Designing the Carbon Sequestering House

Climate Positive Residential Design Toolkit
June 2024

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Content

Introduction

Carbon-negative, Climate-positive

In the face of climate change, we each take steps to shrink our carbon footprint and reduce the strain on the earth's limited resources. This is good for the planet; good for communities; good for people, their families, and their futures. When building a house, we can substantially reduce our carbon emissions. We can go beyond a carbon neutral proposition to design houses that sequester carbon, dipping below Zero Net Carbon, taking on a regenerative stance.

Decarbonization is the process by which we can reduce greenhouse gas emissions that arise from operating a house as well as the initial carbon outlay of constructing one. Over the last few decades, the focus of decarbonization has been primarily on reducing operational carbon emissions. We've raised the bar — designing energy-efficient houses that use less operational carbon over their lifetimes. The next frontier, in critical need of address, is to significantly reduce the upfront or embodied carbon emissions that are inherent to the materials we select to construct our homes.

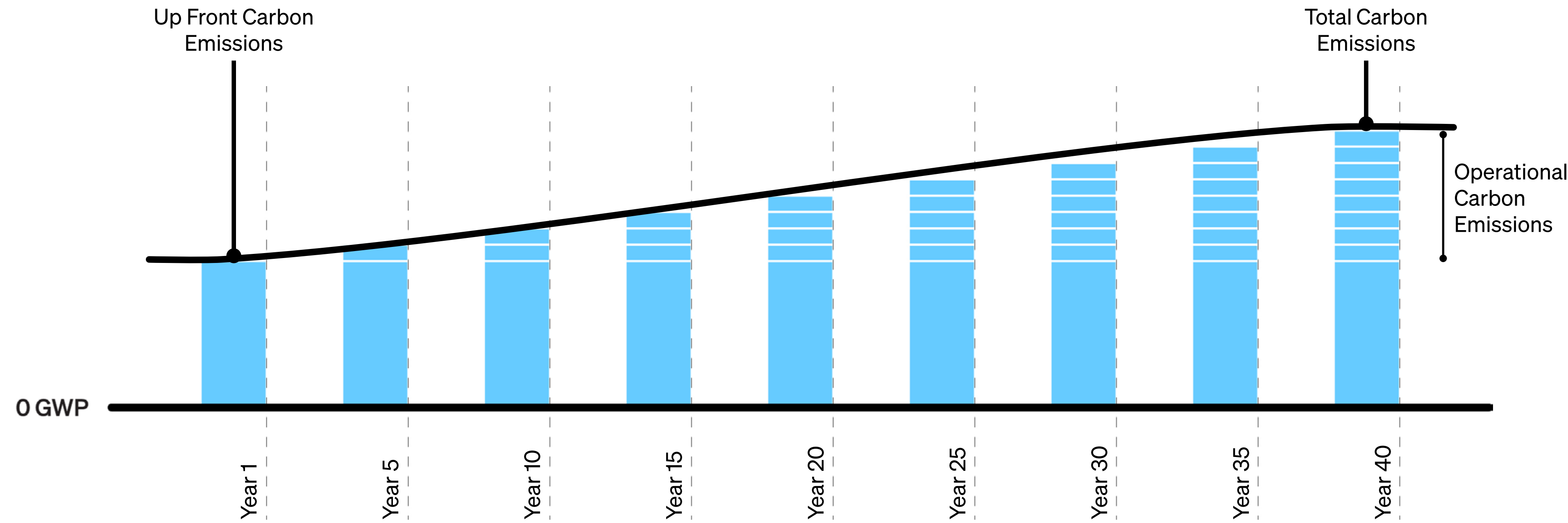
This toolkit considers the major components of a stand-alone house — the exterior walls, roof, and floor — comparing the embodied carbon of standard well-performing construction methods against proposed alternatives that use carbon sequestering materials. As a point of departure for designers, contractors, and homeowners, this toolkit explores pathways to design houses that not only lower their carbon footprint but go further to capture carbon from the earth's atmosphere.

The Impact of Embodied Carbon

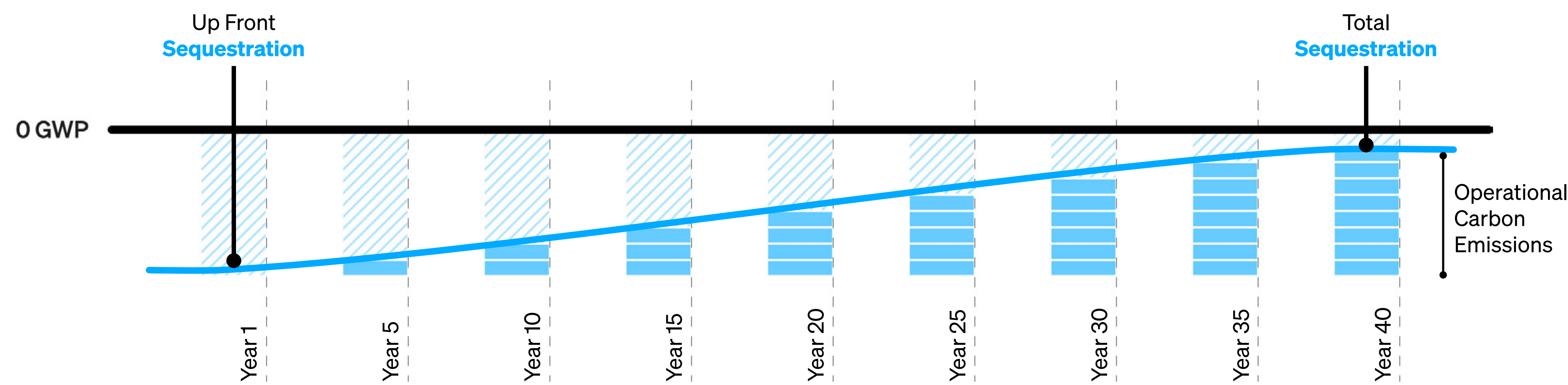
As the houses we design have become increasingly more efficient, their operating emissions have dropped. As a result, the embodied carbon emissions from a house's initial construction can take up a much larger proportion of its total lifetime carbon emissions.

Producing building materials is a major contributor to a house's embodied carbon emissions. This is extracting and transporting raw materials up to and including its manufacture. The methods and material selections proposed within this toolkit can help start the life of a house by sequestering carbon, capturing and storing atmospheric carbon dioxide within the materials used to build the house.

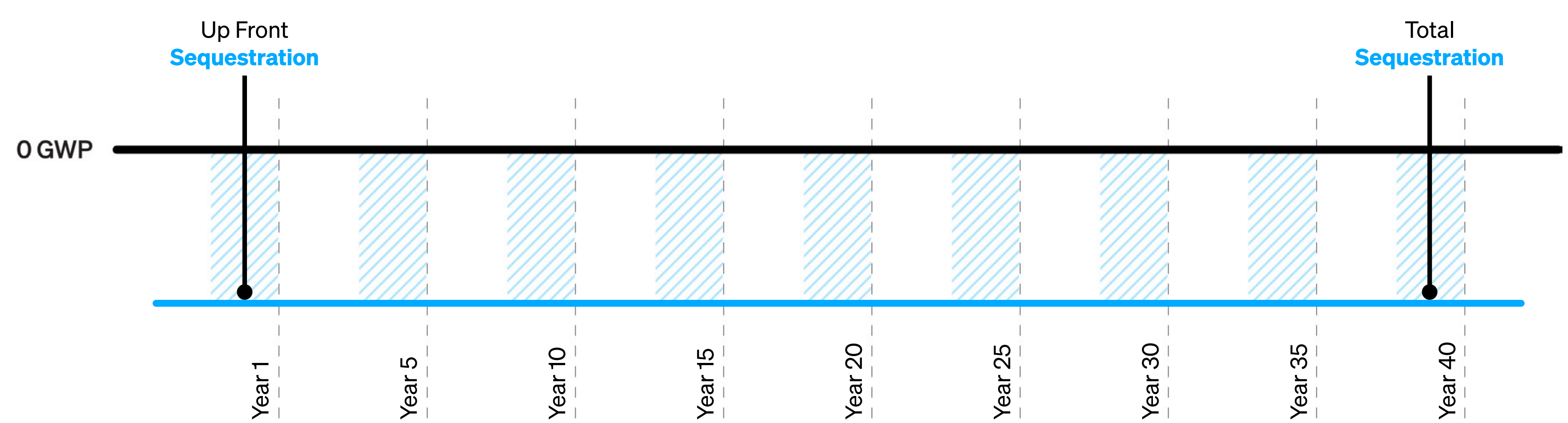
While system upgrades can give homeowners the opportunity to reduce operational carbon emissions over time, first-cost of embodied carbon emissions stay with the house throughout its life. When constructing a new house, there is simply no time like the present to consider its design through the lens of embodied carbon.



Emissions for a standard, new construction house over a 40-year span



Emissions for a carbon sequestering, new construction house over a 40-year span



Emissions for a carbon sequestering, Net-Zero-Energy new construction house over a 40-year span

Fig. 1: Charting total carbon emissions over a 40-year period for new homes that use typical construction methods, those that use carbon sequestering construction methods, and those that both use carbon sequestering carbon methods and net-zero energy systems. The last result is a carbon negative and climate positive outcome.

Common Terms and Definitions

Operational Carbon refers to the greenhouse gas emissions that are associated with the operation of a building.

Embodied Carbon refers to the greenhouse gas emissions arising from the extraction, manufacturing, transportation, installation, maintenance, and disposal of the building materials that go into constructing a house. For this study, our calculations have focused primarily on the “cradle-to-gate” emissions that come from the extraction of raw materials, its transportation, processing, and manufacturing. This accounts for 65%–85% of the materials’ total embodied carbon emissions and remains mostly consistent, notwithstanding regional variations.

A **Construction Assembly** refers to the layers of materials that go into a method of construction of a wall, roof, or floor.

The toolkit proposes ways to build the primary components of a house using carbon sequestering materials. It compares today’s standard methods of constructing high-performing houses in the Northeastern United States against alternative ways to assemble these components using Biogenic materials. **Biogenic** materials refer to those that were produced by living organisms, such as wood, straw, or cork, through natural processes that remove or sequester carbon dioxide from the atmosphere.

Rough sawn wood siding

Cedar shakes and shingles

Cedar wood siding

Lime plaster

Reclaimed wood floors

Locally sourced heart-pine

Straw bale insulation[12]

Wood fiber insulation[13]

Hempcrete[14]

Fig. 2: Biogenic materials and their applications

Methodology

Our comparisons use a metric that considers the environmental impact of the emissions associated with various construction assemblies for every unit of thermal performance. This focuses our study on up-front embodied carbon emissions (although many of the proposed assemblies improve thermal performance).

To compare different assemblies with varying thermal performances, we use a metric of **GWP / R-Value** to help us understand the emissions of an assembly per unit of performance. We compare standard ways to build a well-performing house against proposed alternative methods that sequester carbon while often also improving the thermal performance of the assembly. To keep these comparisons “apples-to-apples”, and focused on the carbon footprint of the assembly, we’ve offset the performance variability through this calculation of **GWP / R-Value**.

We focus our study on the means of construction, the ways a house can be built using carbon sequestering materials, while deliberately disregarding the final finish materials that are applied to a house. This allows the toolkit to be useful regardless of what the house looks like, or specifically, what material wraps its exterior. The selection of the exterior material is important and can have a significant impact on a home’s up-front carbon emissions. We address this in a separate section.

