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# Low-Carbon Rebuilding Strategies for California Communities Impacted by Wildfires

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This Master's Project

**Low-Carbon Rebuilding Strategies for California Communities Impacted by Wildfires**

by

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# Acronyms

| | |
|---|---|
| CalFire | California Department of Forestry and Fire Protection |
| CalRecycle | California Department of Resources and Recovery |
| CASBA | California Straw Bale Association |
| CWPP | Community Wildfire Protection Plan |
| EC3 | Embodied Carbon Construction Calculator |
| EPD | Environmental Product Declaration |
| EPA | Environmental Protection Agency |
| FEMA | Federal Emergency Management Agency |
| GWP | Global Warming Potential |
| IPCC | Intergovernmental Panel of Climate Change |
| LCA | Life Cycle Assessment |
| LEED | Leadership in Energy and Environmental Design |
| RCP | Representative concentration pathways |
| SCM | Supplementary Cementitious Mixes |
| SWOT | Strengths, Weaknesses, Opportunities, Threats |
| USGBC-LA U.S. | Green Building Council – Los Angeles |

# Abstract

In recent years, California's wildfires have intensified and communities that have been impacted by these wildfires are now beginning to rebuild. Materials that are both fire-resistant and low in embodied carbon should be used when rebuilding in fire-prone regions. Embodied carbon in buildings contributes to about 11% of global greenhouse gas emissions. To help California reach its climate mitigation and resilience goals, this study examined the utilization of low-carbon and fire-resistant building materials during the post-wildfire rebuilding process. Embodied emissions are significantly reduced when building designs incorporate low-carbon materials. This study examined low-carbon and fire-resistant exterior building materials that can be used when rebuilding in fire-prone areas to reduce the embodied carbon of new construction. This study also examined opportunities for material reuse that can be used to help further reduce the embodied carbon of buildings and divert waste away from landfills. Low-carbon and material reuse recommendations for rebuilding after a wildfire include: 1) develop a low-carbon building guidance document and incentives program 2) require whole building life cycle assessments for new construction 3) establish a low-carbon concrete requirement 4) create a material reuse and redistribution program for rebuilding after a wildfire 5) develop a universal building materials database. These recommendations will help develop communities that are more resistant to wildfires, and these recommendations will help to mitigate further climate change impacts by reducing embodied carbon in the rebuilding process.

# 1 Introduction

Over the last few years, California has experienced some its most destructive fire seasons in history. These wildfires damaged and destroyed thousands of structures each year. This destruction caused by wildfires resulted in a significant demand for rebuilding. To help shelter those who have been affected by wildfires, housing is either rebuilt atop the rubble in the fire-prone area or in regions elsewhere. This natural disaster will perpetuate as fire seasons in California are growing longer and stronger due to climate change.

In 2017, the average global temperature increased 1°C above pre-industrial levels due to anthropogenic activities (IPCC, 2018). This global temperature change is significant because it impacts interconnected natural systems. As global temperatures continue to rise as a result of anthropogenic activities, this will result in more extreme weather patterns, floods, droughts, sea level rise and biodiversity loss (IPCC, 2018). These extreme weather patterns can then lead to other climate disasters. For example, higher temperatures and droughts create dryer conditions which increase wildfires. The building sector contributes to climate change through the making of building materials, as well as in the operation of buildings. Resource extraction and manufacturing activities needed to produce building materials result environmental degradation and greenhouse emissions. In addition, if electricity is not generated from clean energy sources, a large amount of emissions are created when a building is in use. In order to reduce the impacts of climate change, the building industry must begin to partake in sustainable building practices.

As a result of climate change and anthropogenic activities, wildfires in California will become more frequent, resulting in significant infrastructure damage. Those who are displaced by climate change impacts and move to another region are categorized as climate migrants. As climate change impacts continue to intensify, the number of climate migrants will continue to grow. Projections show that there will be about 150 million climate migrants by 2050 (Faber and Schlegel, 2017). After a wildfire, some will choose to relocate to avoid experiencing future wildfires and others will choose to rebuild their home in these fire-prone areas. These communities are now working to rebuild, but still remain vulnerable to future wildfires. It is essential that the built environment implements climate change adaptation strategies to make buildings more resilient to climate change impacts and protect those who live in vulnerable areas.

## 1.1 Wildland-Urban Interface

While a wildfire needs fuel, oxygen and heat in order to ignite, dry conditions and wind cause wildfires to rapidly spread. Wildfires are increasing in California due to the expansion of developments, modifications in wildfire regimes and climate change (Mockrin et al, 2020). As California's population continues to grow, housing begins to encroach on natural habitats, such as wildlands. This is known as the wildland-urban interface. From 1990 to 2010 in the United States, the development of new houses in wildland-urban interface zones grew by 41% as about 40 million new residential structures were constructed (Radeloff et al., 2017). Although wildfire risk is increasing due to climate change, the number of structures developed in wildland-urban interface regions is still increasing. While wildfires can occur naturally through lightning, most wildfires are caused by humans or infrastructure failure (Mockrin et al, 2020). From 1992 to 2012, about 84% of the wildfires in the United States were human-caused (Balch et al., 2017). In addition, fire seasons have extended into all seasons because of human-ignition (Balch et al, 2017). Therefore, developing communities in regions which are already prone to wildfires contributes to the problem (Radeloff et al., 2017).

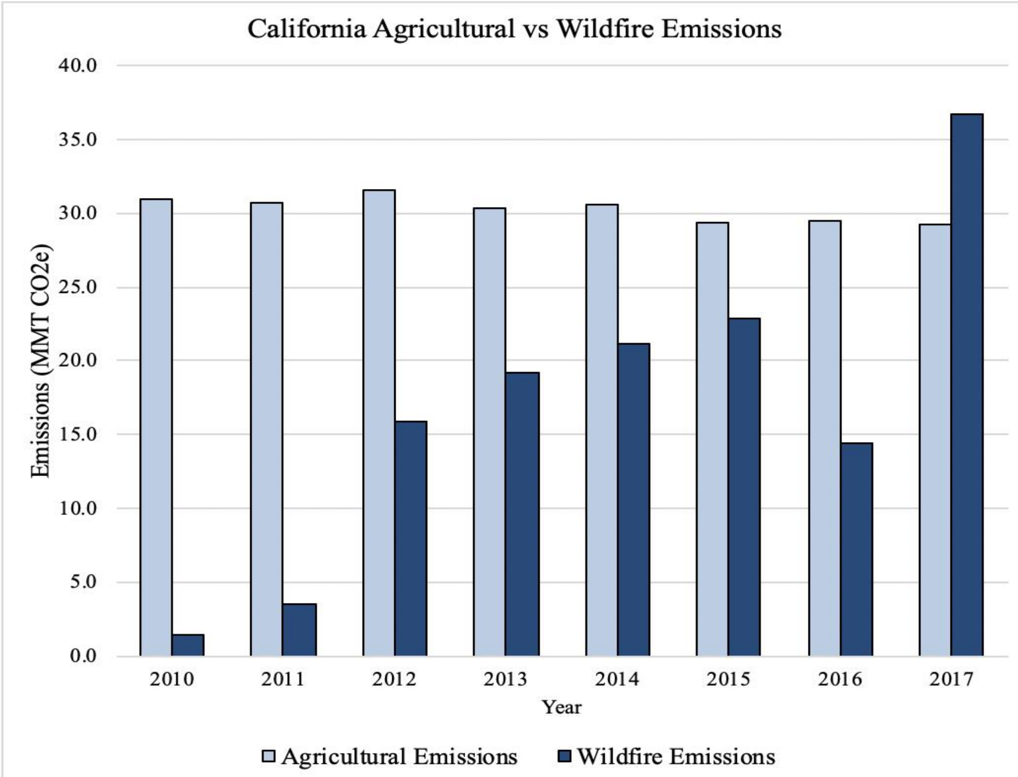
## 1.2 Increasing Destructive Wildfires in California

In 2019, CalFire published a list of the top 20 most destructive fires in California. Of those 20 fires, 10 of the most destructive fires in the state occurred between 2015 and 2018. Out of the 10 most destructive California wildfires, seven of those fires also occurred between 2015 and 2018. California’s most destructive wildfire, known as the Camp Fire, began in November 2018 due to powerline failure in Butte County (CalFire, 2019). The Camp Fire burned 153,336 acres of land, destroyed 18,804 structures and took the life of 85 people (CalFire, 2019). California’s most destructive fire year occurred in 2018 where almost two million acres of land were burned and about 24,000 structures were destroyed or damaged (CalFire, 2020).

## 1.3 California Climate Models

Representative concentration pathways (RCP) are used in climate modeling to help create different future climate scenarios. Climate modeling is important as it can be used to better understand possible climate change outcomes so that better mitigation and adaptation strategies can be created. The RCP 8.5 scenario models climate impacts in the event that emissions continue to rise over the next few decades rather than plateau or decline (Westerling, 2018). According to California's Fourth Climate Change Assessment, it is estimated that wildfires in California will increase 77% by 2050, when compared to 1961 to 1990 data when looking at the RCP 8.5 scenario. The RCP 4.5 scenario models climate impacts in the event that emissions decline by 2050 and plateau by 2080 (Westerling, 2018). California's Fourth Climate Change Assessment estimates that burn areas in the state will increase by 48% by 2050 in the RCP 4.5 scenario. The RCP 8.5 scenario simulates what will happen if we continue with these "business as usual trends" and reveals that wildfires in California are projected to significantly increase.

California Air Resources Board states that California's climate action strategy entails reducing greenhouse gas emissions to 40% below 1990 levels by 2030. California's greenhouse gas inventory only includes fossil-fuel generated emissions and does not include emissions which result from wildfires (California Air Resources Board, 2019). Preliminary estimates show that about 45.5 million metric tons of carbon dioxide (MMT $CO_2$) was released during the 2018 California wildfires (California Air Resources Board, 2019). In 2017, about 36.7 MMT $CO_2$ was emitted from California wildfires (California Air Resources Board, 2019). According to the California 2017 greenhouse gas inventory, about 4.3 MMT $CO_2$ more emissions were created from wildfires than the agricultural sector, which emitted about 32.4 million metric tons carbon dioxide equivalent (MMT $CO_2eq$). Carbon emissions from wildfires should be included in California's emissions targets as wildfires can be a significant source of emissions, as shown in Figure 1.




The data used to create this figure was collected from the California Air Resources Board in 2019.

**Figure 1. California Agriculture Emissions vs Wildfire Emissions**

The agricultural sector is recognized in California's greenhouse inventory. However, wildfire emissions are growing to be a more significant emissions source and these emissions are not accounted for the greenhouse gas inventory. (Source: Author)

Local governments play an important role in reducing wildfires to help protect communities and natural habitats since the federal government does not require localities to reduce wildfires through land use planning (Mockrin et al, 2020). Local governments have the power to reduce wildfires by establishing land use and building code regulations which focus around creating community resilience. In 2003, the federal government created the Healthy Forest Restoration Act to help support local communities with addressing the issue of wildfires. In order to qualify for state and federal mitigation funding from the National Fire plan, a locality must submit a Community Wildfire Protection Plan (CWPP) with the help of its various departments (Mockrin et al, 2020). Unfortunately, these CWPPs usually have a heavy emphasis on forest management and tend to focus less on other strategies which include mitigation around homes (Mockrin et al, 2020).

A study which took place in Oakland, California concluded that community members were more interested in supporting new wildfire regulations under the following circumstances: the risk of wildfires was made evident, equity was incorporated into the policy and there was a strong focus on public education (Mockrin et al, 2020). Wildfires are a significant climate change impact in California. Meanwhile, other states within United States are not as significantly impacted by wildfires. This being so, California's state and local governments must create regulations and standards to ensure that structures built in wildfire-prone areas will be able to adapt to and withstand wildfire impacts.

Wildfires in California are projected to increase as climate change intensifies, putting more structures at risk. Unfortunately, this means that the number of individuals displaced by wildfires is also expected to increase. Communities which have been impacted by wildfires will need to be redeveloped to help shelter those whose home was destroyed or damaged. While communities will need to be rebuilt, greenhouse gas emissions must be reduced in order to achieve California's climate action goals. If we choose to rebuild in areas prone to wildfires, the new structures should use low-carbon and fire-resistant building materials.

