Research Report

Decarbonization of Buildings:

A Review of Climate Science, Policies, Practices, Data, and Recommended Actions for Buildings and Building Materials

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The Foam Sheathing Committee of the American Chemistry Council
Washington, DC

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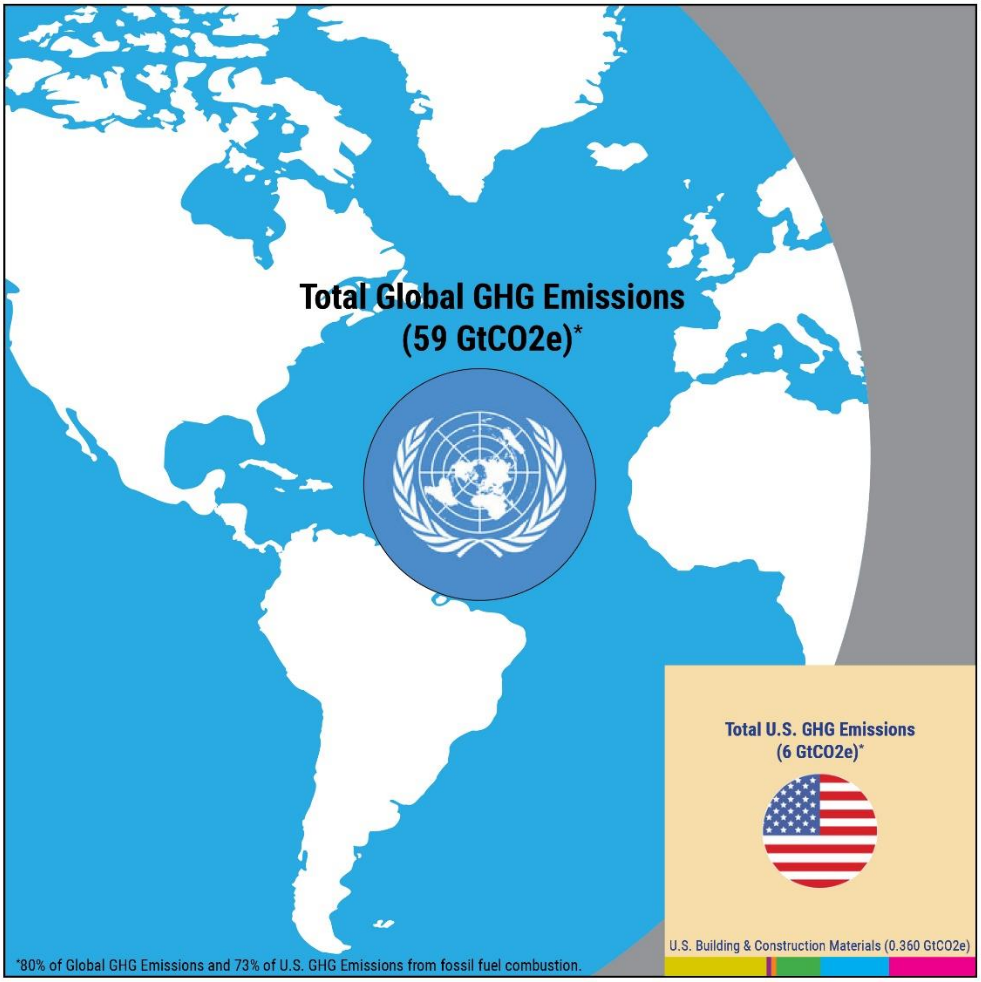

About this Research Report:
Applied Building Technology Group (ABTG) is committed to using sound science and generally accepted engineering practice to develop research supporting the reliable design and installation of foam sheathing. ABTG's work with respect to foam sheathing is provided through a grant by the Foam Sheathing Committee (FSC) of the American Chemistry Council. Foam sheathing research reports, code compliance documents, educational programs, and best practices can be found at www.continuousinsulation.org.

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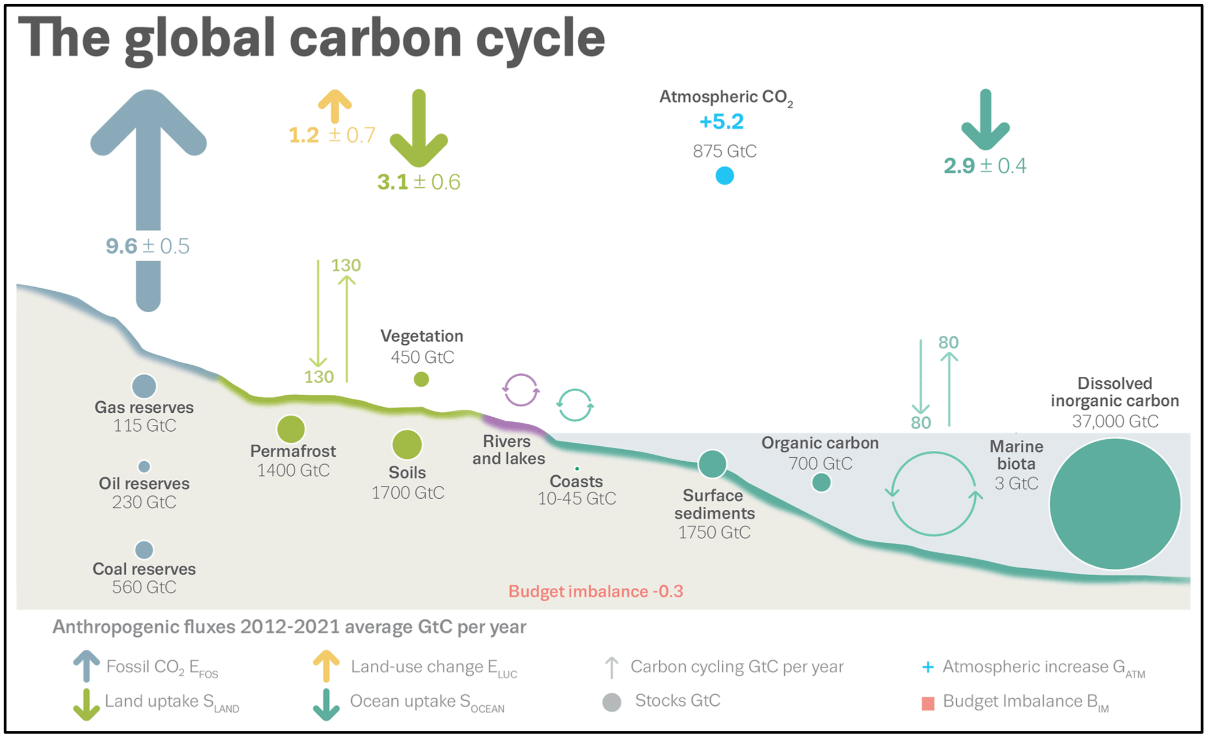

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Finally, this report is considered an "open file" research report. It may be revisited periodically as substantive additional or new information becomes available which significantly adds to or improves the content, findings, and recommendations of this report. Such information from interested parties is welcomed and should be directed to the principle investigator for this work:

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Executive Summary

This report provides a comprehensive review of the following:

- **PART 1**: Climate Science
- **PART 2**: Climate Policy
- **PART 3**: Status of US Energy Use and GHG Emissions
- **PART 4**: Decarbonization of US Buildings

The report also discusses the importance of a "total carbon" approach when setting policy or making decisions related to insulation materials, which deliver substantial benefits for energy efficiency and the avoidance of building operational greenhouse gas (GHG) emissions. It also explores the importance of building insulation to enable the energy demand reductions needed to decarbonize new and existing buildings. Consequently, efficiently insulated buildings also help support the decarbonization of other economic sectors, such as transportation, which rely on the same limited energy supply from a decarbonizing electric grid.