GWP / R Value

$$\frac{\text{kg } CO_2 \text{ e / 100 SF}}{\text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{h / BTU}}$$

Global Warming Potential (GWP) reflects the impact of carbon emissions on the environment.

kg CO_2 e / 100 SF

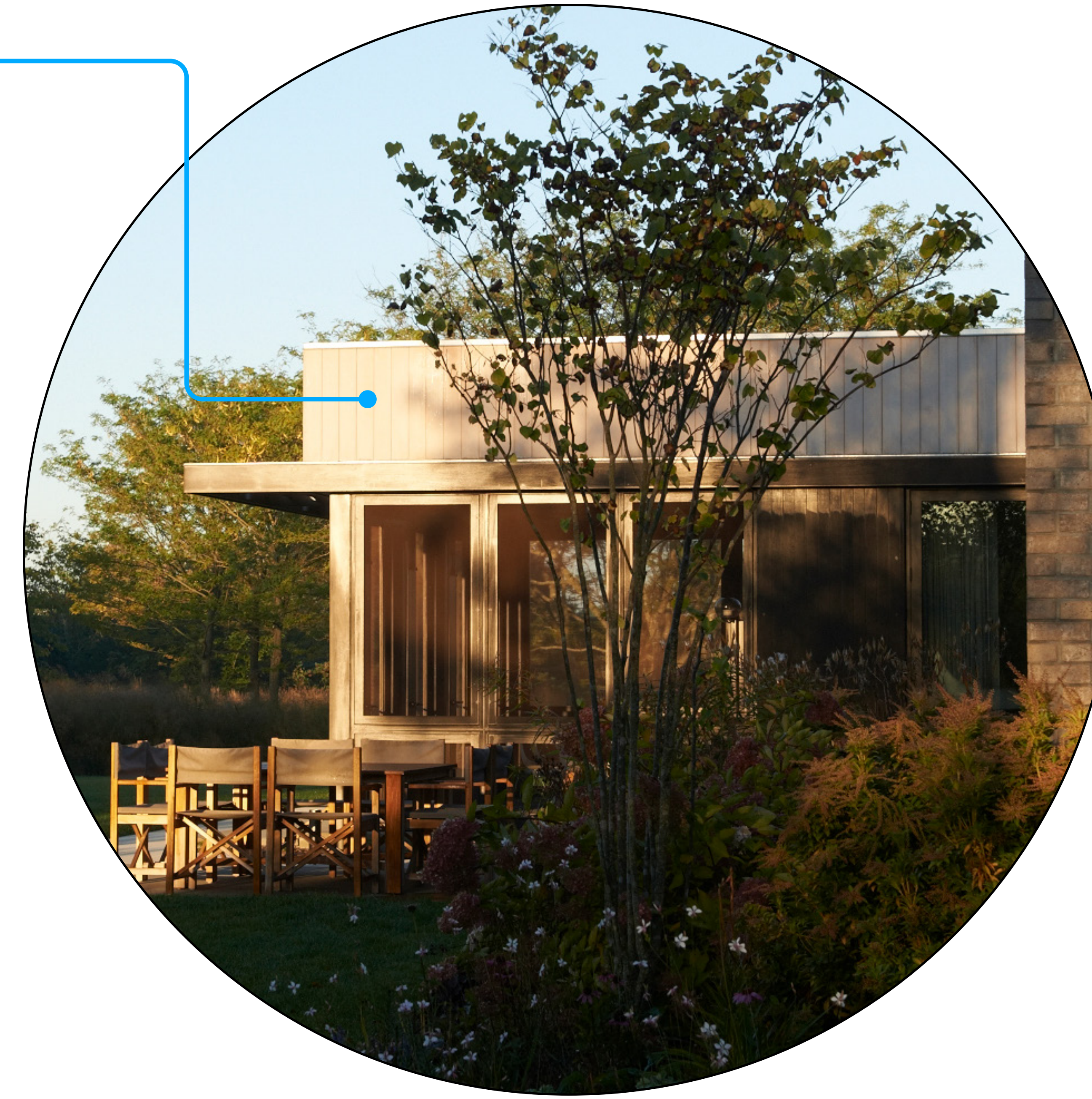
R-Value is a measure assigned to a construction assembly to reflect its insulative properties. For example, the higher the R-Value of a wall assembly, the more insulating and better-performing it is.

$ft^2 \cdot {}^\circ F \cdot h$ / BTU

Fig. 3: The simplified equation we use throughout the toolkit to compare different assemblies with varying thermal performances.

Components of a House

Walls	**8**
Roofs	**16**
Floors	**21**



Replace wall components with **carbon-sequestering** materials

Our analysis began with a typical wall used in high-performing residential projects in the northeast US. We calculated the Global Warming Potential for 100 square-feet of the wall, excluding the exterior finishes. Within this standard assembly, we found the most significant contributor to the wall's Global Warming Potential to be the Mineral Wool Board—more than 75% of the wall's emissions were due to insulation as a class of materials.

We developed an alternative assembly that replaced wall components with biogenic materials. This alternate assembly captures carbon, resulting in upfront carbon sequestration.

Biogenic specialty insulations like wood fiber or cork can lead to high-performing and carbon-negative enclosures. FSC certification for wood members can sequester up to 30% more carbon while ensuring the sustainability of the wood's harvesting.[4]

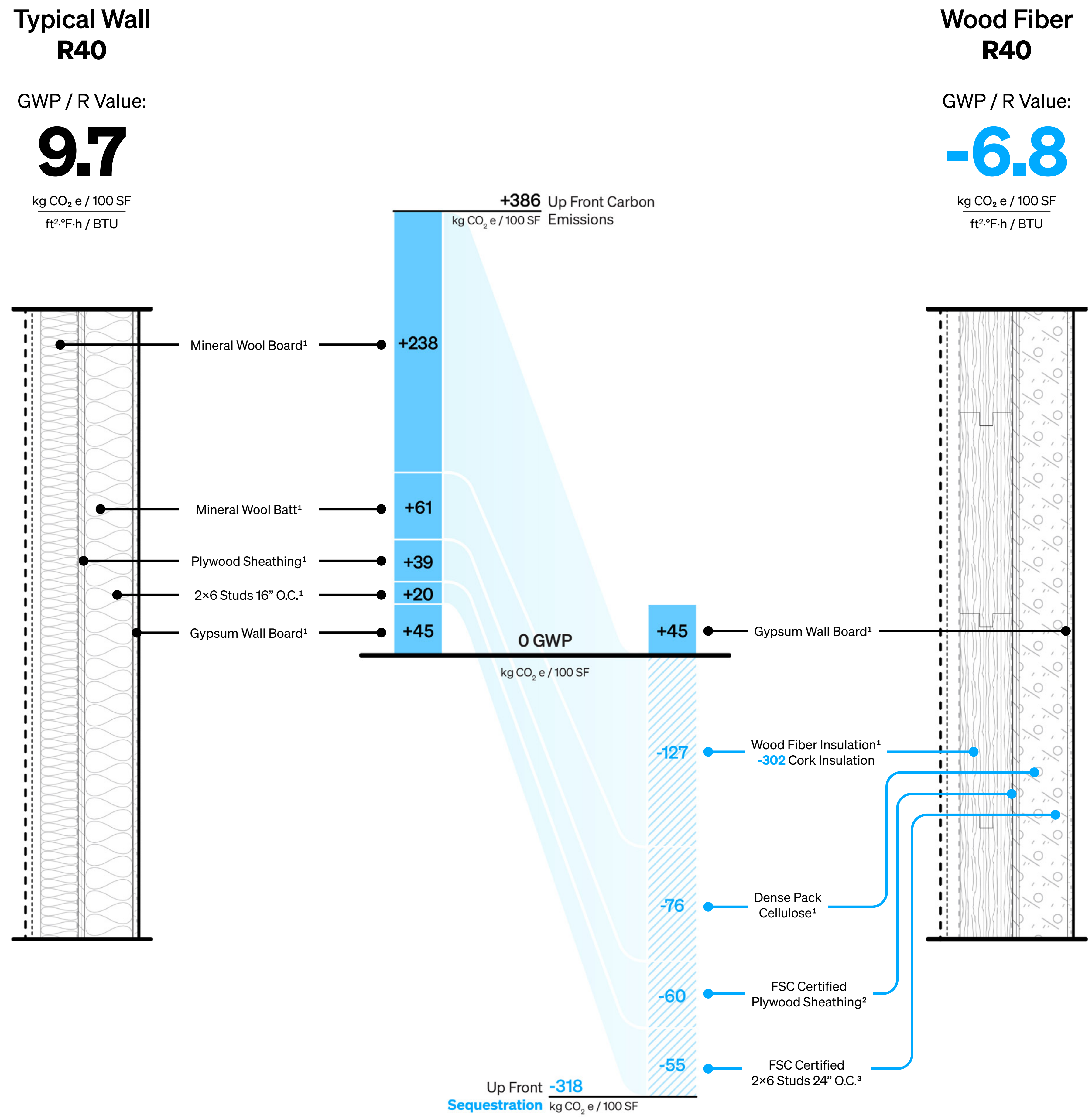


Fig. 4: Comparing Standard Wall materials to Wood Fiber materials

Changing the wall system can **sequester even more carbon**

Acknowledging that wood fiberboard is currently a niche material, we went on to study the use of more commonly available biogenic materials. Less industrialized biogenic products tend to require a greater volume of material to achieve the same insulating capacity. Using these materials would make walls thicker.

We used a double stud wall construction filled with dense-pack cellulose to accommodate this thickness. Cellulose insulation is a post-industrial product often treated with borax to prevent mold growth. Still, its availability, familiarity with contractors, and its negative net carbon emissions made it a good choice. We found that this wall performed similarly to the wood fiberboard, but we believed we could do better.

We replaced one of the structural lines of the wall with straw bales to sequester more carbon. In the northeast US, where most of our work is focused, straw is the most abundant and easily accessible biogenic material that performs at a high R-value. Straw has been used to construct buildings in our region since the 1800s, and new strategies for using this old material are actively being researched.[5] The remaining stud wall functions as the primary structure for the building, which exempted us from many code issues typically associated with straw bale construction. We treated the inner face of the straw with clay and lime plaster, which served as a vapor-permeable air barrier and its finish.

The wall is composed of lay-in boards, which are less industrialized than plywood and do not rely on the adhesives typically used in plywood.[5] Lay-in boards and diagonal bracing were the primary sheathing materials used in most walls before World War II. This substitution could be made in any of the wall systems we've examined, but it seemed best suited for the straw bale wall.