## 1.4 Embodied Carbon

In addition to creating new homes to reduce California's current housing crisis, the state is also working to create new shelter for those who were displaced from wildfires. As the construction industry rapidly continues to grow and build homes for those in need, it is important to recognize emission outputs from construction material. The building and construction industry contributes to about 30% of annual global greenhouse gas emissions (Akbarnezhad and Xiao, 2016). There are two types of carbon emissions associated with buildings: operational carbon and embodied carbon. Operational carbon are emissions produced during the operational stage of a building's life cycle. Embodied carbon, also known as embodied energy, embedded emissions or embedded carbon, are carbon emissions produced during all stages of a building's life cycle. As shown in Figure 2, these stages include material extraction, material processing and component fabrication, operation and service phase and end-of-life (Akbarnezhad and Xiao, 2016). Embodied carbon in buildings contributes to about 11% of global greenhouse emissions due to building materials and construction practices (Architecture, 2030).

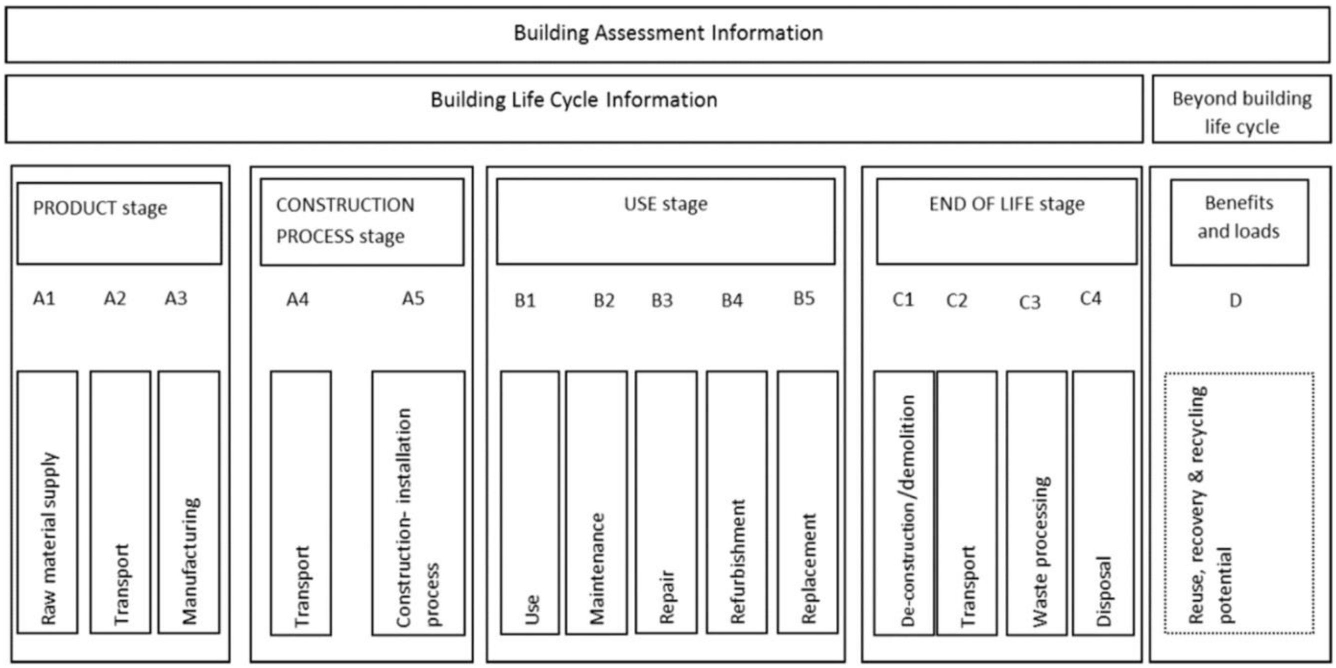



**Figure 2. Building Life Cycle Phases**

The main phases of a building life cycle include production, construction, use and end of life. The embodied carbon of each material contributes to the total embodied carbon of a building. (Source: Pomponi and Moncaster, 2016)

## 1.5 Life Cycle Assessments

Life cycle assessments (LCA) can be used to assess cradle-to-gate, cradle-to-grave or cradle-to-cradle impacts. Life cycle assessments are completed by using life cycle assessment programs. For example, Athena, a life cycle carbon calculator, can be used to quantify embodied carbon by calculating the global warming potential associated with each building material (Shirazi and Ashuri, 2018). The unit typically used to measure embodied carbon is a carbon equivalent ($CO_2$eq). A carbon equivalent unit is used because it converts the quantity of different greenhouse gas emissions to an equivalent of carbon dioxide so that impacts can equally be quantified between gases (Akbarnezhad and Xiao, 2016).

Many embodied carbon studies focus on up-stream impacts and conduct a cradle-to-gate life cycle assessment (Akbarnezhad and Xiao, 2016). This includes material extraction, processing, and component fabrication stages. While it is important to address up-stream carbon emissions, it is equally important to assess embodied carbon produced in post-operational life cycle phases. Complete life cycle assessments help to create and support a circular economy. A circular economy considers production, consumption and waste processes, demonstrating the need for complete cradle-to-cradle life cycle assessments (Foster, 2019).

# 2 Research Questions and Methodology

The main objective of this paper is to better understand how low-carbon, fire-resistant and salvaged materials can help reduce greenhouse gas emissions when rebuilding after wildfires in California. This research is significant because California wildfires are projected to increase and this will result in an increase of displacement as entire communities may be damaged. The following questions will also be addressed to better understand how low-carbon building strategies can be implemented in fire-prone regions. What low-carbon, fire-resistant building materials can be used to rebuild structures? What building material reuse strategies exist and how can they be strengthened? For the purpose of this paper, low-carbon and fire-resistant materials will be researched for the building envelope. Meanwhile, material reuse strategies will be researched for the building structure and interior.

The study design includes a literature review and several forms of analysis. Findings from the literature review will be synthesized. The literature review will provide useful background information on low-carbon building strategies and highlight current building trends. Comparative analysis will be used to compare the embodied carbon content and fire-resistance of materials used in a building envelope. This analysis measures the embodied carbon of a material through its global warming potential of a material and the fire-resistance of a material which is found in fire test reports. Global warming potential values represent the warming impact that a greenhouse gas traps in the atmosphere relative to carbon dioxide. Fire ratings reveal how long a material can withstand a standard fire-resistance test. For the purpose of this paper, the exterior building materials which will be researched include the foundation, insulation, siding and roof.

To assess the success of implementing building material reuse strategies for structural and interior materials, a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis will be conducted. A policy analysis will also be conducted to assess existing building material regulations and research policy options which will help support building with low-carbon materials. Following the completion of the analyses, recommendations for best practice will be made.

# 3 Low-carbon Exterior Building Materials

This section will be focused on researching exterior building materials that have lower embodied carbon and increased fire-resistance than commonly used conventional building materials. The literature review will highlight background information about embodied carbon in buildings. Then a comparative analysis will be conducted to better understand what low-carbon and fire-resistant exterior building materials are available and how these materials compare to conventional building materials. Following the comparative analysis, findings will be discussed and used to create a relative ranking table.

## 3.1 Literature Review

Embodied carbon in new buildings is greater than that of existing buildings (Röck et al., 2019). A building typically contains at least 60 materials and the embodied carbon of each of these materials contributes to the total embodied carbon of a structure (Röck et al., 2019). Structure building components, such as foundation and framing, contribute to about 55% of a building's total embodied carbon (Pearson, 2020). Since structural engineering makes up more than half of a building's embodied carbon, reducing the embodied carbon in these materials should be prioritized. Common strategies which are practiced to reduce embodied carbon in buildings include the use of low-carbon materials, material reuse, recycling and minimization, local material sourcing and optimizing construction practices (Akbarnezhad and Xiao, 2016).

As interest in reducing embodied carbon increases, more low-carbon material alternatives are being developed. Buildings have the opportunity to act as a carbon sink when bio-based materials are used because natural materials store and sequester carbon (Churkina et al., 2020). In addition, natural building materials are generally healthier and safer to use since bio-based materials usually have lower toxicity levels (Magwood, 2016). According to practitioners, economic, technical, practical and cultural barriers can create challenges when opting for low-carbon material alternatives (De Wolf et al., 2016). Despite these barriers, utilizing low-carbon building materials can significantly reduce the embodied carbon of a building. One study demonstrated that switching conventional building materials with low-carbon materials decreased the embodied carbon of the building by 30% (Akbarnezhad and Xiao, 2016). For the purpose of this paper, low-carbon, fire-resistant building envelope materials will be researched. Figure 3 highlights common building envelope components that will be included in this comparative analysis.

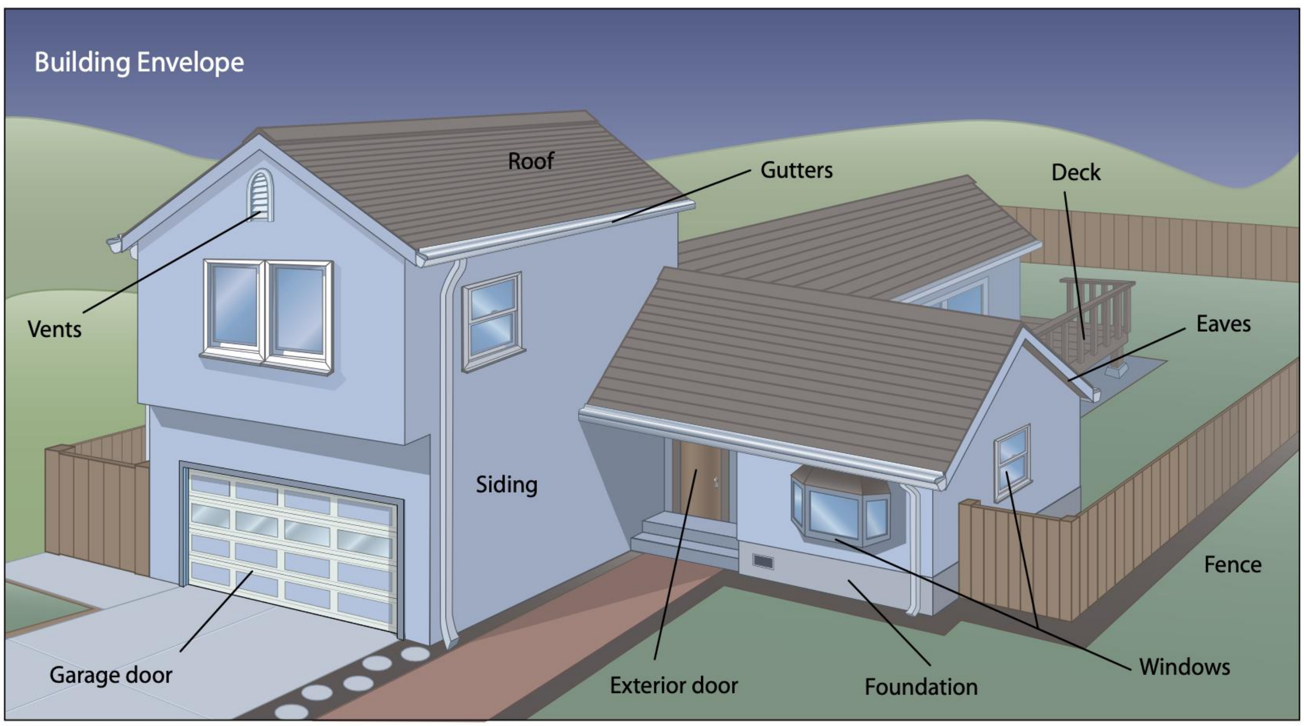



**Figure 3. Main Building Envelope Components**

There are many different components which make up a building envelope and all of these exterior building materials should be fire-resistant to increase the structure's resiliency to withstand a fire. (Source: FEMA, 2008)

## 3.2 Comparative Analysis

To better understand the properties of exterior building materials, a comparative analysis will be conducted. This analysis will compare the embodied carbon and fire rating of exterior building materials including the building foundation, insulation, exterior wall and roofing. The materials researched will either be conventional or naturally-derived materials.

### Foundation

Most foundations in California are made from concrete, which is a material that has high fire-resistance (MPA The Concrete Centre, 2019). Cement is one of the main ingredients in concrete and contributes to about 8% of global greenhouse gas emissions (Orsini and Marrone, 2019). About 60% of emissions associated with cement production are created during the material extraction phase (Orsini and Marrone, 2019). The other two main ingredients in concrete are water and aggregate. Low-carbon and carbon-sequestering cement alternatives are available and can be used to reduce a building's embodied carbon. For example, the use of supplementary cementing materials, such as fly ash, can be used to significantly decrease carbon emissions associated with cement (Schneider, 2019).

