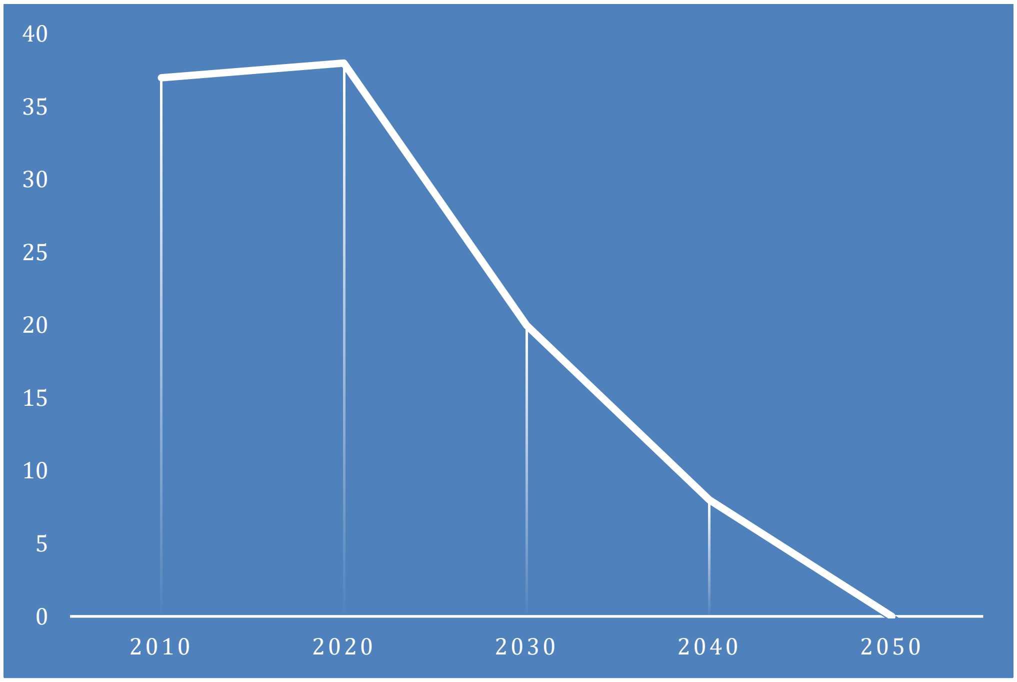
# Achieving Net Zero Embodied Carbon in Structural Materials by 2050



**A White Paper by the Structural Engineering Institute's Sustainability Committee Carbon Working Group**

*Mark D. Webster, Editor*

**March 2020**
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Image inspired by Figure SPM.3a from IPCC Report *Global Warming of 1.5°C* (2018)
https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

# Executive Summary

Structural materials (i.e., steel and concrete) are responsible for over 10% of global carbon dioxide emissions. This paper outlines five paths to achieve a net zero-carbon future within the built environment. These paths include varying levels of adoption of 4 transition tracks: (1) design improvements, (2) greening the electrical grid, (3) material production improvements, and (4) carbon offsets.

Through design optimization, we estimate that between 10% and 25% of emissions can be avoided relative to current practices. Ways in which these emissions can be reduced include the avoidance of over-design, topology optimization, and performance-based design. Likewise, we estimate another 10% to 25% reduction in carbon emissions may be possible by specifying the appropriate materials. For example, concrete mix designs of the same compressive strength can vary significantly in their carbon emissions. Selecting concrete mixtures for both their structural and environmental performance can help structural designers reduce the carbon emissions of their structural systems by up to 40%. In addition, by reducing construction waste, for example through modular construction, we estimate between 5% and 10% reductions in carbon emissions can be achieved. Often the most effective design strategy to reduce carbon emissions from structural systems is to avoid new construction through retrofit and the adaptive reuse of existing buildings. Through retrofit, we estimate that between 5% and 15% of structural system carbon emissions could be reduced. Another design strategy to reduce carbon emissions is the use of substitute structural systems. By building with biogenic carbon (e.g., wood and straw), we estimate potential reductions in carbon emissions between 15% and 25%. Finally, design for resilience may be a contributing strategy, but insufficient research is available to estimate how much this strategy may contribute to embodied carbon reductions by 2050. The structural engineering community's adoption of these design optimization strategies has the potential to reduce carbon emission between 10% and 55%, showing a significant potential for reductions between present day and 2050.

By transitioning the electrical grid from non-renewable, carbon-intensive energy sources to renewable, carbon-free energy, the embodied carbon of structural materials could be reduced by 5% to 10%. Currently, the United States' electrical grid is already becoming increasingly carbon-free due to the decline of coal and state legislation requiring more electricity to be obtained from renewable energy sources. Overall, the reduction of embodied carbon from a renewable electric grid would vary depending on the material type. For structural steel, AISC estimates that carbon-free electricity would reduce the embodied carbon of steel by approximately 50%. However, for concrete, the embodied carbon reduction due to carbon-free electricity would only be approximately 6%.

Improvements in the production of structural materials could provide an embodied carbon reduction ranging from 10% to 30%. Currently, material manufacturers have been steadily reducing the unit carbon footprints of their products over the past decades by incorporating more efficient manufacturing technologies. The carbon intensity of cement in the US has reduced by 33% within the past 50 years, though most U.S. production is already using modern, energy-efficient kilns so additional progress will likely not be as rapid moving forward. The greatest promise for U.S. concrete production is a move towards blended cements, such as those popular in the European markets. For steel manufacturing, the energy intensity dropped by 10% between 1990 and 1998. However, the rate of reduction is slowing due to the minimum theoretical energy required to produce steel. For wood products, carbon reductions are likely to come from sustainable forestry management practices, better understanding and measurement of carbon sequestration, and future harvesting and manufacturing efficiencies.

The final option to achieve net zero carbon emissions is the use of carbon offsets. Carbon offsets are investments in actions that reduce carbon emissions and should be third-party verified.

Combining design strategies, electrical grid improvements, and manufacturing improvements, the built infrastructure can transition to net zero carbon emissions by 2050 even without the use of carbon offsets.

# 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has determined that to limit global warming to 1.5°C we must reduce $CO_2$ emissions by 45% from 2010 levels by 2030 and to net zero by 2050[1]. For buildings, this means we must work towards reducing the $CO_2e$[2] emissions ("carbon" emissions, also called Global Warming Potential (GWP)) associated with materials and construction ("embodied carbon") to zero. How can structural engineers help accomplish this objective?

The SEI Sustainability Committee's Carbon Working Group (CWG) is studying this issue. This paper primarily addresses structural materials, although other design professionals—especially architects—will need to play a central role. Structural materials represent half or more of the embodied impacts of most new buildings,[3] and an even higher proportion of most infrastructure projects such as bridges and dams, so structural engineers must be leaders in the essential transition to net zero embodied carbon and beyond to net-positive carbon-sequestering design.

We identified four transition tracks that have the ability to reduce carbon emissions associated with structural materials:

1. **Design Improvements:** Structural engineers must make design choices and other design improvements, such as material selection and optimization, that reduce the carbon emissions of new construction.
2. **Greening the Electrical Grid:** The electrical power used to manufacture building materials must continue to transition towards renewable sources.
3. **Material Production Improvements:** Material producers must continue to reduce the carbon emissions associated with manufacturing processes and work towards designing products and materials that durably store carbon.
4. **Carbon Offsets:** Any remaining carbon emissions must be offset with investments in validated near-term carbon reduction projects.

Carbon sequestration and storage in building materials will be essential to achieve net zero carbon without relying on offsets. Carbon storage includes the temporary removal of carbon

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[1] IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)] (https://www.ipcc.ch/sr15/chapter/spm/).

[2] $CO_2e$ refers to $CO_2$ equivalent. Emissions other than carbon dioxide, such as methane, also contributes to global warming. $CO_2e$ includes the effect of these other emissions normalized to $CO_2$.

[3] See e.g. Strain, Larry. *Time Value of Carbon*, Carbon Leadership Forum white paper, May 2017 (http://carbonleadershipforum.org/2017/02/09/the-time-value-of-carbon/).

from the atmosphere in products such as wood framing which will eventually return to the atmosphere at building end-of-life. Carbon sequestration refers to the more permanent removal of carbon, for example in chemical reactions that lock the carbon into the molecular matrix of a material.

> *"Carbon sequestration and storage in building materials will be essential to achieve net zero carbon without relying on offsets."*

Carbon can be stored in wood and agricultural products, but careful consideration of their supply chains is essential in order to be effective in reversing climate disruption. Timber harvesting causes an uptick in carbon emissions, mostly due to soil exposure, that can take many years to recover. Experts argue that only wood extracted from sustainably managed forests, such as those certified by the Forest Stewardship Council, are a climate-friendly material choice. Agricultural products made into building materials, such as straw and hemp, more clearly sequester carbon in the near-term because of the annual growing cycle. Designers can select such products to reduce the carbon footprint of their projects.

Material producers can also sequester carbon in their products. Some companies are already offering such technology for concrete and aggregate production.[4] Others are sure to follow.

The path to net zero embodied carbon will surely include various combinations of these transition tracks. We offer five possibilities, as outlined in Table 1-1 and Figure 1-1. Many other combinations are possible. We examine the potential for each track later in this paper.

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[4] Sequestration possibilities include the development of carbon capture and storage technology at production facilities such as cement kilns. Product examples include Blue Planet, which is soon to be commercially available but already performing very well in trials at the San Francisco airport. Blue Planet captures emissions and turns them back into limestone aggregate for new concrete, heralding the possibility of truly carbon-sequestering concrete. Technologies which incorporate organic matter into stable inorganic matrices such as hempcrete also qualify.

| Path ID | Design Track | Electricity Track | Material Production Track | Offsets Track |
|---|---|---|---|---|
| **Design Dominant** | 45% | 5% | 10% | 40% |
| **Electricity and Material Production Dominant** | 20% | 10% | 25% | 45% |
| **Strong Multi-Track without Sequestration** | 45% | 10% | 25% | 20% |
| **Strong Multi-Track with Sequestration** | 55% | 10% | 35% | 0% |
| **Status Quo** | 10% | 5% | 10% | 75% |

Table 1-1: Some Possible Combinations of Transition Tracks to Get to Zero Embodied Carbon

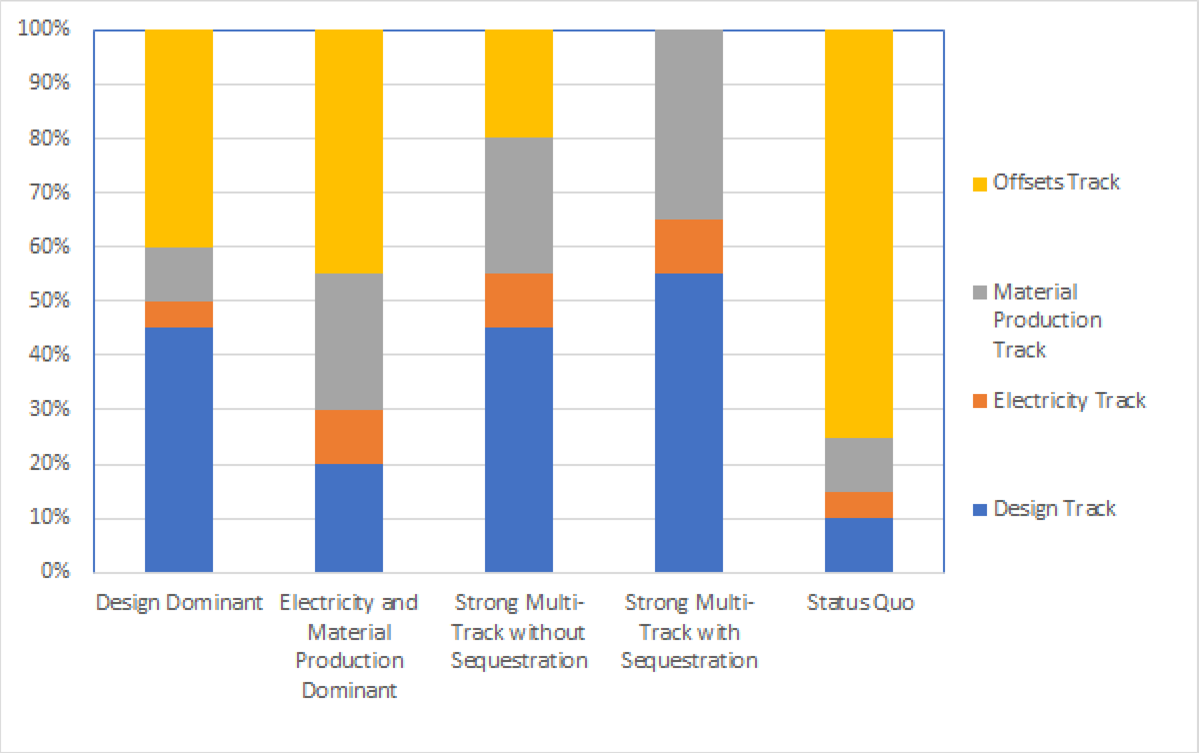

Figure 1-1: Some of the Possible Paths to Net Zero Embodied Carbon by 2050. Each bar represents different combinations of the four available reduction tracks.

