University of Colorado Boulder

Embodied Environmental Impact

U.S Department of Energy

Solar Decathlon 2023

Build Competition

University of Colorado Boulder Team

03/28/2023

Background

Carbon emissions are associated with the manufacturing, construction, use and end of life of building materials. This type of consumption is known as embodied energy [1]. One of the most important considerations in achieving sustainable development is selecting materials with a low embodied energy. The sum of embodied energy and operational energy is the total life cycle energy. Operational energy consumption is responsible for emissions day after day. Understanding the operational energy impact gives insight on the future environmental impact during home ownership. This energy consumption is also an indicator of consumers monthly utility bills, which contributes to the goal of affordable housing developments, reducing cost to the homeowners. “Embodied Energy represents the total energy consumed during manufacture, transportation, construction, maintenance, and disposal of building materials and assemblies” [2].

Climate and building archetype dictate the makeup of embodied energy versus operational energy. Hong (2020) found that the total embodied energy of the residential buildings accounted for 22%–91% of the total life cycle energy over a 60-year period” [2]. Therefore, investigating both embodied energy and operational energy of a home can indicate the overall life cycle energy and environmental impact.

Operational energy still accounts for most of the life cycle energy use of buildings; however, embodied energy has gained importance especially in the case of sustainable building design. It is critical to consider a material’s carbon footprint when making a material decision. Therefore, an in-depth analysis of potential building envelope materials was conducted with embodied energy at the forefront of the decision-making process.

The building envelope is the physical barrier between the indoor environment and outdoor conditions. The CU team conducted a study focusing on exterior wall assembly design as part of the overall building envelope. The exterior wall assembly is a critical design element in protecting inhabitants from the outdoor elements while creating a safe and comfortable shelter. Designing a wall assembly that best benefits low-income communities require an analysis of multiples factors. The five factors determined critical were embodied carbon, operational energy, cost, installation duration, and air quality impact.

Embodied Carbon – Embodied carbon was decided to be analyzed in lieu of embodied energy. Embodied energy only accounts for the energy use in all life-cycle phases of the building, regardless of energy source. Renewable energy makes up some amount of embodied energy and therefore embodied carbon is a better estimate of greenhouse gas emissions [3]. The embodied carbon for each product was found using Environmental Product Declarations (EPD) in the cradle to gate (A1-A3) category.

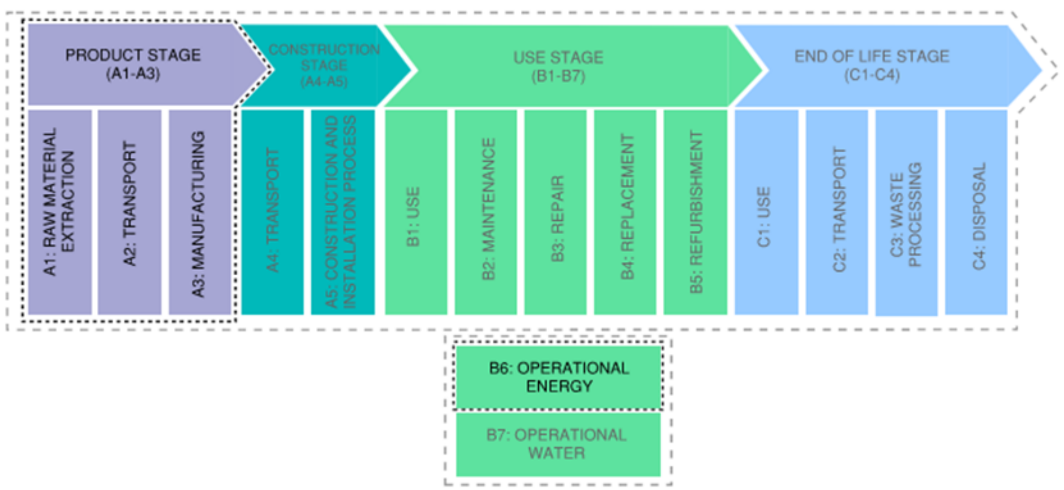


Figure 1: Embodied Carbon System Boundary

<u>Operational Performance –</u> Resistance to heat flow is rated in terms of its thermal resistance, also known as R-value [4]. Out of all the materials investigated, insulation has the highest R-value and is the biggest indicator of operational energy consumption. Insulation has a low thermal conductivity which means the material has a greater ability to resist heat transfer [4]. A larger thickness of insulation would reduce operational energy consumption but could impede the building footprint. The canopy home was subject to affordable housing livability standards [5] and limited space that restricts a larger wall depth, therefore, R-value and R-value per inch were evaluated for each material.