The most common way to reduce the embodied carbon of concrete is to replace a portion of cement with fly ash which is a by-product of coal combustion. For every metric ton of Portland cement that is produced, one ton of carbon dioxide is released (Schneider, 2019). Table 1 shows how fly ash replacement for Portland cement can lead to embodied carbon reductions. If 30% of cement is replaced with fly ash, then the embodied carbon of the concrete can be reduced by 17% (Akbarnezhad and Xiao, 2016). While fly ash can be used to reduce the embodied carbon of concrete, it is important to recognize that fly ash is a by-product of combustion. As clean energy sources become more prominent, fossil fuels will begin to fade away. Incorporating fly ash into concrete is an effective; however, a more efficient low-carbon concrete alternative would not dependent on coal combustion.

**Table 1. Embodied Carbon of Concrete**

The embodied carbon of concrete depends on the concrete grade and cement replacement with fly ash. (Source: Akbarnezhad and Xiao, 2016)

| Concrete Grade | Embodied Carbon (kg $CO_2$-e/kg) | | |
|---|---|---|---|
| | Cement Replacement with Fly Ash (%) | | |
| | 0% | 15% | 30% |
| RC 20/25 (20/25 MPa) | 0.132 | 0.122 | 0.108 |
| RC 25/30 (25/30 MPa) | 0.140 | 0.130 | 0.115 |
| RC 28/35 (28/35 MPa) | 0.148 | 0.138 | 0.124 |
| RC 32/40 (32/40 MPa) | 0.163 | 0.152 | 0.136 |
| RC 40/50 (40/50 MPa) | 0.188 | 0.174 | 0.155 |

Another way to reduce embodied carbon of concrete is by substituting aggregate in cement with synthetic limestone. This production strategy has the potential to sequester carbon, as shown in Figure 4 (Schneider, 2019). For example, gas stored in carbon capture technology can be converted into a solid carbonate when combined with calcium (Schneider, 2019). When this carbonate is incorporated into a cement mix, there is an opportunity to produce concrete which sequesters carbon during the production process.

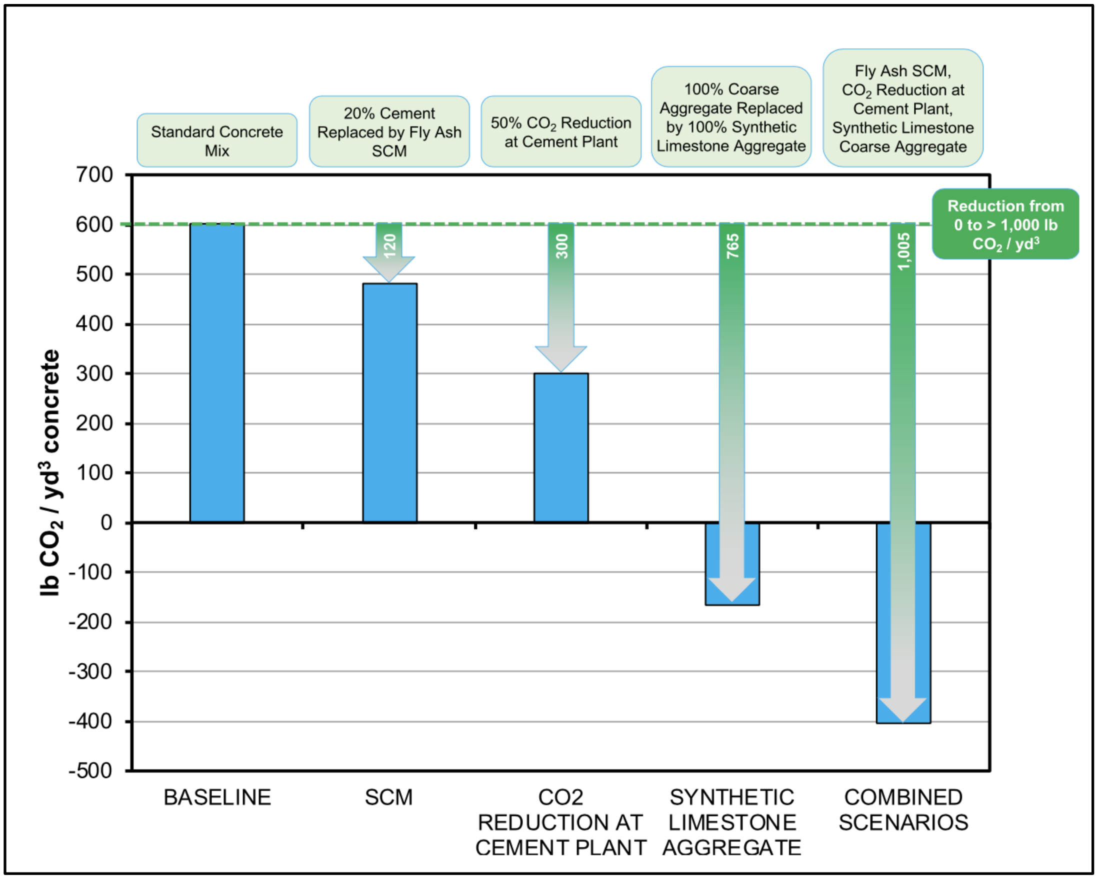



**Figure 4. Concrete Mix Emissions**

Carbon dioxide emissions of concrete can be significantly reduced when supplementary cementitious materials are incorporated into the concrete mix. While the use of fly ash can decrease carbon dioxide emission, the incorporation of limestone can actually help to sequester carbon dioxide. (Source: Schneider, 2019)

Although low-carbon and carbon-sequestering concrete mixes are available, the most effective way to reduce the embodied carbon of a building foundation is to use less concrete. Building designs significantly contribute to the embodied carbon of a structure. Therefore, structures can be designed to use less concrete in the foundation of a building while still remaining seismically safe. If the amount of concrete in a building foundation cannot be reduced, the next best way to reduce the embodied carbon of a building foundation is to use a low-carbon or carbon sequestering concrete.

## Insulation

Insulation is an important exterior building material as it helps to control the heat flow in and out of a structure. Fiberglass is made from fine glass fibers and is the most commonly used insulation material (U.S. Department of Energy, 2020). The embodied carbon by weight of fiberglass batt insulation is 1.35 kg $CO_2$e/kg (Magwood, 2016). While fiberglass alone is not combustible, fiberglass insulation is often paired with other combustible materials, such as paper (Bynum, 2000). Exterior wall materials should be tested by the American Society of Testing Materials using method E119 to test for fire-resistance (FEMA, 2018). FEMA recommends that exterior wall materials have a fire-resistance rating of one hour at a minimum.

A bio-based insulation material which can be used instead of fiberglass is straw bale. The straw used in straw bale insulation is the leftover woody stems from food crops including rice, wheat, barley, oats and rye (CASBA, 2019). Since California has a large agriculture industry many of these crops grow in California. In addition, these crops do not require a lot of time to grow and can be harvested yearly. This being so, resources required to produce straw bale insultation in California appear to be readily available.

Moreover, not only does straw bale have low embodied carbon, it also sequesters carbon. Figure 5 reveals that straw bale insulation has a much less carbon impact than most other insulation materials. About 40% to 50% of straw bale is composed of carbon since it is a natural material (Magwood, 2016). When straw is harvested, the sequestered carbon is then stored in the woody plant material. As long as the straw is not burned and does not decompose, it will continue to store carbon dioxide (CASBA, 2019). A 2,000 square foot straw bale home will store about 5,720 pounds of carbon dioxide and prevent the formation of about 21,000 pounds of carbon dioxide (CASBA, 2019).

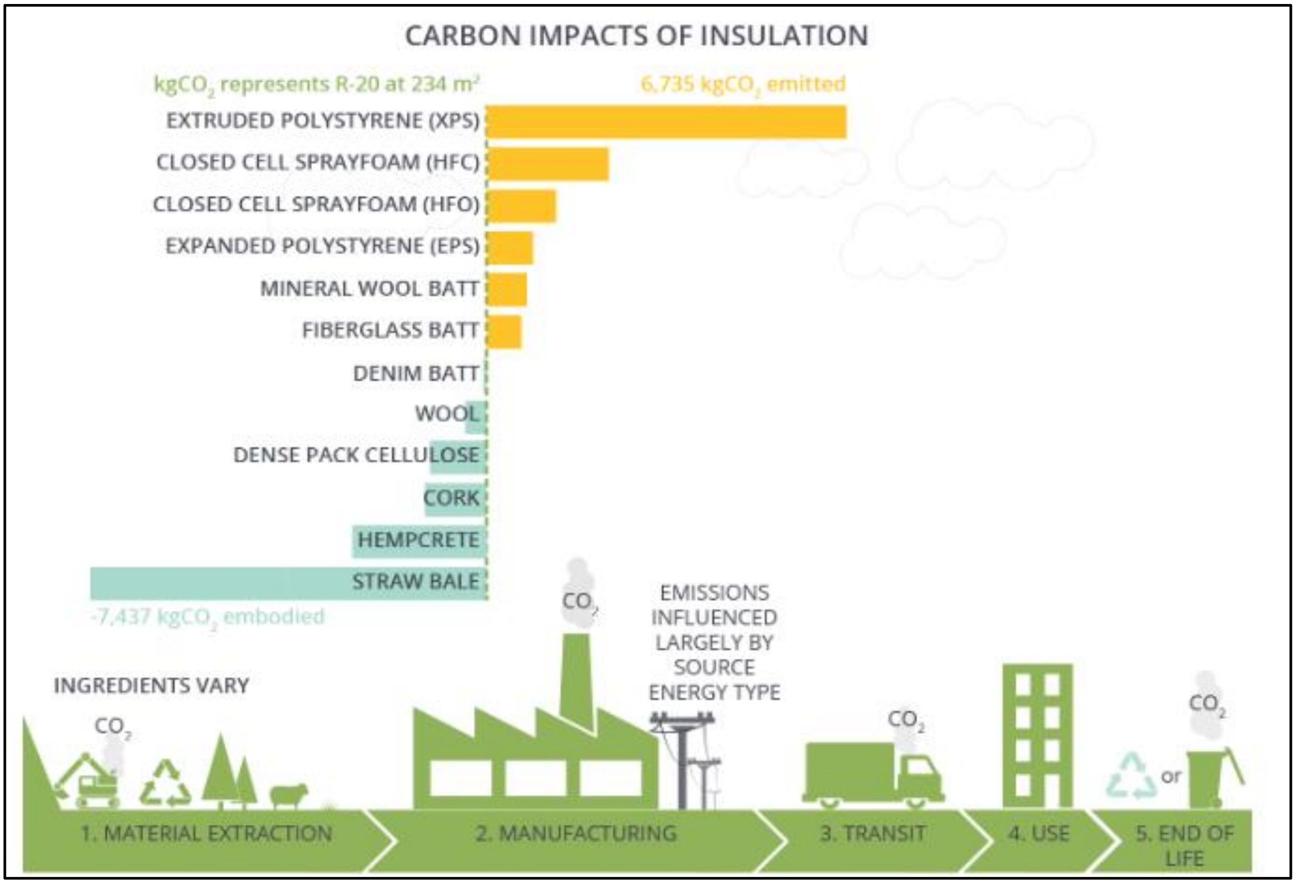



**Figure 5. Carbon Impacts of Insulation**

Straw bale insulation sequesters and stores carbon dioxide while materials that are not bio-based emit carbon dioxide instead of sequestering it. (Source: Architecture 2030, 2020)

In addition, the use of straw bale for insulation reduces methane emissions that would otherwise be released if the straw were to decompose (CASBA, 2019). If straw bale has a cement-lime plaster, it has a two-hour fire rating (CASBA, 2019). If straw bale is paired with an earthen plaster, it has a one-hour fire rating (CASBA, 2019). This suggests that the straw bale is an effective low-carbon and fire-resistant insulation material alternative that can be used to reduce the embodied carbon of buildings in fire-prone areas.

