	3 ½" to 7 ¼"
Stud spacing	24" O.C

2.2 Material properties

Attributes Table to Compare Insulations: This study was initially approached with an excel sheet that was utilized to compare the characteristics and attributes of the insulations in one place. This table (Table 2) also displays two materials that were later removed due to a lack in information.

Cost For Insulation: This excel sheet was used to compare the cost per square foot and the cost for the R-Value per square foot. It takes the given price from a construction material supplier whether it was for one board or measured coverage. If it was a measured coverage the total price was divided by the area that was given by the company. This gave the price per square foot at 1" thick. This price was then multiplied by required thickness (Table 3) of insulation to meet the R-Value from the IECC 2018 code.

Table 2: Insulation comparison

	Brand	R-value per inch	Carbon emissions	Water resistant	Pest resistant	Fire resistant	*Density lb/cft*
Fiberglass batt	Owens	4.06	2.18124 $kgCo_2/M^2$	< 5% ASTM E96	ASTM C1338	ASTM E84 UL723	0.116
XPS – Extruded	Dupont	5	9.03 E1 $kgCo_2$	1.5 ASTM E96	ASTM C1338	ASTM E84 UL723	0.15
XPS - Extruded	Owens -Foamular	5	2.19 $kgCo_2/M^2$	ASTM C578 Type IV	ASTM C 1338	ASTM E84 UL723	0.15
Spray foam (Closed cell)	Demilec Huntsman	7.1	N/A	ASTM E96	ASTM C 1338	NFPA 285	2
Spray foam (Open cell)	Demilec Huntsman	3.8	N/A	ASTM E96	ASTM C 1338	NFPA 285	0.45
Cellulose	Greenfiber	3.7	N/A	ASTM C1338	ASTM C 1338	Extremely Flammable	0.519
Soy-based insulation	Demilec	7.4	> 0.5–4.9 $kgCo_2/M^2$	ASTM E96	ASTM C 1338	ASTM E84 NFPA 286	2.1
Hempcrete	Hempitecture	3	−2454.21 $kgCo_2E/M^2$	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Hempcrete	Hempecosystems	3.1	−2454.21 $kgCo_2E/M^2$	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Rigid cork insulation cork board (IBC)	Corktherm	3.61	−1.91 $kgCo_2/M^2$	0.5 kg/m^2 EN1609	Yes w/Treatment	Euro Class E EN 13501–1	7
Cementitious foam	Airkrete	3.9ASTM C518, 6 per DLS report	D5116 carbon negative	ASTM E96	ASTM C 1338	ASTM E84-81A	5
Mycelium	Ecovative designs	4	Carbon negative	Yes	Yes w/Treatment	Low with no Silica added	59–552 (kg/m^3)

Table 3: Insulation Costs

-	Brand	Cost Given	/	Coverage sqft	=	Cost per SQFT	*	Thickness of Insulation	=	Cost for R-Value / sq ft
Fiberglass Batt	Owens	38.32	/	48.96	=	0.783	*	-	=	$0.783
XPS - Polystyrene Extruded	Dupont	32.98	/	32	=	1.030625	*	4	=	$4.12
XPS - Polystyrene Extruded	Owens - Foamular	23.25	/	32	=	0.727	*	4	=	$2.91
Spray Foam (Closed Cell)	Demilec Huntsman	1.50 @ 1in thick		-	=	1.0 / 1 in	*	2.82	=	$2.82
Spray Foam (Open Cell)	Demilec Huntsman	$0.54 per sqft @1"		-	=	0.54	*	3.421	=	$1.85
Cellulose	Greenfiber	$3.43 for 19 lb	/	22.7	=	0.151	*	-	=	$0.15
Soy Based Insulation (Closed Cell)	Demilec	3.00/ 1in		-	=	3.00 sqft	*	2.703	=	$8.11
Hempcrete	Hempitecture	54.99	/	19.98	=	1.25	*	6.45	=	$8.06
Hempcrete	Hempecosystems	54.99	/	19.98	=	1.25	*	6.45	=	$8.06
Rigid Cork	Corktherm	1.79		1	=	-	*	5.54	=	$9.92
Cementitious Foam	Airkrete	1		1	=	1.00	*	5.13	=	$5.13
Mycelium	Ecovative	1.71	/	1	=	1.71	*	5	=	$8.55

2.3 Wall structuring

Wall Assemblies: To represent the most typical case of residential construction, 2x6 wood stud wall is selected for simulations. The sheathing and interior layers are kept the same for each case. The exterior finish layer that is applied is a wood siding layer and a brick veneer layer. Different types of insulation materials are selected. The simulated cases are named in correspondences to the different insulation materials used in the wall models (Table 4).