A summary of the findings and conclusions of this report is as follows:[1]

- **Climate change is a serious concern.** Current and future impacts of global warming are real and significant, but the magnitude and regional variation of expected future climate impacts remain very uncertain. (See **PART 1**.)
- **Climate goals and policy development would benefit from rational cost-benefit analyses and optimization.** While well-intentioned, the current very ambitious posture of climate goals and related policies is not necessarily founded on robust cost-benefit analyses for optimization. Such analyses would provide an objective science-based accounting of estimated policy costs, harms, and benefits in mitigating estimated future climate impacts. It would serve as a means to better optimize goals, inform policy decisions, and direct priorities. It also would provide meaningful transparency and objectivity to help form a common vision for determining and implementing optimal solution pathways to mitigate climate change. (See **Section 1.4** and **PART 2**.)
- **The social cost of carbon provides a rational cost-benefit basis to assess climate policy.** The social cost of carbon represents the cost of future climate change impacts to humanity and the planet due to carbon dioxide (CO2) and other GHG emissions. It enables cost-benefit analyses whereby the benefits (avoided climate impacts) of a proposed policy to reduce emissions can be compared with the cost of implementing the policy in a climate risk-consistent manner. Consequently, many consider the social cost of carbon to be a key factor in guiding climate policy decisions. It also is potentially the single most effective and efficient means to drive an appropriate economy-wide response to reduce GHG emissions where used as the basis for a responsibly administered carbon tax policy (or tax incentive for decarbonization investments based on realized GHG emission reductions). Unfortunately, application of the social cost of carbon has seen limited use (or has been significantly under-valued) as a means to establish climate goals and related policies, regulations, programs, and mitigation measures. (See **Section 1.4**, **Section 2.3.4**, and **Section 4.8.6**.)
- **Combustion of fossil fuels is the dominant source of global and US GHG emissions.** Combustion of fossil fuels accounts for 92% of US CO2 emissions and 73% of US GHG emissions across all sectors of the US economy. The transportation and electric power sectors of the US account for about two-thirds of the emissions associated with the combustion of fossil fuels in the US (or about half of total US GHG

[1] For each bulleted finding or conclusion, a reference to parts and sections of this report is provided for substantiation and additional information. However, these referenced portions of the report are not necessarily exhaustive of all the information documented or referenced on a given topic.

emissions). Therefore, decarbonization of the electric power sector is a hub for decarbonization of transportation, building, and industry sectors as they strive to increasingly electrify. (See **PART 3**.)

- **Energy efficiency to improve energy productivity is crucial to decarbonization.** Energy efficiency has broad and reliable economic and climate benefits through any future decarbonization pathway. Regardless of the path for or rate of future decarbonization, reducing fossil fuel combustion emissions through increased energy efficiency and improved energy productivity should be the primary focus of any effective plan to decarbonize the US economy. Furthermore, the same investment in energy efficiency also will maximize and extend the productive use of available low-carbon or renewable energy sources, particularly as the electric power generation sector continues its transition to renewable energy from solar, wind, and other renewable resources or low-carbon technologies. (See **PART 2**, **PART 3**, **Section 4.3**, and various other sections in **PART 4**.)
- **Data is lacking to effectively rank building materials in relationship to their significance or contribution to global climate change.** Based on the available data reviewed and assessed in this report, an initial attempt to broadly characterize US building materials' GHG emissions in relationship to total global GHG emissions is shown in **Table A** and visualized in **Figure A**. This approach is similar to the "key category" approach used by EPA to evaluate categories of emissions from within various economic sectors, such as the industry sector as presented in **Section 3.2**. The percentage of total global GHG emissions provides an objective basis for assessing the climate mitigation significance (or potential benefit) of any policy action taken to reduce those emissions. (Data sources used to develop **Table A** and **Figure A** are included in footnote 1 of **Table A**.)
- **Eliminating the embodied GHG emissions of US building materials will have a relatively small effect on global climate change.** As shown in **Table A** and **Figure A**, the annual production of all US building materials represents about 0.4% of total annual global GHG emissions (0.6% if other construction applications are included). While this finding is not meant to suggest that improvements or innovations should not be pursued, it does suggest that embodied carbon policies should be carefully rationalized and focused to avoid unintended consequences with minimal benefit to the climate. This concern is particularly important to building insulation materials. (See **Section 4.8**.)
- **Embodied GHG emissions associated with US building and construction materials have seen significant reductions in the US.** For example, the US iron and steel industrial sector has seen a 64% decrease in CO2e emissions from 1990 to 2020 due to restructuring, technology improvements, and increased scrap steel use (see **Section 3.2**). In addition, products such as foam plastic insulation materials have GHG embodied emissions that are as little as $1/100^{th}$ of the what it was in the 1970s and reduced by 75 to 90% (or more) in recent years by innovative advancements in low global warming potential (GWP) blowing agents (see **Section 4.7.4**). These improvements far surpass the recommended goal of a 30% reduction in GWP for building materials in US federal climate policy by the National Academies of Science, Engineering, and Medicine (see **Section 2.3.4**). Commonly used insulation materials in the US now have generally low GWP values of typically less than about 9 $kgCO2e/m^2$-RSI (see **Section 4.7.4**.)

Table A. Greenhouse Gas Emissions for World, US, US Economic Sectors, and US Building & Construction Materials (2020)[1]

Source	Gross GHG Emissions ($GtCO2e$)[2]	% of Total Global GHG Emissions (see Figure A)	% of Total US GHG Emissions	% of Total US Bldg & Const Mat'l Emissions
Global Total (~80% FFC)	59	100%		
US Total (~73% FFC)	6.0	10.1%	100%	
GHG Emissions by US Economic Sectors (EPA, 2022)				
Transportation	1.63	2.8%	27%	
Electric Power	1.48	2.5%	25%	
Industry[3]	1.43	2.4%	24%	
Buildings	0.79	1.3%	13%	
Agriculture	0.64	1.1%	11%	
GHG Emission by US Building & Construction Material Types (Embodied Emissions – Subset of Industry Emissions Reported Above)[3]				
Concrete	0.100	0.17%	1.7%	28%
Gypsum Board & Panels	0.080	0.14%	1.3%	22%
Steel (structural)	0.052	0.09%	0.9%	13%
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Building Insulations (all types)	0.006	0.01%	0.10%	1.7%
Flat Glass for Glazing	0.005	0.008%	0.08%	1.4%
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All Others (unquantified)	0.12	0.2%	2.0%	34%
TOTAL - all bldg.& const. mat'ls: TOTAL - bldg. mat'ls only:	0.36 0.24	0.61% 0.41%	6% 4%	100% 68%

% FFC = percentage of GHG emissions from fossil fuel combustion

TABLE NOTES:

1. Sources of data in TABLE A include IPCC (2022), EPA (2022), NASEM (2021), USCA (2021a), and DOE (2022) as reported and analyzed in this report including **Figure 11** of Part 2, **Figure 17**, and **TABLE 6** and **TABLE 7** of Part 3, and material data evaluated in several subsections of Part 4 from sources as indicated therein (in particular see **Section 4.7.4** for building and construction materials).
2. 1 GtCO2e = 1 billion metric tons of CO2e = 1 trillion kg of CO2e emissions (equivalent to CO2 emissions from the combustion of about 110 billion gallons of gasoline); data in table is based on gross emissions, excluding carbon sinks.
3. About 25% of industry emissions (1.43 GtCO2e) are associated with emissions that are attributed downstream to building and construction materials as embodied emissions (0.36 GtCO2e).