The first two paths in the table and figure include strong action in some but not all the tracks. The third path represents strong action in all three tracks, but without sequestration, and therefore leans on offsets to make up the difference. The fourth path is the most desirable: strong action on all tracks as well as sequestration to compensate for remaining emissions rather than offsets. The final path represents the business-as-usual scenario, where emissions continue to drop at a slow rate, necessitating major investments in offsets to get to net zero.

## Status of Construction in the United States

To plot a route to net zero embodied carbon, we must understand where the opportunities lie. We used public information from the U.S. Census Bureau[5] and the U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS)[6] to estimate the proportion of construction in the commercial and residential sectors by structural frame type, as shown in Figure 1-2. The data shows that about two-thirds of new construction is in the residential sector and one-third in the commercial sector. Residential construction is dominated by wood-framed single-family homes. Most commercial construction is steel- and concrete-framed.

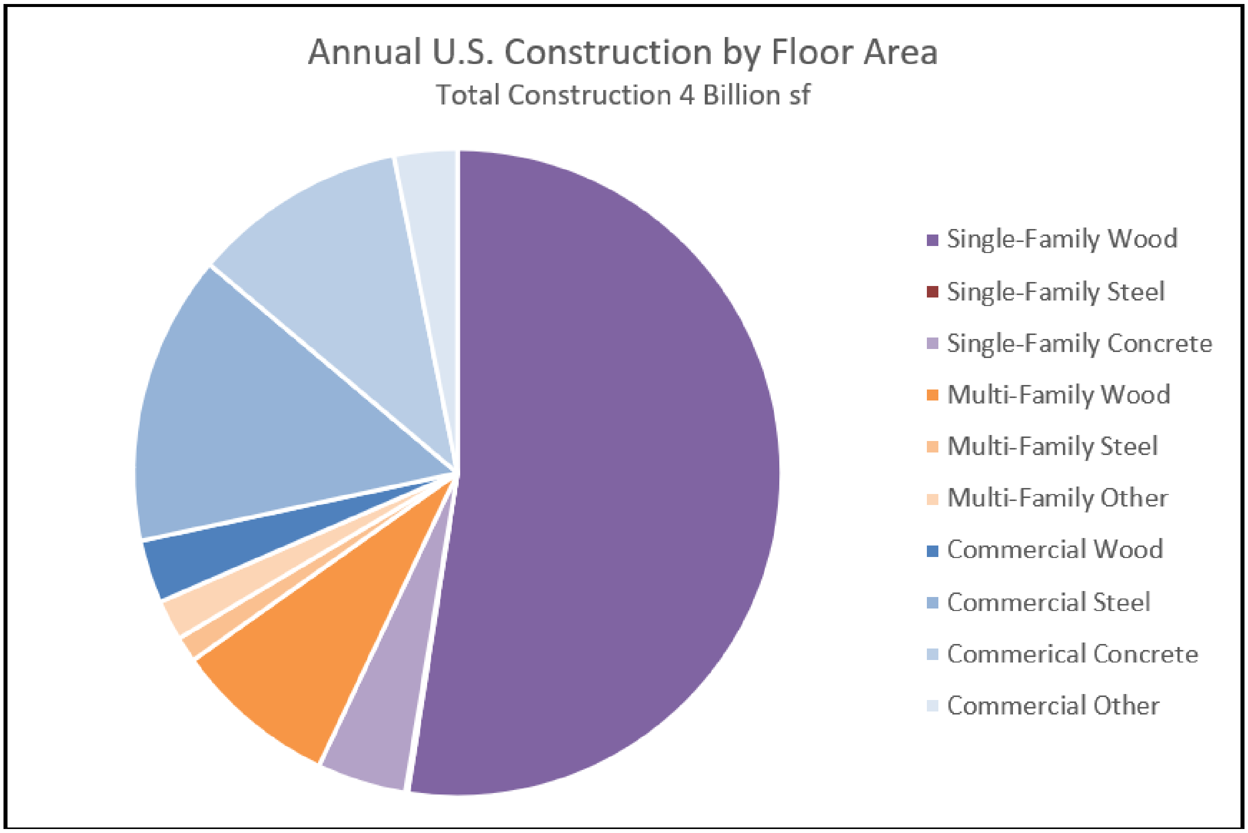

Figure 1-2: Annual New Construction in the United States by Building Type and Type of Structural Frame

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[5] U.S. Census Bureau, New Residential Construction, 2017 https://www.census.gov/construction/nrc/index.html.

[6] U.S. Energy Information Administration, Commercial Buildings Energy Consumption Survey, 2012 https://www.eia.gov/consumption/commercial/.

*"...about two-thirds of new construction is in the residential sector and one-third in the commercial sector."*

We estimated the U.S. consumption of the primary structural materials—concrete, steel, and wood—in building construction using data from the American Institute of Steel Construction,[7] the National Ready Mix Concrete Association,[8] and the Forest Products Lab.[9] Using information from industry-average Environmental Product Declarations (EPDs), we estimated the carbon emissions associated with these materials, as shown in Figure 1-3. Unlike Figure 1-2 which is by framing type, Figure 1-3 includes all concrete whether the building is steel-framed, wood-framed, or concrete-framed, including concrete foundations and floors. (It bears noting that almost all new buildings use at least some wood, steel, and concrete; we designate them as wood, concrete, or steel structures based on which material predominates in the structural system.) We see that the emissions associated with concrete, even without including plant-mixed precast concrete and steel reinforcement, account for over three-quarters of the total emissions associated with these three materials. Although most single-family homes are constructed with wood framing, the contribution of wood to carbon emissions is small relative to the emissions associated with concrete in these structures.[10] The carbon emissions from residential construction exceed the emissions from commercial construction. Although structural engineers play a limited role in most residential construction projects, this sector must be addressed.

*"...the emissions associated with concrete...account for over three-quarters of the total emissions associated with these three materials."*

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[7] American Institute of Steel Construction, Structural Steel: An Industry Overview, August, 2018.

[8] National Ready Mixed Concrete Association, Historical US Ready Mixed Concrete Production, unpublished, provided 14 March 2019.

[9] United States Department of Agriculture, Forest Products Laboratory, U.S. Forest Products Annual Market Review and Prospects, 2013–2017, Research Note FPL–RN–0348, July 2017.

[10] The wood EPDs that are the data source for this assessment treat biogenic carbon emissions as carbon neutral.

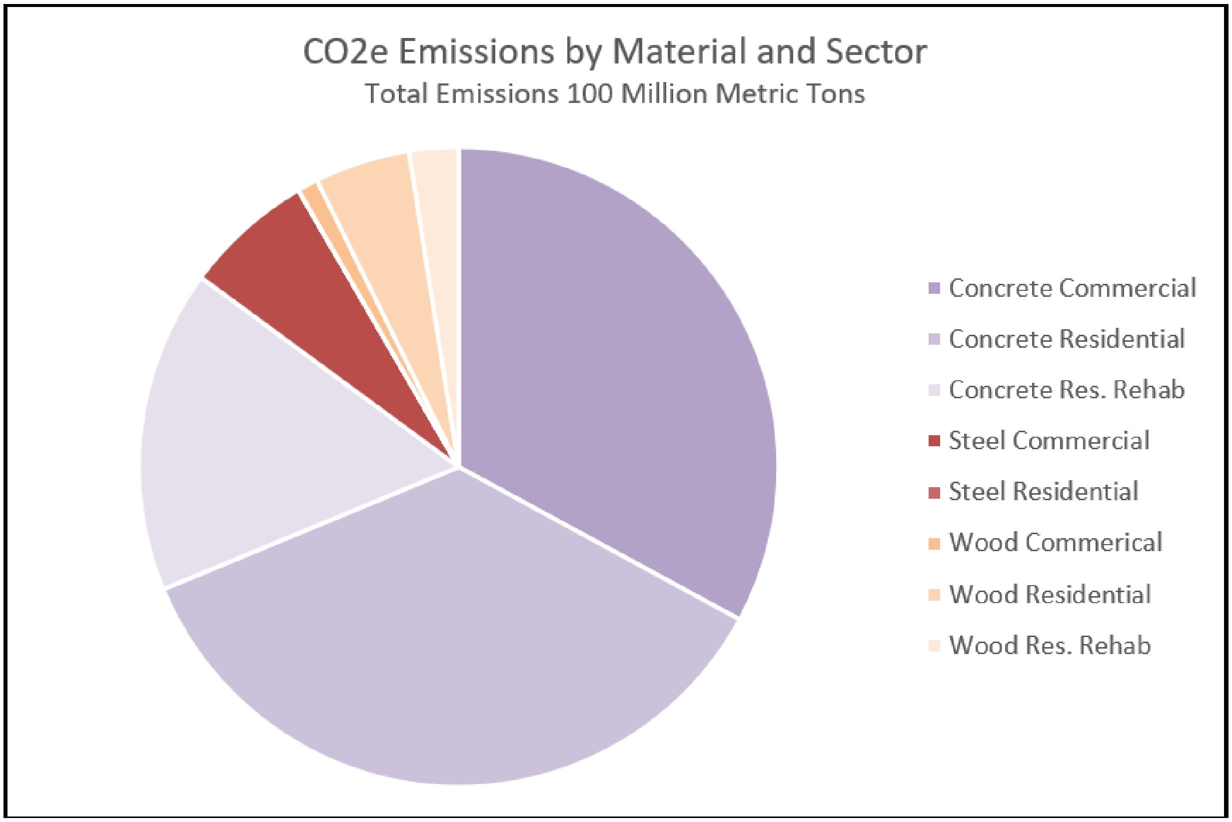

Figure 1-3: Annual $CO_2e$ Emissions Associated with Structural Materials Used in New Construction in the United States by Building Sector

# 2: Reduced Carbon Footprint through Design

Designers have the most control over reducing the embodied carbon of the buildings they design. This section provides a roadmap of different measures that designers can use to reduce the embodied carbon intensity of buildings. This section briefly introduces strategies, leaving it to the structural engineer and design team to determine which are best employed for their project. More comprehensive discussions of each of these strategies are included in the Whole Building LCA Practice Guide[11] published previously by the committee.