## Exterior Walls

While not all low-carbon exterior wall building materials are fire-resistance, plasters can be applied over siding to help increase fire-resistance. Plaster is a protective coating that is applied to both interior and exterior walls. One type of plaster that is commonly used is cement plaster. As discussed in the section above, cement has a high fire-resistance and high embodied carbon. A natural alternative to cement plaster is earth plaster. Although a majority of building techniques used to apply earth plaster are labor intensive, there is a growing interest in building with earth materials to reduce embodied carbon (Melià et al., 2013). The main components in earth plaster are sand, clay and vegetal fibers (Melià et al., 2013). One study concluded that the production of earth plasters is less carbon intensive than cement plasters, as shown in Figure 6 (Melià et al., 2013). In this study, the base earth plaster emitted 0.88 kg $CO_2$eq per $m^2$ of wall covering while the cement plaster emitted 5.86 kg $CO_2$eq (Melià et al., 2013). This demonstrates the carbon reduction opportunity which earth plasters can provide.

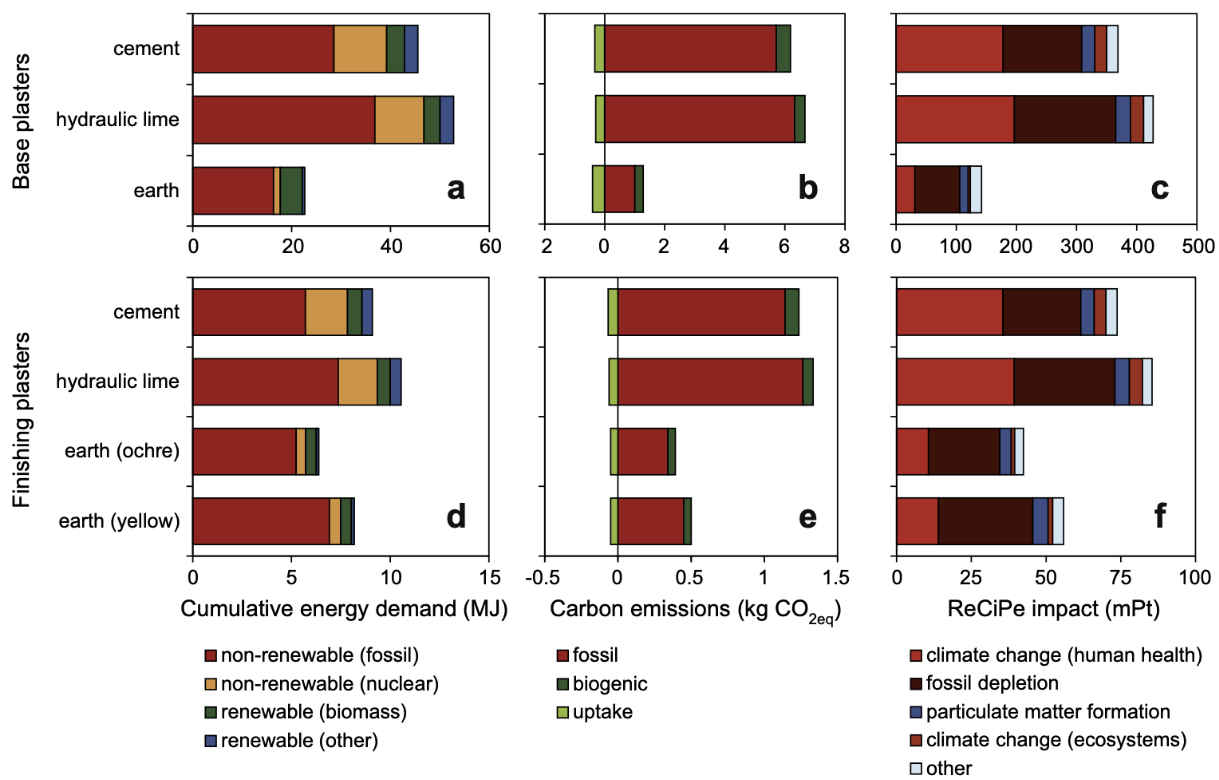



**Figure 6. Carbon Impacts of Plaster**

Earth base plasters and earth finishing plasters are less carbon-intensive than cement or lime plasters (Source: Melià et al., 2013)

It is important that exterior walls are comprised of noncombustible that is also not susceptible to melting (FEMA, 2008). FEMA recommends that materials used for exterior walls should have a fire-resistance rating of one hour, at a minimum. Although there are greater opportunities to build with salvaged wood or recycled metal, these materials should not be used as siding since wood is not fire-resistant and heated metal is likely to warp (FEMA, 2008). Plasters can be applied to walls to help increase fire-resistance. As mentioned in the section above, earthen plaster has a one-hour fire rating, meeting the recommended fire-resistance rating (CASBA, 2019). Earth plaster can be paired with fire-resistant siding materials, which may not necessarily be low-carbon, to help construct structures that are more resilient during wildfires while also demonstrating embodied carbon reductions.

## Roofing

When wildfires embers are released into the air, the embers can travel a great distance and come in contact with the roof of structures that are not in the direct vicinity of the fire. Roofs are one of the most vulnerable building envelope components because of its horizontal orientation (FEMA, 2008). Once the roof of a structure is ignited, there is a greater chance that the fire will spread into the interior of a building (FEMA, 2008). Therefore, if a roof is fire-resistant, the probability that the structure will be able to withstand a fire will increase. The roof design also contributes to the likelihood of whether or not the roof will ignite. For example, if a roof has valleys, combustible debris can become trapped within the roof (FEMA, 2008). The American Society of Testing Materials (ASTM) tests the fire-resistance of roof materials by using the test method E108 and rates materials from highest (Class A) to lowest (Class C). FEMA recommends that structures located in wildfire zones should only use Class A roof materials, such as clay tiles.

Clay tiles have a large thermal mass which makes the material noncombustible (FEMA, 2008). Clay tiles are derived from natural materials as clay is produced as a result of weathering rocks and soils (USGS, 1999). In addition, clay roof tiles can be 90% recycled, which helps to reduce the embodied carbon of clay tiles (Gargari et al., 2016). According to the Inventory of Carbon and Energy database, the embodied carbon for clay building material is 0.255 kg COe/kg. Clay tiles are better to use during new construction since clay is typically heavier than other roofing material. This being so, the structure must be designed to support the added weight of clay tiles.

While lightweight clay tiles are available, FEMA recommends using normal-weight tiles since the increase in mass increases its resistance to fire.

Another roofing materials which FEMA identifies as a Class A material are metal shingles and panels. Since metal is a highly recyclable material, using metal shingles also has the potential to result in reduced embodied carbon. Although metal shingles are noncombustible and highly recyclable, metal easily transfers heat, which can be dangerous during a wildfire (FEMA, 2008). Since metal shingles weigh less than clay tiles, embodied carbon of the overall building structure can be reduced as less material is required to support of weight of the roof. However, metal can warp and the metal may transfer heat to another part of the building which may contain combustible materials. This being so, clay roofing is recommended if it will increase the overall fire-resistance of a structure because rebuilding a structure results in more embodied carbon than the extra materials needed to support a clay tile roof.

## 3.3 Findings

For the purpose of this study, only select materials were researched. The embodied carbon and fire ratings of these materials are presented in Table 2. This research demonstrates that natural building materials can be more fire-resistant than conventional materials that must be treated with fire retardant chemicals. In addition, these natural materials are less carbon intensive than commonly conventional materials.

**Table 2. Exterior Natural Building Materials**

Exterior natural building materials can be used in fire-prone regions to help reduce embodied carbon of a building.

| Material | Use | Embodied Carbon | Fire Rating |
|---|---|---|---|
| Concrete Grade 20/25 MPa with 30% fly ash | Foundation | 0.108 kg COe/kg | The fire rating for concrete is Class A |
| Straw Bale | Insulation | 0.063 kg COe/kg | 2 hour with cement-lime plaster<br>1 hour with earthen plaster |
| Earthen Base Plaster | Exterior Wall | 0.88 kg $CO_2$e | -- |
| Clay Tile | Roof | 0.255 kg COe/kg | The fire rating for clay tiles is Class A |

The comparative analysis data was used to produce a relative ranking table since the embodied carbon values for some materials are not available. Materials ranked as “high” exhibit low embodied carbon and are more fire-resistant. Therefore, these materials should be prioritized over materials ranked as “low”. Materials ranked as “low” should not be utilized as these materials are carbon intensive and may not be fire-resistant. The relative ranking table compares the natural materials listed in Table 2 to conventional building materials that are often used today.

**Table 3. Relative Ranking of Exterior Building Materials**

A relative ranking table helps to compare natural and conventional exterior building materials. Materials ranked “high” should be prioritized over materials ranked as “medium” or “low” since these materials are less carbon intensive. (Source: Author)

| Material | Use | Relative Ranking |
|---|---|---|
| Portland Cement | Foundation | Low |
| Concrete Grade 20/25 MPa with 30% fly ash | Foundation | Medium |
| Concrete with limestone instead of coarse aggregate | Foundation | High |
| Straw Bale | Insultation | High |
| Fiberglass Batt | Insulation | Medium |
| Earthen Plaster | Exterior Walls | High |
| Cement Plaster | Exterior Walls | Low |
| Clay Tiles | Roofing | High |
| Metal Shingles | Roofing | Medium |

## Foundation

Studies have shown that the production of Portland cement may contribute to up to 5% of global carbon dioxide emissions (Metlton, 2018). Therefore, this material is ranked as low since it is responsible for a vast amount of greenhouse gas emissions. Concrete with fly ash is ranked as medium because fly ash is derived from coal combustion and it is important to transition away from fossil fuels in order to reach climate action goals. Concrete with synthetic limestone instead of coarse aggregate is ranked as high since this concrete mix allows for carbon sequestration. As discussed previously, concrete has a high fire-resistance for the relative ranking of these concrete mixes was mainly determined by the carbon intensity of each material.

## Insulation

Fiberglass batt insulation is the most commonly used insulation in the United States and is significantly less carbon intensive than polystyrene and sprayfoam insulation. Although fiberglass batt insulation has a lower embodied carbon then many other conventional insulation materials, it is ranked as medium because it does not sequester carbons like natural materials. In addition, fiberglass is non-combustible. However, this material is sometimes combined with other combustible materials to form the insulation. This is another reason by fiberglass batt insulation is categorized as medium. There is an opportunity to increase the fire-resistance of fiberglass batt insulation by pairing fiberglass is non-combustible materials rather than combustible material. A better insulation alternative to conventional fiberglass batt insulation is straw bale. Straw bale insulation is ranked as high since this natural material sequesters carbon and can be harvested in California. In addition, then paired with earth plaster, straw bale insulation has a fire rating of one hour.

## Exterior Walls

Plaster can be applied to both interior and exterior walls to act as a protective layer. Cement-based plaster is often used in buildings and has a high embodied carbon value since this plaster utilizes cement. This being so, cement plaster is ranked as low because there are more efficient plaster alternatives available. Earth plaster has a significantly less embodied carbon value than cement plaster since it is derived from natural materials, including clay and sand. These natural materials used in earth plaster increase the fire-resistance of the material. As discussed in the section above, earthen plaster has a fire rating of one hour.

## Roofing

Metal shingles have the potential to be less carbon intensive since metal shingles can be made from recycled metal, reducing the demand for material extraction. While metal shingles have a Class A fire rating, metal quickly transfers heat. Therefore, metal shingles are categorized as medium since there is a potential that metal shingles may transfer heat to another combustible material within the structure. Clay tiles also have a Class A fire rating and have reduced embodied carbon since it is created from natural materials. Although clay tiles are heavier than metal shingles, clay tiles are ranked as high because it is safer when exposed to fire.

# 4 Structural and Interior Building Material Reuse

This section will explore material reuse opportunities for structural and interior building materials. The literature review will highlight how material reuse can reduce the embodied carbon of buildings. Following the literature review, building material waste trends will be highlighted at the national level and state level. In addition, building practices which promote material reuse and materials available for reuse will be discussed. A SWOT analysis will then be conducted to better understand material reuse opportunities that can be utilized for those who are rebuilding after a wildfire and these findings will be further discussed.

## 4.1 Literature Review

About 50% of global waste is generated through demolition (Akinade et al., 2016). In addition, the building industry is responsible for consuming more than half of global resources (Iacovidou and Purnell, 2016).  In the United States, about 90% of construction and demolition waste is produced from building demolitions and renovations (Iacovidou and Purnell, 2016). Demolition waste can be reduced through reuse and recycling practices. When a material is reused it is recirculated so that it is used as the same function on a different site, rather than discarded (Iacovidou and Purnell, 2016). Meanwhile, when a material is recycled, the material is reprocessed back into a raw material which can then be used to create a new product (Iacovidou and Purnell, 2016). While recycling materials is better than discarding materials, recycling practices require more energy and resources than material reuse.