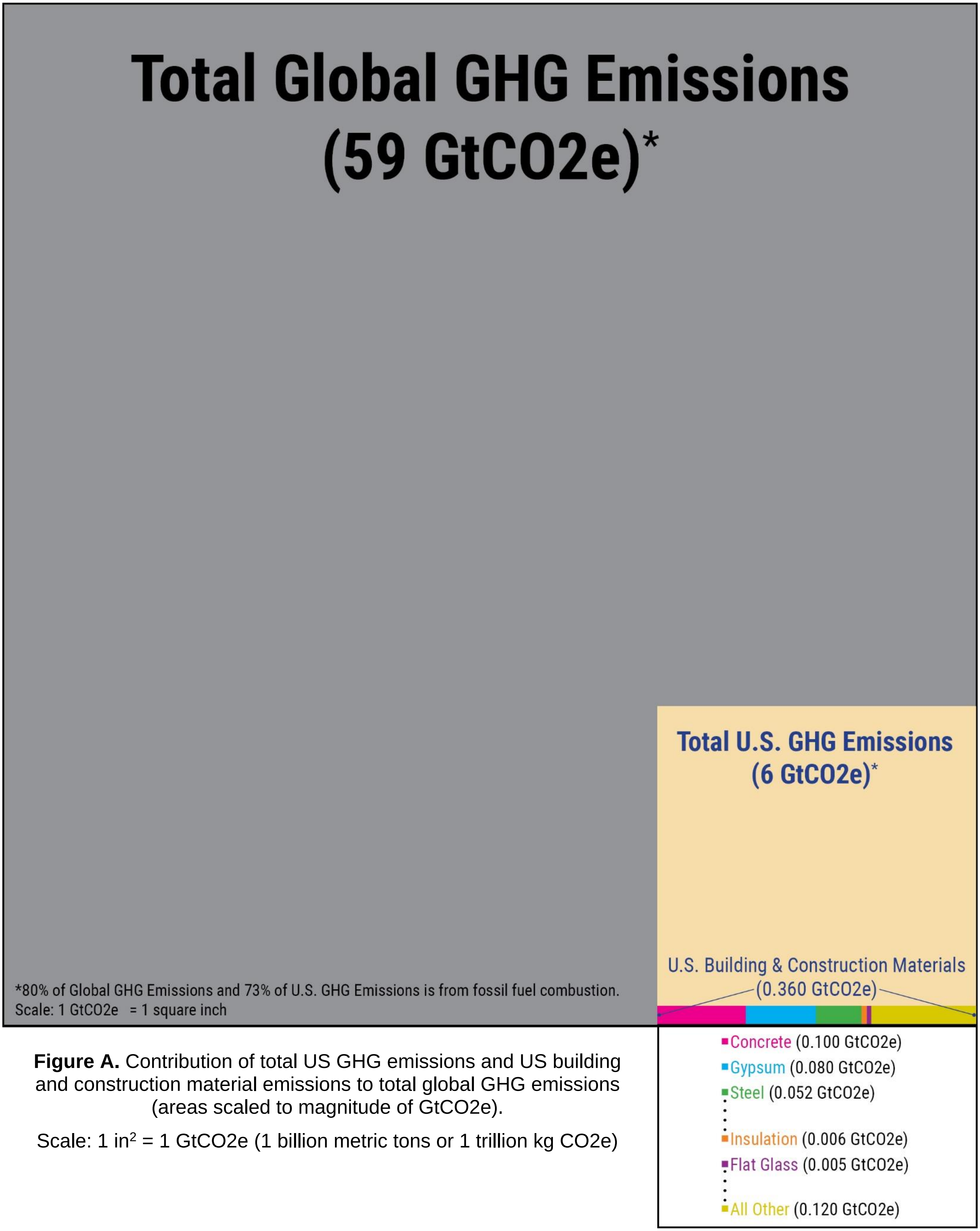

Figure A. Contribution of total US GHG emissions and US building and construction material emissions to total global GHG emissions (areas scaled to magnitude of GtCO2e).

Scale: 1 in^2 = 1 GtCO2e (1 billion metric tons or 1 trillion kg CO2e)

- **Insulation materials reduce “total carbon” emissions.** Building insulation materials save more operational carbon emissions through their use than is invested in their manufacturing as embodied carbon emissions. Insulation materials of all types commonly used in the US generally provide an embodied carbon payback within one year after initiation of building operation. Thus, the approximate 0.01% ($1/100^{th}$ of a percent) of total annual global GHG emissions attributed to US insulation product manufacturing in a given year (see **Table A**) is typically paid-back in the first year of use in new buildings. Furthermore, typical insulation material applications for US buildings yield life-cycle carbon savings ranging from 20x to 300x greater than the initial embodied carbon investment. (See **Section 4.8.1**.)
- **Insulation materials provide diverse functions and often under-recognized opportunities for building performance optimization, resource efficiency, resiliency, and affordability.** For materials like insulation that provide energy efficiency and are a key solution to the global warming problem, special care must be taken to avoid unintended consequences of controlling their use through narrowly focused material embodied carbon policies. These efforts often promote substitutions on the basis of the functional units and small differences in the magnitude of GWP, while inadvertently downplaying important end use considerations related to building operational emissions savings, energy demand reduction, and optimization of building assemblies through multi-functional insulation materials and methods of use that promote energy efficiency, durability, safety, resilience, resource efficiency, and cost-effectiveness of high-performance buildings. (See **Section 4.3**, **Section 4.4**, **Section 4.8.4**, and **Section 4.8.5**.)
- **The building material embodied carbon movement is strong and their message is urgent.** Many organizations and thought leaders claim building material embodied carbon emissions will be “100% of the problem” once building operational emissions become net zero in the future. Therefore, building material embodied emissions must be completely and urgently eliminated to avoid the most severe future climate consequences (see examples in **Section 4.2**). Consequently, over 40 federal, state, or local policies are now focused on embodied emissions of building and construction materials (see **Section 4.6**). While initially focused on higher carbon intensity materials (like concrete as shown in **Table A**.), some embodied carbon policies are beginning to address other materials like insulation that have more than an order of magnitude lower contribution to global GHG emissions (see **Table A**) and provide significant total carbon savings in use (see **Section 4.8.1** Evaluating Embodied + Operational Emissions is Crucial). Many non-government organizations have produced or are working on codes, standards, guides, and voluntary programs similarly aimed at minimizing or eliminating material embodied carbon emissions by 2050 and favoring use of bio-based or carbon-sequestering materials without necessarily considering important functional implications (see **Section 4.6**, **Section 4.8.4**, and **Section 4.8.5**).
- **The US building material industry in general, and the insulation industry in particular, lack a coordinated and proactive engagement in decarbonization policy-making processes and related developments.** The absence of effective engagement presents a risk of missed opportunities to guide rational policy solutions and avoid those that may be considered ineffective. The findings and recommendations of this report are intended to provide a foundation for informed and effective engagement in policy development. The policy development venues of interest may include federal, state, or local governments; voluntary programs administered by various non-government organizations; standards developers; and US model building or energy code developers.

A summary of the recommendations in this report is as follows:

A. **Build strong alliances with industry partners and rational thought-leaders.** Industry needs to effectively engage in policy development already in progress. While the goal of such advocacy should align with the reality of climate change and interest in mitigating its impacts, industry should aim to build a common vision and strategy to influence and support rational policies for the US building industry.

B. **Advocate for cost-benefit analyses and optimization of decarbonization policy.** Cost-benefit analyses incorporating the social cost of carbon should be routinely conducted to evaluate policy options and help optimize actions and priorities related to building operational and material embodied carbon emissions. Such analyses should be conducted with transparency and in a manner that bounds uncertainties (high and low extremes) in characterizing climate impact cost, climate policy cost, and climate policy effectiveness. In addition, the focus of such analyses and optimization should consider categories of operational emissions and material embodied emissions based on their magnitude and relevance to global GHG emissions and mitigating global climate change (see **Table A** and **Figure A**).

C. **Implement public policy and public/private investment that encourages the development and use of viable low-carbon energy sources across major sectors of the economy.** This action will have multiplying effects throughout the economy, including the reduction of building sector operational GHG emissions and embodied emissions associated with the manufacturing of building materials.

D. **Focus continued effort on energy efficiency regardless of energy source as a means to improve energy productivity and reduce energy demand and GHG emissions.** Energy efficiency of buildings – efficiently insulated building envelopes and efficient heating and cooling equipment – will reduce overall US energy demand. Energy demand reduction is needed to effectively enable decarbonization of buildings together with the electric power generation system that serves as a hub for decarbonization of other sectors such as industry and transportation. Therefore, energy efficiency has a broad and inter-related application across all US economic sectors.

E. **Structure embodied GHG emissions policies to promote and protect investment in building material decarbonization.** Building materials will tend to decarbonize as US energy sources decarbonize in tandem with efficient use of energy as core policy objectives addressed in recommendations C and D.[2] Therefore, policies specifically focused on influencing material embodied carbon emissions downstream from the actual emissions must be carefully considered as supplementary actions. Such policies should incentivize and protect the upstream investments made by industry to innovate and employ technology advancements that actually reduce material embodied emissions.

F. **Promote a "total carbon" optimization approach for the evaluation of building insulation materials and assemblies.** A total carbon approach would properly account for both embodied GHG emissions and operational GHG emissions savings such that optimal building assembly and system solutions can be intelligently considered. Unlike most other building materials, insulation materials are inextricably linked to their purpose of supporting building energy efficiency to reduce operational energy demand and associated emissions. Furthermore, essentially all modern US insulation materials provide substantially more carbon savings during use than emitted during their production. Therefore, single metric evaluations – like GWP used to evaluate only the embodied carbon of an assembly or product – are especially inappropriate as a means for insulation material selection decisions or policies. This concern is particularly true for insulation products that have multifunctional capabilities important to the overall optimization of building envelope assembly construction and performance. Also, different insulation applications that impact functional performance characteristics of actual building assemblies in end use are not adequately represented by the functional units used to quantify GWP. These factors can be properly addressed only by use of a total carbon approach in combination with functional performance optimization of overall building assemblies.