## Design Optimization

Design teams can optimize their designs to reduce their structures' embodied carbon. Many design strategies exist, such as optimizing column grid layout and beam spacing to minimize the total weight of materials used. Material quantity reduction strategies are often building and architecture specific, yet general principles apply for different materials. Some strategies for reducing material quantities for the three main structural materials follow:

> **Concrete:** Utilize voided slab systems or post-tensioned slabs to reduce total concrete quantities, and/or use higher strength concrete (but also accounting for the increased environmental impacts). Also, slabs on grade and foundation walls can sometimes be made thinner without reduction in performance, and the use of frost-protected shallow foundation designs can reduce required concrete foundation volume by 50% or more.
>
> **Steel:** Utilize composite design, braced frames instead of moment frames, long-span deck systems to eliminate intermediate framing, and/or lightweight concrete to reduce the weight of the structure. Also, the use of optimized element sizes rather than keeping all elements of similar size, can reduce steel tonnage even though this may not be the least expensive option.
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> **Wood:** Optimize framing from a value engineering perspective to reduce the total volume of wood. These techniques, often described as "Optimum Value Engineering" or "Advanced Framing," include incorporating single top plates, 24-inch stud spacing, eliminating headers in non-load-bearing walls, and using two studs at corners. Further information is available at the APA website[12] and elsewhere.
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> **Masonry:** If possible, designing masonry walls without steel reinforcement eliminates the footprint of the grout, which is essentially a cement-rich flowable

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[11] Yang, F. (Ed.). (2018). Whole Building Life Cycle Assessment: Reference Building Structure and Strategies. American Society of Civil Engineers. Access at: https://doi.org/10.1061/9780784415054

[12] https://www.apawood.org/advanced-framing

concrete, as well as the reinforcing bars. If reinforcement is required, use partially-grouted masonry walls over fully-grouted.

These savings can be evaluated using LCA. The reader is referred to the WBLCA Practice Guide produced by the SEI Sustainability Committee previously referenced.

*Supporting Research*

Kaethner & Burridge (2012) studied three commercial building types from cradle-to-site using alternative structural systems (steel-framed, concrete-framed, and long-span) and found that no particular structural system was consistently the lowest in embodied carbon. The margin of uncertainty due to variability in material impact factors was greater than any advantage between structural materials. However, once a structural system was chosen, Kaethner & Burridge found that there was significant opportunity for embodied carbon reduction through careful specification and efficient design. Kaethner & Burridge found that the embodied carbon of the building's structure was more than half the embodied carbon of the entire building and that adding a long-span scheme added about 10% to the whole building impact.

Research shows that there is a large opportunity to reduce embodied carbon by increasing the efficiency of steel design. Moynihan & Allwood (2014) found in a study of 23 steel buildings with more than 1,000 steel beams that the average beam utilization was below 50%. Repetition across floor plates eases the design and fabrication burden; Moynihan & Allwood found that in the buildings studied, 5 beam sizes accounted for more than 75% of the beams in the floor plates, suggesting many buildings are designed based on worst-case loading. Thirion (2012) explored the reduction in embodied carbon possible if a steel cross section is varied along its length and found the potential reduction is up to 30%. Thirion acknowledges, however, that a large portion of this reduction is due to the overdesign of steel beams, similar to Moynihan & Allwood's findings. When design and fabrication costs are factored in, it is likely that varying the cross section of a beam over its length is not cost-effective and that most of the reduction can be realized by designing beams closer to their ultimate strength.

Advanced design techniques can also lead to reductions in structural material and thus embodied carbon emissions. Topology design is a computational mathematical method that finds an optimal solution based upon loads and boundary conditions. One case where topology optimization has been used to reduce structural material use is in post-tensioned concrete. Avelino and colleagues (2018)[13] used topology optimization to inform the layout of the post-tensioning and optimized for gravity loads and geometry. In contrast to a typical orthogonal grid of post tensioning, "wave-shaped" post tensioning led to reductions in slab material of up to 35%. While using topology requires more design time, it has the potential to significantly reduce the amount of structure required for buildings, thus reducing the embodied carbon of the built environment.

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[13] Avelino, R. M., Shook, D., Beghini, A., Long, E., & Sarkisian, M. (2018, July). Efficient flat-slab post-tensioning layouts guided by Topology Optimization. In *Proceedings of IASS Annual Symposia* (Vol. 2018, No. 3, pp. 1-8). International Association for Shell and Spatial Structures (IASS).

Another design strategy that engineers may employ to optimize their designs is performance-based design (PBD). PBD approaches can result in more efficient designs than designs based on prescriptive requirements. See the discussion under “Design for Resilience” below.

**Conclusion: We estimate that** optimization strategies could reduce embodied carbon in building structures by 10% to 25% relative to current practice.

## Material Specifications

**Concrete:** Material specifications can have a profound impact on the embodied carbon of a structure. In concrete, cement is the primary contributor to emissions. Several strategies can reduce these emissions. The most effective means of specifying low-embodied carbon concretes is to reduce the amount of cement in a mix design. Depending upon the performance requirements, material suppliers can work with structural engineers to reduce the cement intensity of concrete without the need for any additional materials. For example, specifying a 56-day or even 112-day compressive strength rather than 28-day compressive strength will lead to significant reductions in cement intensities; designers should give the concrete all the time to cure that the project schedule allows. Another common method of cement reduction is to replace cement with supplementary cementitious materials (SCMs), such as fly ash or slag. Over 40% cement replacement can be achieved. Engineers should engage material suppliers to discuss mix designs rather than specifying target SCM replacements to ensure that strength objectives are met but not unnecessarily exceeded.

A recent study by the Structural Engineers Association of California (SEAOC) Sustainable Design Committee quantified the environmental impacts of over 300 concrete mixes used in California projects over the last 5 years. Figure 2-1 shows the global warming potential of the concrete mixes collected versus the compressive strength. These results show that for a specified compressive strength, a concrete mix could have up to 3.4 times more environmental impact than an alternate mix of the same compressive strength. Out of all of the components in a concrete mix, this study found that the amount of cement in the mix has the most impact on the environmental impact. The study emphasizes the impact structural engineers have in specifying the concrete mix requirements for a project. For more information, see the paper published in the 2019 SEAOC Convention Proceedings.[14]

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[14] Miley, Nicholas et. al. Embodied Carbon Impacts of California Concrete Mix Designs. In the 2019 SEAOC Convention Proceedings (pp 486-495). Squaw Creek, CA (https://www.seaoc.org/store/ViewProduct.aspx?ID=14829558).

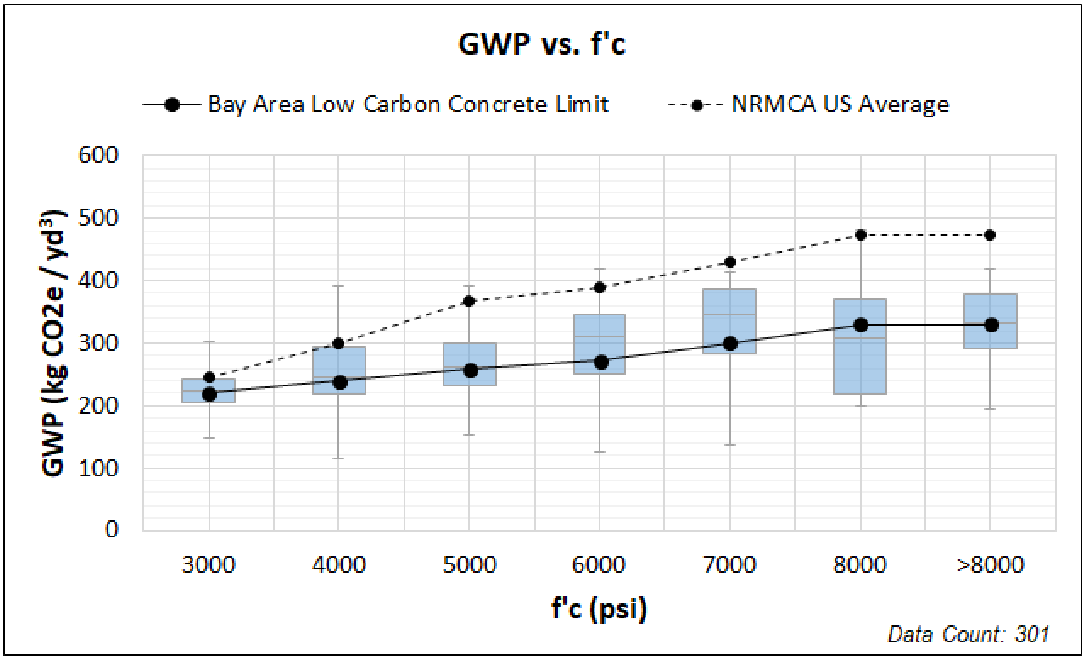

Figure 2-1: GWP of concrete mixes relative to strength

The data from the SEAOC study was used to inform the concrete GWP limits set in the new Bay Area Low-Carbon Concrete Code, intended to serve as the basis of low-carbon concrete codes across North America. More information on this project, including template low-carbon concrete specification language for residential and commercial projects, is available at https://www.marincounty.org/depts/cd/divisions/sustainability/low-carbon-concrete-project.

While cement is the largest contributor to the embodied carbon of concrete mixes, there are other technologies that can be specified to reduce concrete's embodied carbon. One technology uses accelerated carbonation of fresh-state concrete to slightly increase the strength, which reduces the cement quantities needed. Modest reductions in embodied carbon of up to 5% can be achieved. Another technology captures $CO_2$ to create synthetic aggregates which can replace traditional aggregates in concrete. Still in early stages of development, this carbon capture and storage technology holds promise to not just reduce the embodied carbon of concrete, but to go so far as to make it a new absorber of emissions. For more information see Section 1 of this white paper.

Low-alkali cement is used fairly commonly, particularly in western North America, to address the potential for alkali-aggregate reactions (AAR). However, the production of low-alkali cement comes with a greater carbon footprint. Gases and particulates containing alkali metals are released from the kiln, creating greater amounts of cement kiln dust (CKD), which reduces the amount of clinker that is produced. Thus, for the same energy input to the kiln, less cement is produced, so the cement that is produced has a greater embodied carbon content per ton. Engineers should consider whether standard portland cement may be an option, particularly in cases where the concrete will remain dry, resulting in a lesser risk for developing AAR.

**Steel:** When specifying steel sections, considering the source of steel sections can lead to embodied carbon reductions. While electric arc furnaces (EAF) typically have lower embodied carbon than basic oxygen furnaces (BOF), care should be taken to ensure that reductions are achieved. For example, specifying HSS sections sourced from EAFs rather than BOFs does not always lead to embodied carbon reductions because HSS shapes are more efficient in compression compared to wide-flange sections. Another strategy to consider is specifying high strength steel, which would reduce overall steel tonnage while providing the same performance.

**Wood:** Forest management varies significantly across the US. The embodied carbon of wood framing depends upon forest management practices, which is not well reflected in most Life Cycle Inventory (LCI) data.[15] Specifying wood from sustainably managed forests, such as those certified by the Forest Stewardship Council (FSC), increases the likelihood that it has low or even negative embodied carbon; transportation impacts must be considered since these can be significant. Additionally, specifying grade stamps on all wood members can help for future retrofitting and salvaging of materials, contributing to a circular economy in the built environment.

**Masonry:** Specify the use of 20% to 30% supplementary cementitious materials to offset portland cement in concrete blocks. Many manufacturing plants can provide low-cement units with properties similar to normal units, for little or no increase in price. Specifying lightweight blocks results in lower carbon emissions from transportation. Finally specifying strength-based grout rather than proportion-based usually reduces the amount of portland cement required, and the corresponding carbon footprint, by as much as 33%.[16]

**Conclusion:** Given the prevalence of concrete in structures and the opportunities for embodied carbon reductions, we estimate that material specification strategies could reduce the embodied carbon in structures by 10% to 25% relative to current practice.

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[15] Beverly Elizabeth Law and Mark E Harmon, “Forest sector carbon management, measurement and verification, and discussion of policy related to climate change,” *Carbon Management* (2011) 2(1), 73–84.

[16] SEI Sustainability Committee member James D’Aloisio did an informal study on proportion-based vs. performance-based grout mixes a few years ago. A typical proportion-based grout mix design has about 820 pounds of cement per cubic yard of grout. Mr. D’Aloisio reasons that reducing this cement content by 33% to 549 pounds per cubic yard would certainly provide 2,500 psi strength.

## Design for Resilience

*Introduction*

The link between resilience and embodied carbon has been discussed in previous documents,[17,18] but the implementation into calculations has been less developed than separate LCA or resilience-based assessment tools.[19] Much of the focus of the link between damage and embodied carbon has been related to seismic events, so this section will focus predominantly on earthquake damage. Note that other disasters (wildfires, hurricanes, etc.) could utilize a similar methodology. Because hazards are location-specific, the guidelines for any resilience-carbon design vary by region and many buildings may not find any benefits from this type of design strategy.