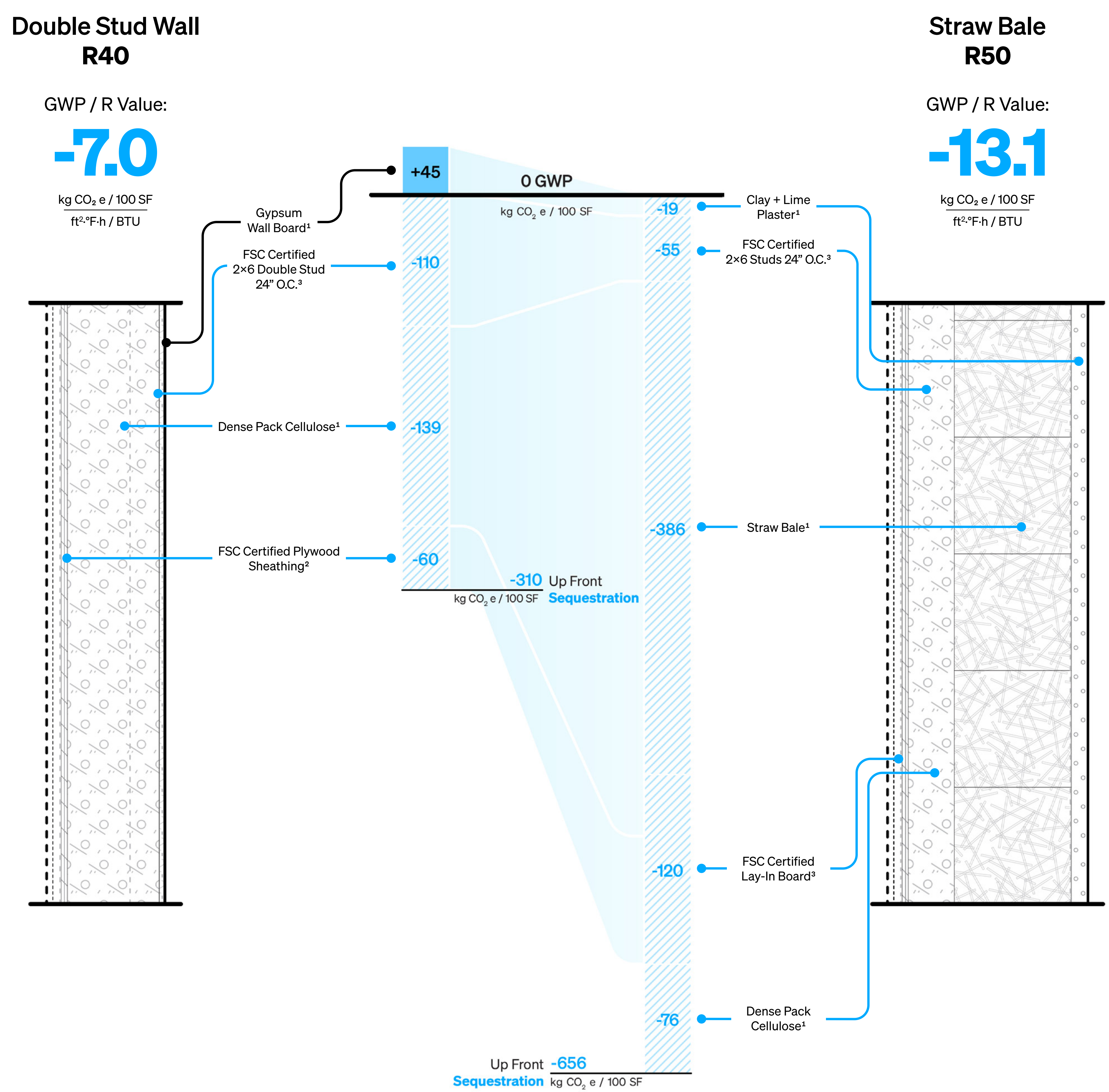


Fig. 5: Comparing double stud assemblies

Straw in the Northeast

In the last twenty-five years, there has been a renewed interest in building with straw by natural builders across the globe. Pioneers of this way of building in our region have found a way to marry this construction technique with high-performance principles for our cold, humid climate. Along with these developments, the prevalence of organic, chemical-free wheat farming in the Northeast makes it a viable and attractive building material in this region.

Straw is a by product of wheat. In the farming of the wheat plant, straw is left remaining after the consumable components of the plant are harvested — wheat grain for human consumption, and wheat hay for animal consumption. If not used in the construction of buildings, straw has no beneficial use, and is destined to be composted or burned, emitting additional carbon and methane through these processes.

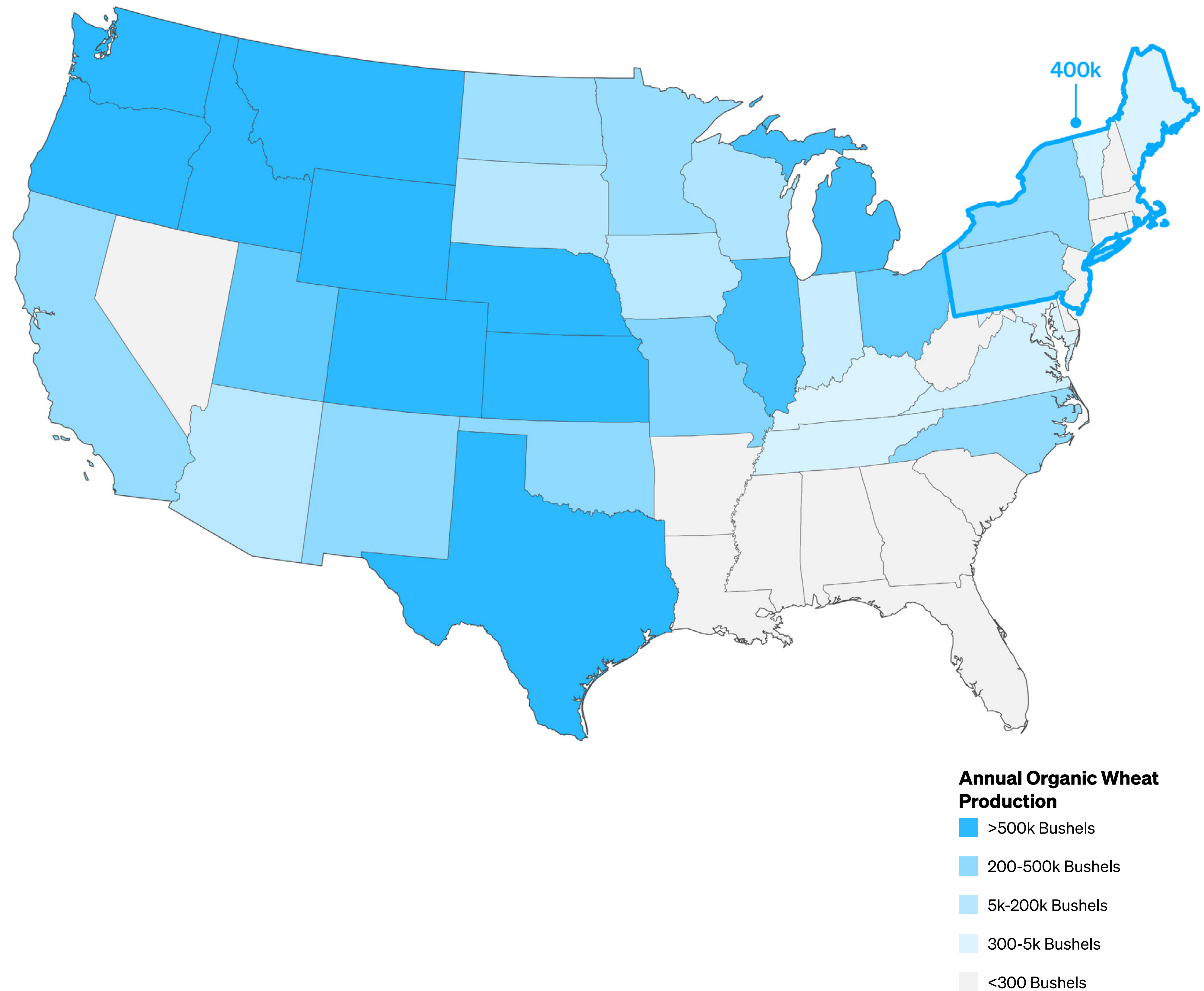


Fig. 6: Organic wheat production throughout the United States in 2021[7]

Biogenic Insulation

Although straw is a fast-growing and carbon-sequestering material, there are many other biogenic insulators available if straw is not a feasible option for a particular project.

Dense-packed cellulose is growing in use as builders gain familiarity with its installation. Hempcrete is also becoming an increasingly attractive alternative due to technological advancements and availability.

The choice between biogenic insulations should certainly factor in regional availability. It is essential to support the development of a local network of manufacturers and farmers to establish resilient supply chains.

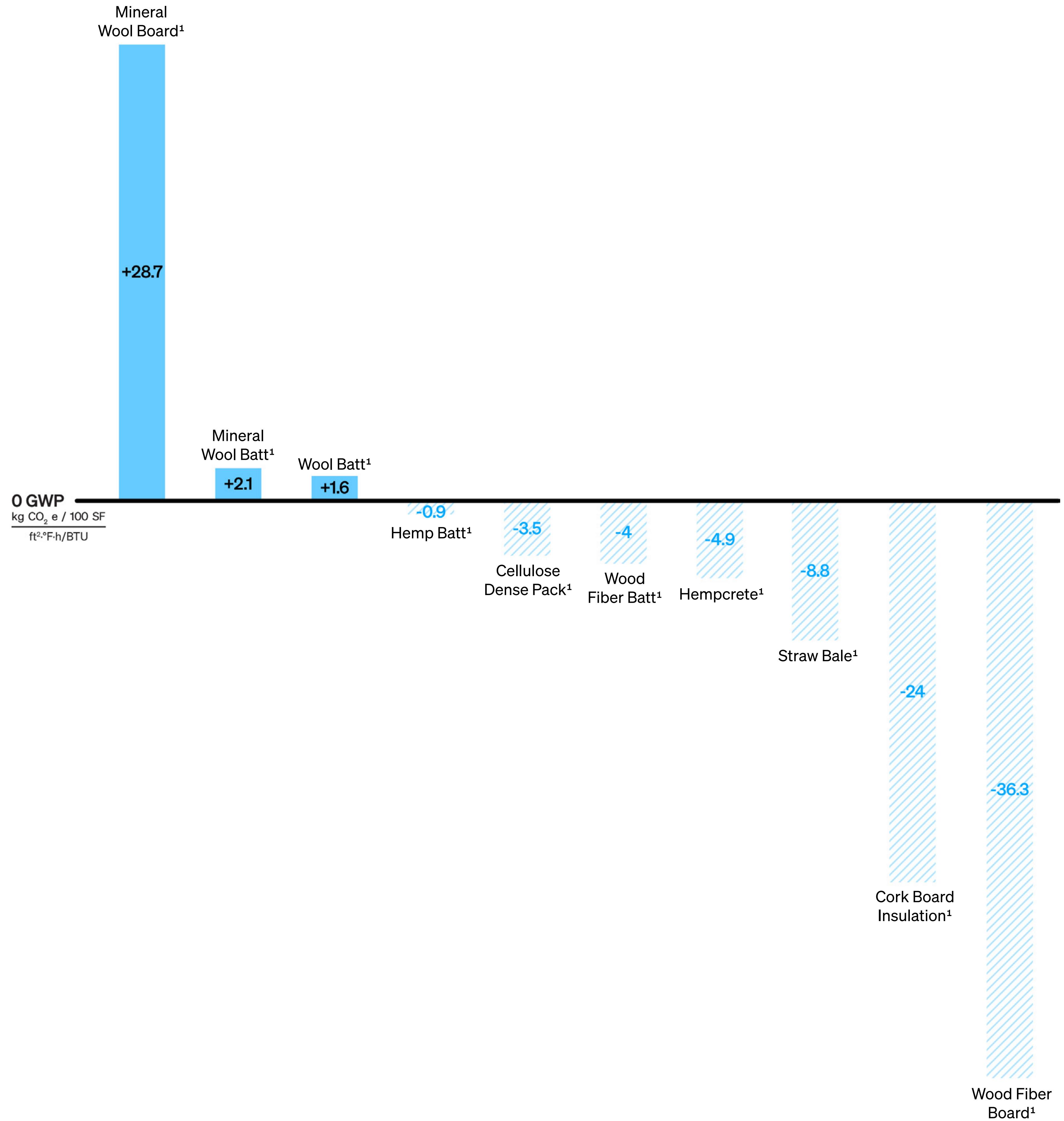


Fig. 7: Comparing the GWP of biogenic insulation material per insulative unit

Finishes play an outsized role in the total GWP of a wall

The choice of exterior finish material for a wall assembly can play a crucial role in determining the wall's Global Warming Potential (GWP). The GWP of exterior materials can vary significantly, with biogenic materials emerging as the top performers due to their ability to sequester carbon. Additionally, biogenic materials are usually lighter and can use simpler attachment systems, reducing their environmental impact.