Additional specific recommendations include the following:

1. **Request that the US EPA or others investigate a means to provide a break-down of building material emissions that are attributed to building and construction materials.** Currently, there are significant gaps in knowledge of the global GHG contribution of various US building materials. Such information is needed to provide a rational ranking and prioritization to guide the focus of public policy and private-sector efforts to achieve the largest potential climate benefit with the least effort, cost, and

[2] For non-energy-related GHG emissions associated with materials or their manufacturing processes, specific policies should be considered on a case-by-case basis and recognize non-energy-related uses of fossil fuels (for feedstock, not combustion) as necessary for many valuable US products and not a significant contributor to global warming. The CO2e emissions from non-energy use of fuels (e.g., feedstock for manufacturing) is less than 3% of the total emissions from fossil fuel combustion for energy based on EPA data (see **Figure 16** in Section 3.2 of this report).

uncertain return on mitigation investment. (See **Table A** and **Figure A**, which attempt to provide this information for a limited portion of US building and construction materials.)

2. **Update the Product Category Rule (PCR) for building thermal envelope insulation to include an accounting of the operational GHG emissions savings (avoidance) that occur as a result of insulation material use in building thermal envelopes.** Such rules should specifically mention and permit quantification of operational carbon savings (or avoidance) and payback period (i.e., the time required during use to offset the upfront embodied carbon of the insulation material). The PCR should provide necessary assumptions for such calculations. It should also recognize a simplified method of analysis of operational carbon emissions savings for indexing purposes. Sophisticated whole-building energy models and characteristic building population datasets should not be necessary to reasonably index the carbon avoidance and payback time for common uses of building insulation materials.

3. **Create a voluntary "carbon smart" material certification program (or standard) customized for insulation materials that rewards or incentivizes market use.** This program would consider: (1) Environmental Product Data (EPD) showing a history of reduced or optimized carbon footprint over time, (2) the ability to achieve tiered ranges of carbon emission payback time or carbon emission avoidance ratio based on representative building or building assembly end-use conditions by climate zone or national average, or (3) both. This opportunity also relates to the recommendations included in item 2 above and item 4 below, but is not dependent on them.

4. **Develop a simplified "total carbon" analysis tool for whole buildings or specific building assemblies for evaluation of insulation strategies.** The tool should be focused on assessing insulation materials as used in complete building assemblies. The tool should include a simplified means to assess energy use and operational carbon emission savings and be able to quickly assess different combinations of assembly materials in a fast and transparent manner to facilitate design optimization (e.g, resource efficient assemblies, optimized use of multifunctional insulation and building materials, etc.). Output metrics should include a combination of checks (those for code compliance and those related to total energy use and carbon emissions), as well as a carbon emissions payback period and avoidance ratio for a specified baseline building condition and climate zone. This tool could be used to support policy positions, market education (see item 5 below), and other efforts (see items 2 and 3 above).

5. **Develop case studies to demonstrate the use of foam plastic insulation materials to optimize "total carbon" and overall performance of code-compliant building assemblies.** For example, foam plastic continuous insulation on foundations can significantly reduce concrete volume and carbon emissions for foundation construction in cold climates with significantly reduced first cost. For above grade walls, multi-functional foam plastic continuous insulation can be used to economize wall assemblies while eliminating the need for other materials such as vapor retarders and water-resistive barriers. Case studies can reveal these opportunities in a way that can be readily understood by the building industry and design practitioners, as well as policy developers. The tool described in item 4 above would provide the means to generate various case studies.

6. **Advocate for a rational and risk-consistent value for the social cost of carbon.** The social cost of carbon should be included as a requirement in various cost-benefit policy instruments and regulations at the federal and state levels, including adopted building energy codes and standards. Where such cost-benefit analyses use a rational and climate-risk-consistent value for social cost of carbon, they should be deemed to be compliant with US federal, state, and local climate policy objectives and goals that, generally, are not similarly cost-benefit justified in a manner consistent with the economic impacts of future climate change and the cost to mitigate.

7. **Implement a "total carbon" approach for US model energy codes and standards.** Operational GHG emissions costs (not just market-priced operational energy cost) should be included in the currently required cost-benefit analysis methods to address their omission of "hidden costs" of GHG emissions from fossil energy sources. This can be achieved by use of a rational science-based value for the social cost of carbon (see item 6 above). The total carbon approach would help guide and

advance energy codes in an objective and cost-effective manner to promote energy efficiency and meet climate goals. It will also help to avoid the potential harms or unintended consequences to energy efficiency and building performance that an embodied carbon insulation material selection approach might otherwise cause, particularly as US buildings and operational energy sources become increasingly decarbonized.

8. **Include event-based triggers in existing buildings policies for energy efficiency and decarbonization improvements.** Existing buildings remain the largest and most challenging problem for decarbonization of buildings in the US. Current building performance standard (BPS) approaches tend to use a fixed timeline for meeting their targets. This tends to result in untimely and costly building upgrades that can be a strong deterrent to achieving existing building improvements. BPS policies should be coupled with specific maintenance and renovation events that provide an opportunity for energy efficiency and decarbonization improvements at a time when they are most cost effective to execute. Such an approach for building alterations is currently an approved change for the pending 2024 edition of the International Energy Conservation Code (IECC).
9. **Provide guidance documents that properly caution against making EPD comparisons of insulation materials solely based on a material's functional unit.** Different insulation materials have different compressive strength capabilities, moisture resistance properties, moisture management capabilities, fire performance characteristics, and functional applications that can even affect structural material usage. Such considerations in decarbonization policies and voluntary programs addressing embodied carbon appear to be significantly lacking. There is an apparent lack of understanding of these factors associated with the appropriate, effective, or optimal use of modern insulation products in the integrated design of various building assemblies and applications.
10. **Encourage the demonstration of ongoing improvement through EPD GHG emissions reporting to reward investment in embodied GHG emissions reductions, irrespective of how a given product might compare with others of similar kind or function.** This approach promotes investment by individual US manufacturers to reduce manufacturing emissions attributed to materials as embodied emissions. Current policy approaches that arbitrarily benchmark and periodically shift material GWP limits in the downstream market, deselect materials that exceed those shifting limits, and perhaps eventually exclude materials with any amount of attributed carbon emission (despite the manufacturers having made significant and beneficial carbon emission reduction investments) should be avoided or used very judiciously. The goal should be to incentivize and protect investment in decarbonization, not discourage or penalize it. One concept is presented in item 11 below.
11. **Prevent "carbon infiltration" of imported materials from undermining US manufacturer investment in decarbonization.** Setting a GWP "cap" for US insulation materials in a way that does not exclude US manufacturers will serve to protect past and future investment in decarbonization rather than penalizing US material choices that have different performance and functional attributes.

Introduction

Decarbonization involves a broad range of practices and policies that aim to reduce anthropogenic (i.e., human activity generated) greenhouse gas (GHG) emissions which, once mixed in the earth's atmosphere, force global temperature rise leading to a myriad of impacts to the environment and human welfare.

The policy drivers for decarbonization include establishing global, national, and local climate goals that aim to limit global temperature rise and expected climate impacts to a tolerable level. These goals then lead to specific policies intended to achieve those goals. These policies and associated implementation strategies are necessarily related to the production and use of energy (e.g., combustion of fossil fuels) and other sources of GHG emissions (e.g., methane gas, refrigerants, etc.). Ultimately, goals, policies, and implementation strategies aim to reduce or eliminate the emission of GHGs, particularly carbon dioxide (CO2) from the combustion of fossil fuels, which is the dominant source of GHG emissions. GHG emissions occur in all economic sectors including transportation, industry, agriculture, buildings, and construction.

This paper focuses on buildings and the GHG emissions associated with operational energy use (e.g., electricity or gas for heating, cooling, appliances, lighting, etc.) and also the materials used to construct buildings (e.g., wood, steel, concrete, aluminum, gypsum panels, glass, insulation, etc.). These building materials and products represent GHG emissions that primarily occur upfront, prior to completion and use of a building. The GHG emissions associated with materials are considered "embodied" emissions. These embodied emissions are associated with the life cycle impacts of the material or product spanning raw material extraction, transport, manufacturing, distribution, installation on a building, maintenance, and final end-of-life treatment. In general, embodied emissions are dominated by manufacturing process energy use (e.g., combustion of fossil fuels for processes requiring heat). Other manufacturing process or material-related emissions contribute to varying degrees. In this paper, where possible, industry sector and specifically building material and product data related to GHG emissions are connected to their contributions to total global GHG emissions. This approach ensures that their actual impact to climate goals is more clearly and rationally identified and understood. It also is intended to help guide decision-making for private sector and public policy actions related to building decarbonization as a means to address climate change.

To provide the necessary context and data:

- Part 1 reviews the status of the global climate on a scientific basis.
- Part 2 reviews various global climate policies and model plans or strategies intending to achieve specified goals related to mitigating climate change.
- Part 3 assesses relevant energy use and GHG emissions data for the United States (US) at a broad scale and also for the US economic subsectors, including industry which produces various goods supporting the US economy and welfare such as materials used in the building sector.
- Part 4 addresses various inter-related building decarbonization topics, including the relevance of US building material embodied GHG emissions to global climate change. It also highlights the importance of considering building energy efficiency and operational emissions, especially for materials like insulation that will deliver net GHG emission reduction benefits for years to come.