*Procedure*

The calculation of embodied carbon associated with seismic design requires the probabilistic assessment of damage during the service life of a building. In simplified terms, this would include calculating a "repair embodied carbon" associated with the materials and construction associated with the repair (or replacement) of a structure during its service life. This repair could include construction work on structural materials and of non-structural components, such as partition walls, exterior cladding, and floor finishes, that suffered damage during an earthquake. Additionally, the repair scope needs to include elements that may not have suffered damage but would need to be replaced to access damaged components (e.g., floor finishes over cracked slabs and ceilings covering damaged moment frame connections). All of the components of the repair would then be assessed for global warming potential in a similar procedure to a typical new building LCA. FEMA P-58 provides a methodology for completing this type of integrating study using its PACT tool, based on material quantity and GWP assigned to each component repair in the P-58 assessment.[20]

*Limitations*

The procedure to assess and design for embodied carbon seismic damage poses a number of challenges. Most critically, the procedure requires an assessment over a prescribed building service life and needs to include considerations for when the seismic event occurs. That is, if a building is assumed to have a 50-year service life and an earthquake causes near collapse of that building a few years after construction, the carbon effects are great because effectively two

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[17] Rodriguez-Nikl, Tonatiuh et. al. (2015). "Disaster Resilience and Sustainability." Accessed from: https://sites.google.com/site/seisustainabilitycommittee/working-groups/disaster-resilience-white-paper

[18] Souto-Martinez, A., Sutley, E.J, Liel, A.B, and Srubar, W.V III. "Embodied Carbon of Wood and Reinforced Concrete Structures Under Chronic and Acute Hazards," Chapter 4 of *Embodied Carbon in Buildings*, ed. by F. Pomponi, C. De Wolf, and A. Moncaster, 2018.

[19] Hasik, V., Chhabra, J.P.S., Warn, G.P., Bilec, M.M. "Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair," *Engineering Structures*, Volume 175, 15 November 2018, Pages 123-137.

[20] FEMA (2018), FEMA P-58-4 Seismic Performance Assessment of Buildings, Volume 4 - Methodology for Assessing Environmental Impacts.

full structures need to be constructed to serve the same programmatic goal. However, if the earthquake occurs near the end of the service life, the embodied carbon effects of that damage are nearly zero. Furthermore, one could argue that the building material advancements during the service life would mean that the carbon associated with that future repair is much lower than today's construction. Including these probabilistic assessments at different time frames complicates this procedure.

Additionally, to truly grasp the embodied carbon improvements of a resilient design (and use it as a strategy to "get to zero"), the LCA methodology of all buildings should include a probabilistic future damage component so that realistic reductions can be calculated. This discussion raises a larger question of the scope of LCA in general, because the assessment does not include building performance during its service life; an LCA only includes the construction and possibly demolition with no considerations in between.

*Studies*

Huang and Simonen[21] completed studies of multiple buildings in seismic zones and used the P-58 PACT tool to quantify the embodied carbon associated with repair of structural materials and with exterior cladding, floor finishes, partitions and HVAC systems. These studies suggest that the embodied carbon benefits of resilient design may eventually prove to be more beneficial for non-structural components. The embodied carbon of non-structural components is a key aspect of sustainable building design but is not fully covered in this document.

Welsh-Huggins and Liel[22] performed a probabilistic assessment of the environmental implications of designing buildings in regions of high seismicity for higher lateral loads. The authors found that this strategy can reduce life-cycle embodied carbon in some cases but that the higher stiffness of the stronger lateral systems can lead to greater non-structural losses.

*Design Strategies*

For conventional structural systems, the calculation of embodied carbon in relation to resilient design can be complicated. For example, a more ductile system may reduce the probability of collapse and thus reduce the risk of carbon associated with demolition and replacement. However, that more ductile structure would likely see larger seismic drifts during a smaller event and may result in more damage to non-structural components. On the other hand, increasing the stiffness of a lateral system may both reduce risk of collapse and reduce seismic drifts but may require an upfront investment in structural material and associated carbon.

For seismic design, strategies that both reduce design seismic demands and provide for better future performance have the most benefit for reducing embodied carbon. For example, seismic

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[21] Huang, M. & Simonen, K. (2019) "Comparative Environmental Analysis of Seismic Damage in Buildings." *Journal of Structural Engineering*, Vol. 146, Issue 2.

[22] Welsh-Huggins, Sarah J. and Abbie B. Liel. "Is a Stronger Building also Greener? Influence of Seismic Design Decisions on Building Life-Cycle Economic and Environmental Impacts." (2016).

isolation or damping systems can reduce superstructure seismic demands in the design stage, leading to an immediate reduction in materials. Additionally, the reduced drifts and/or floor accelerations of these systems in a seismic event would lead to less damage in an earthquake, and the repair carbon could be demonstrated to be reduced as well. Sarkisian et al[23] showed a reduction of 15% to 20% embodied carbon for a residential building in San Francisco accounting for damage and repair from seismic events over a 50-year life-span, when comparing a fixed base to isolated structure.

### *Scope*

The resilient design strategies that lead to greater reductions in carbon may need to be on a larger scale and governed more by policy than on individual building decisions. Examples include project sites, where policies limiting construction of buildings in flood-prone or fire-prone areas could lead to an overall reduction in a community's repair embodied carbon. On the structural side, reductions in lateral forces from developments of codes and analysis methods could provide material savings.

### *Conclusion*

There are definite ties between resilient design and embodied carbon, but the method of calculation and accounting is not fully defined when making comparisons. One possibility is to include a type of embodied carbon credit system for projects that can demonstrate a reduction of probabilistic embodied carbon over a building's life span as compared to a baseline building which would allow for a reduced amount of carbon offsets.

Regardless of carbon calculation, it should be acknowledged that resilient design and considerations of recovery time and repair should be critical in the design process. There are building types, such as hospitals, civic facilities and housing, which have a great impact on the overall community in the time following a large disaster. Especially in these situations, resilient-design strategies should be considered critical and in concert with other carbon considerations, even if the resilient-design strategies do not directly lead to carbon savings.

Since resilience needs to be considered on a community scale, the carbon effects of resilient design strategies should be considered on this larger scale as well. After a large earthquake or other disaster, there is a great amount of waste and pollution created and power generated from inefficient sources as the city gets back to functionality. The environmental impacts of these types of immediate shocks should be considered and decisions can be made at the community scale of which buildings and infrastructure should look at enhanced recovery-based design strategies to both limit environmental impacts and best shelter, protect and assist the community residents immediately after a disaster.

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[23] Sarkisian, Mark et. al. (2018) "Developing a Basis for Design – Embodied Carbon in Structures" *Proceedings from IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges*.

Conclusion: Since research in this strategy is on-going, we do not have the basis at this time to estimate the potential contribution of this strategy to embodied carbon reduction by 2050.

## Reduced Construction Waste

Currently, 10% to 15% of residential construction materials produced are wasted during the construction of a building[24]. Minimizing construction waste is therefore another strategy that can reduce the embodied carbon of structural systems. For example, in light-frame wood construction, plan dimensions and stud spacing may be laid out to accommodate the industry-standard two-foot incremental dimensional sizes of plywood and gypsum board.

### *Modular Construction*

Prefabricating structural assemblies in factories has been shown to reduce the carbon emissions from the construction cycle, in addition to providing economic and quality benefits.[25] This is especially true of wood-framed wall panels and has been widely practiced in recent construction of four to six-story “podium”-style multifamily residential buildings. The reductions result from less field labor travel to and from construction sites, as well as reduction in the volume of waste material.

**Conclusion:** We estimate that improved construction waste strategies could reduce embodied carbon in building structures by 5% to 10% relative to current practice.

## Retrofit of Existing Buildings

Often the most effective design strategy to reduce embodied carbon is to avoid new construction through retrofit and adaptive reuse of existing buildings. While new buildings are needed to accommodate an increasing population, retrofitting old buildings to extend their lifetimes can avoid large quantities of embodied carbon associated with new construction. While the choice of rehabilitating a building vs. demolishing and replacing it with new construction is typically an owner decision, building designers can still advocate for the rehabilitation of existing buildings.

In order to determine whether building retrofit or new construction is more advantageous for a specific project, a life cycle assessment for each option should be carried out. There are two main reasons for this; new construction often is more energy efficient than retrofitted existing construction and existing building retrofits often come with renovations and building upgrades. It is important to understand the environmental impacts of each of these options, which life cycle assessment can measure.

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[24] Monahan, J., & Powell, J. C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, *43*(1), 179-188.

[25] Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., “Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States,” *Journal of Industrial Ecology*, Vol. 16, Issue 2, April 2012.

Preservation Green Lab (PGL) published a study in 2011, The Greenest Building: Quantifying the Environmental Value of Building Reuse, which thoroughly compares and documents the total carbon footprint of building reuse vs.new construction through seven case studies in four cities. Details of the study are available on the organization's website.

For its base case, PGL assumed that both the reuse and new construction options have equal energy consumption. To evaluate the possibility that the new construction options may be more energy efficient than the reuse options, PGL also compared the reuse vs. new cases assuming 30% less energy use in new buildings. While PGL used a 75-year time-frame for its base case, it also looked at time-frames ranging from 1 to 100 years.

The results of the PGL show that the net embodied carbon associated with new vs. reuse options varies widely depending upon the use-phase energy consumption assumptions. In the baseline case, where the energy consumption is assumed equal, the 50-year $CO_2$ impacts are 12% to 17% less for the reuse option. In the case where the new building is 30% more energy efficient, the 50-year $CO_2$ impacts are 1% to 12% less than the new options. Over a 75-year lifetime, the 30% more energy efficient new buildings have carbon footprints that are 5% to 16% less than the retrofitted buildings. Over the critical 30-year time period leading to 2050, the retrofitted office building in Chicago performs about 18% better than the newly constructed building assuming equal use-phase energy performance, whereas the new construction with 30% better energy performance has a 4% lower embodied carbon after 30 years than the retrofit option.

The PGL study shows that over a 30-year life cycle, retrofitting existing buildings can significantly reduce carbon emissions compared to replacing them, as long as the two options have similar use-phase energy performance. However, retrofits must address energy performance, since even over a 30-year time-frame more energy efficient new construction can offset the initial embodied carbon associated with construction.

Prior to the publication of the PGL study, two other studies using life cycle assessment tools to compare new construction to retrofitted existing buildings were published. The British Empty Homes Agency published a study in 2008 comparing the global warming impact of three refurbished homes over a 50-year time period. Based on actual projects with real bills of material, the retrofitted buildings performed marginally better than the new construction (~3%) over the 50-year time period and marginally worse (4%) over the 75-year time period. The results of this study demonstrate that while the reuse buildings use more energy per square foot per year (an average of 2.76 vs. 2.23 kg/sf/yr), the embodied impacts are so much lower that at the end of the 50-year or even the 75-year time-frames the differences in total emissions are small. On the 30-year return, the retrofitted existing building has about a 14% lower carbon footprint than the newly constructed building.

Similarly, in 2009, the Athena Sustainable Materials Institute (ASMI) published a study for Parks Canada comparing the energy use and carbon emissions of four real buildings to the impacts of demolishing the existing buildings and constructing similar buildings in their place. This study did not attempt to quantify the embodied impacts associated with renovating the existing buildings. Even without including the embodied footprint of renovation, only one of the existing buildings performed better than the newly constructed building; in the other three cases, the new construction had a lower carbon footprint. Looking at a 30-year time-frame, the retrofitted buildings averaged about an 8% lower carbon footprint.

In summary, studies show that building reuse can significantly reduce embodied carbon compared to new construction, especially when the retrofits address energy performance. This conclusion is even more decisive when considering the time-value of carbon emissions, since the up-front emissions associated with the construction of a building have a greater effect when considering the 30-year period leading to 2050 than those associated with later use-phase emissions.

**Conclusion:** We estimate that building reuse could reduce embodied carbon in building structures by 5% to 15% relative to current practice. Retrofits must also address building energy performance to maximize reductions in carbon emissions over the building life.