Prior to removing a structure, building materials, fixtures and appliances can be salvaged for reuse. This will help to reduce waste generation from building demolitions and reduce the demand for resource consumption. Material reuse helps to promote circularity and encourages systems change. The circular economy is an economic development model which prioritizes maximum material reuse and recycle strategies to decrease emissions from production to recovery, thus supporting the idea of recovering salvageable building materials (Ghisellini et al, 2017). When salvaged building materials are reused or recycled instead of demolished, greenhouse gas emissions are reduced by at least 50% (Diyamandoglu and Fortuna, 2015). Moreover, the use of locally produced materials can significantly decrease transportation emissions and lower embodied carbon (Pomponi and Moncaster, 2016). Therefore, redistributing salvaged building material to local development sites can significantly reduce embodied carbon. As we continue to build to meet the housing needs for our growing population, it is important to recognize that natural resources are declining due to over-consumption and material reuse will help to conserve resources (Iacovidou and Purnell, 2016).

## 4.2 Construction and Demolition Waste Trends

Construction and demolition waste trends vary both nationally and at the state level. Building material waste trends for the United States are different than trends in California because building activities vary between states. In addition, building material is processed differently throughout the country as some states have more stringent recycling requirements and processing facilities than others. This section highlights how California's building material waste trends compare to national trends.

### United States

In 2017, the United States generated 569 million tons of construction and demolition waste (EPA, 2019). The construction and demolition waste was produced from building, road and bridge projects (EPA, 2019). Table 4 highlights construction and demolition waste produced specifically from buildings. On average, demolition projects produce about 90% and construction projects produce about 10% of total construction and demolition waste (EPA, 2019). This being so, a majority of the values presented in Table 3 represent waste generated from demolition rather than construction. In 2017, approximately 40 million tons of wood waste was generated (EPA, 2019). This wood waste could have been salvaged for reuse rather than discarded. If the wood is not in the condition to be reused as structural material, the wood could have been used to create other products, such as flooring and furniture.

**Table 4. 2017 Construction and Demolition Debris Generated in the U.S.**
In 2017, approximately 184 million tons of construction and demolition debris was generated from buildings. Almost half of the building debris generated was concrete. (Source: Author)

| 2017 Construction and Demolition Debris Generated in the United States | |
|---|---|
| **Material** | **Millions of tons** |
| Concrete | 98.8 |
| Wood Products | 38.9 |
| Drywall and Plasters | 15.3 |
| Steel | 4.6 |
| Brick and Clay Tile | 12.2 |
| Asphalt Shingles | 14.4 |
| **Total Generated: 184.2** | |

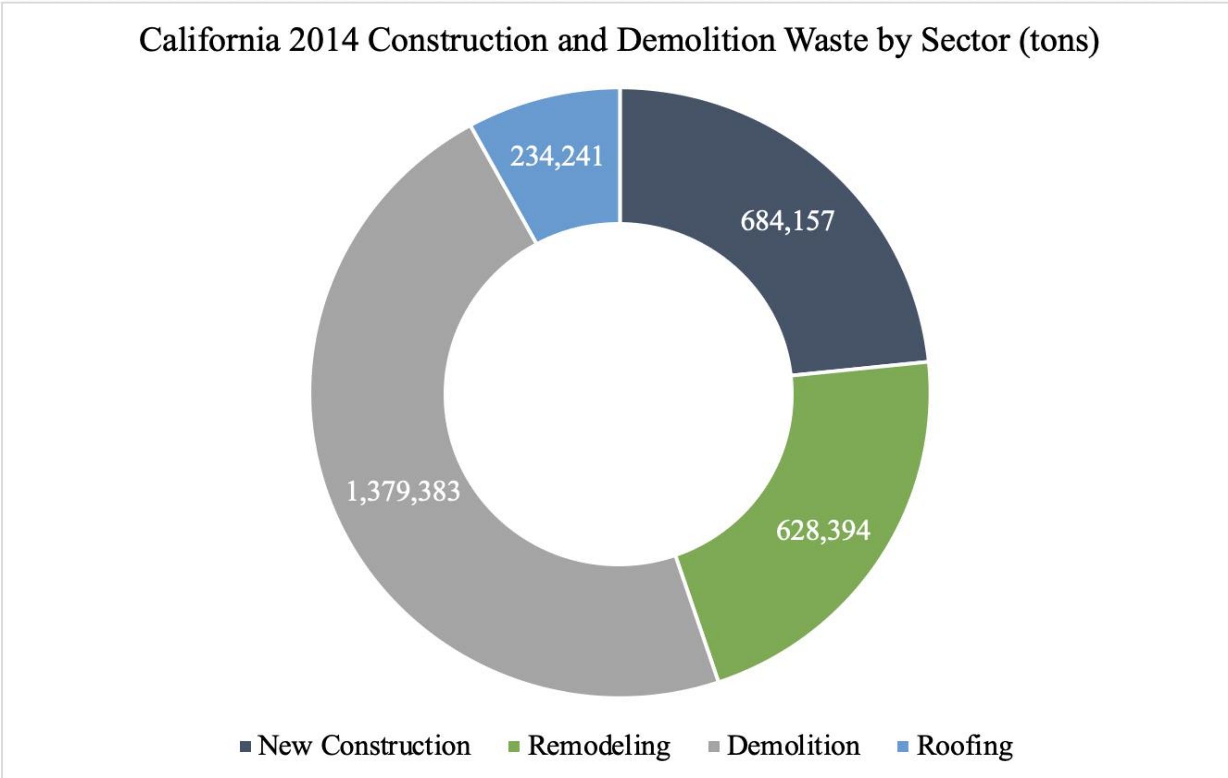
T*he data used to create this table was* collected by the *EPA in 2017*.

The EPA released a Construction and Demolition Debris Management document for waste generated in 2015. In this report, construction and demolition waste was either landfilled or sent to be used for another purpose. The construction and demolition waste that was not sent to the landfill was categorized into the following next-use categories: compost, soil amendment, fuel, manufactured products or aggregate. The materials analyzed consisted of concrete, wood, gypsum drywall, metal, brick and clay tile, asphalt singles and asphalt pavement. In 2015, approximately 8 million tons of wood was transformed into fuel and 1.5 million tons of brick and clay tile were crushed into aggregate and (EPA, 2019). While the EPA report examined next use options for construction and building materials, material reuse for building was not considered.

## California

In 2014, construction and demolition waste accounted for 21.7% to 25.2% of California's waste stream (CalRecycle, 2015). Much of the construction and demolition waste included lumber, metals, masonry, carpet, plastic, and piping (CalReycle, 2015). Figure 7 reveals that about 1,379 million tons of waste was created from demolition activities, making up about half of all construction and demolition waste generated. Renovation projects are commonly performed in California and these projects generated about a quarter of construction and demolition waste in

California. A majority of California's construction and demolition waste could be reduced if building materials were salvaged prior to demolition.




The data used to create this table was collected by CalRecycle in 2015.

**Figure 7. California 2014 Construction and Demolition Waste by Sector**
In 2014, almost half of the construction and demolition waste generated in California resulted from new construction projects. About 684,000 tons of waste was generated from demolition and this could be reduced if material reuse strategies were more prominently exercised. (Source: Author)

## 4.3 Design Strategies that Promote Reuse

There are various building strategies that can be practiced to help promote material reuse. This section will discuss the benefits associated with building deconstruction. In addition, this section will highlight how buildings can be designed in a way that makes it easier to salvage materials during a building removal.

## Deconstruction

Rather than demolishing a building, it can be deconstructed. When a structure is deconstructed, it is disassembled in the reserve order that it was built which minimizes material damage (Chau et al., 2016). Deconstruction has many other benefits in addition to reducing waste. For example, when a building is deconstructed rather than demolished, it decreases health hazards (Akinade et al., 2016). When a building is demolished, the building particles that are released into the air can be hazardous. On the contrary, when a structure is deconstructed, dust production is significantly reduced and the use of heavy machinery is minimal. This then results in better air quality. In addition, for materials that cannot be reused, deconstruction improves source separation to make sure that materials are properly recycled.

There are many factors which determine whether a structure is suitable for deconstruction. It is much easier to deconstruct a building which uses bolts, screws and nails rather than adhesives (Akinade et al., 2016). It is also easier to deconstruct a building which was created with minimal building elements (Akinade et al., 2016). The concept of design for disassembly and deconstruction can help increase material reuse (Akbarnezhad and Xiao, 2016). When a building is designed with premeditated plans that it will later be deconstructed, it is easier to salvage the materials for reuse and recycling. While minimizing materials in a building can be complex, it can result in cost, weight and material reduction (Akbarnezhad and Xiao, 2016). Designers can also reduce embodied carbon in a building by choosing materials which can easily be recycled or reused, thus decreasing post-operational life cycle impacts (Akbarnezhad and Xiao, 2016).

## Design for Reuse

While design for deconstruction makes it easier to recover salvaged materials, design for reuse is a concept which incorporates those recovered materials into the design of a new structure (Iacovidou and Purnell, 2016). While design for reuse is a sustainable building strategy, there are some limitations as material choices and quantities are limited. This being so, the recovered materials available largely determine the building design. It is important that design for reuse incorporates energy-efficient and water-efficient fixtures into the design as some of the available salvaged materials may not be as environmentally-efficient.

## 4.4 Materials Available for Reuse

Some building materials are easier to reuse than others. This section will discuss interior and structural building materials that are commonly reused. For the purpose of this research, this section will not include exterior building material reuse as it is more challenging to build an exterior structure that is fire-resistant using salvaged building envelop materials.

### Interior Materials

Some materials are easier to reuse than others. Important factors which determine if a material can be reused include material quality, function and durability (Iacovidou and Purnell, 2016). According to the EPA, commonly reused construction and demolition materials include doors, hardware, appliances and fixtures. In a Vermont deconstruction case study, interior materials which were salvaged and reused included cabinets, counter tops, sinks and toilets (Diyamandoglu and Fortuna, 2015). CalRecycle also includes carpet and piping as other common construction and demolition materials. These materials can be salvaged for donation or reused on the project site itself (EPA, 2020). If it is not possible to fully deconstruct a structure, partial deconstruction can still salvage useful materials, such as windows, fixtures and cabinets CalReycle, 2020).

### Structural Material

In 2010, about 17 million tons of wood was recovered in the United States for reuse (Diyamandoglu and Fortuna, 2015). Structural wood has a high reuse potential as it can be reused more than 50% of the time (Iacovidou and Purnell, 2016). Recovered wood can be used to create cross-laminated timber, furniture and flooring. Cross-laminated timber panels are made with multiple layers of timber boards arranged crosswise and can be equally as strong as reinforced concrete panels (Hashemi and Quenneville, 2020). In addition, studies have shown that cross-laminated timber panels are seismically safe (Hashemi and Quenneville, 2020). Moreover, creating structures with sustainably grown timber instead of cement can reduce embodied carbon due to the natural sequestration of carbon by wooden materials. Salvaged wood can only be reused or repurposed if it has not been contaminated with toxic substances. Often times salvaged wood has metal, such as nails and screws, within it and these materials must carefully be removed in a way which does not impact the integrity of the wood.

## SWOT Analysis

The potential for material reuse varies by location, structure type and other circumstances. For the purpose of this study, a SWOT analysis will be conducted to better understand the opportunity for utilizing salvaged materials to rebuild structures impacted by wildfires. The SWOT analysis is presented in Table 5.

**Table 5. Material Reuse SWOT Analysis**

Summary of findings from a SWOT analysis focused on the potential of material reuse strategies which can be used to rebuild in fire-prone regions. (Source: Author)

| **Material Reuse SWOT Analysis** | |
|---|---|
| **Strengths**<br>• Reduces embodied carbon<br>• Reduces resource consumption<br>• Reduces waste generation<br>• Secondhand materials are cheaper<br>• Materials can be locally sourced<br>• Can obtain materials more quickly | **Weaknesses**<br>• Limited choice of materials and fixtures<br>• Appliances and fixtures may not be environmentally-efficient<br>• Must be in good condition to be reused<br>• Materials must be stored until needed<br>• May not be fire-resistant<br>• Social stigma against reuse |
| **Opportunities**<br>• Support material reuse market<br>• Materials can be donated so recipients can receive material for free<br>• Promote deconstruction<br>• Increase community engagement through willingness to participate in local reuse program | **Threats**<br>• Unhealthy materials<br>• Policy barriers<br>• Lack of materials<br>• New materials may be cheaper due to subsidizing<br>• Exposure during prior life of material may be unknown |

## 4.5 Findings

The SWOT analysis helped to identify the benefits and disadvantages of using salvaged materials to rebuild buildings located in fire-prone areas. The findings for each component of the SWOT analysis are discussed in the sections below.