The paper concludes with a summary of findings, conclusions, and recommendations regarding policy, technical needs, and opportunities or challenges associated with the building decarbonization landscape in the US.

PART 1: Climate Science

1.1 Global Climate Change Science

According to EPA (2022):

> "Greenhouse gases absorb infrared radiation, thereby trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by humans include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2020, concentrations of these greenhouse gases have increased globally by 47.9, 168.4, and 23.3 percent, respectively (IPCC 2013; NOAA/ESRL 2022a, 2022b, 2022c)."

Further,

> For over the past 200 years, the burning of fossil fuels such as coal and oil, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (IPCC 2021). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.
>
> Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2021). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect and a negative number represents a cooling effect (IPCC 2021). IPCC concluded in its most recent scientific assessment report that it is "unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC 2021).
>
> As concentrations of greenhouse gases continue to increase from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 2.0 degrees Fahrenheit from the 1850 to 1900 period to the decade of 2011 to 2020 (IPCC 2021). The last four decades have each been the warmest decade successively at the Earth's surface since at least 1850 (IPCC 2021). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase by up to 8.3 degrees Fahrenheit above 2011 to 2020 levels by the end of this century, depending on future emissions and the responsiveness of the climate system (IPCC 2021), though the lowest emission scenario would limit future warming to an additional 0.5 degrees (best estimate).
>
> For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC, the U.S. Global Change Research Program (USGCRP), and the National Academies of Sciences, Engineering, and Medicine (NAS).

Climate change is a global issue. The global warming potential (GWP)[3,4] of anthropogenic GHG emission contributions of any one region or country, no matter how big or small, become “mixed” together in the earth’s atmosphere. The net effect of these GHG contributions, mainly carbon dioxide (CO_2) emissions from fossil fuel combustion , are most clearly represented by the increasing trend in the global atmospheric concentration of CO_2 since the 1960s (Figure 1). Similar increasing trends for CH_4 (methane) and N_2O (nitrous oxide) are also reported by IPCC (2021). The global climate response to these anthropogenic GHG emissions is most clearly represented by global annual average surface air temperature warming trend of Figure 2. Similar trends are also observed for ocean surface water temperatures, especially in the past several decades.[5] According to IPCC (2021), the earth’s global annual average surface temperature has already risen about 1.1^{o}C (2.0^{o}F), mainly occurring over the past 60 years. The following high-level observations are made in the IPCC (2021) report:

> “Human influence on the climate system is now an established fact … It is unequivocal that the increase of CO_2, methane (CH_4) and nitrous oxide (N_2O) in the atmosphere over the industrial era is the result of human activities and that human influence is the main driver of many changes observed across the atmosphere, ocean, cryosphere and biosphere.” (p.41)

> “…over the past several decades, key indicators of the climate system are increasingly at levels unseen in centuries to millennia and are changing at rates unprecedented in at least the last 2000 years.” (p.41)

> “Since 2012, strong warming has been observed, with the past five years (2016–2020) being the hottest five year period in the instrumental record since at least 1850 (high confidence)” (p.41)

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[3] According to EPA (2022): “The IPCC developed the global warming potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas. The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2013); therefore, GWP-weighted emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).” The GWP of various GHGs used in EPA (2022) are based on a 100-year time horizon in terms of effect on the “forcing” of climate warming and are as follows: CO_2 – 1, CH_4 – 25, N20 – 298, and various HFCs, PFCs, and other GHGs are assigned GWP values of up to 12,200 or more relative to CO_2.

[4] According to IPCC (2022): “A wide range of GHG emission metrics has been published in the scientific literature, which differ in terms of: (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, to emissions sustained over a period of time, or to a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission, or compared to a reference emissions level or climate state… Parties to the Paris Agreement decided to report aggregated emissions and removals (expressed as CO_2-eq) based on the Global Warming Potential (GWP) with a time horizon of 100 years (GWP100) using values from IPCC AR5 or from a subsequent IPCC report as agreed upon by the CMA, and to account for future Nationally Determined Contributions (NDCs) in accordance with this approach. Parties may also report supplemental information on aggregate emissions and removals, expressed as CO_2-eq, using other GHG emission metrics assessed by the IPCC… All metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. For this reason, the WGIII contribution to the AR6 reports emissions and mitigation options for individual gases where possible; CO_2-equivalent emissions are reported in addition to individual gas emissions where this is judged to be policy-relevant. This approach aims to reduce the ambiguity regarding actual climate outcomes over time arising from the use of any specific GHG emission metric.”

[5] https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature, last accessed 11/5/2023

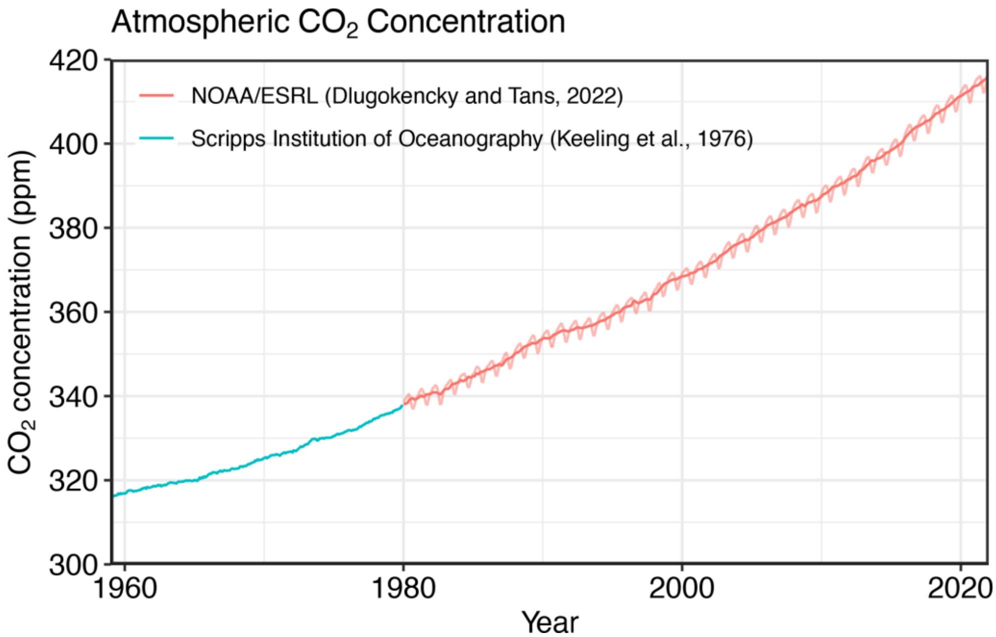

Figure 1. Change in atmospheric CO2 concentration since 1960.
1 ppm CO2 concentration = 2.124 GtC in atmosphere
Source: Friedlingstein et al., 2022

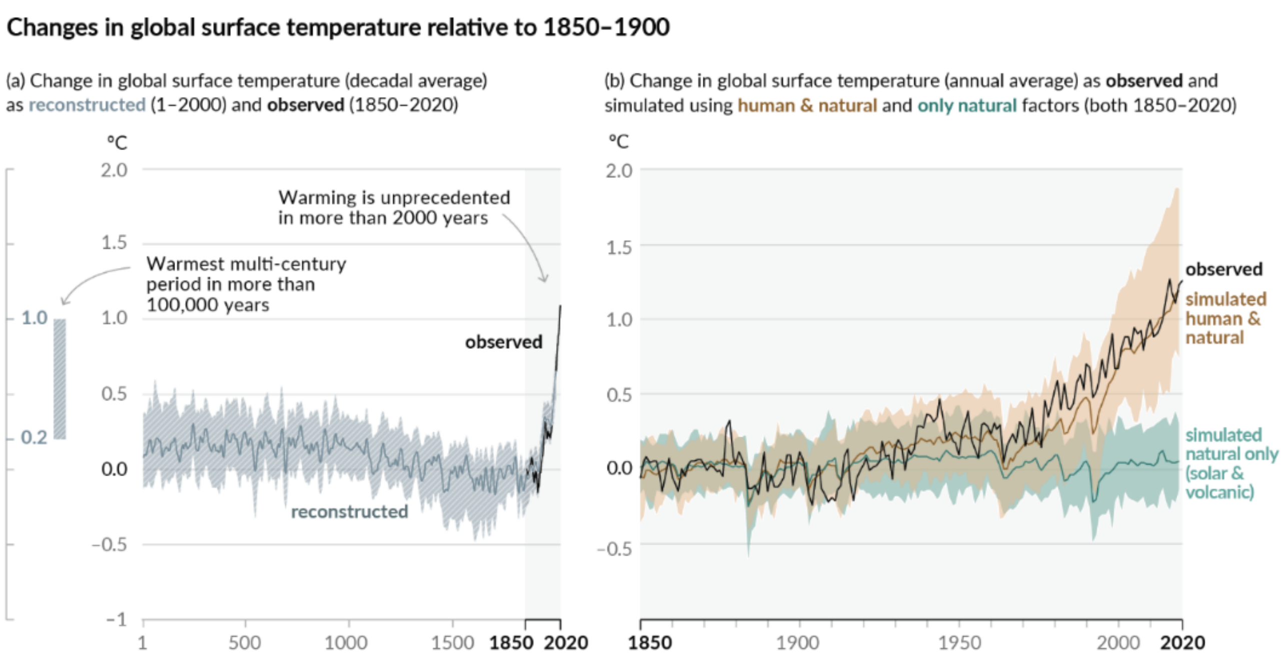

Figure 2. Changes in global surface temperature relative to 1850-1900.[6]
Source: IPCC, 2021