## Using Salvaged Materials

Similar to rehabilitating existing buildings, using salvaged materials is an effective carbon reduction design strategy since it avoids the production of new materials. Furthermore, designing for deconstruction and reuse increases the supply of salvageable materials and encourages their re-use; however, these benefits may not be realized until decades in the future so are of limited benefit in reducing embodied carbon before 2050.

Salvaged materials incur transport and sometimes refabrication impacts, but these impacts are commonly 10% or less of the impact of new materials. Where salvaged materials are used in place of new materials, therefore, embodied carbon reductions of 80% to 90% are feasible.

**Conclusion:** Since the supply of salvaged materials is limited, we estimate that using salvaged materials could reduce embodied carbon in building structures by 5% to 10% relative to current practice.

## Substitution of Structural Systems

Structural system substitution is a design approach where the engineer compares structural system alternates to a baseline or reference system. The substituted structural system has lower embodied carbon than the baseline system. This strategy offers a large opportunity for the reduction of embodied carbon. For example, designing with biogenic carbon in the form of wood or agricultural products such as straw or bamboo in lieu of other materials with higher embodied carbon will likely be a key strategy to achieve net-zero embodied carbon in the built environment.

Much of the mass of wood is carbon, which originated from the $CO_2$ molecules that were absorbed by the tree during its lifetime. However, timber harvesting generally reduces both the stored carbon in the forest and the ability of the forest to absorb atmospheric carbon, which can take many years to recover, even when saplings are planted for each tree felled. Forest management impacts vary widely, from clear-cutting to Forestry Stewardship Council-certified practices. Other agricultural products such as straw and hemp made into building materials store carbon in the near-term because of their shorter annual growing cycle. In any case, if biogenic carbon is included in a project's carbon tally it should be offset by the products' end-of-life impacts, since the carbon will only be stored for the service life of the material.

Use of alternative structural systems should be supported using project-specific whole building LCA as buildings using low-embodied carbon materials for the structural system do not necessarily have lower embodied carbon than those using higher embodied carbon materials. Wood sourced from sustainably managed forests is more likely to have lower embodied carbon than wood sourced from conventionally managed forests. It is possible that the use of wood products from well-managed forestry practices can result in an overall negative carbon impact--a material that absorbs more atmospheric $CO_2$ that it emits during its overall service life.

We also note that data sources vary in how they account for environmental impacts.[26] Thus, when evaluating alternatives, it is recommended that the designer compare structural systems using a single source of LCA data.

Many LCA studies of alternative structural systems show the potential benefits of considering alternate structural materials and systems. For four buildings ranging in height from 3 to 21 stories, Skullestad et al. found reductions in GHG emissions of 34% to 84% by substituting steel and concrete with timber. The large range in reductions is due to the range of building heights and methodological assumptions.[27] Further, Pierobon et al. conducted an LCA-based comparative study of prototype commercial mid-rise office buildings made of mass timber with a baseline concrete building and found that the GWP of the wood prototype buildings ranged from 394 to 405 kg $CO_2e/m^2$ while the GWP of the concrete baseline building was estimated at 530 kg $CO_2e/m^2$.[28]

An LCA conducted by MOSO in cooperation with INBAR and Delft University of Technology[29] found that the lifecycle of bamboo beams is $CO_2e$ negative. One way bamboo beams are

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[26] Stringer, Megan, & Comber, Matthew. Differences in Embodied Carbon Assessments of Structural Systems. In the 2015 SEAOC Convention Proceedings (pp 131-141). Seattle, WA.

[27] Skullestad, Julie Lyslo; Bohne, Rolf Andre; and Lohne, Jardar. (2016). High- Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives.

[28] Pierobon, F., Huang, M., Simonen, K., Ganguly, I. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. Journal of Building Engineering.

[29] Vogtlander, J. G., & van der Lugt, P. (2015). The Environmental Impact of Industrial Bamboo Products: Life-Cycle Assessment and Carbon Sequestration. 2nd Ed., Beijing, China. *The International Network for Bamboo and Rattan.*

produced is by placing rough bamboo strips in resin and compressing them into molds to form high-density beams. A carbon negative material means that carbon dioxide was removed from the atmosphere rather than releasing or offsetting $CO_2$ released during the life cycle of the material. Attributes of bamboo that help achieve making it a carbon negative material in the LCA study are carbon sequestration during growth and the assumption that 90% of the bamboo would be burned in an electrical power plant to generate electricity or heat. Although the carbon sequestered during the growth of the bamboo is released back into the atmosphere when burned, the authors state that the burning of bamboo is replacing the need to use fossil fuels to produce electricity and heat, thus providing bamboo a 'carbon credit.'

The burning of wood/garbage to produce electricity and heat is common in Europe, where the LCA study took place, however in other parts of the world, like North America, energy production from the burning of garbage or organic material does not make up a large percent of total energy consumed to make electricity.

Most bamboo is sourced from Asia, and therefore it is essential to consider the $CO_2$ used for transporting material to the manufacturing plant where bamboo beams are produced and to the construction site they are utilized.

Another critical aspect of the life-cycle analysis of bamboo is whether it was harvested from a plantation or forest where proper forest management is practiced. When there are no changes in the area of forest versus the amount of bamboo consumed, there will be no carbon sequestration.

When all of the parameters above are properly considered in a whole building LCA, bamboo can be a feasible material even with its limited availability in North America and lower strength properties, so long as transportation impacts are considered. Some potential structural applications for bamboo are framing of non-structural interior partition walls and primarily framing for single-story structures.

Robertson et al. also worked on quantifying and comparing the environmental impacts of alternative structural systems.[30] Using TRACI characterization of the USEPA, the authors found that timber offered lower environmental impact in 10 out of 11 assessment categories. In fact, they found that the Global Warming Potential for the timber-framed option was 71% lower than its concrete counterpart.

Teshnizi et al. at the University of British Columbia, Vancouver compared the tallest timber building (Brock Commons) to a concrete building (Cedar House) of the same scale.[31] The Global Warming Potential (GWP) of the wood-framed dormitory per square meter was found to be 25% less than that of concrete.

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[30] Robertson Adam, et al. (2012). A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete.

[31] Teshnizi Zahra, et al. (2018). Lessons learnt from Life Cycle Assessment and Life Cycle Costing of Two Residential Towers at the University of British Columbia.

Court et al. compared 8 different structural/seismic systems (two concrete, two masonry, two steel, and two timber) for a prototype 5-story office building in Los Angeles, CA to assess the relative environmental impacts of these functionally equivalent alternative designs.[32] The study focused on the structural systems in isolation and did not address the non-structural impacts or operational impacts. For each structural/seismic system, the study used a building of the same size and dimension, with the same column layout, core area layout, perimeter curtain wall system, and equivalent floor quality in terms of sound-proofing and solidness. While for some materials, this did not produce the most efficient structural designs, it was how the authors decided to create functionally equivalent buildings. This study found that the timber buildings generally had significantly less impact (on the order of 3 times less) than the steel buildings and the steel buildings generally had less impact than the concrete and masonry buildings. While this was the case for this particular study, no general conclusions should be made about which material is the most environmentally efficient. It does however illustrate the importance of doing an LCA early in design before the primary structural system has been chosen.

While using timber for a structure that is typically constructed out of concrete or steel will likely have great environmental benefits, timber is not always the best material for a project. Project goals and the pros and cons of any structural system should be considered in addition to the structure's environmental impact. For example, Zeitz et al. found that for parking garages, timber loses its advantages under best practices scenario when comparable garages use high cement replacement and recycled steel.[33]

Other substituted systems to consider include:

- Structural Insulated Panels (SIPs). While they are not appropriate for every project, SIPs can if specified properly result in lower carbon emissions than a steel-framed or concrete wall system.
- Straw bale. Straw bale structures, where appropriate and practical, can have a very low carbon footprint, especially if lime-based parging is used instead of portland cement-based parging.
- Insulated Concrete Forms (ICFs). ICFs can allow the use of high volume SCM (up to 50%) and minimal formwork and waste and can compare favorably to a standard wall assembly including structure and similar-performing thermal envelope elements.

Other alternative systems commonly used in other countries, such as Autoclaved Aerated Concrete and “Ziegel blocks,” may emerge in the U.S. as carbon-efficient construction systems. We have not researched LCA studies comparing these options to “conventional” construction techniques, so encourage designers to evaluate them on a case-by-case basis, as with any substitute system proposal.

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[32] Court, Anthony B., Podesto, Lisa, and Harburg-Petrich, Patti. SEAOC LCA Study Comparing Environmental Impacts of Structural Systems. In the 2013 SEAOC Convention Proceedings (pp 137-153). San Diego, CA.

[33] Zeitz, C.T. Griffin and P. Dusicka (2019). Comparing the embodied carbon and energy of a mass timber structural system to typical steel and concrete alternatives for parking garages.SEAOC.

**Conclusion:** We estimate that structural system substitution could reduce embodied carbon in building structures by 15% to 25% relative to current practice.

## Additional Strategies

Refer to the previously cited *Structural Materials and Global Climate* and *Sustainability Guidelines for the Structural Engineer* for additional design strategies for reducing embodied carbon.

## Design Strategies Summary

Table 2-1 summarizes our estimates of how much each design strategy could contribute to achieving net zero embodied carbon of structural systems by 2050. These percentages are multiplicative, not additive. If the design optimization strategy were fully maximized, the other strategies would apply to the proportion of emissions remaining.

| Design Strategy | Potential Contribution to Reaching Net Zero |
|---|---|
| Design Optimization | 10% to 25% |
| Material Specifications | 10% to 25% |
| Design for Resilience | Further Research Needed |
| Reduced Construction Waste | 5% to 10% |
| Retrofit of Existing Buildings | 5% to 15% |
| Using Salvaged Materials | 5% to 10% |
| Structural System Substitution | 15% to 25% |

Table 2-1: Potential Contribution of Each Design Strategy

# 3. Decarbonizing the Grid

The U.S. electrical grid is becoming increasingly carbon-free as renewable energy sources such as solar, wind, and hydroelectric supplant fossil fuels. The decline of coal used for energy production is also aiding the trend (Figure 3-1).

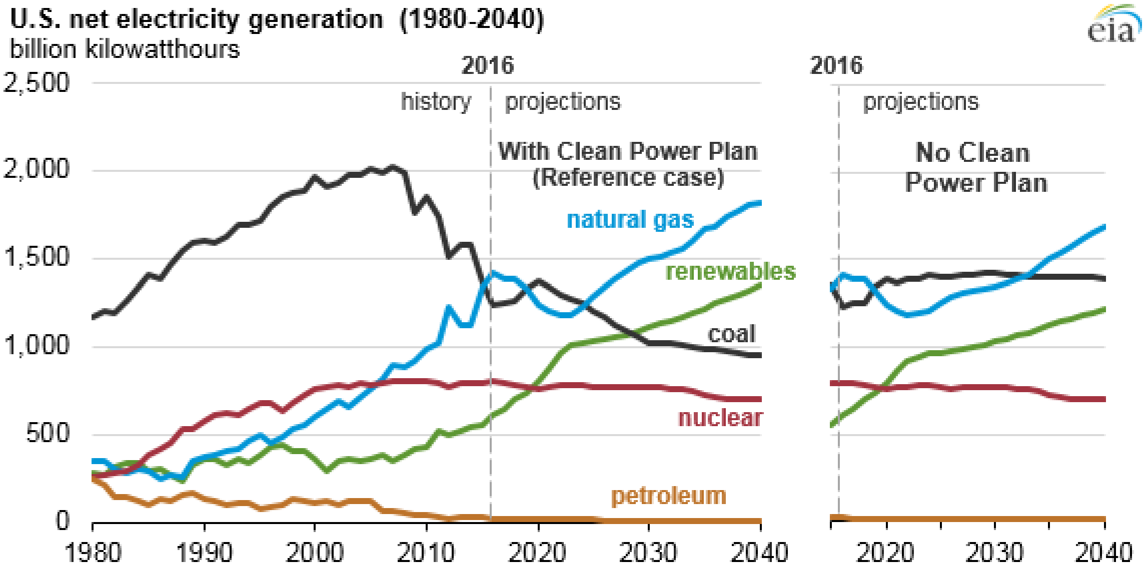

Figure 3-1: Historical and Project U.S. Electricity Generation (U.S. Energy Information Administration, Annual Energy Outlook 2017 )

The U.S. Energy Information Administration (EIA) projections in Figure 3-1 do not consider the aggressive drive towards more renewable electricity generation by many states and municipalities. For example:

- In September 2018 Gov. Jerry Brown of California signed a bill mandating 100% zero emission electricity by 2045 and issued an executive order calling for statewide carbon neutrality by the same year (https://www.npr.org/2018/09/10/646373423/california-sets-goal-of-100-percent-renewable-electric-power-by-2045).
- The 2015 New York State Energy Plan targets 50% of its electricity sources to be renewable by 2030, resulting in a 40% reduction in $CO_2e$ emissions from 1990 levels. The plan calls for an 80% reduction in $CO_2e$ emissions by 2050. (https://energyplan.ny.gov/Plans/2015.aspx).
- The 2008 Massachusetts Global Warming Solutions Act requires the state to reduce its total GHG emissions by 80% by 2050 relative to 1990 (https://www.mass.gov/service-details/clean-energy-and-climate-plan-for-2020). The state's targets will require most electricity to be produced using zero-emission sources by 2050.