## Strengths

Based on this analysis, there are many environmental strengths associated with material reuse. Rebuilding with interior salvaged materials will reduce embodied carbon of these materials as these materials are given a second life instead of being disposed of in the landfill. Material reuse helps to decrease the embodied carbon of a building as emissions which result from the creation of new materials are eliminated. Material reuse also has the potential to reduce transportation emissions. Building materials often need to be transported with large trucks which consume fossil fuels and emit significant amounts of greenhouse gas emissions. If salvaged materials are used for local building projects, then transportation emissions are reduced as the materials do not have to travel large distances to reach the building site.

In addition to reducing greenhouse gas emissions, building with salvaged material also reduces resource consumption. As the global building industry continues to grow, it is important to acknowledge that natural resources are limited. When materials are reused, this limits the need for resource extraction and helps to preserve the biodiversity of ecosystems. For example, when building projects use salvaged wood, this eliminates the need for fresh cut wood. This then results in a decrease of deforestation and conserves natural resources. Moreover, salvaging materials for reuse decreases waste generation as materials are diverted away from landfills.

In addition to environmental benefits, there are economic benefits associated with material reuse. Collecting salvaged materials from local sites can be faster than ordering materials which are manufactured and shipped from facilities overseas. If materials can be obtained more quickly, then building projects have the opportunity to begin sooner. Secondhand materials are generally cheaper than new materials. This helps to reduce building costs which is important for individuals who have previously lost their home due to climate change impacts. Furthermore, materials can also be reused in ways which they were not originally created for. For example, porcelain toilets can be turned into tiles and old bleachers can be transformed into decorative wall paneling. Sometimes the style of salvaged materials may appear to be outdated. However, these materials can be transformed into modern interior materials.

## Weaknesses

Today, designers have an endless amount of material and fixture choices due to the globalization of building materials. However, with material reuse, material and fixtures options are more limited as only a set amount of material types and styles are available. In addition, some of the styles available for reuse options may be outdated. Materials must be in good condition in order to be reused. This also limits the amount of salvaged material available. This can be seen as a significant weakness of material reuse since residents enjoy having many options when customizing their spaces. Moreover, there is a negative social stigma around secondhand practices. These practices are often associated with those who are struggling economically, resorting to thrifted items. There is also the notion that secondhand materials may be contaminated or faulty. In recent years, the concept of reuse has become more popular as some view salvaged items as “trendy”, though this idea is more prevalent in younger generations.

While options are limited, some of the available fixtures may not be environmentally-efficient. For example, installing a salvaged toilet would reduce embodied carbon, waste generation and resource consumption. High efficiency toilets generally use less than two gallons of water per flush. However, if the salvaged toilet uses five gallons of water per flush, it may not be beneficial to reinstall this fixture. Salvaged fixtures must be up to code if they are going to be reinstalled, especially since California appliance efficiency standards will continue to become more stringent within the coming decades. In addition, storing salvaged materials requires a large amount of land and these materials may be stored for long amounts of time before they are transported to new sites for reuse. Since land is very expensive in California, this may be a limiting factor for salvage yards and reduce the potential for material reuse.

## Opportunities

There are a number of financial and societal opportunities associated with material reuse. If salvaged materials are transported to help rebuild homes that were previously damaged during a wildfire, there is a potential that this will increase community engagement. Some choose not to participate in donation programs because they do not know where their donated materials are going. In addition, some donation programs send the materials that they receive to dumping sites rather than transferring the materials to other locations for reuse. Community members and businesses may be more willing to participate in local material reuse programs if they are aware of how their donation can help local community members.

There is also an opportunity to improve the reuse market if salvaged materials are used to rebuild communities after a wildfire. Reuse facilities are currently limited because there is not a large enough demand for salvaged materials. However, there is an opportunity to increase the demand for salvaged materials if they are actively used in the rebuilding process. If the demand for salvaged building material increases, this has the potential to also increase deconstruction projects. Currently, most buildings are demolished rather than deconstructed. Therefore, if there is an increased interest in deconstruction, this would also help to create new jobs.

Moreover, materials which are salvaged for reuse are typically liquidated or donated. This being so, there is also an opportunity for those rebuilding to receive building materials and fixtures for free. This is an important opportunity that could be available as rebuilding a house is costly. Overall, the societal and economic strengths associated with material reuse have the potential to significantly benefit individuals who have been impacted by wildfires.

## Threats

One of the main issues with material reuse is that you do not know what the material was exposed to during its previous use. For example, the material could have been exposed to hazardous material, such as asbestos, during the salvage process. It is important to ensure that materials are not contaminated prior to reuse and employ strong quality control to prevent health impacts. This means that the materials should be disinfected before being redistributed to prevent the spread of disease. However, it can be very difficult to guarantee that the materials are free of contamination. This being so, sometimes clean materials are often thrown away out of safety precaution.

Material availability is another large factor which may threaten the success of material reuse. If there is not enough salvaged material available for reuse, then building projects will not be able to rebuild using reclaimed materials, threating reuse opportunities. In addition, policy barriers can potentially threaten the success of material reuse as there are not incentives for material reuse and some building standards do not approve of salvaged material. Standards are often stringent for structural and foundational building components. Often times there are not standards for interior materials, which makes interior materials easier to reuse. While purchasing salvaged materials is generally cheaper than purchasing new materials, subsidies may encourage the use of new materials rather than salvaged materials, thus threatening the opportunity for reuse.

# 5 Low-Carbon and Fire-Resistant Home

The comparative analysis of low-carbon exterior building materials and SWOT analysis of salvaged materials demonstrates that there are many different low-carbon building materials that can be used to help increase the fire-resistance of structures. Figure 8 highlights low-carbon building material alternatives for main building components.

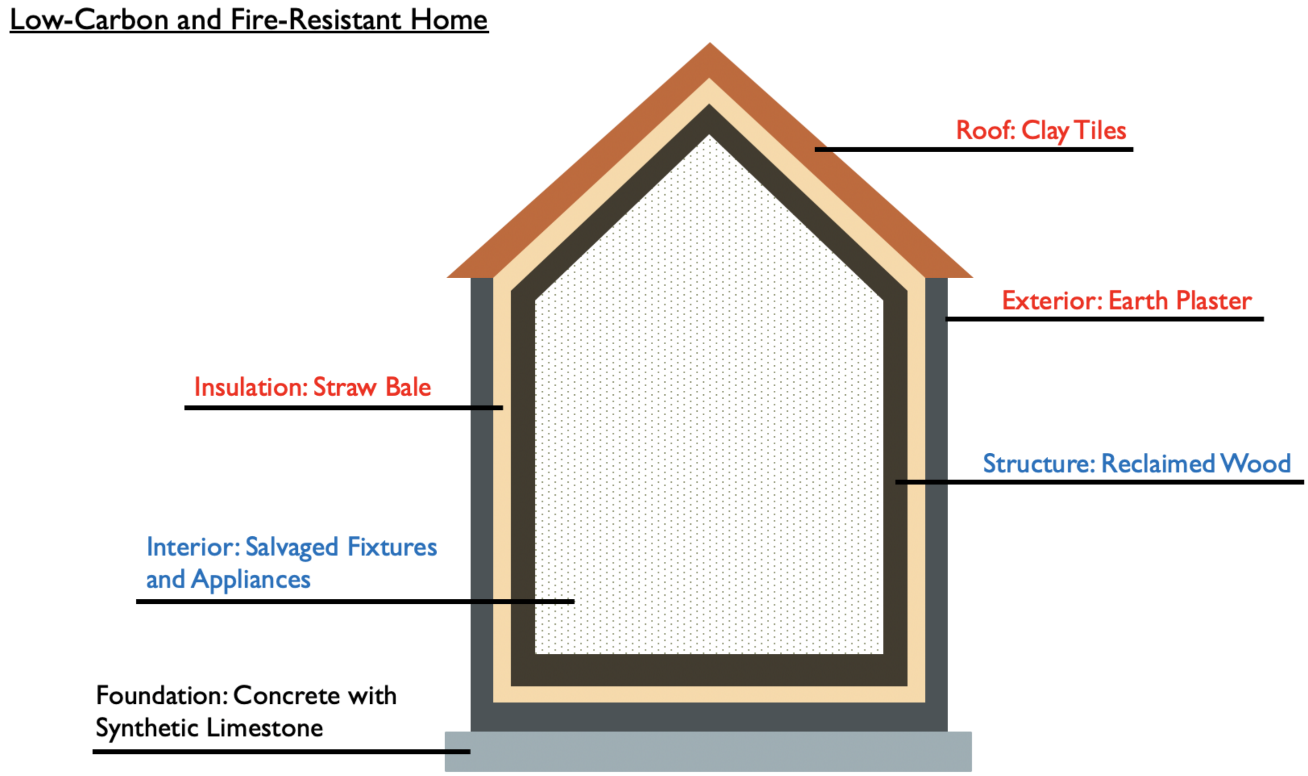



**Figure 8. The Low-Carbon and Fire-Resistant Home**

Low-carbon materials, including naturally derived materials, can be used to create a more fire-resistant home. Materials in red text are naturally derived and materials in blue text are salvaged. (Source: Author)

To create a low-carbon structure that is more resilient to wildfires, the building should be constructed with a combination of natural building materials and reclaimed materials. Natural building materials can be used for exterior components of the building while salvaged materials can be used for structural and interior building components. Building materials which sequester carbon should be prioritized. For example, straw bale insulation and concrete that is created with synthetic limestone. Since not all-natural materials can sequester carbon, the next best option is to choose materials which contain natural materials and require less processing, such as earth plaster and clay tiles.

Salvage materials can help reduce the rebuilding cost as materials are often donated or liquated. Salvaged water-efficient and energy-efficient appliances should be installed into these structures to help reduce the total embodied carbon of the building. Reclaimed wood which has been deemed as structurally safe can be transformed into structural material. Reclaimed wood that is not suitable for structural reuse can be used for flooring or interior walls instead.

As climate change impacts intensify, this will result in more infrastructure damage. Therefore, the demand for housing is expected to grow to help rebuild impacted communities. When new construction is required, natural and reclaimed materials should be the primary materials used. Figure 8 only highlights some of the low-carbon building material alternatives available to help increase the fire-resistance of structures. As the interest in embodied carbon grows and policy implementation becomes more prominent, the number of low-carbon building materials available will increase with demand.

# 6 Policies and Programs

This section will discuss existing embodied carbon policies, standards and programs both at the local level and internationally. After reviewing current policies and programs, a policy analysis will be conducted to better understand what types of policies can be implemented to promote low-carbon building practices for those rebuilding after a wildfire. The results from the policy analysis will then be further discussed.

## 6.1 Existing Policies and Standards

For the last century, there has been a political focus on managing operational carbon (Pomponi and Moncaster, 2017). As sustainable building practices, such as electrification, become normalized, operational carbon in buildings are bound to decrease. To reach climate action goals, it is imperative that embodied carbon in buildings must be reduced. Reducing embodied carbon in buildings while continuing to develop new communities for those impacted by wildfires will be challenging, but it is necessary to help reduce climate change impacts, such as wildfires. Table 6 highlights embodied carbon related policies and standards, which are further discussed in the sections below.

**Table 6. Existing Embodied Carbon and Material Reuse Policies**

Embodied carbon and material reuse policies which are applicable in California. (Source: Author)

| Existing Embodied Carbon and Material Reuse Policies and Standards | |
|---|---|
| Architecture 2030 Embodied Carbon Challenge | Architecture 2030 established three different embodied carbon targets to influence architects and builders to design structures with low-carbon materials. |
| Marin Low Carbon Concrete Code | This code sets new concrete requirements to help reduce the embodied carbon on projects which utilize concrete. |
| San Francisco Construction and Demolition Debris Recovery Ordinance | This ordinance requires that construction and demolition debris is either recycled or reused rather than landfilled. |
| Buy Clean California Act | California state building projects must obtain environmental produce declarations for structural steel, steel rebar, flat glass and mineral wool. Eventually, maximum global warming potential for these materials will be established. |
| LEED V4 Building Life Cycle Reduction Credit | This credit requires adaptive reuse, material reuse or a building life cycle assessment. |
| LEED V4 Building Disclosure and Optimization Credit | This credit requires environmental product declarations for building materials. |

## Organizations

By 2050, projections show that embodied carbon will make up half of global new construction emissions (Architecture 2030, 2020). Architecture 2030 has created the *2030 Challenge for Embodied Carbon* to help motivate architects and builders to reduce embodied carbon in buildings by choosing materials with reduced global warming potentials (GWPs). The targets for the 2030 Challenge are as follows: use building materials which have a GWP 40% below the industry average immediately, 45% by 2025, 50% by 2030 and zero GWP by 2050. While these targets are optional, practitioner interest in reducing embodied carbon is growing. For example, the Embodied Carbon Network was created by the Carbon Leadership forum to allow individuals, such as practitioners and local government staff, to share research findings to help influence the creation of embodied carbon reduction strategies.