It is important to note that this analysis has yet to consider the GWP of the attachment system in these wall assemblies. Apart from the carbon emissions associated with the attachment systems, they can diminish a wall's insulative properties due to thermal bridging, where the conducting attachments form low-resistance pathways for the transfer of heat or cold.

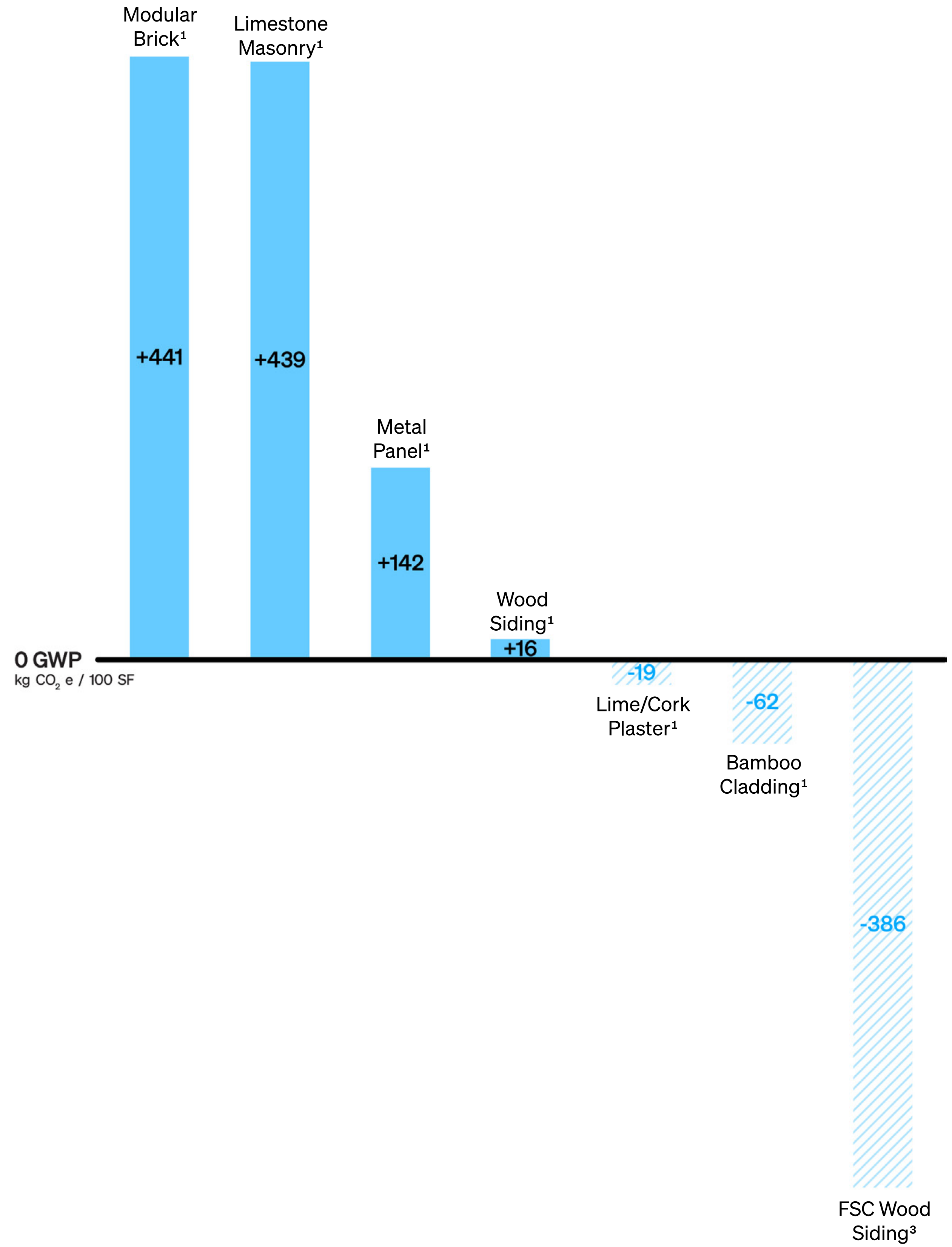


Fig. 8: Comparing the Global Warming Potential of biogenic insulation material per insulative unit

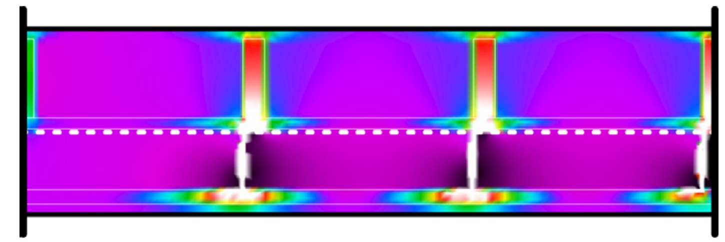
Consider the implications of attachment

Temperature fluctuations and mold growth can compromise the integrity of a building's structure, so it is essential to protect against this. One way to achieve this is by installing outboard insulation. However, a heavy façade that requires a continuous steel girt system that cuts through the exterior insulation can increase the transfer of heat and cold, reducing the wall's performance by up to 40%.

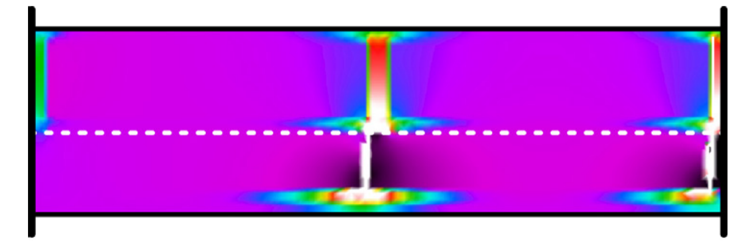
One strategy to address this reduction is to space the studs more widely. According to our analysis, spacing the studs 24" on center instead of 16" on center can reduce the thermal bridging effect by 22%.

Another option is to consider using a double stud wall. This design moves the wall's sheathing towards the finish and can help sequester more carbon.

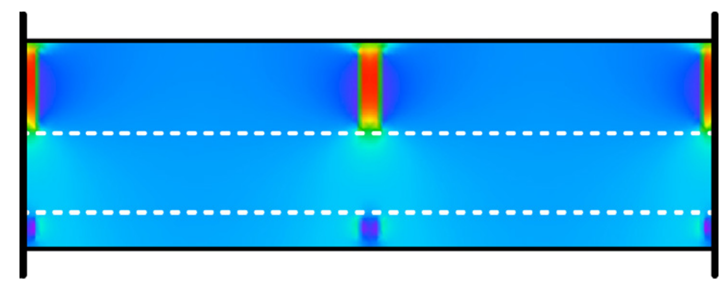
The double stud walls offer some additional benefits. They provide excellent sound insulation and can be more airtight than other wall systems.



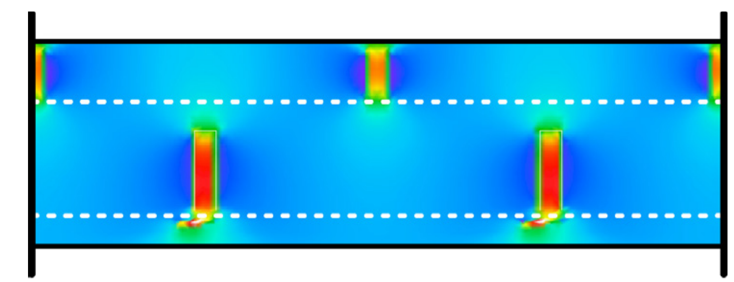
Typical Wall with a heavy stone façade[6]
The steel Girt system derates the wall's R-Value 40%, from R40 to R24.



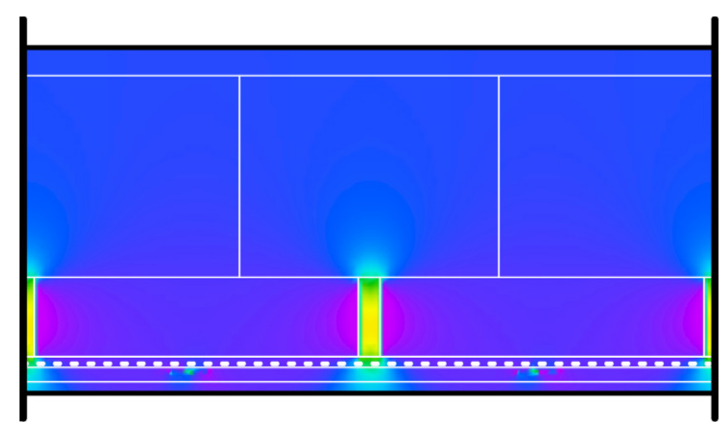
Typical Wall with studs 24" on center with a heavy stone façade[6]
The steel Girt system derates the wall's R-Value 18%, from R40 to R33.



Wood Fiber wall with wood rainscreen[6]



Double Stud wall with a heavy stone façade[6]
Moving the sheathing out protects the insulation from being derated.



Straw bale wall with wood rainscreen[6]

Heat Flux

- 5 BTU/ h • ft^2
- 4 BTU/ h • ft^2
- 3 BTU/ h • ft^2
- 2 BTU/ h • ft^2
- 0 BTU/ h • ft^2

Fig. 9: Performance of various wall attachment systems

Keep it Dry

Moisture intrusion is the primary cause of failure in all residential construction. As humidity-laden air entering an assembly brings far more moisture into the assembly than bulk moisture drives through the control layers, protecting natural insulation from mold growth requires careful consideration and the use of air barriers. The threat of mold growth begins when the relative humidity in an assembly reaches around 80%. Our task is to recognize when and where that is happening inside the wall and locate control layers to protect the insulation.

Protecting biogenic materials with airtightness is a complex endeavor. We need an air barrier on the warm side to stop humidity from reaching the wall's interior. However, this is challenging when we puncture the interior finish for switches, electrical boxes, and hooks.

To maintain the integrity of an air barrier, we adopt Passive House strategies such as constructing service cavities and using visually inspectable, repairable air barriers made of clay and lime. These barriers protect insulation from moisture and can be designed to "breathe" — to allow moisture to escape through vapor-open, airtight control layers.

The warm and humid side of the wall should be five times less permeable than the cool and dry side to encourage vapor migration out of the assembly. In the Northeast, the warm and cool sides of the wall switch with the seasons, posing a unique challenge. However, the most significant vapor intrusion risk occurs during the heating season, so the less permeable layer should be our interior barrier.