Table 4: IECC 2018 Wall Thickness (IECC 2018).

-	Brand	Total R-Value	/	R-Value per Inch	=	Thickness for R-Value	Wall Stud Frame
Fiberglass Batt	Owens	20	/	4.06	=	4.926108374	2 × 6
XPS - Polystyrene Extruded	Dupont	20	/	5	=	4	2 × 6
XPS - Polystyrene Extruded	Owens - Foamular	20	/	5	=	4	2 × 6
Spray Foam (Closed Cell)	Demilec Huntsman	20	/	7.1	=	2.816901408	2 × 4
Spray Foam (Open Cell)	Demilec Huntsman	20	/	3.8	=	5.263157895	2 × 6
Cellulose	Greenfiber	20	/	3.7	=	5.405405405	2 × 6
Soy Based Insulation (Closed Cell)	Demilec	20	/	7.4	=	2.702702703	2 × 4
Hempcrete	Hempitecture	20	/	3	=	6.666666667	2 × 8?
Hempcrete	Hempecosystems	20	/	3.1	=	6.451612903	2 × 8?
Rigid Cork	Corktherm	20	/	3.61	=	5.540166205	2 × 6
Cementitious Foam	Airkrete	20	/	$3.90	=	$5.13	2 × 6
Mycelium	Ecovative	20	/	4	=	5	2 × 6

3. TESTING AND RESULTS

3.1 Conventional data

To analyze the conventional materials, Tally was used to create diagrams representing each type of insulation under this category. Tally's database had the selected brands information available to study the lifecycle analysis of each material within a wood stud wall with typical wood siding or brick siding. (Fig. 1).

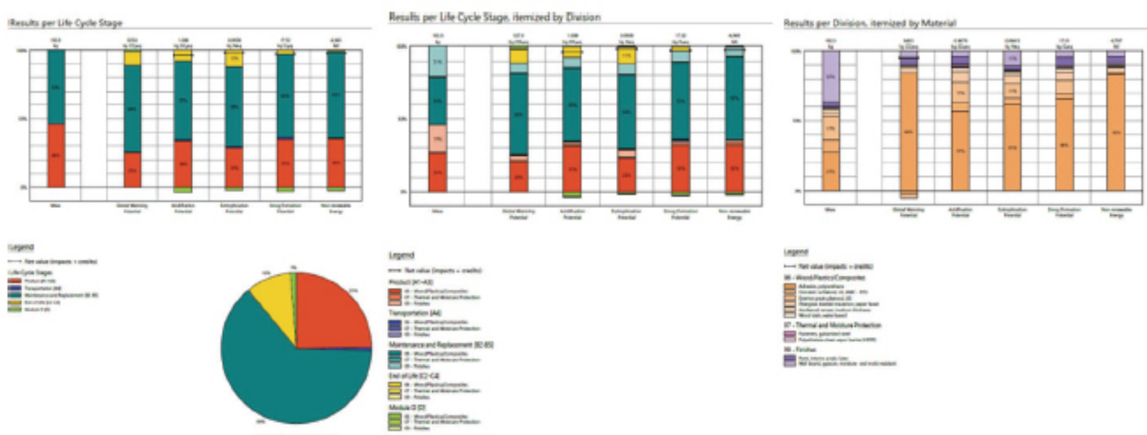


Figure 1: Tally results. (Author 2021).

Each set of data given determined what portion of the product had the greatest impact in terms of carbon emissions by lifecycle stage (left), division (center), and material (right). The lifecycle stage diagram breaks down which portion of the material's life has the most global warning potential within a vertical bar chart and pie chart. By division takes the lifecycle stage further and breaks it down into components based on finishes, thermal and moisture protection, and wood/plastics/composites. Lastly, the final diagram displays what material within the insulation is causing the most output. The data obtained for wall assemblies was similar because the masonry brick and standard lime mortar produced the most carbon. This unfortunately overrode the data about the insulation due to the large amounts of carbon released during the production of masonry.

- *Fiberglass Batt / Wood Wall:* Lifecycle Stage: Most impactful stage: Maintenance and Replacement.

Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.