[6] Figure SPM.1 in IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY,USA, pp. 3−32, doi: 10.1017/9781009157896.001

As shown in Figure 3, the data clearly point to anthropogenic carbon emissions as the primary cause or driver of recent climate change. Based on data reported by Friedlingstein, et al. (2022), fossil fuel CO2 emissions from human activity account for 70% and land-use changes account for 30% of total anthropogenic emissions from 1850 to 2021. The cumulative fossil fuel CO2 emissions since 1850 are estimated to be 465 +/- 25 GtC [1,705 GtCO2][7] with the following attribution by fossil fuel type: 46% coal, 35% oil, and 15% natural gas. Over the same 1850-2021 (172-year) period, the top three contributors based on cumulative emissions account for most of the world's GWP contributions:

1. United States of America (USA) =	115 GtC	(24% of world total)
2. European Union (EU) =	80 GtC	(17 % of world total)
3. China =	70 GtC	(14% of world total)
Total:	265 GtC	(57% of world total)

Also shown in Figure 3, the annual (left graph) and cumulative (right graph) impacts of increasing fossil emissions and net land use emissions have resulted in a release of the massive amounts of carbon sequestered in fossil reserves into the earth's available carbon "sinks," which are its oceans, lands, and atmosphere. (See the "global carbon cycle" graphic on the inside cover page.) This effect on the earth's carbon cycle aligns with and helps to explain the atmospheric CO2 concentration increase shown in Figure 1.

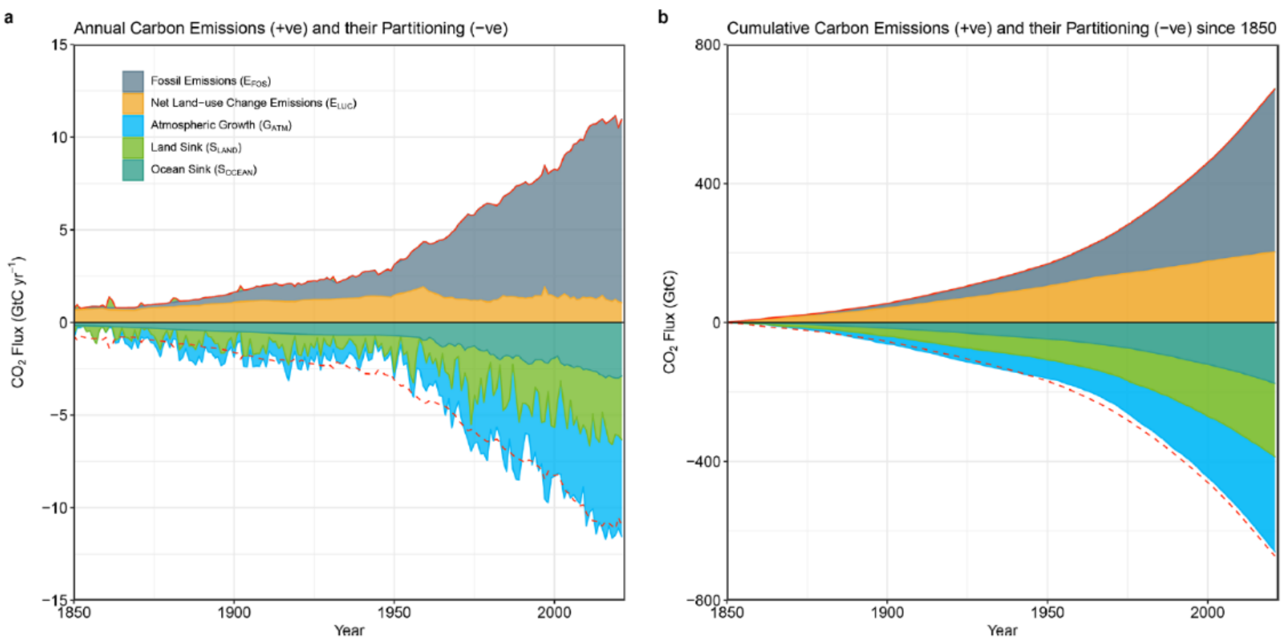

Figure 3. Annual and cumulative carbon emissions and their partitioning since 1850.
Source: Friedlingstein et al., 2022, Earth System Science Data, "Global Carbon Budget 2022"

[7] **1,705 GtCO2 = 1,705,000,000,000 (1.7 trillion) metric tons of carbon dioxide = 1,705,000,000,000,000 (1.7 zillion) kilograms of carbon dioxide = 3,760,000,000,000,000 (3.8 zillion) lbs of CO2.** The magnitude and significance of this amount of carbon dioxide gas emissions from fossil fuel use is hard for the average person to fathom. This huge mass of CO2 gas at atmospheric pressure has a volume of (1.705 x 1015 kgCO2 / 1.98 kg/m^3) x (1 km / 1000m)3 = 861,000 km3 (207,000 mi^3). This volume of cumulative CO2 emissions is equivalent to covering the entire surface area of the earth with CO2 gas at a thickness of (861,000 km^3 / 5.10x108 km^2) x (1000 m / 1 km) = 1.7 m (5.5 ft) deep with CO2 gas. More important than the cumulative quantity of CO2 emissions is the manner in which the earth's climate responds to it as shown in Figures 2 and 3. This response causes a variety of global warming impacts discussed later.

For 2021, the total global fossil fuel CO_2 emissions (excluding other GHG emissions) are estimated at 9.9 +/- 0.5 GtC/yr [36.3 $GtCO_2$/yr][8] which is about 2.1 percent of total cumulative CO_2 emissions since 1850. The 2021 emissions are attributed proportionately to the following fossil fuel types: 41% coal, 32% oil, and 22% natural gas (Friedlingstein et al., 2022). Except for the trend of greater use of natural gas relative to coal and oil, the global mix of fossil fuel usage in 2021 appears little different than it has been on average for the past 172 years.

Since 1960 the land-use change component dropped to 18% and in the last 10-years its percentage dropped further to 11% such that an estimated 89% of anthropogenic carbon emissions in 2021 were due to fossil fuel emissions. The good news is that average growth in global fossil CO_2 emissions peaked in the 2000s, driven by rapid growth in emissions in China. In the past decade, the global emissions growth rate has declined to a low of 0.5% per year, including the effects of COVID 19 in 2020 and the emissions rebound in 2021.

In 2021, the top four national contributors accounted for 59% of the total 36.3 $GtCO_2$ global emissions as follows (Friedlingstein et al., 2022):

1. China = 31%
2. USA = 14%
3. EU27 = 8%
4. India = 7%

Trends in the global carbon emission rate and the emission rates attributed to each of these top four contributors are shown in Figure 4. China's annual emissions over the past two decades have significantly increased while US and EU27 emissions have struck a downward trend, somewhat offsetting China's increased contribution. Also, India continues to show an increasing trend in annual carbon emissions. Note that while China's absolute emissions rate has increased well above that of the US (Figure 4(b)), the per capita emissions are still about half as much as those of the US population (Figure 4(d)).