Building this way will achieve higher airtightness than traditional assemblies, reducing operational energy use, a hallmark of the Passive House standard.[10]

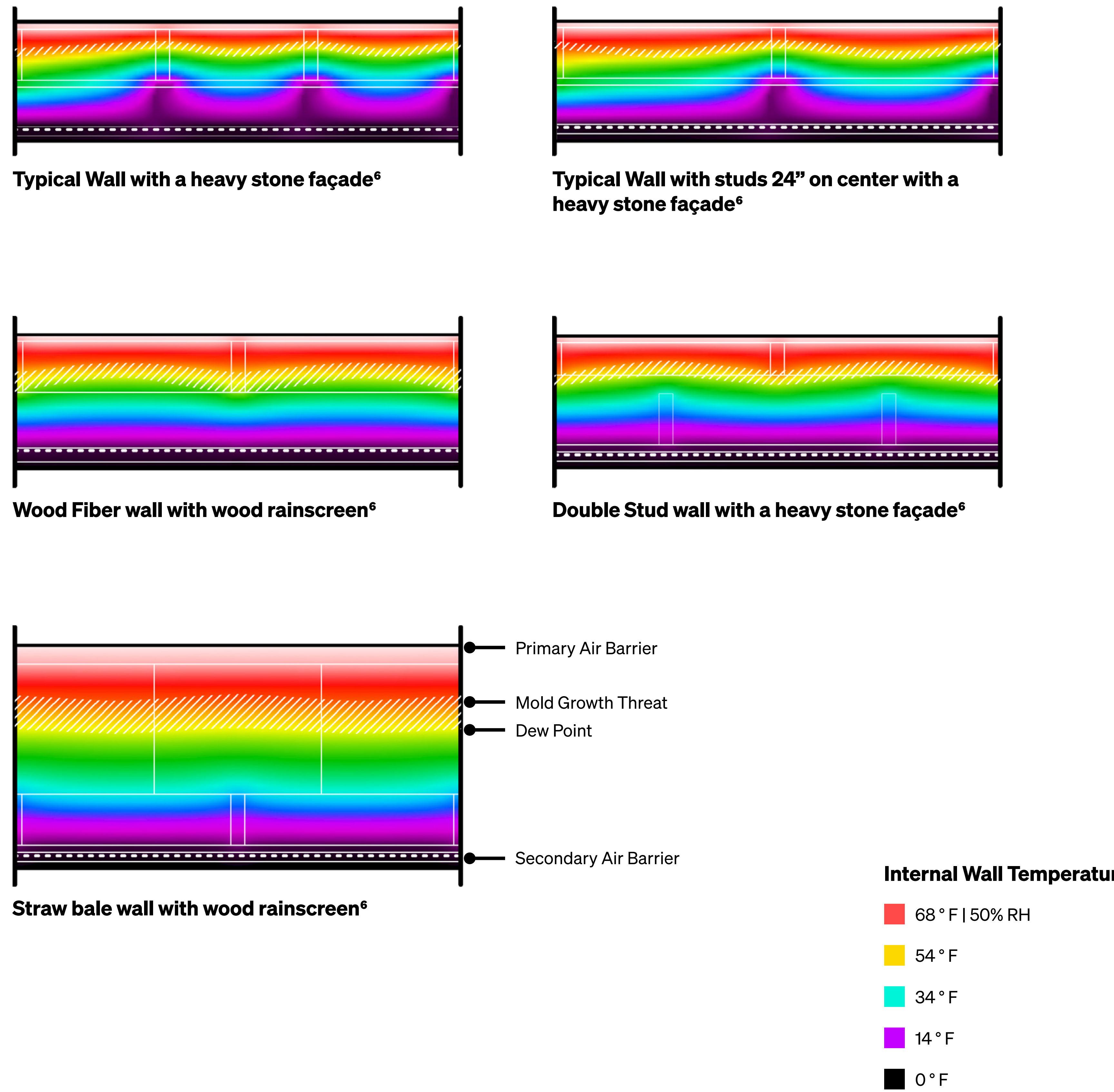
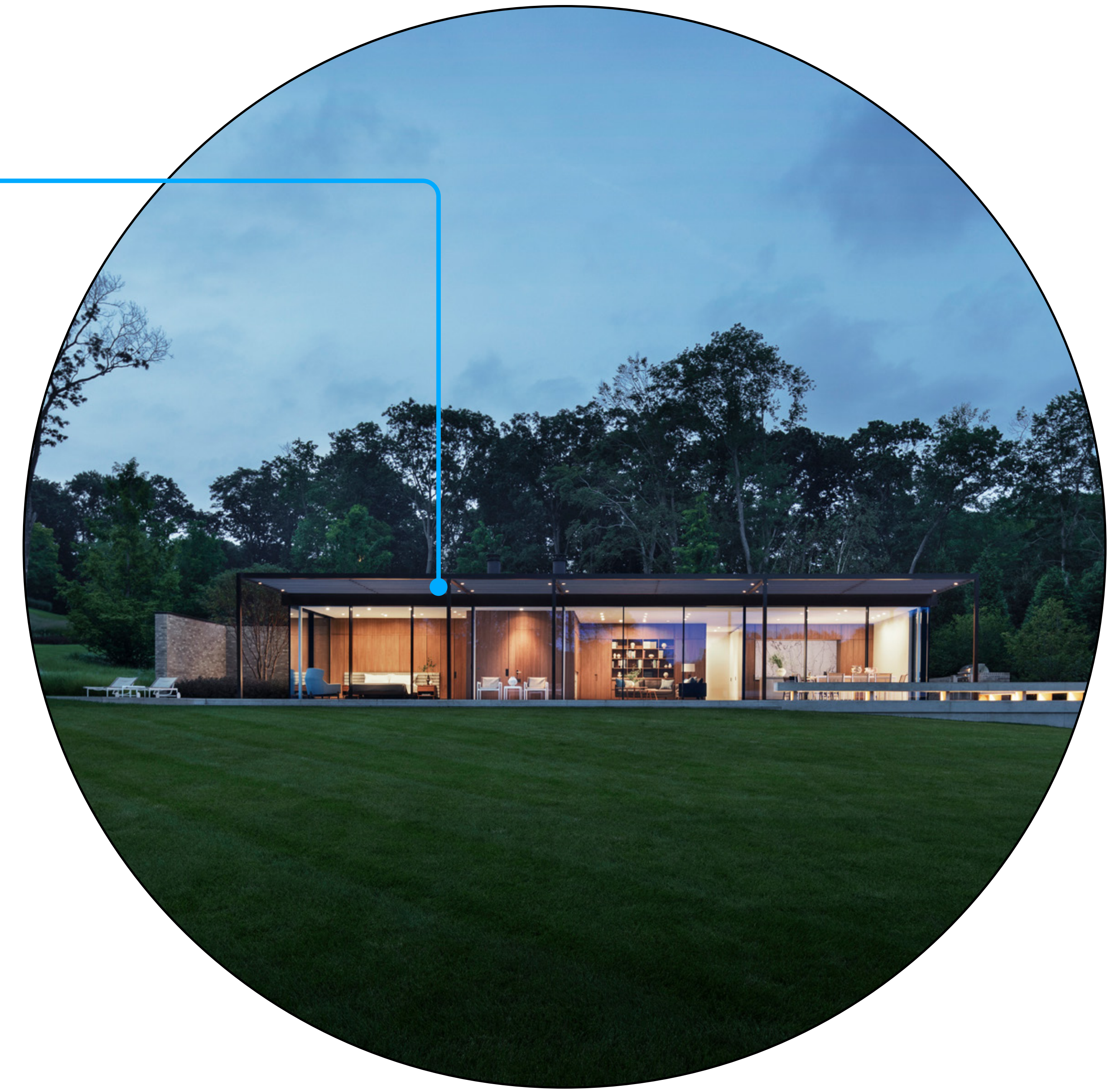


Fig. 10: Keeping moisture out to protect the natural materials

Components of a House

Walls	**8**
Roofs	**16**
Floors	**21**



Changing roof components can **sequester even more carbon**

When it comes to reducing the embodied carbon of the roof construction, the strategies we studied are similar to those we explored for the walls. Again, in typical roof construction used in high-performing houses in the northeast, we see that the insulation is the worst offender, contributing the highest embodied carbon emissions. While hydrofluoroolefin (HFO)-based chemical spray foams present a marked improvement from previous chemical blends, they are still the most significant contributor to the embodied carbon of our roofs.

Substituting the XPS foam board and HFO spray foam with biogenic wood-fiber insulation and dense-packed cellulose can result in a construction that sequesters carbon.

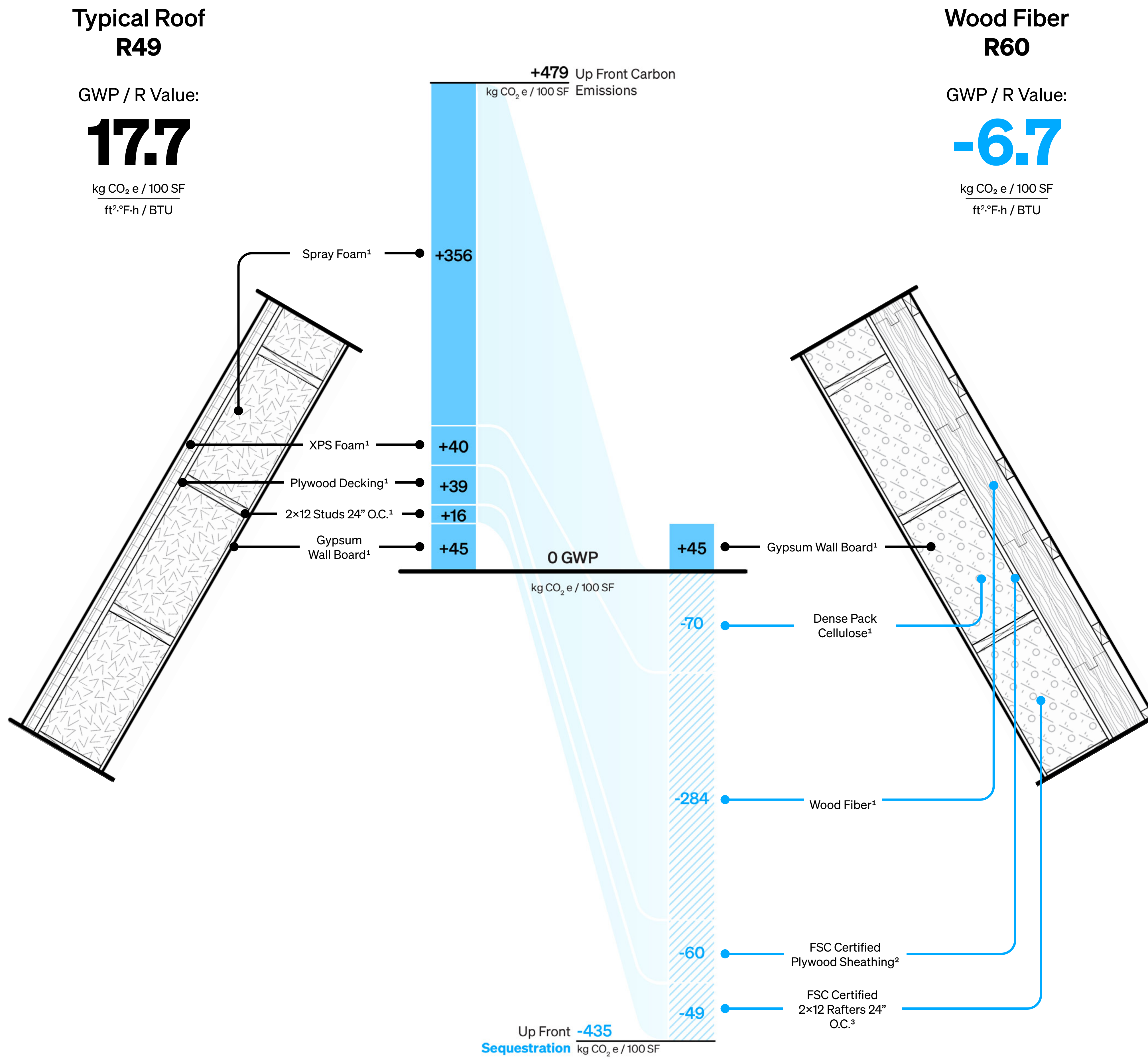


Fig. 11: Typical roof materials compared to a wood fiber roof

Replace roof components with carbon-sequestering materials

Another way to approach the roof assembly using carbon-sequestering biogenic materials is to consider a double-rafter construction, with each layer filled with more commonly available dense-pack cellulose insulation.