<u>Cost –</u> Since minimizing cost is at the forefront of affordable housing, material and install costs were investigated to provide information regarding what products fit within the allotted budget. Material cost estimates were either provided by a vendor, obtained from a building supply store's online ordering platform, or found using RS Means and adding an inflation factor.
Construction Duration – Construction duration was decided as an important factor in affordable housing as it relates to constructability. With a lack of skilled labor, lower construction duration means an easier installation. Install duration was found using the RS Means database.

<u>Air Quality Impact –</u> "Lower-income families pay a larger share of their incomes toward health care than do higher-income families" [6]. When Americans spend more than 50% of their time at home [7], a healthy indoor environment in affordable homes is critical to equity. To assess the category of air quality impact, the chemical makeup of each product was reviewed against the "Red List". "The Red List represents the 'worst in class's materials, chemicals, and elements known to pose serious risks to human health and the greater ecosystem that are prevalent in the building products industry."

Material Selection

As a starting point for identifying materials, the project was required to meet the City of Boulder code requirements. The City of Boulder adopted the International Energy Conservation Code as well as the 2020 City of Boulder Energy Conservation Code [8]. The City Energy Conservation code requires R-20 cavity insulation or R-13 cavity insulation with R-5 continuous insulation as shown in Figure 2.

TABLE R402.1.2
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT[a]

FENESTRATION *U*-FACTOR[b]	SKYLIGHT[b] *U*-FACTOR	GLAZED FENESTRATION SHGC[b, e]	CEILING *R*-VALUE	WOOD FRAME WALL *R*-VALUE	MASS WALL *R*-VALUE[i]	FLOOR *R*-VALUE	BASEMENT[c] WALL *R*-VALUE	SLAB[d] *R*-VALUE & DEPTH	CRAWL SPACE[c] WALL *R*-VALUE
0.27	0.50	0.40	49	20 or 13+5[h]	13/17	30[g]	15/19	10, 2 ft	15/19

NR = Not Required.

For SI: 1 foot = 304.8 mm.

a. *R*-values are minimums. *U*-factors and SHGC are maximums. Where insulation is installed in a cavity that is less than the label or design thickness of the insulation, the installed *R*-value of the insulation shall be not less than the *R*-value specified in the table.

b. The fenestration *U*-factor column excludes skylights. The SHGC column applies to all glazed fenestration.

c. "10/13" means R-10 continuous insulation on the interior or exterior of the home or R-13 cavity insulation on the interior of the basement wall. "15/19" means R-15 continuous insulation on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall. Alternatively, compliance with "15/19" shall be R-13 cavity insulation on the interior of the basement wall plus R-5 continuous insulation on the interior or exterior of the home.

d. R-5 insulation shall be provided under the full slab area of a heated slab in addition to the required slab edge insulation *R*-value for slabs. as indicated in the table. The slab edge insulation for heated slabs shall not be required to extend below the slab.

e. There are no SHGC requirements in the Marine Zone.

f. Basement wall insulation is not required in warm-humid locations as defined by Figure R301.1.

g. Alternatively, insulation sufficient to fill the framing cavity and providing not less than an *R*-value of R-19.

h. The first value is cavity insulation, the second value is continuous insulation. Therefore, as an example, "13+5" means R-13 cavity insulation plus R-5 continuous insulation.

i. Mass walls shall be in accordance with Section R402.2.5. The second *R*-value applies where more than half of the insulation is on the interior of the mass wall.

Figure 2: City of Boulder Energy Code for Insulation Requirements [9]

Continuous insulation eliminates the likelihood of thermal bridging. Thermal bridging typically occurs when a material of higher thermal conductivity, such as framing, interrupts a layer of low thermal conductivity material, such as insulation [10]. Even though Boulder code allows for just cavity insulation, an assembly incorporating continuous insulation was selected for analysis to reduce the likelihood of thermal bridging.