[8] **36.3 $GtCO_2$/yr = 36,300,000,000 (36.3 billion) metric tons of carbon dioxide emissions per year = 36,300,000,000,000 (36.3 trillion) kilograms of CO_2 emissions per year = 80,000,000,000,000 (80 trillion) lbs of CO_2 emissions per year.** This annual rate of global CO_2 emissions is hard for the average person to fathom. With a world population of about 7.9 billion in 2021, this equates to an annual per capita fossil fuel emission rate of about 4,600 kg CO_2/yr/person (10,100 lbs CO_2/yr/person) or about 1.25 tC (4.6 metric tons CO_2) emissions/person/yr as confirmed in Figure 4. The US annual per capita carbon emissions is more than 3 times greater than the world average. This amount of fossil fuel emissions is equivalent to each person of the world of all ages using 530 gallons of gasoline per year (or about 1,700 gallons/person/yr in the US). This represents the net effect of all of the embodied CO_2 fossil emissions in the making and delivering of purchased goods to the point of consumption (e.g., food, building materials, equipment, clothing, tools, smart phones, computers, cars, toys, etc.) and the direct consumption of energy to heat and cool homes and businesses, cook food, pump and heat water, mow the lawn, commute to work, and travel. One gallon of gasoline weighs about 6.3 lbs and contains about 5.3 lbs of Carbon atoms (12 molecular weight) which when combusted is combined with two atoms of oxygen (16 molecular weight) such that the total weight of CO_2 emissions is about 3.6 times heavier (44/12) than the original gallon of gasoline due to oxidation during combustion. Granted, the types of energy used for various human activities do not all come from gasoline (a derivative of fossil oil), but gasoline provides a useful point of reference because it is routinely purchased and used by consumers for transportation.

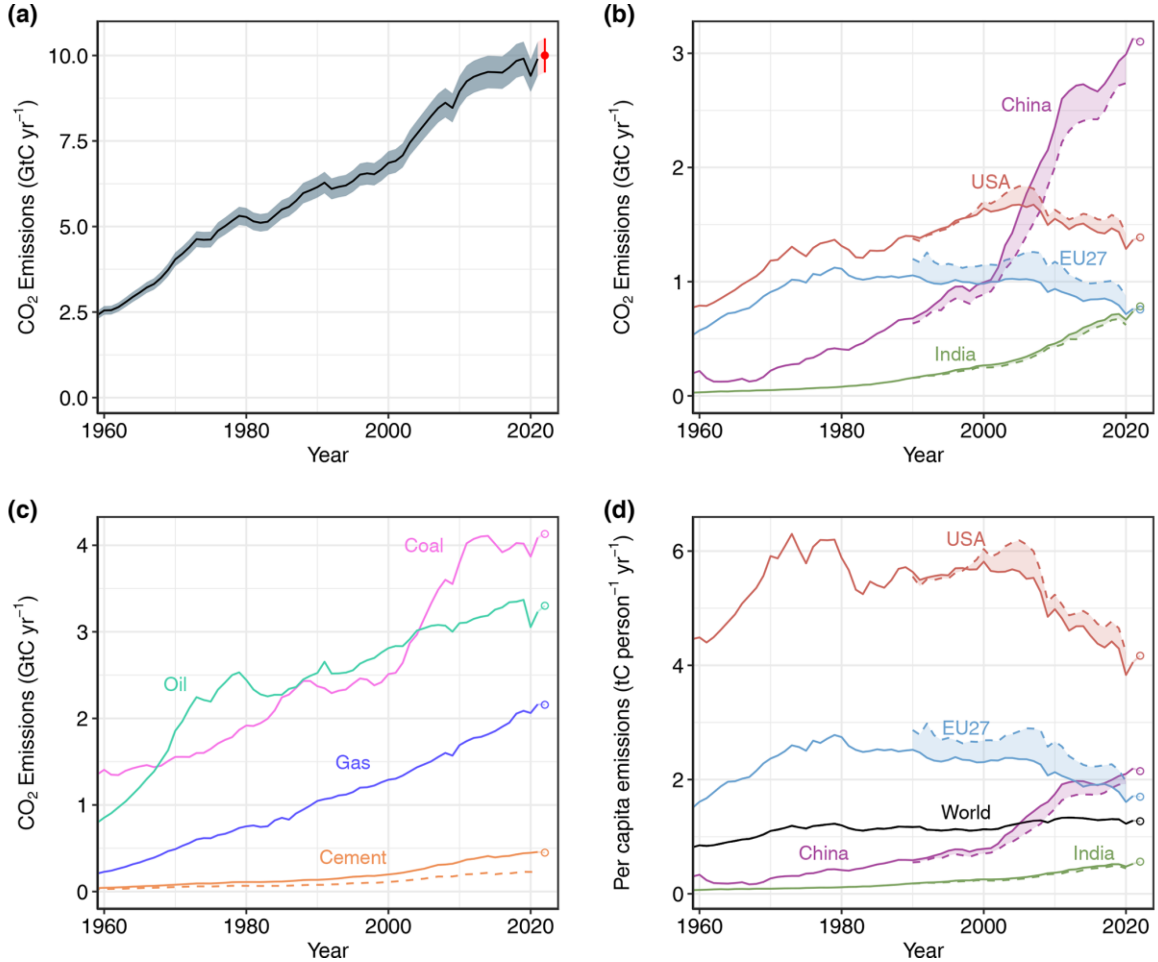

Figure 4. Carbon emissions showing (a) global total annual rate, (b) contribution by top four countries, (c) contribution by fossil fuel type (including also cement) and (d) contribution by the top four countries on a per capita basis.

Source: Friedlingstein et al., 2022, Earth System Science Data, “Global Carbon Budget 2022”

At this point, it may be important to note that these massive fossil CO2 emissions are not simply the “waste” material of human existence. They are largely associated with the production and use of goods and services that deliver many benefits to humanity including food, housing, work, mobility, productivity, protection, recreation, technological advancement, medical technologies and services, among many other things that provide for public welfare. However, the use of energy and its associated emissions also are associated with impacts that are harmful to humanity including things such as war, pollution, and climate change impacts to weather, agricultural productivity, sea level rise, and other factors potentially affecting certain regions or peoples more or less than others.

Perhaps the greatest opportunity to address concern with climate change is to increase energy productivity (e.g., become more efficient at using fossil energy while transitioning to cleaner energy sources – both of which can significantly reduce CO2 emissions). However, the policy challenge lies in guiding a transition process in a way that maximizes benefits of avoided climate change impacts while minimizing the harms of increased cost of goods and services which tend to most affect those who are among the poorest and most vulnerable of the world’s or a nation’s population. Therefore, the efficient and responsible use of energy and the means of funding a transition to cleaner energy sources involves fundamental humanitarian concerns related to public welfare and equity.

1.2 Remaining Carbon Emissions Budget to Limit Global Warming

Based on the analysis of Friedlingstein, et al. (2022), the remaining global carbon emissions budget allowance starting in 2023 to limit global warming (with 50% likelihood) to 1.5, 1.7, and 2°C is estimated to be about 105, 200, and 335 GtC (380, 730, and 1290 $GtCO_2$)[9], respectively. Furthermore, these remaining carbon emission budget allowances correspond respectively to an estimated 9, 18, and 30 years from the beginning of 2023 assuming the current global CO_2 emission rates persist. These estimates are updates to and remain consistent with the prior IPCC (2021) report that concluded:

> "…combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, … assuming no major volcanic eruption." (p.42)

The above estimates strongly indicate that the time remaining to reach a 1.5°C global warming temperature rise limit is short and will likely occur within the next decade in the absence of drastic, immediate, and multilateral global reductions in carbon emissions (unless a major volcanic eruption occurs and releases aerosols into the atmosphere that reflect sunlight and, for a period of time, may offset the effect of GHGs). Consequently, it is understandable that the perceived urgency of concern with global warming and need for rapid world-wide decarbonization has escalated to a very high level. But, it also raises big questions: Where did the 1.5°C limit come from? How was it established? What happens if global warming proceeds to 2°C temperature rise (or more) instead of 1.5°C? What are the differences in future consequences and benefits for any given policy target or actual path forward into our uncertain future climate and world?

1.3 Assessment of Global Warming Impacts

The answer to the important questions raised at the end of the previous section requires an understanding of an aspect of climate science that goes beyond just an empirical understanding of what has happened in the past. It enters into the realm of predicting or modeling the climatic and geophysical future of the earth system and includes the following components:

- Estimating potential future climate impacts at regional and global levels attributed to various types of climate impact drivers such as:
  - Regional water cycle (drying or wetting trends), atmospheric CO_2 concentrations that fertilize biomass growth, and temperature change climate impact drivers causing a climate impact to agricultural crop yields for either a net loss or gain in productivity by region;
  - Regional weather and temperature change variations causing more intense and longer duration heat waves together with air pollutants causing a net impact on all-cause temperature-related mortality considering also the counteracting effect of warming in colder climates;
  - Future sea level rise driving increased frequency and magnitude of damages from coastal flooding (and mitigation cost for coastal communities to adapt);
  - Regionally varied water cycle changes driving increased rainfall amounts and intensity in some regions resulting in increased frequency and magnitude of inland flooding while other regions experience the opposite outcome; and,
  - Increased frequency and intensity of extreme weather events like cyclones resulting in incremental changes to future damage or mitigation cost to adapt.
- Monetizing the above estimated future climate impacts (positive and negative) as a means to aggregate the diverse future climate impacts on human and ecological welfare into a single metric (dollars), and
- Discounting those future monetized impacts back to a present-day dollar value.