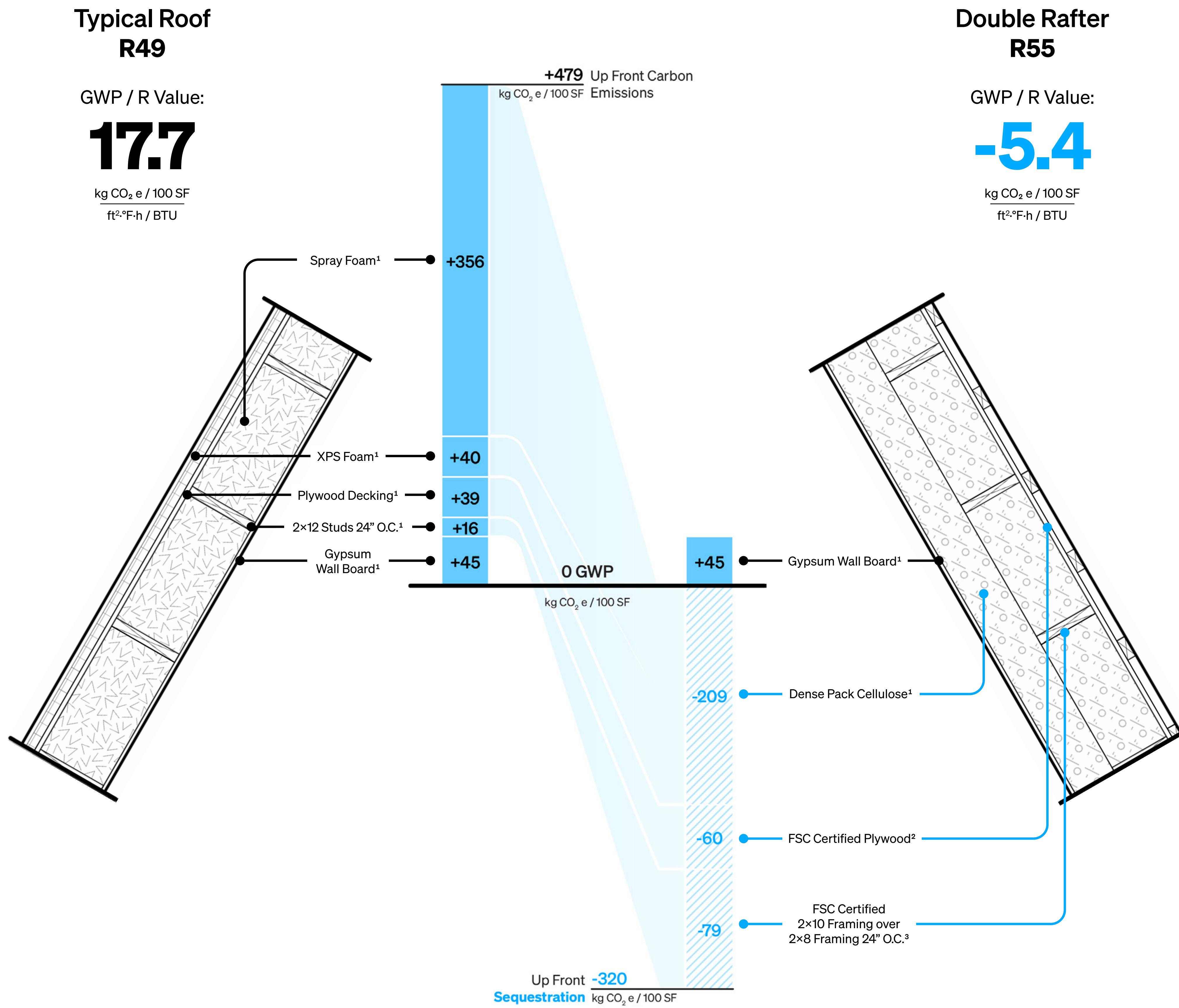


Fig. 12: Typical roof materials compared to a double rafter roof using wood fiber materials

Roofing materials tend to be carbon positive

Most roofing finish materials that we use commonly are manufactured through processes that generate greenhouse gas emissions. Selecting roofing materials should account for a roof's maintenance and lifespan. Wood shingles or shakes require more maintenance, but can have a lifespan of 20 years or so, which is similar to the lifespan of asphalt shingles. Tile and metal roofs longer lifespans. Metal roofs can also be readily disassembled for reuse or recycling.

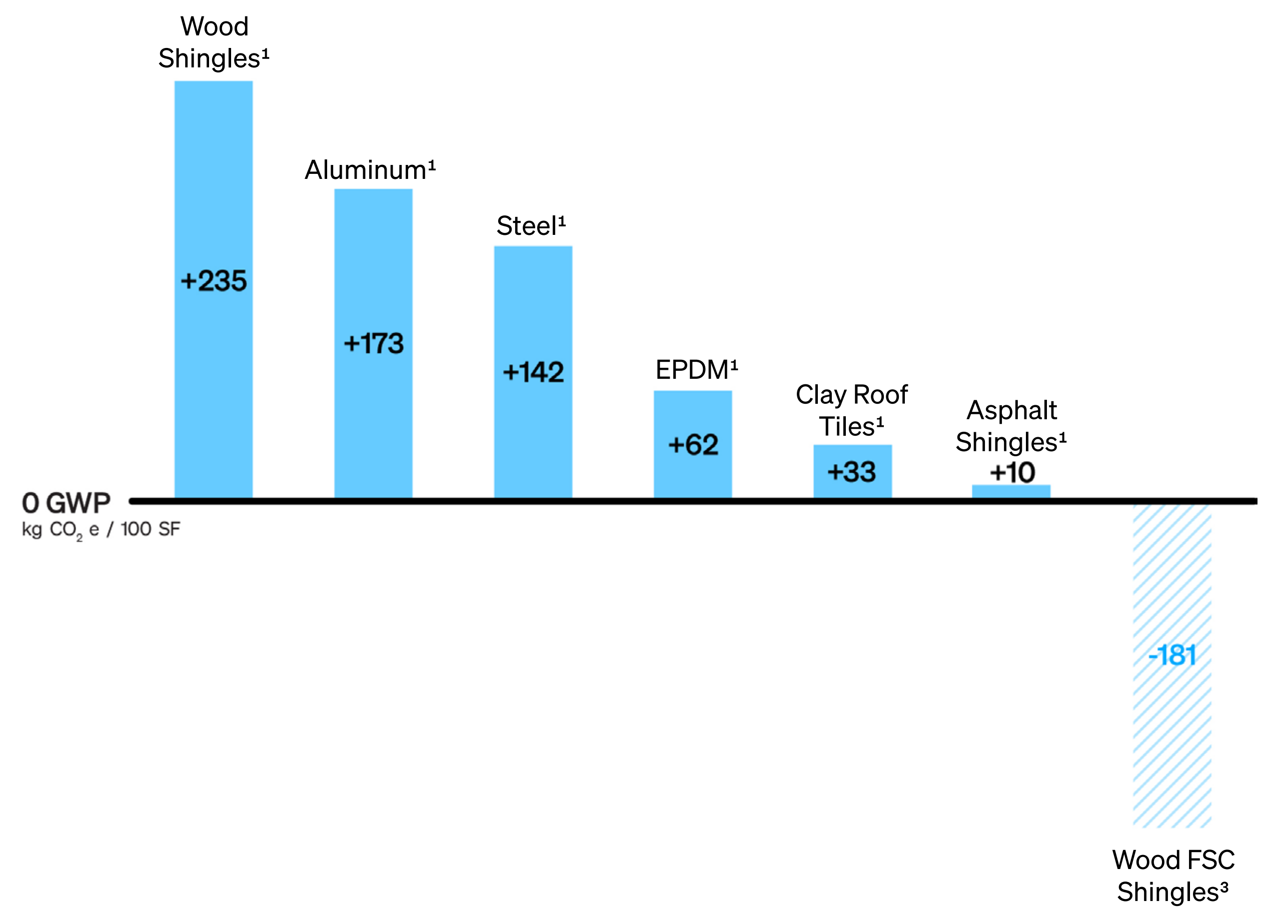
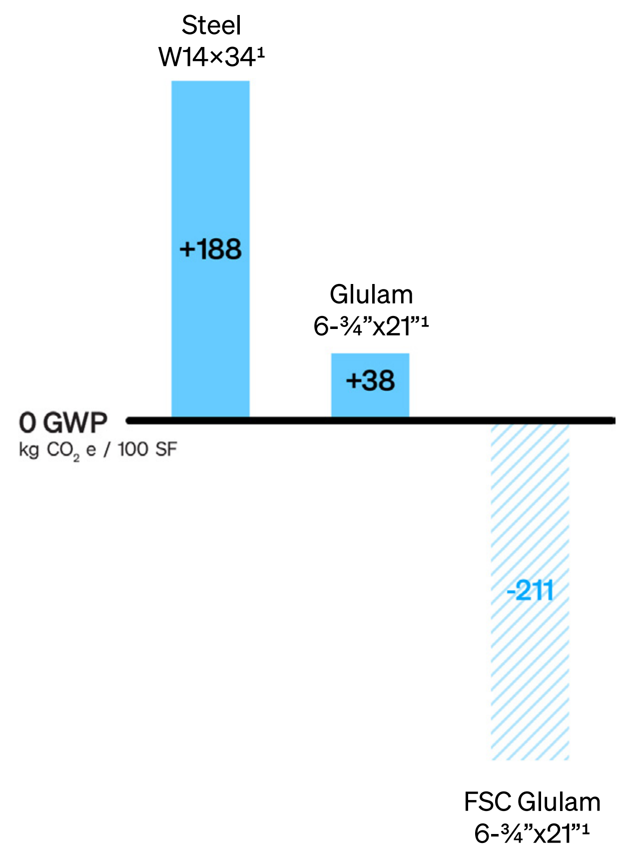
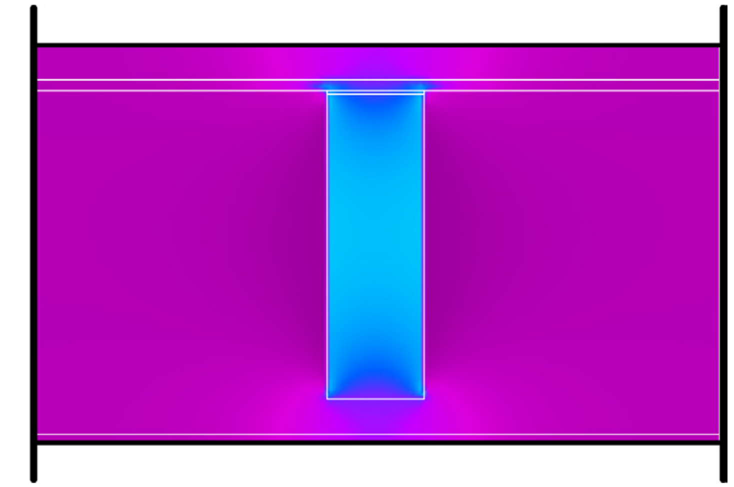