Specific materials for each component of the wall system were selected based on feasibility research, conventional and non-conventional precedent design and material availability for the area.

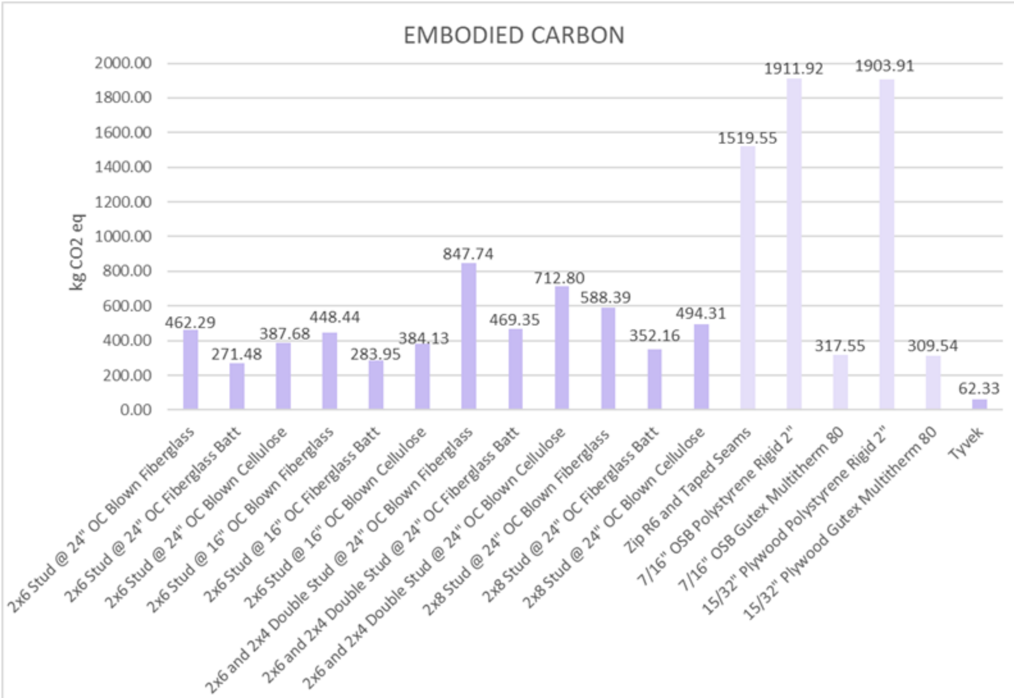
The final list of the various assembly materials that were analyzed can be found in Table 1 below. The three categories of material are: stud and cavity insulation, sheathing and exterior insulation, and air barrier.