## City Policies

Over the last few years, many cities have begun to implement policies which are aimed at reducing embodied carbon of building materials. In November 2019, the Marin County Board of Supervisors adopted the Marin Low Carbon Concrete Code. Several standards are incorporated into the code to help reduce the embodied carbon of concrete while ensuring that the material still maintains a safe level of structural strength. These standards include replacing Portland cement with supplementary cementitious mixes (SCM), minimizing the cement in mixes, aggregate selection and altering the concrete cure time requirements (Ehrlich, 2020). Commonly used SCMs include fly ash, slag and ground glass (Ehrlich, 2020). The code was effective on January 1, 2020 and applies to both residential and commercial projects located within the jurisdiction.

Many cities and states have chosen to implement low-carbon concrete policies since cement is a large contributor to global greenhouse gas emissions and commonly used during construction projects. For example, another city that has implemented requirements related to low-carbon concrete is Portland, Oregon. The City of Portland began to require concrete EPDs beginning January 1, 2020 and hopes to establish a maximum GWP for Portland Cement Concrete by April 2021 (Spitler, 2019). In addition, Portland implemented a deconstruction ordinance which requires that residential structures built before 1940 are deconstructed rather than demolished to promote material reuse.

While the City of San Francisco does not have deconstruction requirements, it encourages building material reuse through a different approach. The San Francisco Construction and Demolition Debris Recovery Ordinance requires that construction and demolition debris are recycled or reused rather than sent to the landfill or incineration. The San Francisco Department of the Environment estimates that approximately 8% of construction and demolition waste was salvaged for reuse and 83% of materials were recycled between 2012 and 2018. During this time period, demolition debris recovery plans indicated that about 30,100 tons of material were either reused directly on the jobsite or salvaged for reuse on future projects and about 327,000 tons of material were recycled. Wood, pallets and lumber contributed to about 210 tons of the salvaged materials while fixtures contributed to about 35 tons. Concrete made up more than half of the total materials salvaged for reuse.

## State Policies

Currently, federal embodied carbon regulations do not exist in the United States. However, local and state governments are now beginning to research possible policy actions and opportunities. For example, California's AB 262, also known as the Buy Clean California Act, was created to help establish maximum global warming potentials for four types of building materials: structural steel, steel rebar, flat glass and mineral wool. As of January 1, 2020, the Buy Clean California Act requires that state building projects include the EPDs of the four materials listed above (USGBC-LA, 2018). The Department of General Services will then use these EPDs to establish maximum acceptable GWPs for the four materials by January 1, 2021 and compliance will be gauged beginning July 1, 2021 (Department of General Services, 2020). Several cities in California have adopted resolutions to support the Buy Clean California Act, including Berkeley, Cupertino and Richmond. The U.S. Green Building Council-Los Angeles (USGBC-LA) chapter has developed a series of webinars and implemented in-person training to help educate workers in the building industry. In addition, the USGBC-LA offers incentives up to $15,000 to help California manufacturers that produce the four target materials obtain EPDs (USGBC-LA, 2018).

## International Policies

Other countries and international cities are also advancing embodied carbon policies. The Netherlands created the world’s first embodied carbon policy in 2018. This policy requires that all new residential and office buildings must account for embodied carbon (World Green Building Council, 2019). In addition, the City of Vancouver has set a target to reduce embodied carbon by 40% by 2030 (World Green Building Council, 2019). To help achieve this goal, Vancouver has a policy which requires a whole building life cycle assessment and disclosure of results whenever a rezoning request is made (World Green Building Council, 2019). Moreover, the Ministry of Environment in Finland published a low carbon roadmap for its construction industry in 2017 (World Green Building Council, 2019). The roadmap states that whole life carbon footprinting will be required for new buildings by 2025 and a legislation dedicated to reducing embodied carbon will be implemented by the mid-2020s.

## Certification Programs

There are also many certification programs which include embodied carbon reduction credits. In Leadership in Energy and Environmental Design (LEED) version 4, the Building Life Cycle Reduction credit encourages builders to think about embodied carbon by offering four different credit options. Option 1 includes historic building reuse, Option 2 includes the renovation of an abandoned or blighted building, Option 3 includes material reuse and Option 4 includes performing a full building life cycle assessment. The number of points received for Option 3 depends on what percentage of the completed project surface area consisted of salvaged materials (LEED, 2020). For Option 4, the results from the life cycle assessment of the project's structure and enclosure must demonstrate a 10% reduction in embodied carbon, at a minimum (LEED, 2020). In addition, the Building Disclosure and Optimization LEED credit requires environmental product declarations (EPDs) for building materials. This credit can influence designers to think about choosing more sustainable building materials as environmental impacts, such as global warming potentials, are highlighted in EPDs. One study concluded that LEED certified buildings generally have lower embodied carbon than non-LEED certified buildings (Pearson, 2020). The LEED certified buildings had an average embodied carbon of 510 $kg/m^2$ while the non-LEED certified buildings had an average embodied carbon of 590 $kg/m^2$ (Pearson, 2020).

## 6.2 Policy Analysis

As communities impacted by wildfires rebuild, low-carbon material alternatives should be considered. Title 24 of the California Building Standards code establishes new progressive construction requirements for the State every three years (Bay Area Regional Energy Network, 2020). Local governments have the opportunity to establish building requirements that are more stringent than the State's requirements by establishing reach codes (Peninsula Clean Energy, 2020). Local and state governments have the power to help reduce embodied carbon of buildings by implementing various policies. Policies which should be considered include building standards, incentive programs, guideline documents and training programs. Some policies will be more effective at the local level while other policy options may prove to be more successful when implemented at that state level. It is important to consider the barriers and opportunities associated with each policy type. In addition, all policies which are implemented should be equitable for all communities which it will impact. Possible policy options will be analyzed and discussed in the following sections.

### Building Standard

It would be ideal if California established a building standard which required the use of low-carbon building materials. However, it takes time to develop a building standard with stringent building requirements. In addition, progressive standards would have to be implemented in phases to allow stakeholders to prepare and adjust to new requirements. For example, the Buy Clean California Act is being implemented in phases because establishing maximum global warming potentials for multiple types of material is a complex process.

Since establishing state-level building standards can be timely, it may be more effective to establish low-carbon building standards at the local-level. This would then create an opportunity for localities to develop low-carbon building standards that consider future climate change impacts that may impact its local communities. Thus, local building standards can mitigate climate change impacts while helping to build resilient communities. For example, areas that are vulnerable to wildfires can develop a building standard which utilizes low-carbon and fire-resistant materials.

The building standard could require that a percentage of the building materials come from low-carbon materials or salvaged materials. Moreover, rather than establish embodied carbon thresholds, the standard can require the use of an embodied carbon calculator for each project to demonstrate the emission impact of each material. The results from the embodied carbon calculator must then be submitted upon receiving a construction permit and must demonstrate the use of low-carbon building strategies.

## Incentive Programs

California could develop an incentive program to encourage building with low-carbon materials. While Buy Clean California is attempting to establish maximum global warming potentials for four types of material -- this regulation will take years to implement and is only focused on a select materials. Encouraging the use of natural building materials will help to sequester carbon. In addition, the use of natural materials helps to create a healthy home since natural building materials do not pose significant toxicity issues unlike other highly processed materials.

An incentives program can be issued state-wide to encourage the use of natural and salvaged building materials. As an incentive, building permits can be obtained more quickly or a rebate can be provided if low-carbon materials are used. For example, USBGC-LA offers up to $15,000 for manufacturers who are looking to obtain an EPD to help track the embodied carbon of is products. A similar incentives program could be implemented for those interested in using low-carbon building materials. If a financial incentive were to be used, the State may need to set some limitations as to who can apply for the incentives program to ensure that there will be enough funding for projects throughout the year. This being so, these incentives could be available to communities that have been severely impacted by climate change, such as wildfires.

## Guideline Pocketbook and Training Program

The California state government could also develop a low-carbon building guideline document to help guide and encourage low-carbon building strategies for fire-prone regions. This document would provide builders with a list of low-carbon exterior and structural building materials which meet building codes. The list can also include the corresponding fire rating of each materials. In addition, strategies for designing structures with low-carbon interior materials, such as salvaged materials, can also be included in this document. Along with the low-carbon building guideline document, the California state government could develop a training program to help builders better understand how to work with low-carbon materials since building practices vary with material type. This training can also increase awareness around the importance of low-carbon building and help to prepare stakeholders for future building policies that the state may implement.

## 6.3 Findings

Based on the policy analysis, there are a variety of policy options which can be implemented. The results of the policy analysis are summarized in Table 7. California's state government can create incentive programs, guideline document and training programs to help accelerate the use of low-carbon building materials. Local governments would then have the option to utilize these resources to develop policies and programs at the local-level. If the State provides these resources, it will be easier for localities to create building standards centered around low-carbon building strategies as resources will be readily available to share for reference.

**Table 7. Low-Carbon Building Policy Analysis**

Summary of policy analysis findings regarding low-carbon building strategies. (Source: Author)

| Policy Type | Scale | Opportunities | Barriers |
|---|---|---|---|
| Low-Carbon Building Standard | Local-level | New structures must comply with building standards. Therefore, this will ensure that embodied carbon in buildings is reduced. The standard can also include qualifications to determine if salvaged material meets building requirements. | May be difficult to monitor compliance of a building standard. If most builders are not complying, then the standard will not be effective. |
| Low-Carbon Building Material Incentives Program | State-wide | An incentives program provides building owners with opportunities to save money when low-carbon materials are used in new construction projects rather than penalizing them. | Incentive programs are not required. Therefore, success of incentives may be limited. In addition, education and outreach must be conducted to promote incentive programs to ensure that the program is utilized properly. |
| Low-Carbon Building Guideline Document | State-wide | A guidance document provides builders with the resources needed to better understand how to build with low-carbon materials and its importance. | A guidance document may not incentivize designers and builders to use low-carbon building materials. In addition, it is difficult to monitor the effectiveness of the document. |

## Local-level Building Standard

Based on this analysis, building standards which require the use of low-carbon or salvaged materials should be implemented at the local-level. Implementing standards is an effective way to enforce low-carbon building as all construction projects must comply. Different regions in California will be impacted by climate change differently. This being so, localizing building standards can help to create communities that can adapt to future climate change impacts. For example, materials used to construct buildings in fire-prone areas will be more limited than buildings located in coastal areas that are vulnerable to sea level rise. When a standard is implemented, it is essential to monitor compliance to assess the success of this policy so that adjustments can be made if necessary. If the standard requires the use of salvaged materials, it will be important to assess the reuse market as salvaged material reuse markets will vary throughout the state.

## State-wide Incentive Program

California should consider creating a state-wide low-carbon building material incentive program. Incentive programs can provide building owners with financial saving opportunities when building with low-carbon building materials. In addition, incentive programs cannot result in penalties unlike building standards. These benefits associated with incentive programs make incentive programs more appealing for new construction projects and can increase interest in low-carbon building strategies. However, participation in incentive programs is voluntary, unlike a building standard. This being so, there is a possibility that builders will not take advantage of this incentive program and continue building with carbon-intensive materials. Since interest in embodied carbon has recently emerged, a significant amount of education may be required to help promote a low-carbon building material incentive program to ensure its success.

## State-wide Guidance Document and Training Program

California should also consider creating a state-wide low-carbon building guidance document and training program. These educational resources can benefit both a building standard and incentives program since they can be used as supplemental materials. As the interest in embodied carbon increases, more low-carbon building materials are being developed. Although the number of available low-carbon building materials is increasing, builders may not work with low-carbon building materials often. This being so, a state-issued guidance document can help familiarize builders with the properties of low-carbon building materials. In addition, the guidance document can help inform architects about low-carbon building material options. Similar to an incentive program, it is not mandatory to follow building strategies listed in the guidance document and may not incentivize architects to design buildings with low-carbon materials. It may also be difficult to monitor the effectiveness of a guidance document.