Project Drawdown issued a report detailing the path to zero-emission electricity by 2050 (https://www.drawdown.org/solutions/electricity-generation), with utility scale on-shore wind turbines and distributed solar hot water generation leading the way. Figure 3-2 summarizes Project Drawdown's findings regarding opportunities for carbon reductions.

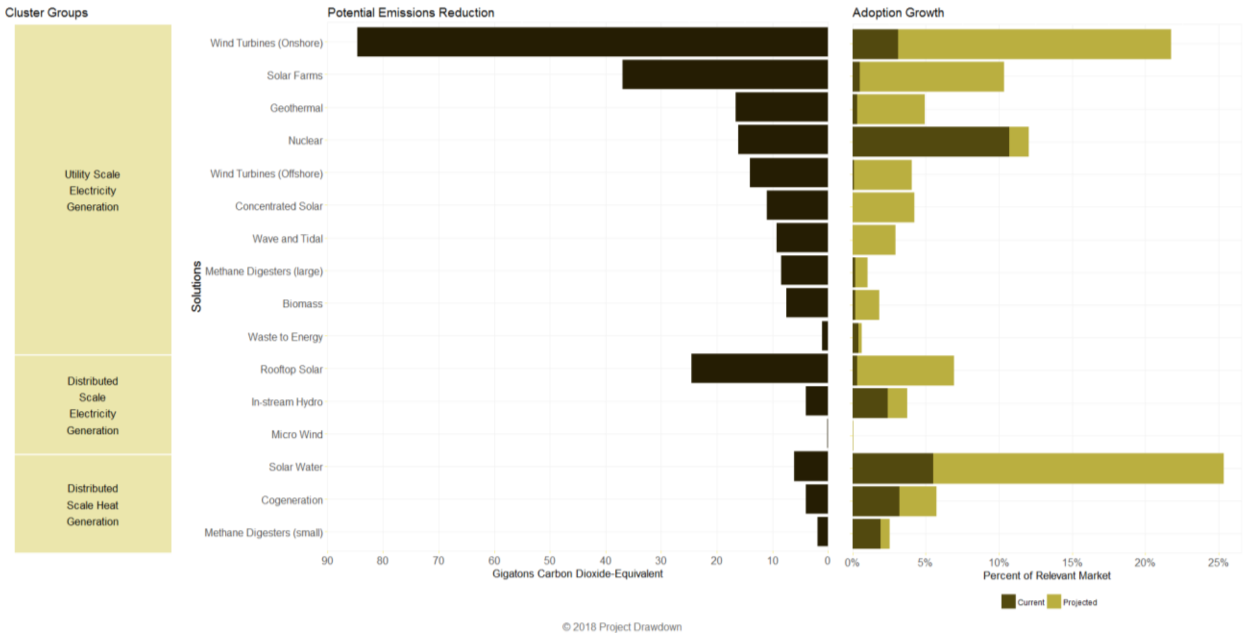

Figure 3-2: Project Drawdown

How much would carbon-free electricity reduce the embodied carbon of structural materials?

AISC estimates that about 50% of the carbon emissions associated with EAF-produced rolled shapes is attributable to electricity. Thus transitioning to carbon-free electricity would cut the carbon footprint of EAF steel in half. If steel presently produced in BOFs shifts towards EAFs, the embodied carbon footprint would be reduced by both the changes in production as well as the changes to the grid, since the $CO_2e$ emissions associated with BOFs are higher than EAFs.

*"...transitioning to carbon-free electricity would cut the carbon footprint of EAF steel in half."*

Electricity contributes much less to the embodied carbon of concrete. The EIA estimates that in 2014 the U.S. cement industry consumed 11,180 million kWh of electricity (EIA 2017). The USGS estimates the U.S. cement production was 82,600 thousand metric tons the same year (USGS 2017). The EIA estimates that in 2017 U.S. electricity production emitted 1009 lb of $CO_2$/MWh (EIA 2017). Using these factors, we find that the electricity used in cement production emits about 124 lb of $CO_2$ per ton of cement. The EPD for portland cement reports a GWP of 1,040 kg $CO_2$e/metric ton of cement, or about 2,080 lb/ton, so about 6% of the $CO_2$e associated with cement production is due to electricity consumption. Using cement as a proxy for concrete, we estimate that electricity consumption contributes a similar percentage of the $CO_2$e emissions associated with concrete. The transition to a carbon-free electrical grid, in other words, will not by itself result in a large reduction in the carbon emissions associated with concrete use.

Accounting for the relative total carbon emissions associated with all the structural steel, concrete, and wood consumed in the United States (see the Introduction), we conclude that the transition of the electrical grid to carbon-free sources would reduce the total emissions associated with structural materials by only about 10%.

# 4. Manufacturing Improvements Reducing Emissions

This section addresses concrete and steel production. Production improvements in structural wood products are also likely, including forestry management practices and engineered wood processes and adhesives, but are not addressed in this paper

Material manufacturers have been steadily reducing the unit carbon footprints of their products over the past decades by incorporating more efficient manufacturing technologies. For example, the carbon intensity of cement in the US has been reduced by 33% since 1975[34] and is expected to decrease further by increasing thermal efficiencies, switching fuels, reducing the clinker-to-cement ratios, and using carbon capture techniques[35]. Between 1990 and 1998, the energy intensity of steel dropped 10% to 18 Mbtu per ton. Yet, the rate of reduction is slowing due to the theoretical minimum energy required to produce steel (14 MBtu/ton)[36]. Reducing the carbon-intensity of building materials is a key opportunity for the building sector to achieve zero embodied carbon.

This carbon reduction track is somewhat outside of the building designer's control. Yet, building designers have the ability to create demand for lower carbon building products by specifying them for their projects.

## Concrete and Cement

It is well known that portland cement manufacture contributes significant $CO_2e$ emissions to the atmosphere. Recent estimates are that 7% of global $CO_2e$ emissions are due to the manufacture of portland cement.[37] It's not true, however, that embodied $CO_2e$ emissions in concrete are equal to those in portland cement. Portland cement is a grayish powder that serves as the binder in concrete. By volume, cement is used in the smallest proportion of the four primary components of concrete (water, cement, fine aggregate, and coarse aggregate), but it typically contributes approximately 90 percent of the total $CO_2e$ emissions associated with the concrete. For this reason, reductions in cement content in concrete is an important strategy in reducing embodied carbon in concrete, as was discussed previously.

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[34] 2007 Report on Sustainable Manufacturing, Portland Cement Association, Skokie, IL, 2007, http://www.cement.org/smreport07/index.htm.

[35] https://www.iea.org/newsroom/news/2018/april/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050.html

[36] https://pdfs.semanticscholar.org/41d0/b702c1e70f3677676a033d771bac7857b27b.pdf

[37] IEA. (2018). Technology Roadmap—Low-Carbon Transition in the Cement Industry (p. 66). International Energy Agency (https://webstore.iea.org/technology-roadmap-low-carbon-transition-in-the-cement-industry).

To explain potential reductions in $CO_2$e emissions from cement manufacturing, it is important to first understand the sources of $CO_2$e emissions. A detailed explanation of these processes are included in *Structural Materials and Global Climate*.[38] Cement requires energy to produce, which generates some of the $CO_2$e emissions. But $CO_2$e emissions are also generated from calcination, which is the process in which calcium carbonate is heated and broken down to calcium oxide. The relative breakdown of $CO_2$e emissions from the two different sources during the cement manufacturing process are:

1. approximately 40% of the $CO_2$e generated is due to the use of fossil fuels in the kiln, and
2. approximately 60% of the $CO_2$e generated is due to calcination.

## Emissions from Burning Fossil Fuels during Cement Manufacturing

To bring about conditions sufficient to produce the chemical conversion of the raw materials into clinker, the kilns must be heated to approximately 1450ºC in their hottest zones. The amount of energy required to operate a cement kiln (and thus the amount of fuel that must be burned) varies depending on the specific type of kiln that is used. Several advances have occurred in cement kiln technology over the years that have improved energy efficiency significantly.

There are four main types of cement-production kilns used in the United States: wet, long dry, dry with preheater, and dry with preheater and precalciner. The thermal energy required between these four types of production can vary widely, with the dry with preheater and precalciner kilns using 85% less thermal energy than wet kilns on average. Currently, about 93 percent of the cement produced in the United States is manufactured using dry process technology, up from 75% in 1999.[39]

In order to generate such high temperatures in a kiln, energy is supplied through the burning of fuel. The average energy input required to make one ton of cement is 4.4 million Btu—the equivalent of about 389 pounds of coal.[40] Coal is the primary fuel source burned for heating cement kilns in the United States—about 12.6 million tons annually.[41] Because the amount of $CO_2$e released during fuel burning will vary not only with fuel type but also with kiln type, it is difficult to assess carbon emissions associated with fuel burning with a single number. However, using average data, Van Oss and Padovani computed a value of 0.43 tons of $CO_2$e emissions

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[38] Webster, Mark D., ed., *Structural Materials and Global Climate: A Primer on Carbon Emissions for Structural Engineers*, American Society of Civil Engineers, Structural Engineering Institute, Carbon Task Group, 2017 (https://ascelibrary.org/doi/book/10.1061/9780784414934).

[39] Ernest Orlando Lawrence Berkeley National Laboratory (LBNL). (2008). *Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making*.

[40] PCA. (2012). U.S. and Canadian Labor-Energy Input Survey 2012

[41] PCA. (2019). PCA website <accessed March 20, 2019> https://www.cement.org/structures/manufacturing/Cement-Industry-Overview

from fuel combustion per ton of clinker produced in the U.S.[42] For cement composed of 95 percent clinker by weight, fuel combustion would generate 0.41 tons of $CO_2e$ per ton of cement.

To summarize, the two primary sources of carbon emissions in cement manufacturing are the calcination of limestone and the burning of fuel. These result in roughly 0.48 and 0.41 tons, respectively, of $CO_2e$ emissions per ton of cement produced. In total, approximately 0.89 tons of $CO_2e$ are released for each ton of cement that is produced. Based upon data from the Cement Sustainability Initiative, the total carbon footprint for cement ranges from approximately +50% to -20% from average depending on manufacturing efficiency and fuel source.

> *"...the total carbon footprint for cement ranges from approximately +50% to -20% from average depending on manufacturing efficiency and fuel source."*

## Opportunities for Improvements in Existing Technology

The greatest opportunity for reducing energy use (and the resulting embodied carbon) in the cement manufacturing process occurs when kilns are converted from wet to dry processes. Switching away from coal and petroleum coke to natural gas may also prove a viable strategy because the "$CO_2$ emissions intensity of natural gas ($kgCO_2$/GJ) is less than 60% of coal and petroleum coke" (Hasanbeigi and Springer 2019).