Fig. 13: Comparing GWP of typical roofing materials

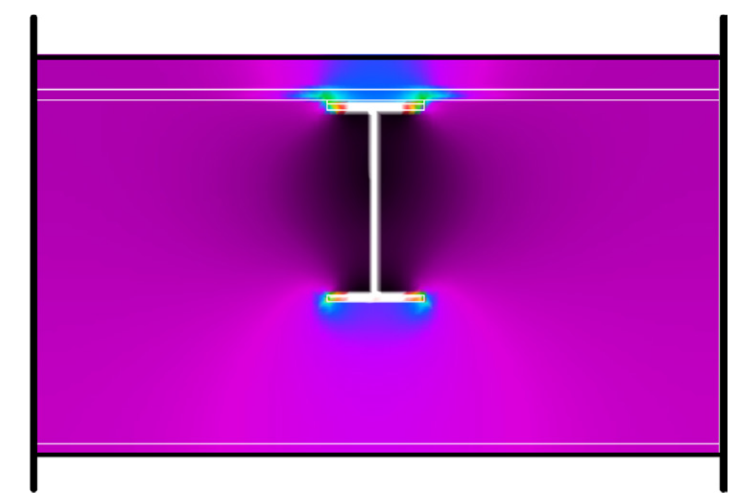
Go Glu-lam

Steel roof structural members carry high embodied carbon while also acting as a thermal bridge, conducting heating and cooling and increasing the risk of mold development. Substituting steel with glued laminated timber, commonly referred to as glulam, reduces the carbon emissions associated with the roof construction while also avoiding thermal bridging issues.





Heat flux analysis of a 6-3/4”x21” Glulam member
The bridging of this wooden member derates this four foot section of the roof’s R-Value 20%.



Heat flux analysis of a wood framed roof with a steel W14×34 member[6]
The bridging of this steel member derates this four foot section of the roof’s R-Value 35%.

Heat Flux

- 5 BTU/ h • ft^2
- 4 BTU/ h • ft^2
- 3 BTU/ h • ft^2
- 2 BTU/ h • ft^2
- 0 BTU/ h • ft^2

Fig. 14: Comparing Steel & Glulam as roofing materials

Fig. 15: Heat Flux analyses of roofs with various materials

Components of a House

Walls	**8**
Roofs	**16**
Floors	**21**

Replace floor components with **carbon-sequestering** substitutions

Concrete is commonly used in floor construction where the house abuts the ground. The embodied carbon impact of concrete is high. Replacing cement replacement can reduce the carbon impact.

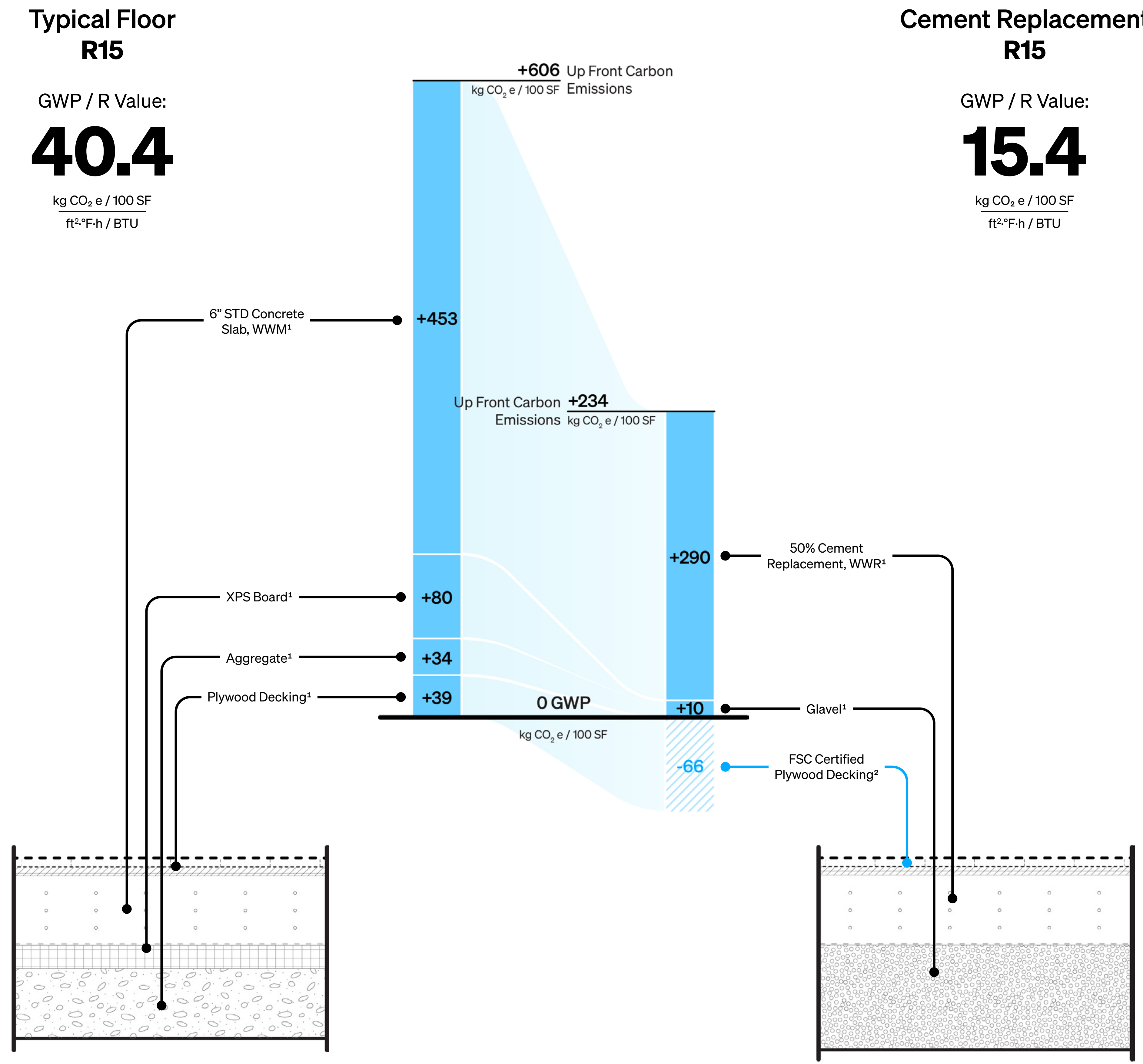


Fig. 16: Comparing typical floor materials to cement replacement

Replace concrete whenever possible

To achieve a carbon sequestering floor assembly, concrete must be eliminated from the build-up. This system is called a “slabless slab” and has been installed in many homes all over the country. Two layers of plywood replace the slab; when the plywood is sustainably sourced, we can account for the biogenic carbon capture associated with the wood. This floor assembly has the added advantage of being able to be disassembled.

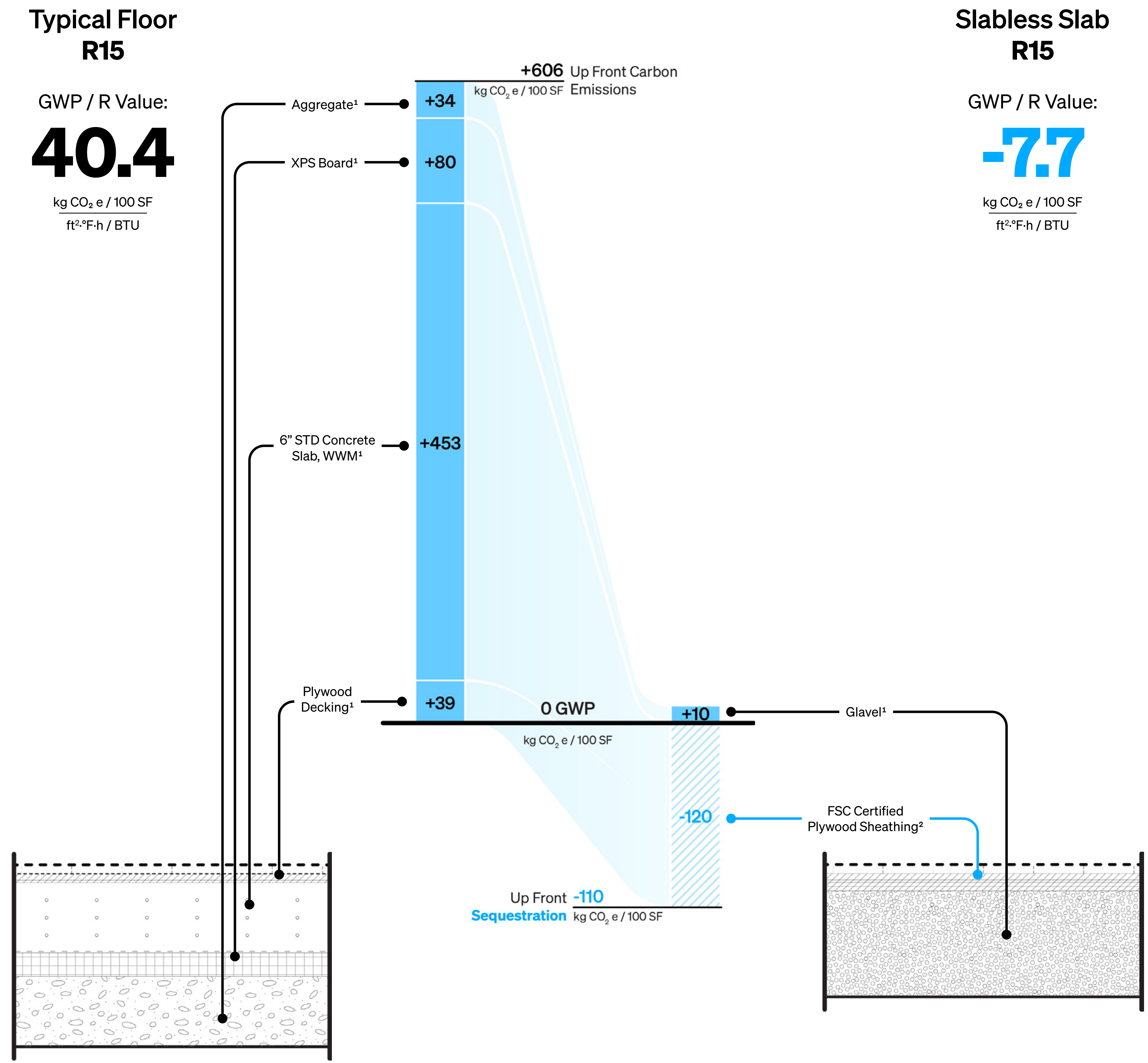


Fig. 17: Typical Floor vs Slabless slab

Natural finishes to pick from

There is a wide range of flooring material commonly available. Biogenic natural materials that are sustainably sourced can help sequester carbon.