# 7 Conclusion and Recommendations

Wildfires in California are projected to increase as climate change impacts intensify in the coming years. California has suffered from its most destructive wildfires over the last few years. Unfortunately, these fires damaged and destroyed thousands of homes, displacing many families and individuals. This provides California with the opportunity to reduce its greenhouse gas emissions when rebuilding homes by utilizing low-carbon building strategies. Approximately 80% of a structure's environmental impact is determined during the design phase (Morini et al., 2019). This being so, it is easiest to reduce the embodied carbon of a structure if low-carbon building materials are incorporated into the building design. Low-carbon materials can include naturally-derived materials or salvaged materials. The low-carbon materials incorporated into a building's design helps mitigate climate change and allows the building to adapt to future climate change impacts, such as wildfires.

In order for a structure to withstand a wildfire, exterior building materials must be fire-resistant. Buildings that are built in fire-prone areas should be built with more fire-resistant materials.
If structures are resilient to fire, then this will help to reduce greenhouse emissions over time as more structures will be able to survive wildfires, thus reducing the need to rebuild. There are natural building materials that are better at tolerating fire than some carbon-intensive conventional building materials. Building with natural building materials also provides opportunities for carbon sequestration. For example, when straw is transformed into straw bale insultation, carbon is stored within the straw after it is harvested instead of released through decomposition. Low-carbon and fire-resistant building materials can help to reduce the embodied carbon of a building while increasing the overall fire-resistance of the structure.

Since salvage materials may not be fire-resistant, it can be difficult to use salvaged materials for exterior building components. However, salvaged materials can be used to help reduce the embodied carbon of structural and interior building materials. In addition to the environmental benefits associated with material reuse, there are also economic and social benefits. Salvaged materials are often donated or liquidated, thus providing those who are looking to rebuild with free or discounted materials. In addition, this may encourage more community members to deconstruct rather than demolish materials during building removals or renovations.

While interest in reducing embodied carbon is gaining momentum, there are very few existing policies which support this movement. Some cities have developed low-carbon concrete requirements while others have mandated building deconstruction to help promote material reuse. There are also certification programs, such as LEED, which have credits that can be achieved by reducing the embodied carbon of the structure. In addition, several organizations, including the Embodied Carbon Network and Architecture 2030, publish embodied carbon reduction goals and provide more insight into the latest low-carbon building materials. Local and state governments must support and develop low-carbon building requirements if California wishes to reach it climate action goals.

Climate change impacts are intensifying and the building industry continues to significantly contribute to environmental degradation through resource extraction, pollution, waste production and greenhouse gas emissions. Systems thinking must be used to help reduce the impacts of the building industry while increasing housing availability for those who have been displaced by climate change. New construction projects must be able to mitigate and adapt to climate change. Circularity must be instilled in California's future policies to help protect the planet and its people.

California policymakers should consider the following recommendations to help reduce the embodied carbon of new construction projects while providing support to individuals who were impacted by California's wildfires. These recommendations are aimed at increasing available low-carbon building material resources, increasing awareness around embodied carbon in buildings, reducing embodied carbon in main building components and prioritizing material reuse to assist individuals who are rebuilding after a wildfire. These recommendations are intended to be coupled together as they support one another.

### Recommendation #1: Develop a low-carbon building guidance document and incentive program.

More educational resources around low-carbon building strategies need to be created to help increase awareness about embodied carbon in structures. The California state government should develop a low-carbon building guidance document and training program. The guidance document should include a list of approved low-carbon building materials. The list should also include other properties of the building material, such as the fire rating. This will make it easier for builders to identify low-carbon materials that are suitable to build within fire-prone areas. It is essential that the low-carbon building materials are seismically safe since California is susceptible to earthquakes.

Overall, less is known about natural low-carbon building materials than conventional building materials. This being so, the state should also develop a natural building material training program. Working with natural materials is different than working with conventional materials and this learning gap may prevent builders from utilizing natural materials in construction projects. The training program could highlight techniques needed to work with common natural building materials. If the state developed educational resources, such as the ones recommended above, these materials can then become useful reference documents that local governments can use to encourage local builders to use low-carbon materials.

Builders would be more likely to use natural low-carbon materials if these materials were more widely used. One way to encourage the use the low-carbon building materials is through an incentives program. It is recommended that the California state government should develop a low-carbon building material incentives program. An incentive program would provide builders with a financial motive for using low-carbon materials in new construction projects. In order for an incentives program to be successful, outreach must be conducted and resources must be provided to highlight the purpose behind the program. Therefore, if the state were to develop a low-carbon building material incentives program, the creation of a guidance document and training program would also be necessary to help increase education around natural low-carbon building materials.

The primary purpose of this recommendation is to increase education around low-building materials and strategies because there is currently a lack of educational resources. While it is true that many organizations are creating low-carbon building material education resources, such as Architecture 2030's Materials Palette, it is essential that the government contributes to this movement as well. Builders are more trusting of resources provided by the government rather than an organization. California's construction industry is thriving and the state government has an opportunity to significantly reduce building emissions by publishing low-carbon building resources and incentive programs. These resources can be coupled together to help encourage the creation of a low-carbon building standard at the local level. For example, local governments can use the low-carbon resources provided by the state government as reference documents if a low-carbon building policy is implemented.

## Recommendation #2: Require whole building life cycle assessments for new construction.

Whole building life cycle assessments should be required for every new construction project in California. In order for builders to obtain a construction permit, whole building life cycle assessment results must be submitted along with the permit application. The life cycle assessment must include cradle-to-grave impacts rather than cradle-to-gate impacts. This will ensure that impacts of all life cycle stages are accounted for. There are several life cycle assessment tools available, some of which are free. Requiring whole building life cycle assessments for new construction projects will not result in significant financial burdens due to the availability of free tools. For example, Athena is one example of a free tool commonly used and it is also accepted by LEED. Other life cycle assessment tools that are commonly used in the United States are One Click LCA and Tally. The increased cost associated with these programs equates to better software that produce more detailed results.

Life cycle assessments can be performed by architects that are designing the building or contracted to green building consultants. If California implements a policy requiring the completion of a whole building life cycle assessment for new construction projects, the state must also create some reference documents to help guide stakeholders who are unfamiliar with building life cycle assessments. This reference sheet should include a list of life cycle assessment tools that are available and approved by the state. In addition, the document should highlight the cost and complexity associated with each tool. This document can also include other tools that can help architects and builders compare carbon intensity of different materials. For example, the Embodied Carbon Construction Calculator (EC3) is a free tool which uses EPDs to compare the carbon impacts of different materials. While this tool cannot be used to conduct a whole building life cycle assessment, it is a convenient way to research low-carbon material alternatives.

The state will also need to identify the building components that must be analyzed in a whole building life cycle assessment. A whole building life cycle assessment typically only analyzes the building structure and envelop. Since there are thousands of materials within a building, it is most efficient to conduct a life cycle assessment for the largest building components. This includes the building foundation, structure, roof, flooring and windows as a minimum. Architects are welcome to analyze more than the required components if they feel inclined to do so.

The primary purpose of this recommendation is to increase awareness about embodied carbon in buildings and reiterate that reductions in embodied emissions are just as important as reductions in operational building emissions. Conducting a whole building life cycle assessment will allow architects and builders to identify carbon intensive materials. While this policy will not establish maximum embodied carbon threshold values, it may influence architects to alter their original building design by incorporating low-carbon materials. In addition, this policy will help the state collect data on embodied carbon in buildings. The data can be used to better understand the average embodied carbon within a building while also highlighting high-emitting materials. This data can be used to help shape future policies that may limit the use of carbon intensive building materials.

## Recommendation #3: Establish a low-carbon concrete requirement.

Cement is one of the main ingredients used in concrete and cement is responsible for almost 10% of global greenhouse gas emissions. In California, most building foundations are made with concrete. An easy way to reduce the embodied carbon of a structure is to substitute a carbon intensive concrete mix with a low-carbon concrete mix. Since the production of cement is extremely carbon intensive, a building's overall embodied carbon can be significantly reduced simply by using a concrete mix that has a lower cement content.

California should establish a low-carbon concrete requirement for building construction. The Buy Clean California Act is currently working to collect data for structural steel, steel rebar, flat glass and mineral wool through EPDs. The ultimate goal of this policy is to develop a maximum global warming potential for these four types of materials. After these maximum global warming potential values are established, builders must choose low-carbon material alternatives to avoid violating the Buy Clean California Act. Concrete is one of the most carbon intensive materials, yet the California state government did not include concrete in the Buy Clean California Act.

Since the carbon impacts of cement are widely recognized, there low-carbon concrete alternatives that exist and new mixes are currently being developed. These materials include low-carbon concrete, carbon-sequestering concrete, or materials that can be used in place on concrete. Therefore, if California were to establish a maximum global warming potential for concrete, low-carbon alternatives are vastly available in the marketplace. California state government agencies will have to ensure that building projects do not use concrete that surpasses the established embodied carbon threshold. Local governments would then have the option to adopt and implement this policy at the local-level and make adjustments as needed.

The primary purpose of this recommendation is to reduce the embodied carbon of all new construction projects by simply using a low-carbon concrete mix rather than a carbon-intensive concrete mix. While the first two recommendations are centered around increasing education and awareness, this recommendation would result in a reduction of embodied emissions. It takes time to transition away from conventional construction practices. This recommendation would allow builders to become familiar with low-carbon materials by focusing on one component of the building.

### Recommendation #4: Create a material reuse donation and redistribution program for those rebuilding after a wildfire.

Free building materials should be distributed to those who are working to rebuild their home that was damaged in a wildfire. This will help to ease the hardships they are forced to endure as a result of climate change. A dedicated material reuse donation program should be created for individuals looking to rebuild after a wildfire. The program would encourage low-carbon building through material reuse and reduce the financial burden of rebuilding after a climate change induced event. This program can help connect those looking to rebuild with available salvaged material. To make this program more feasible, salvage items made available for reuse should be interior items, such as floors, fixtures and appliances. The redistribution of exterior building materials that are not fire-resistant should not be encouraged in fire-prone areas.

The material reuse donation program for those rebuilding after a wildfire should be subsidized by the California state government. The government can work with salvage centers and other non-profit organization that focus on material redistribution and disaster relief. For example, the non-profit disaster relief organization can work with local salvage centers to help redistribute interior building materials to individuals who are rebuilding their home. In addition, the government can help to subsidize this program so that individuals impacted by wildfires can receive these materials for free. It is essential that the government helps to finance this program because salvage centers are costly to operate since they require a large amount of land to store materials. In addition, since materials are resold at low costs it is challenging to operate a reuse business. One way to help overcome this barrier is to increase the reuse market. Salvage centers often have to donate or recycle materials that are not purchased because public interest in material reuse is limited.

The primary purpose of this recommendation is to provide individuals who lost their homes in a wildfire with free building materials which will ultimately reduce the embodied carbon of the rebuilding process. This will help to improve the material reuse market while redirecting materials away from the landfill. In order for this program to be successful, the salvaged materials must be in good condition so that they are actually desirable. When helping individuals who have lost their home in a wildfire, it is important to be mindful of all that they endured. Therefore, donation materials offered should go through a quality assurance process.

## Recommendation #5: Develop a universal building material database.

While conducting this research, it was difficult to find the embodied carbon values for materials as these values may not be publicly available. Although there are many tools available to calculate embodied carbon, there is not a standardized method used to calculate embodied carbon. Therefore, the results from each life cycle assessment tool vary. This being so, a universal building material database and standardized embodied carbon calculator should be developed as there appears to be a lack of research publicly available regarding building material properties.

The database should list various properties associated with each material. These properties should include the global warming potential, fire rating, seismic stability, environmental toxicity and human toxicity. To help create this database, builders should report the building materials that will be used in the structure in the construction permit application. Localities can then enter these materials into the database so that they can be further researched. To create the database the California state government may commission green building consultants. These consultants can then analyze the various properties of the materials and make this data available for viewing. The primary purpose of this recommendation is to create a building material database so that the properties of building materials can easily be obtained and compared. The database would make it easier for architects to identify low-carbon, healthy and fire-resistant materials. If the state were to create a publicly accessible and easy-to-use database, this would encourage architects to design structures that are less carbon intensive, healthy and safe as it is often complicated to create a structure which prioritizes all three of those categories.

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