Additional improvements can be realized through updating of manufacturing techniques and machinery to lower-energy or more-efficient processes. Changes in staff behavior and attitude may also have a greater impact on reducing energy use. Through proper training, staff at all levels should be able to recognize how their behavior impacts energy use. Staff should be made aware of the plant's general approach to energy efficiency and objectives for energy efficiency improvement.

Other programs or lean-manufacturing techniques, such as participation in EPA's energy star or implementing ISO 14001 environmental management standards, can play a role in reducing energy use in cement manufacturing facilities. Simply monitoring energy usage can assist plants in reaching energy efficiency targets.

One measure of the embodied carbon of cement is the clinker-to-cement ratio. In this formulation, "cement" includes portland cement and other materials, such as SCMs, natural pozzolans, calcined clay, limestone dust, and gypsum. Presently the global average clinker-to-cement ratio is 65%. The IEA estimates that this ratio could drop to 60% by 2050, reducing the

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[42] van Oss, Hendrik G. and Padovani, A. (2003). "Cement and the environment; Part II—Environmental challenges and opportunities." J. of Industrial Ecology 7, no. 1: 93-120.

process $CO_2$ intensity of cement by 30%. China today leads the world with a clinker-to-cement ratio of under 60%. In contrast, this figure is over 70% for the Americas.[43]

## Low-Carbon Cement

Several lower-carbon cements are emerging in the marketplace in an effort to compete with ordinary Type I portland cement. These different cements vary in carbon-reduction potentials, availability, and commercial scalability.

### *Belitic clinker*

Technology to create belitic cement is very similar to that of portland cement thus allowing it to be produced in existing plants with little additional investment. Lower temperatures are required, which reduces the amount of carbon dioxide released during production by about 10%.[44] Because these types of cements are less reactive, their lower heat of hydration can be advantageous in mass concrete applications. However, the potential $CO_2$ savings of this type of cement are also reduced due to its reduced reactivity.

### *Calcium sulfoaluminate cements*

Calcium sulfoaluminate (CSA) cement can also be produced with the same technology as ordinary portland cement. Its reduced carbon footprint is due to its chemical composition. CSA cement relies on less calcium (from limestone) in its primary reactive phase, which reduces the kiln emissions from the decarbonization of limestone. Like Belitic clinker, firing temperatures are also lower, and post processing (grinding) is easier, than for ordinary portland cement. These unique characteristics lead to a potential $CO_2$ savings of 20% to 30%.[45] Challenges to adoption of CSA cement are related to:

- Setting time: The setting time of CSA cement can be fast and variable, so they are better suited to use in precast concrete applications.
- Durability: There has been little research into the long-term durability of CSA cement in various environments.
- Expense: The high-alumina raw materials, primarily bauxite, required for CSA cement is expensive and less available. If all bauxite currently used for aluminum production was used for CSA cement, only 15% of the current cement demand could be met by CSA cement.[46]

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[43] IEA. (2018). Technology Roadmap—Low-Carbon Transition in the Cement Industry (p. 66). International Energy Agency (https://webstore.iea.org/technology-roadmap-low-carbon-transition-in-the-cement-industry).

[44] Favier, Aurélie; Catherine De Wolf; Karen Scrivener; and Guillaume Habert. 2018. *A sustainable future for the European Cement and Concrete Industry*. https://doi.org/10.3929/ethz-b-000301843.

[45] Ibid.

[46] Ibid.

### *Calcined Clay*

Calcined clay can be substituted for clinker in ordinary portland cement production to reduce the carbon footprint. The clay must be fired prior to use, but the energy required to do this is much less than that required in a cement kiln. The calcined clay reduces the early age strengths of concrete, compared to straight portland cement mixtures, but that low-early-age strength may be offset with the addition of finely ground limestone.[47]

### *Carbonated calcium silicate concrete*

Low-lime calcium silicate cement (CSC) production uses less limestone and lower kiln temperatures than OPC, "the carbon dioxide emissions at the cement kiln from 810 kg/t for OPC to 565 kg/t for CSC."[48] During the curing process, CSC cures due to reaction with gaseous carbon dioxide, which embodies up to 300 kg $CO_2$/t of cement used in the concrete, instead of water. However, there are several limitations to their use and applications are limited to prefabricated products.[49] Because the CSC reacts with $CO_2$, elements must be thin enough for the carbon dioxide to penetrate and small enough to fit into a special curing chamber. Also, because of the reduced alkalinity of the matrix, convention steel reinforcement will not be protected from corrosion as in a normal hydraulic cement matrix.

### *Alkali-activated binders*

Alkali-activated binders, also known as geopolymers, are an alternative binding system that does not contain any portland cement. Instead, the binders consist of precursors (aluminosilicates) and alkaline activators. Common precursors include pozzolanic materials, such as slag, fly ash, in addition to calcined clays. Alkali-activated binders have been used for the past decades at scale in countries such as the US, Russia, and Australia. A notable project which used alkali-activated binders in lieu of OPC is the Brisbane West Wellcamp Airport which consisted of 40,000 cubic meters of concrete. While alkali-activated binders cover a wide variety of binding systems, the environmental impacts have shown 40% to 80% reductions in $CO_2$ emissions as compared to OPC.[50]

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[47] Hasanbeigi, Ali and Cecilia Springer. 2019. *California's Cement Industry: Failing the Climate Challenge*. Report for Global Efficiency Intelligence.

[48] Jain, Seth and DeCristofaro. "Environmental impact and durability of carbonated calcium silicate concrete." Proceedings of the Institution of Civil Engineers. http://dx.doi.org/10.1680/jcoma.17.00004

[49] Favier, Aurélie; Catherine De Wolf; Karen Scrivener; and Guillaume Habert. 2018. *A sustainable future for the European Cement and Concrete Industry.* https://doi.org/10.3929/ethz-b-000301843.

[50] Provis, J. L. (2018). Alkali-activated materials. *Cement and Concrete Research*, *114*, 40–48. https://doi.org/10.1016/j.cemconres.2017.02.009

### *Carbon-sequestering aggregate*

As described in the section above on material specifications, a company is already utilizing carbon sequestration in aggregates. This technology is still being developed and could become more widespread in the future. See Section 1 of this paper for further information.

We conclude that there is little opportunity to further reduce the embodied carbon of domestically produced OPC. However, the use of blended cements and cement substitutes have the potential to reduce carbon dioxide emissions from the cement and concrete industries by 30% by 2050. Experts predict that CSA and CSC cements have the greatest potential for market penetration.[51] Given the dominant contribution of concrete to structural system emissions, we estimate that improvements in concrete production technologies could reduce overall structural embodied carbon by 15% to 20% by 2050.

> *“...the use of blended cements and cement substitutes have the potential to reduce carbon dioxide emissions from the cement and concrete industries by 30% by 2050.”*

## Structural Steel

While this section is focused on structural steel, many of the conclusions apply to steel reinforcement and cold-formed steel as well.

Recent estimates are that 7% of global $CO_2e$ emissions (2.3Gt $CO_2$ per year)[52] are due to the manufacture of steel. The primary cause for emissions is the energy needed for high-temperature processes required in melting iron ore or rolling steel (Figures 4-1 and 4-2). Coal is also a large contributor to the $CO_2$ emissions as it fuels roughly 75% of global steel production energy.

Significant advancements have been made since the era of the open hearth in the early 1900’s to improve efficiency by over 60% per ton over the last 50 years[53]. Improvements in technology have come from using electric arc furnaces (EAF) rather than coal blast furnaces and developing the chemical composition. Current manufacturing methods are transitioning to energy optimized furnaces (EOF) and using a high percentage of scrap material in EAF production. However, as demand for steel continues to grow, $CO_2$ emissions are expected to

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[51] Favier, Aurélie; Catherine De Wolf; Karen Scrivener; and Guillaume Habert. 2018. A sustainable future for the European Cement and Concrete Industry. https://doi.org/10.3929/ethz-b-000301843.

[52] Energy Transitions Commission (2018). *Mission Possible, 41*. http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

[53] World Steel Association (2019). *Steel’s Contribution to a Low Carbon Future.*. https://www.worldsteel.org/publications/position-papers/steel-s-contribution-to-a-low-carbon-future.html

increase to 3.3Gt by 2050 under business as usual. Potential for improvement comes in the form of advancing carbon capture methods, using hydrogen as a reducing agent for iron ore, and application of electrolysis in the reduction process. Improvements to $CO_2$ through electrification are highly dependent on a transition to renewables in the electric grid.

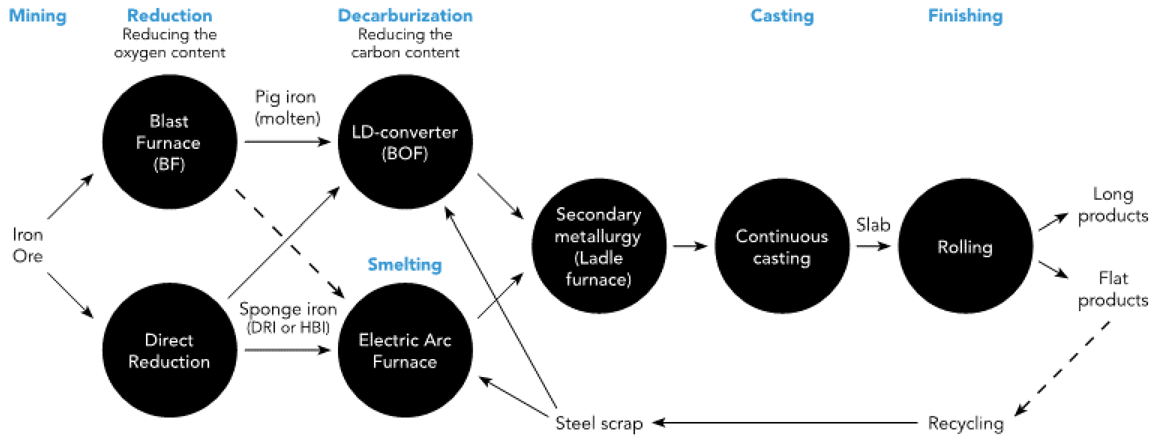

Figure 4-1. Steel Manufacturing Process[54]

## Current Practice and Industry Direction

Steel is currently created in one of two ways: either new (virgin) steel is made from breaking down iron ore or recycled steel is melted down and repurposed. Blast furnace-blast oxygen furnace (BF-BOF) process is used to make over 95 percent of the world's virgin steel. BF-BOF production is a coal-powered process by which iron ore is reduced and melted at temperatures around 1,200 °C.[55] This is the largest contributor of $CO_2$ emissions from steel manufacturing as it takes four times as much energy to make virgin steel than recycled steel.

The remaining 5 percent of virgin steel is created through direct reduction of iron (DRI) followed by smelting through an electric arc furnace (EAF). EAFs break down and recycle scrap steel.

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[54] Åhmana, M., et all (2018). *Hydrogen steelmaking for a low-carbon economy*. Stockholm Environment Institute working paper WP 2018-07.

[55] de Pee, A., et al (2018). *Decarbonization of industrial sectors: the next frontier.* McKinsey and Company.