- *Fiberglass Batt / Brick Wall:* Lifecycle Stage: Most impactful stage: Product. Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, the increase in global warming potential it likely because of the brick veneer. By Division: Most impactful stage: Maintenance and Replacement – Masonry. Conclusion: The masonry that added to the amount of embodied carbon in this wall assembly. By Material: Most impactful Material: Generic Brick and Lime Mortar. Conclusion: Itemizing the wall assembly by the material, Tally gave the results that 73% of the resulting global warming potential is marked up to the masonry in the envelope.
- *Extruded Polystyrene XPS:* Wood Wall Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Common insulation, however once it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.
- *Spray Foam Closed Cell / Wood Wall:* Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane. Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case.
- *Spray Foam Open Cell / Wood Wall:* Lifecycle Stage: Most impactful stage: Maintenance and Replacement Conclusion: Common insulation, however it cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle. By Division: Most impactful stage: Maintenance and Replacement - Wood/Plastics/Composites. Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Material: Adhesive Polyurethane Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.
- *Cellulose / Wood Wall:* Lifecycle Stage: Most impactful stage: Maintenance and Replacement. Conclusion: Cellulose is another common insulation type that is somewhat being phased out due to its health risk, and amount of maintenance of the product. Due to the cellulose fibers settling, it needs to be replaced so that the R-value may be maintained. Its embodied carbon is likely released as it ages and it will eventually cost more due to the consistent replacement. By Division: Most impactful stage: Maintenance and Replacement - Wood/Plastics/Composites Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment. By Material: Most impactful Cellulose. Conclusion: The breakdown of the wall assembly shows that the polyurethane adhesive and the blown-in cellulose insulation is what contributes the most to the overall global warming potential of this specific wall assembly.

3.2 Innovative data

Unfortunately, due to the limitations of the LCA programs, there was not a similar way to organize the data for the Innovative insulations that were reviewed for this study. Instead, a qualitative analysis was performed using a point system that was inspired by the LEED points and accreditation system. To the Left (Top) the table shows the selected attributes of the insulations in the first column. This covers the basics for renewability, carbon emissions, safety features, market presence, and many more. The table then compares the attributes of the selected insulations from a scale of −2 to 2 and these are labelled as such (Tables 5 and 6):

Table 5: Qualitative data for innovative insulations. (Author 2021).

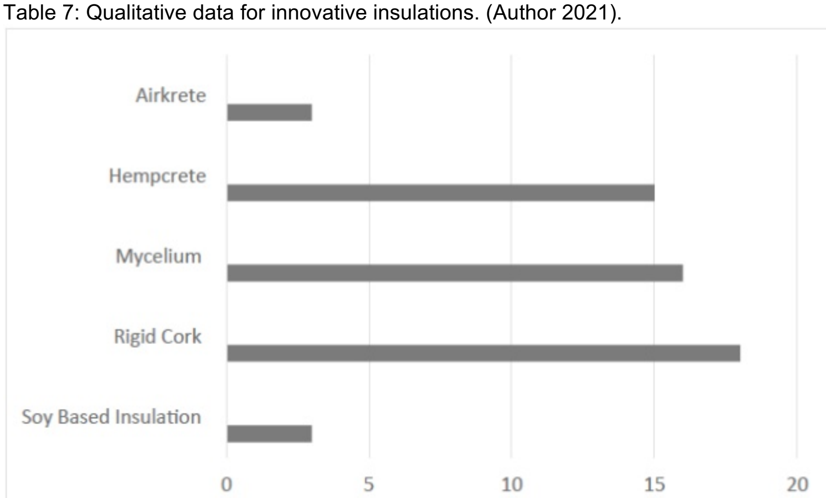
-	Soy Based (Closed Cell	Hempcrete	Rigid Cork	Cementitious Foam	Mycelium
Carbon Absorption	0	2	2	2	2
Carbon Emissions	-2	0	-1	0	0
Fire Resistant	2	2	1	2	1
Water / Mold Resistant	2	2	1	1	-1
Pest Resistant	2	2	1	2	-1
Renewable	-2	2	2	-2	2
Recyclable	-2	-1	2	-1	2
Biodegradable	-2	1	2	-2	2
Availability	2	2	-1	1	2
Market Presence	2	1	2	-1	1
Skilled Labor Required	-2	-1	2	-1	1
Waste Production	-2	1	2	-2	2
Certifications	1	-1	-1	1	-1
Sound Absorption	2	2	2	1	2
Added Air Barrier	2	1	2	2	2
Total Points	3	15	18	3	16

Table 6: Point system for innovative insulations. (Author 2021).

−2	Negative environmental impact and/or no
−1	Possibly but not proven
0	Not applicable/Not available
1	Yes, but does not have certifications
1	Yes, and has been certified by company

The insulations were then measured according to whether the information was available, had a positive impact on the environment, had no information available, and had a negative environmental impact. The chart to the Left (bottom) then measures the insulations in comparison to each other based on the score that they received from the qualitative insulations (Table 7).

Table 7: Qualitative data for innovative insulations. (Author 2021).



3.3 EC3 Sankey Diagram

EC3 used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly. The resulting chart shows what materials are demanding the most carbon. These Sankey diagrams summarize all the energy transfers taking place in the lifecycle process of the wall assembly. The thicker the line or arrow, the greater the amount of energy involved (Fig. 2).