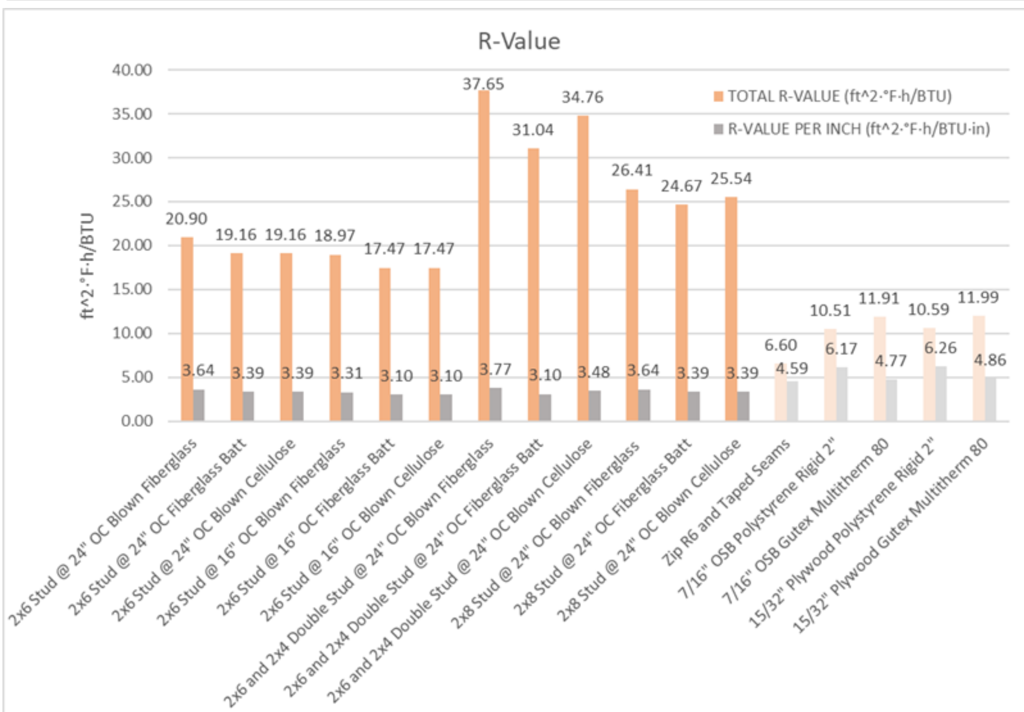
ASSEMBLY MATERIALS
STUD AND CAVITY INSULATION
2x6 Stud @ 24" OC
Blown Fiberglass
Fiberglass Batt
Blown Cellulose
2x6 Stud @ 16" OC
Blown Fiberglass
Fiberglass Batt
Blown Cellulose
2x6 and 2x4 Double Stud @ 24" OC
Blown Fiberglass
Fiberglass Batt
Blown Cellulose
2x8 Stud @ 24" OC
Blown Fiberglass
Fiberglass Batt
Blown Cellulose
SHEATHING AND EXTERIOR INSULATION
Zip R6
7/16" OSB
Polystyrene Rigid 2"
Gutex Multitherm 80
7/16" OSB Gutex Multitherm 80
15/32" Plywood
Polystyrene Rigid 2"
Gutex Multitherm 80
EXTERIOR AIR BARRIER
Taped Seams
Tyvek
Solitex Mento