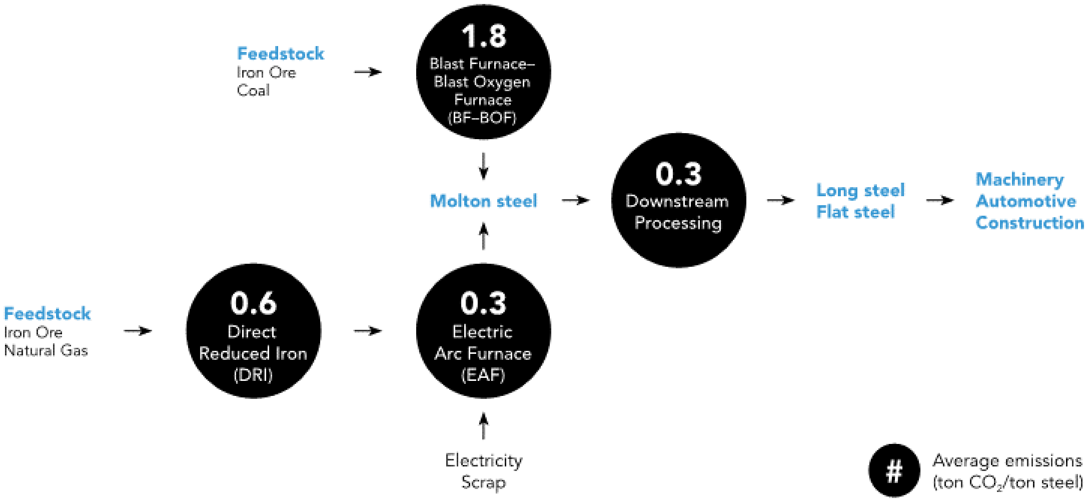

Figure 4-2. $CO_2$ Contribution in Steel Manufacturing[56]

It is much more efficient and environmentally friendly to produce steel using EAF rather than BOF. However, availability of scrap steel is highly dependent on geographic location and a history of steel production. Nearly all the steel in the US, where there is a healthy scrap market, is made using EAFs. But due to varying stages of development and access to scrap metal, countries are expected to transition to EOF at different times (Figure 4-3). China is an important example. China, the largest producers of steel globally and significant contributors to global emissions, produced 89 percent of its steel using BOFs[57] as of 2015. A transition to recycled steel production is essential to curb global emissions. At present, however, there is a concern that there is insufficient scrap available to fully meet the demand for steel, especially in developing economies. Furthermore, even as emissions due to virgin steel production plateau, recycled steel demand is expected to double, causing a projected 30% increase in emissions.[58]

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[56] Ibid.

[57] Vercammen, S., et al (2017). *The growing importance of steel scrap in China*. McKinsey and Company.

[58] WSA 2016, McKinsey Basic Materials Institute.

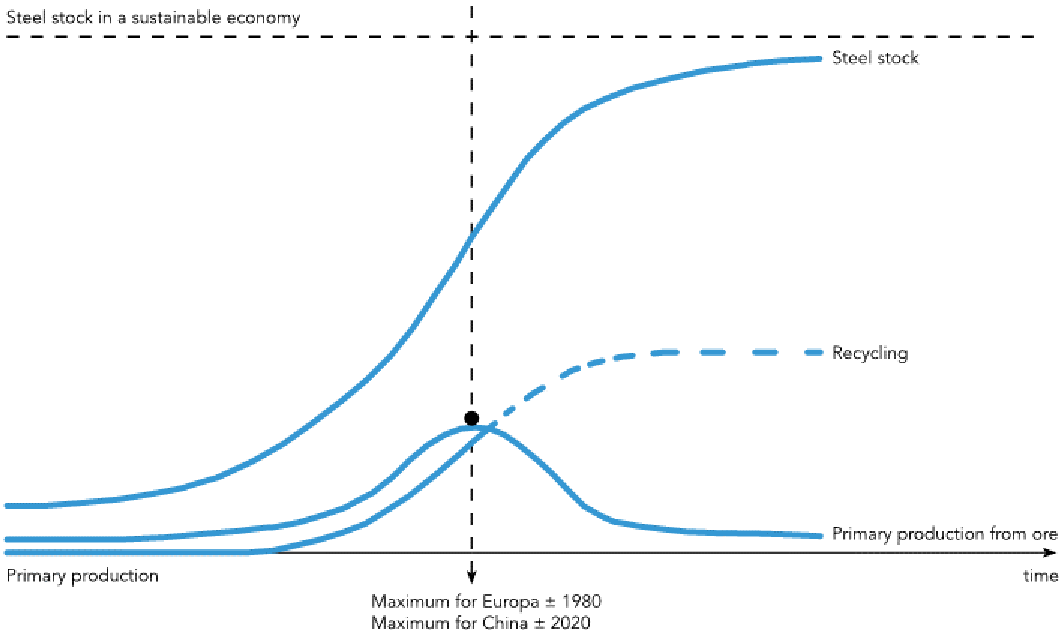

Figure 4-3. $CO_2$ Contribution in Steel Manufacturing[59]

## Opportunities for Improvement

Research and pilot programs have begun for both BOF and EAF processes. The optimal route for decarbonization will be different by location and determined by local electricity prices and the local feasibility and cost of carbon capture and storage.

In locations where the ***BOF process*** is needed to produce virgin steel, innovative techniques to optimize production for carbon capture and sequestration (CCS) are being developed. HISarna and top gas recycling (TGR) are two ultra-low carbon dioxide steelmaking (ULCOS) methods aiming to reduce $CO_2$ by at least 50%. These lower emissions by reducing coal and increased percentage of $CO_2$ in exhaust so that it can be captured at a lower cost.

- HISarna[60] is a process that involves a top-injected reactor where ore is liquefied in a high-temperature cyclone. This requires less pre-processing, and as a result, there is a 20% reduction in required energy. HISarna doubles the theoretical maximum steel scrap from traditional BOF production to 50% scrap. Additionally, the $CO_2$ produced is in high-concentration, making it highly viable for CCS.
- Top Gas Recycling[61] technology lowers the usage of coke and coal by recycling reducing agents (CO and H2). Rather than hot air, oxygen is blown into the BF,

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[59] Sustainable in Steel (n.d.). Production routes for steel. https://www.sustainableinsteel.eu/p/531/production_routes_for_steel.html

[60] Tata Steel (n.d.). Sustainable in every sense. https://www.tatasteeleurope.com/en/sustainability/hisarna

[61] Satyendra (2019). Top Gas Recycling Blast Furnace Process. https://www.ispatguru.com/top-gas-recycling-blast-furnace-process/

eliminating nitrogen in the top BF gas. Part of the top BF gas containing CO and H2 is utilized again as the reducing agent. $CO_2$ from the BF top gas is captured and then stored using pressure swing absorption (PSA).[62]

Neither top gas recycling or HISarna require altering existing plant processes. However, a challenge of CCS is converting $CO_2$ into useful chemicals consumes a lot of energy, resulting in increased costs and strong demand for zero-carbon electricity.

Biofuel as feedstock can also reduce $CO_2$ emissions in BOF steel production. Brazil has found ways to reduce coal inputs to BOF by using charcoal. However, this has been found to reduce efficiency by ~40%, requires small furnaces, and existing facilities functioning on coal cannot be adapted.

The ***EAF process*** also plays a critical role in decarbonization. As more scrap material is available, a transition is made to EAF. The primary carbon emitter is heating scrap steel in the Direct Reduced Iron (DRI) process. Future developments aim to reduce $CO_2$ by replacing natural gas with biogas or hydrogen.[63] This transition would not require a large retrofit. German steelmaker, Thyssenkrupp, has done so successfully with hydrogen and state a target of reducing $CO_2$ by 20 percent as a result of the change.[64]

Additional EAF research efforts include:

- Hydrogen Breakthrough Ironmaking Technology, i.e. HYBRIT, is an effort in Sweden to replace coal with hydrogen. Their research suggests approximately two decades to develop and implement this technology, but offers potential for 10% reduction in greenhouse gas emissions for the country.[65] Notably, this process is expected to come at some cost premium. As such, researchers anticipate political policy to be a driving risk factor for developing this technology and ensuring a market for “green” steel.
- Coke dry quenching (CDQ)[66] is a heat recovery system to quench red hot coke from a coke oven to a temperature appropriate for transportation. It is an energy saving system in which, during the quenching process, sensible heat of the red hot coke is recovered and utilized for power generation or as steam.
- Electrolysis is a process that extracts iron from ore using electricity rather than heat. Advancements in chemistry, specifically inexpensive, nonconsumable anodes have contributed to the viability of this process. MIT researcher, Donald Sadoway, suggests

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[62] Perez-Fortez, M., et all (2014). $CO_2$ Capture and Utilization in Cement and Iron and Steel Industries. European Commission, Joint Research Centre, Institute for Energy and Transport

[63] Vogl, V., Ahman, M., Nilsson, L. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production, p 736-745.

[64] Wettengel, J. (2019). Thyssenkrupp tests use of hydrogen in steel production to bring down emissions. https://www.cleanenergywire.org/news/thyssenkrupp-tests-use-hydrogen-steel-production-bring-down-emissions

[65] http://www.hybritdevelopment.com/

[66] Steel Plantech (2015). Coke Dry Quenching (CDQ). https://steelplantech.com/product/cdq/

30% more energy efficient than conventional methods.[67] Reducing energy can result in a cost savings in production as well as reduce carbon dioxide emissions by 10% when clean electricity grid is used. This process is currently in practice for aluminum production. However, this method would require redesign of existing blast furnace facilities or construction of new facilities.

As discussed in Section 3, decarbonization of the electric grid plays a key role in decarbonization of steel manufacturing, but this is outside the control of the manufacturing facility, unless they intentionally shift production to locations with lower carbon electricity.

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[67] Ifran, U. (2013). Cleaner, Cheaper Way to Make Steel Uses Electricity. ClimateWire.

# 5. Offsets for Remaining Emissions

Any remaining emissions that are not addressed by design improvements, decarbonization of the grid, and advances in manufacturing may be addressed by purchasing offsets.

Carbon offsets are investments in actions that reduce carbon emissions. Offsets should pay only for actions that would not take place without the support of the offsets, a concept known as "additionality."

Certified Emission Reductions (CERs) and Verified Emissions Reductions (VERs) are two forms of carbon offsets with additionality. Both are accepted by the International Living Futures Institute for its Zero Carbon Certification.[68]

CERs are issued by the United Nations' Clean Development Mechanism (CDM), which was established by the Kyoto Protocol. CERs cover emission reduction activities that also support sustainable development in developing countries. Typical projects supported by CERs include:

- destruction of HFCs
- reduction of methane emissions
- renewable energy
- efficient cookstoves

VERs (sometimes known as "Voluntary Emission Reductions") are third-party verified carbon credits that are not recognized by the CDM. Certification standards include Verra's Verified Carbon Standard (VCS) Program (https://verra.org/project/vcs-program/) and the Gold Standard program (https://www.goldstandard.org/) supported by WWF and many other non-profit organizations. VERs are mostly generated by wind energy projects, REDD+ (Reduced Emissions from Deforestation and Forest Degradation) projects, and landfill methane projects.[69]

Although offsets must be third-party verified, many are controversial. Demonstrating additionality is difficult. CERs have even supported coal-fired electrical generation plants.[70,71] It is always better to utilize all means of reducing embodied carbon directly before turning to offsets.

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[68] International Living Future Institute, *Embodied Carbon Guidance: A Resource for Calculating and Reducing Embodied Carbon*, 18 December 2019.

[69] *Unlocking Potential: State of the Voluntary Carbon Markets 2017*, Forest Trends' Ecosystem Marketplace, May 2017 (https://www.cbd.int/financial/2017docs/carbonmarket2017.pdf)

[70] Nathanial Gronewold, "U.N. Panel Calls for Offsets to New Coal-Fired Plants to Be Suspended," Scientific American, July 11, 2011 (https://www.scientificamerican.com/article/un-panel-suspends-offsets-new-coal-fired-plants/).

[71] Stephen Lacey, "In The 'Crazy' World Of Carbon Finance, Coal Now Qualifies For Emission Reduction Credits, ThinkProgress, September 19, 2012 (https://thinkprogress.org/in-the-crazy-world-of-carbon-finance-coal-now-qualifies-for-emission-reduction-credits-a4c853ebb999/).

> *"It is always better to utilize all means of reducing embodied carbon directly before turning to offsets."*

According to a carbon offset specialist we contacted in 2019, the current cost of carbon offsets is in the range of \$1.40 to \$2.50 per metric ton of $CO_2$, depending upon the size of the purchase. The cost of offsetting the embodied carbon in a 10,000 square foot building with 80 pounds of embodied carbon per square foot would therefore cost about \$725 if the offsets cost \$2.00/metric ton. The specialist told us that the price of carbon offsets has been fairly constant over the past decade and that the future price will depend on the capitalist forces of supply and demand.

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