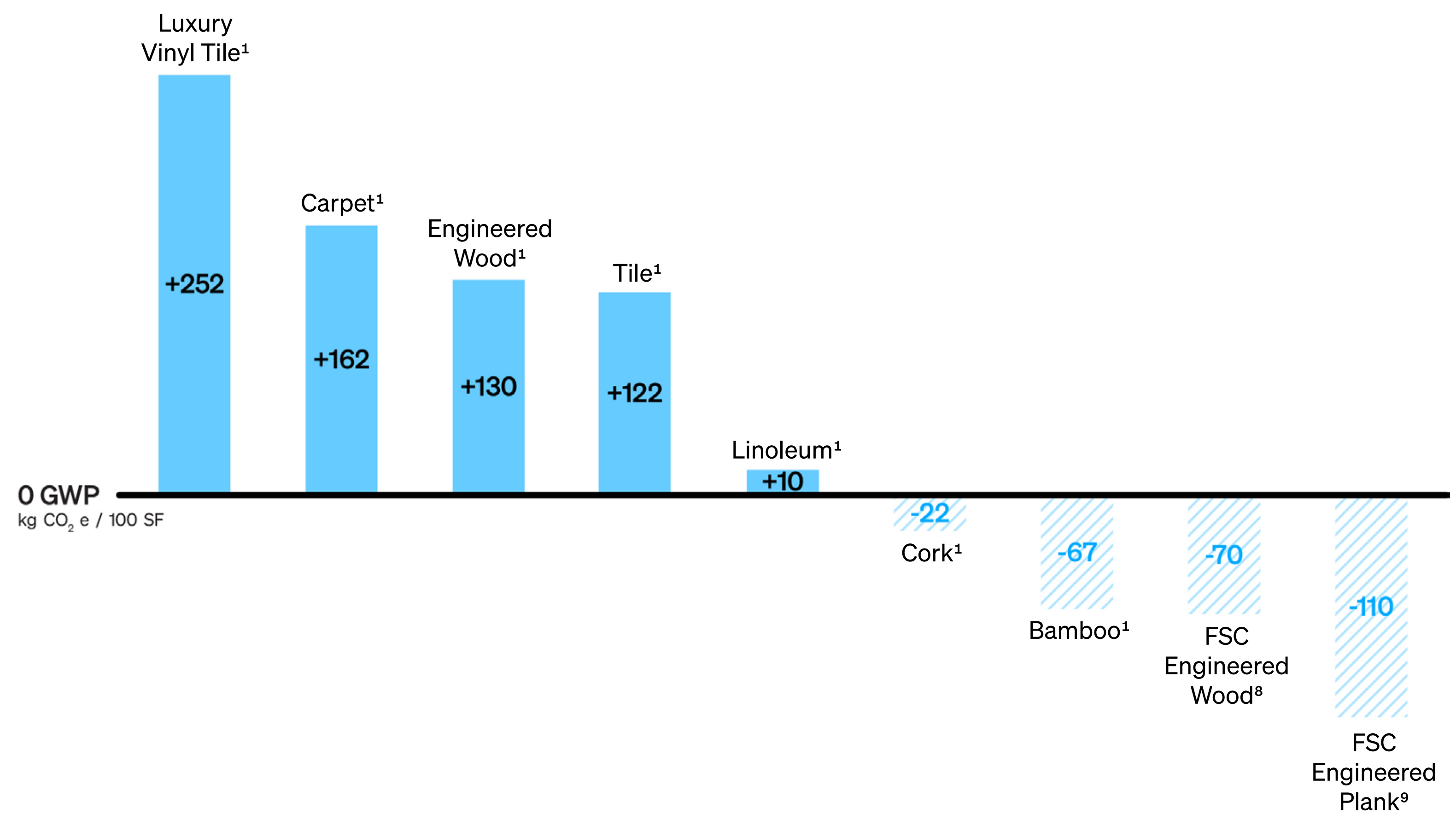


Fig. 18: Comparing GWP to typical floor finishes

Deconstruction Methods

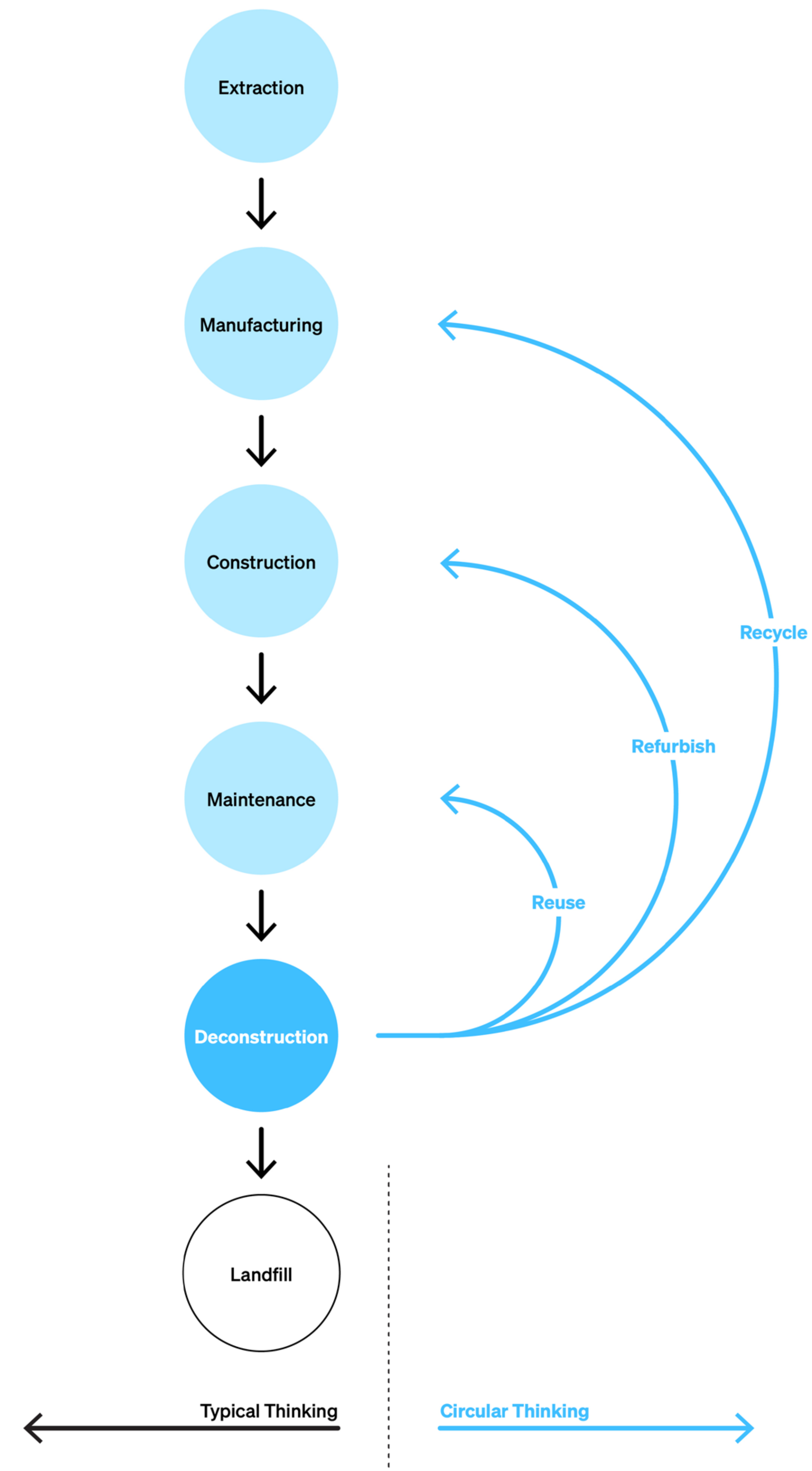
Circularity

Biogenic materials are carbon sequestering as long as they remain preserved in the built environment. In many cases, the utility of the materials outlives the utility of the building, and in that case, designing in such a manner that allows for the graceful deconstruction of our projects allows us to mine them for future projects, and skip the carbon-intensive stages of extraction and manufacturing.

The EPA asks us to consider the following strategies:[11]

- Maximize clarity and simplicity
- Minimize different types of materials and components
- Minimize the number of fasteners
- Use mechanical fasteners instead of adhesives
- Simplify and make visible connections
- Separate building layers or systems
- Disentangle utilities from the structure
- Use materials worth recovering
- Minimize toxic materials
- Minimize composite materials
- Use of modular building components/assemblies
- Provide access to components and assemblies
- Provide access to information:
  - Construction drawings & details
  - Identification of materials and components
  - Structural properties

Deconstruction is commonly associated with carbon, but it is also important to consider the social and economic benefits. To establish a successful deconstruction industry with a skilled workforce of craftsmen, we must begin to think of our projects circularly.



Conclusion

The time to act is now

Climate change is the defining issue of our time. Reducing global greenhouse gas will require fundamental, structural changes to the economy and the way we build. We know that we are past the point of harm reduction and must acknowledge that we are at the stage of climate emergency where direct and immediate steps must be taken to reduce our carbon emissions.

This Toolkit aims to provide a comparative analysis, raise questions about material selection, and explore the potential of constructing buildings in a restorative way for our planet. The authors sincerely hope that this conversation will quickly expand beyond the scope of our document and its "replacement" thinking towards a new paradigm — where construction begins within the earth and building components survive beyond the project's useful life.

We hope this document can motivate this change for ourselves and be useful for our team and others in navigating the complicated world of material selection. We aim to continue our learning, research, and application of these strategies.

Appendix

Methodology

All of the Global Warming Potential values reported in our Toolkit are evaluated over 100 square feet of material, and the A1-A3 stages of an Environmental Product Declaration (EPD) are considered. The other stages of the EPD — transportation, construction, maintenance, and end-of-life — are important but too complex to generalize for our Toolkit's purposes.

We have included the biogenic savings from FSC-certified products, because of the carbon sequestration seen in FSC certified forests in the Pacific Northwest.[11] The favorable outcomes observed in these forests may not be generally applicable. Moreover, the carbon expenditure associated with the disturbance of soils, roots, and the intricate systems of carbon-based life beneath the ground due to tree harvesting remains unclear. Moreover, wood sourced from any sustainably managed forest, regardless of FSC classification, may exhibit similar carbon sequestration, albeit with the same caveats.

These assumptions are baked into the BEAM tool, our primary reference when we developed this Toolkit. We used a beta version of the tool, and the Builder's for Climate Action's website hosts a new, full version and a robust user's guide that details these assumptions.

It is also important to note that our Toolkit does not consider the carbon costs of fasteners, paint, trims, etc. The numbers in our Toolkit are provided for comparison purposes rather than accounting purposes, and a detailed Life Cycle Assessment (LCA) should be conducted to determine the actual carbon cost of the series of assemblies that make up a house.

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Credits

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