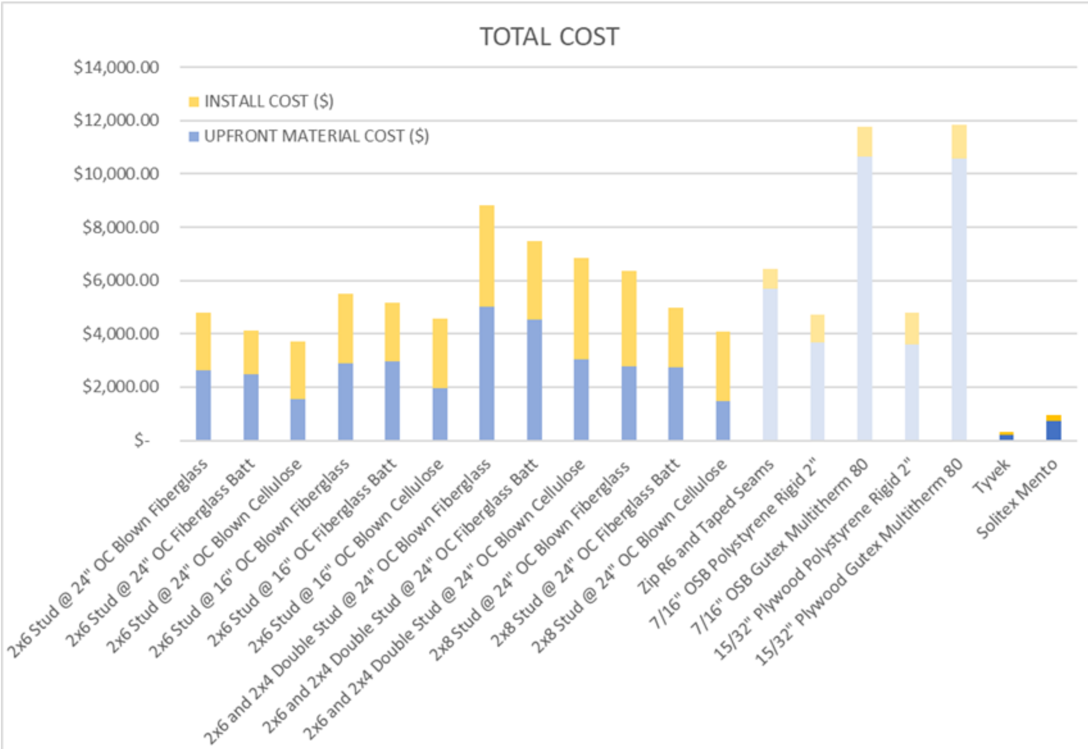
Table 1: Wall Component Selection

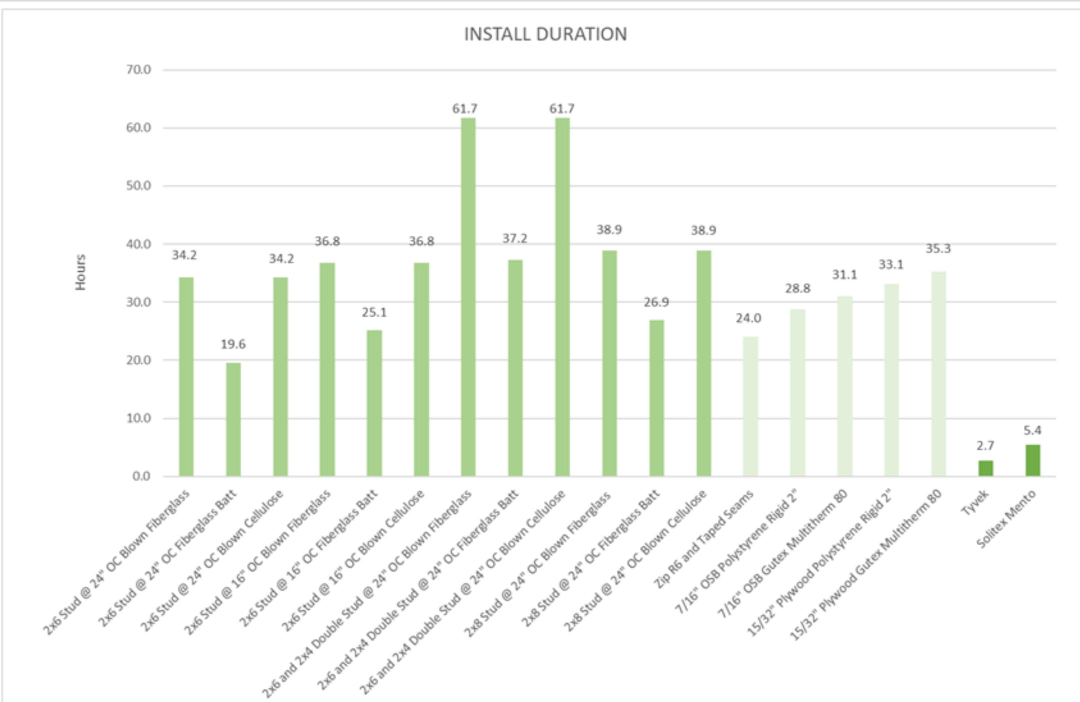
For this analysis interior and exterior finishes were excluded. The canopy home is part of a larger development that limited the exterior façade options available for selection. Interior finish had a more subjective analysis for material selection as described in Section "A", Architecture. Additionally, our team would have liked to investigate a sheathingless diagonal bracing option, however, that option was not possible with our structural loads. Therefore, the only sheathing options investigated were OSB or plywood.