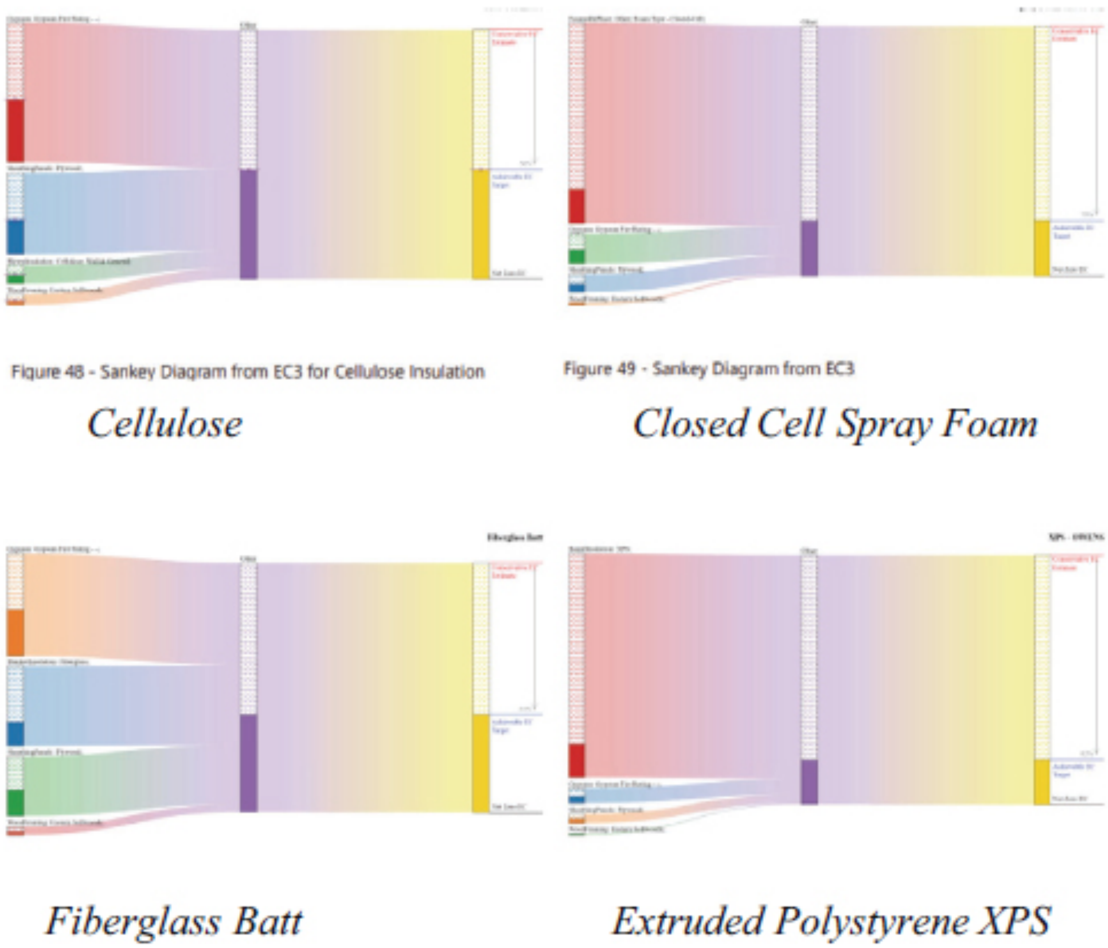


Figure 2. Sankey diagram from Ec3. (Author 2021).

CONCLUSION

In this study, the carbon emissions and characteristics of a residential wall assembly are studied by modeling two different wall assemblies in Oklahoma's climate zone 3A. A side-by-side comparative study was performed for different types of building insulation materials, which provide a better understanding and design alternatives for this field of study. The results show that insulation materials have a significant influence on the carbon footprint and overall performance of the building. Among all the types of insulation materials discussed in this research, ICB (Insulative Cork Board) is the best performing one regarding both carbon absorption, lightweight density, and thermal capabilities. Using ICB will allow for carbon to be absorbed from the built environment and still perform thermally while being the most sustainable material. The only negative is that the market is available more in the European area, however the United States would be capable of growing the Cork Oak in a simulated climate! The one issue with the study that occurred during the duration of the research was the limitations of the LCA data programs. A lot of the innovative insulations have not sought-after certifications and therefore are not in any of the cradle-to-cradle databases. This was a limitation that I specifically found with Tally. Tally's database does not contain the capability to access new forms of data outside of the initial library, nor does it allow for any customization of the materials in the program in order to manipulate the library for the specific needs of innovative insulations. This does prove that our studies in a more sustainable insulation have a lot more work to do but there are large steps that have already been taken towards the future of our built environment.

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