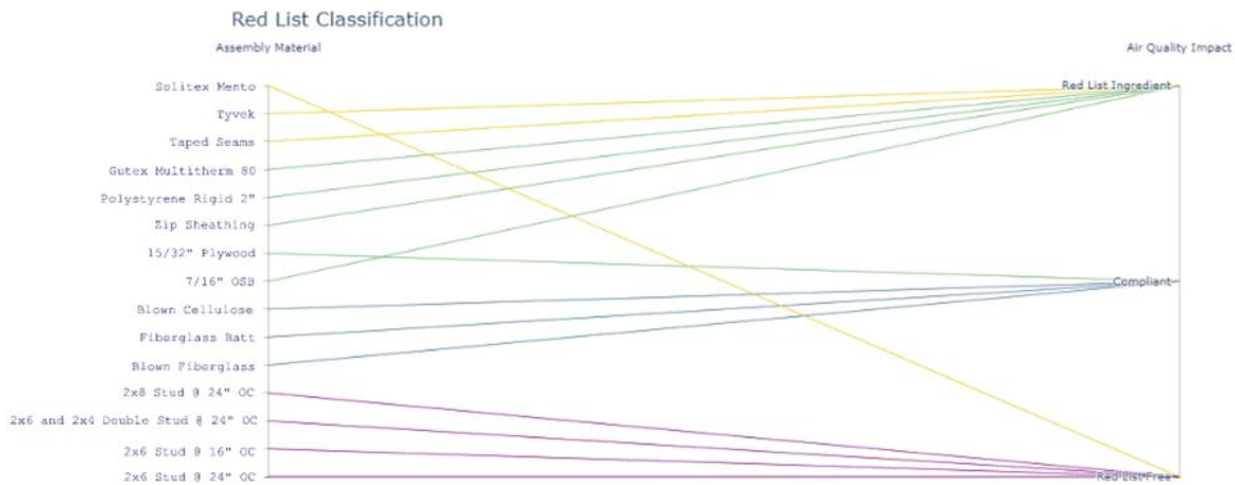
The following provides the findings for each material component in each of the five criteria; embodied carbon, operational energy, cost, install duration, and air quality impact. The shading on the left is for stud and cavity insulation, the light shading in the middle represents the sheathing and exterior insulation, and the dark shading on the far right is for the air barrier.


EMBODIED CARBON
kg CO2 eq
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
462.29
271.48
387.68
448.44
283.95
384.13
847.74
469.35
712.80
588.39
352.16
494.31
1519.55
1911.92
317.55
1903.91
309.54
62.33
2x6 Stud @ 24" OC Blown Fiberglass
2x6 Stud @ 24" OC Fiberglass Batt
2x6 Stud @ 24" OC Blown Cellulose
2x6 Stud @ 16" OC Blown Fiberglass
2x6 Stud @ 16" OC Fiberglass Batt
2x6 Stud @ 16" OC Blown Cellulose
2x6 and 2x4 Double Stud @ 24" OC Blown Fiberglass
2x6 and 2x4 Double Stud @ 24" OC Fiberglass Batt
2x6 and 2x4 Double Stud @ 24" OC Blown Cellulose
2x8 Stud @ 24" OC Blown Fiberglass
2x8 Stud @ 24" OC Fiberglass Batt
2x8 Stud @ 24" OC Blown Cellulose
Zip R6 and Taped Seams
7/16" OSB Polystyrene Rigid 2"
7/16" OSB Gutex Multitherm 80
15/32" Plywood Polystyrene Rigid 2"
15/32" Plywood Gutex Multitherm 80
Tyvek


R-Value
ft^2·°F·h/BTU
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
TOTAL R-VALUE (ft^2·°F·h/BTU)
R-VALUE PER INCH (ft^2·°F·h/BTU·in)
20.90
19.16
19.16
18.97
17.47
17.47
37.65
31.04
34.76
26.41
24.67
25.54
6.60
10.51
11.91
10.59
11.99
3.64
3.39
3.39
3.31
3.10
3.10
3.77
3.10
3.48
3.64
3.39
3.39
4.59
6.17
4.77
6.26
4.86
2x6 Stud @ 24" OC Blown Fiberglass
2x6 Stud @ 24" OC Fiberglass Batt
2x6 Stud @ 24" OC Blown Cellulose
2x6 Stud @ 16" OC Blown Fiberglass
2x6 Stud @ 16" OC Fiberglass Batt
2x6 Stud @ 16" OC Blown Cellulose
2x6 and 2x4 Double Stud @ 24" OC Blown Fiberglass
2x6 and 2x4 Double Stud @ 24" OC Fiberglass Batt
2x6 and 2x4 Double Stud @ 24" OC Blown Cellulose
2x8 Stud @ 24" OC Blown Fiberglass
2x8 Stud @ 24" OC Fiberglass Batt
2x8 Stud @ 24" OC Blown Cellulose
Zip R6 and Taped Seams
7/16" OSB Polystyrene Rigid 2"
7/16" OSB Gutex Multitherm 80
15/32" Plywood Polystyrene Rigid 2"
15/32" Plywood Gutex Multitherm 80


TOTAL COST
INSTALL COST ($)
UPFRONT MATERIAL COST ($)
$14,000.00
$12,000.00
$10,000.00
$8,000.00
$6,000.00
$4,000.00
$2,000.00
$-
2x6 Stud @ 24" OC Blown Fiberglass
2x6 Stud @ 24" OC Fiberglass Batt
2x6 Stud @ 24" OC Blown Cellulose
2x6 Stud @ 16" OC Blown Fiberglass
2x6 Stud @ 16" OC Fiberglass Batt
2x6 Stud @ 16" OC Blown Cellulose
2x6 and 2x4 Double Stud @ 24" OC Blown Fiberglass
2x6 and 2x4 Double Stud @ 24" OC Fiberglass Batt
2x6 and 2x4 Double Stud @ 24" OC Blown Cellulose
2x8 Stud @ 24" OC Blown Fiberglass
2x8 Stud @ 24" OC Fiberglass Batt
2x8 Stud @ 24" OC Blown Cellulose
Zip R6 and Taped Seams
7/16" OSB Polystyrene Rigid 2"
7/16" OSB Gutex Multitherm 80
15/32" Plywood Polystyrene Rigid 2"
15/32" Plywood Gutex Multitherm 80
Tyvek
Solitex Mento


INSTALL DURATION
Hours
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
34.2
19.6
34.2
36.8
25.1
36.8
61.7
37.2
61.7
38.9
26.9
38.9
24.0
28.8
31.1
33.1
35.3
2.7
5.4
2x6 Stud @ 24" OC Blown Fiberglass
2x6 Stud @ 24" OC Fiberglass Batt
2x6 Stud @ 24" OC Blown Cellulose
2x6 Stud @ 16" OC Blown Fiberglass
2x6 Stud @ 16" OC Fiberglass Batt
2x6 Stud @ 16" OC Blown Cellulose
2x6 and 2x4 Double Stud @ 24" OC Blown Fiberglass
2x6 and 2x4 Double Stud @ 24" OC Fiberglass Batt
2x6 and 2x4 Double Stud @ 24" OC Blown Cellulose
2x8 Stud @ 24" OC Blown Fiberglass
2x8 Stud @ 24" OC Fiberglass Batt
2x8 Stud @ 24" OC Blown Cellulose
Zip R6 and Taped Seams
7/16" OSB Polystyrene Rigid 2"
7/16" OSB Gutex Multitherm 80
15/32" Plywood Polystyrene Rigid 2"
15/32" Plywood Gutex Multitherm 80
Tyvek
Solitex Mento



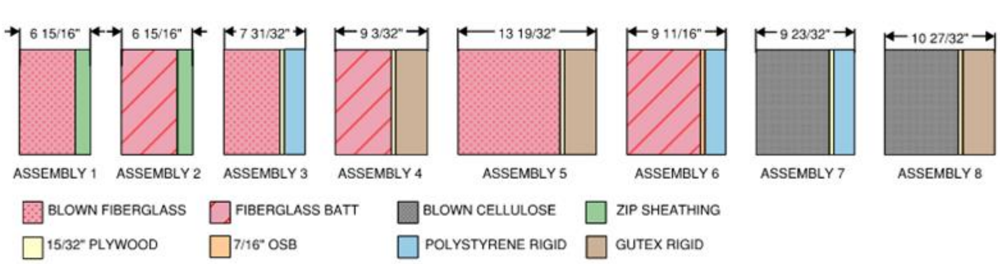
From these results, the conclusion can be drawn that while a double stud wall may perform the best operationally, the embodied carbon impact due to additional materials and overall thickness of the wall impeding on the livable area may not be worth the upfront cost.

As for continuous insulation, polystyrene insulation and Zip R6 products have substantially larger environmental impacts than any other material in the analysis. In this category analysis, Gutex insulation would be the best performing continuous insulation product and would be worth the investment.

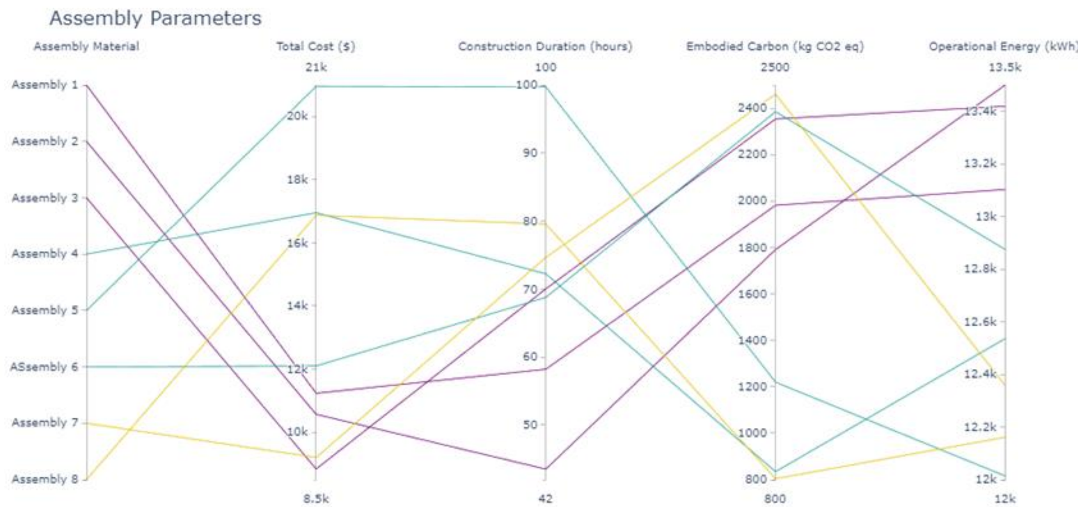
The air quality plot shows that plywood is the best sheathing selection because it is the only sheathing product that is considered compliant instead of containing a Red List ingredient. The plot also shows the Solitex barrier is red-list free while the other option, Tyvek, contains a red list ingredient. Because the cost of Solitex is not substantially higher than Tyvek, it was selected as the exterior air barrier.

From this data, 8 assemblies were determined to be the best for further analysis.

	ASSEMBLY 1	ASSEMBLY 2	ASSEMBLY 3	ASSEMBLY 4	ASSEMBLY 5	ASSEMBLY 6	ASSEMBLY 7	ASSEMBLY 8
STUD	2x6 Stud @ 24" OC	2x6 Stud @ 24" OC	2x6 Stud @ 24" OC	2x6 Stud @ 24" OC	2x6 and 2x4 Double Stud @ 24" OC	2x8 Stud @ 24" OC	2x8 Stud @ 24" OC	2x8 Stud @ 24" OC
CAVITY INSULATION	Blown Fiberglass	Fiberglass Batt	Blown Cellulose	Fiberglass Batt	Blown Fiberglass	Fiberglass Batt	Blown Cellulose	Blown Cellulose
SHEATHING			15/32" Plywood	15/32" Plywood	15/32" Plywood	7/16" OSB	15/32" Plywood	15/32" Plywood
EXTERIOR INSULATION	Zip R6	Zip R6	Polystyrene Rigid 2"	Gutex Multitherm 80	Gutex Multitherm 80	Polystyrene Rigid 2"	Polystyrene Rigid 2"	Gutex Multitherm 80
EXTERIOR AIR BARRIER	Taped Seams	Taped Seams	Tyvek	Tyvek	Tyvek	Tyvek	Tyvek	Solitex Mento
ASSEMBLY DECISION FACTOR	H4H Base Design	Shortest Duration	Lowest Cost	Lowest Embodied Carbon	Highest R-Value	Material is Above or Close to Median Value in Each Category	Material is Above or Close to Average Value in Each Category	High Performance Balance



The figure below shows these assemblies with the values for each design parameter including operational energy consumption in kilowatt-hours.



In the end, assembly 8 was selected as the final envelope design. If the structural engineer would have allowed, the 24" spacing would be preferred over the 16" spacing due to a lower cost and less thermal bridging.

	ASSEMBLY 8
STUD	2x8 Stud @ 16" OC
CAVITY INSULATION	Blown Cellulose
SHEATHING	15/32" Plywood
EXTERIOR INSULATION	Gutex Multitherm 80
EXTERIOR AIR BARRIER	Solitex Mento

Other considerations were made regarding embodied energy when it came to roofing material and interior finishes. Asphalt shingles were required for the neighborhood aesthetics but time was spent researching products with high recycled content and sustainable building practices. That is why our team selected Malarkey roofing materials. Additionally, our partnership with Habitat for Humanity lends itself to be involved with their ReStore program where gently used furniture, appliances, home goods, building materials and more is sold.

References

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