[9] The prior carbon budget estimate of the IPCC (2021, p95 and p98) starting from January 1, 2020 was 500 $GtCO_2$, 850 $GtCO_2$, and 1350 $GtCO_2$ for 1.5°C, 1.7°C, and 2.0°C limits to global warming, respectively, based on the 50th percentile estimate of the transient climate response to cumulative CO_2 emissions (TCRE) of 1.65°C (1.0 – 2.3°C) per 1000 GtC or 0.45°C (0.27 – 0.63°C) per 1000 $GtCO_2$.

To begin, it is important to consider the nature, magnitude, and uncertainty of various climate impact drivers associated with global warming or climate change in general. These drive the future climate impacts that ultimately affect potential future changes to human and ecological welfare. The IPCC (2021) report makes the following high-level observations regarding some key climate impact drivers:

> "Evidence of observed changes and attribution to human influence has strengthened for several types of extremes since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including fire weather)." (p.42)
>
> "The AR6 further projects with high confidence an increase in the variability of the water cycle in most regions of the world and under all emissions scenarios." (p.42)
>
> "The frequency of extreme temperature and precipitation events in the current climate will change with warming, with warm extremes becoming more frequent (virtually certain), cold extremes becoming less frequent (extremely likely) and precipitation extremes becoming more frequent in most locations (very likely)." (p. 66)

The IPCC (2021) report continues with more specific observations and predictions with varying degrees of certainty:

> TROPICAL CYCLONES: "It is likely that the proportion of major (Category 3–5) tropical cyclones (TCs) and the frequency of rapid TC intensification events have increased over the past four decades…There is high confidence that average peak TC wind speeds and the proportion of Category 4–5 TCs will increase with warming and that peak winds of the most intense TCs will increase." (p. 71)
>
> OCEANS: "Over the past four to six decades, it is virtually certain that the global ocean has warmed, with human influence extremely likely the main driver since the 1970s, making climate change irreversible over centuries to millennia (medium confidence)… The amount of ocean warming observed since 1971 will likely at least double by 2100 under a low warming scenario (SSP1-2.6) and will increase by 4–8 times under a high warming scenario (SSP5-8.5). Stratification (virtually certain), acidification (virtually certain), deoxygenation (high confidence) and marine heatwave frequency (high confidence) will continue to increase in the 21st century." (p. 74)
>
> SEA LEVEL RISE: "Global mean sea level (GMSL) increased by 0.20 [0.15 to 0.25] m over the period 1901 to 2018, with a rate of rise that has accelerated since the 1960s to 3.7 [3.2 to 4.2] mm yr^{-1} for the period 2006–2018 (high confidence)… By 2100, GMSL is projected to rise by 0.28– 0.55 m (likely range) under SSP1-1.9 and 0.63–1.01 m (likely range) under SSP5-8.5 relative to the 1995–2014 average (medium confidence). Under the higher CO_2 emissions scenarios, there is deep uncertainty in sea level projections for 2100 and beyond associated with the ice-sheet responses to warming. In a low-likelihood, high-impact storyline and a high CO_2 emissions scenario, ice-sheet processes characterized by deep uncertainty could drive GMSL rise up to about 5 m by 2150. Given the long-term commitment, uncertainty in the timing of reaching different GMSL rise levels is an important consideration for adaptation planning." (p. 77)
>
> LAND CLIMATE & BIOSPHERE & EXTREMES: "Land surface air temperatures have risen faster than the global surface temperature since the 1850s, and it is virtually certain that this differential warming will persist into the future. It is virtually certain that the frequency and intensity of hot extremes and the intensity and duration of heatwaves have increased since 1950 and will further increase in the future even if global warming is stabilized at 1.5°C. The frequency and intensity of heavy precipitation events have increased over a majority of those land regions with good observational coverage (high confidence) and will extremely likely increase over most land regions with additional global warming.
>
> Over the past half century, key aspects of the biosphere have changed in ways that are consistent with large-scale warming: climate zones have shifted poleward, and the growing season length in the Northern Hemisphere extra-tropics has increased (high confidence). The amplitude of the seasonal cycle of atmospheric CO_2 poleward of 45°N has increased since the 1960s (very high confidence), with increasing productivity of the land biosphere due to the increasing atmospheric CO_2 concentration as the main driver (medium confidence). Global-scale vegetation greenness has increased since the 1980s (high confidence)." (p.82)

WATER CYCLE: "Human-caused climate change has driven detectable changes in the global water cycle since the mid-20th century (high confidence), and it is projected to cause substantial further changes at both global and regional scales (high confidence).

Global land precipitation has likely increased since 1950, with a faster increase since the 1980s (medium confidence). Atmospheric water vapour has increased throughout the troposphere since at least the 1980s (likely). Annual global land precipitation will increase over the 21st century as global surface temperature increases (high confidence). Human influence has been detected in amplified surface salinity and precipitation minus evaporation (P–E) patterns over the ocean (high confidence).

The severity of very wet and very dry events increase in a warming climate (high confidence), but changes in atmospheric circulation patterns affect where and how often these extremes occur. Water cycle variability and related extremes are projected to increase faster than mean changes in most regions of the world and under all emissions scenarios (high confidence).

Over the 21st century, the total land area subject to drought will increase and droughts will become more frequent and severe (high confidence). Near-term projected changes in precipitation are uncertain mainly because of internal variability, model uncertainty and uncertainty in forcings from natural and anthropogenic aerosols (medium confidence).

Over the 21st century and beyond, abrupt human-caused changes to the water cycle cannot be excluded (medium confidence)." (p.85)

Applying the above described climate impact drivers to quantitatively assess regionally varying and uncertain future incremental climate impacts and then to monetize those net impacts (or benefits) is a complex process that requires multiple disciplines and lines of evidence. This process is explained in the next section on the social cost of carbon.

1.4 The Social Cost of Carbon Emissions

"The social cost of carbon is the single most important number for thinking about climate change."
Marshall Burk, Assoc. Professor of Earth System Science, Stanford University[10]

The Stanford University article quoted above provides a brief and clear explanation of the social cost of carbon and its application to public policy and private-sector decision making. The potential net economic benefit of avoiding future climate change impacts in comparison to the cost of any particular mitigation policy action may be understood by considering the process of estimating the social cost of carbon (SC-CO2) which represents the cumulative effect and present dollar value (cost) of expected future climate impacts. For a broader and more in-depth review of the social cost of greenhouse gas (SC-GHG) emissions, refer to The Social Cost of Greenhouse Gases (USCA, 2022b).

The future climate impacts of CO2 emissions from fossil fuel use are not reflected in current market pricing for these fuels as commonly used to evaluate the cost-benefits of energy efficiency or conservation measures. Therefore, SC-CO2 provides a means to account for the real but "hidden cost" of using fossil energy (NAP, 2010) in terms of CO2 emission impacts to the climate so that the true cost of fossil energy is properly valued when assessing cost-benefits of various climate policy options to reduce CO2 emissions, including those related to energy efficiency or conservation.

For example, if the market price of gasoline is $3.50/gallon and the SC-CO2 is $200/tCO2 (or about $0.10/lbCO2) and given that the combustion of a single gallon of gasoline in an internal combustion engine (ICE) vehicle results in about 20 lbs of CO2 emission from exhaust, then the actual climate risk-consistent cost of the gallon of gasoline should be $3.50/gallon + (20 lbs CO2/gallon) ($0.10/lb) = $3.50/gallon + $2.00 gallon = $5.50/gallon. Increasing productivity of energy use by doubling the efficiency of the vehicle would effectively

[10] https://news.stanford.edu/2021/06/07/professors-explain-social-cost-carbon/, last accessed 12/22/2022

cut fuel expenditures in half (not considering rebound effects) and also cut the climate impact of $2.00/gallon in half for a given level of activity (e.g., miles driven). If SC-CO2 were included in the cost of gasoline, it would surely influence the market toward more efficient mobility solutions (e.g., higher efficiency ICE vehicles and electric vehicles (EVs)). The same would apply to decisions related to the means of heating and cooling of buildings and making buildings more energy efficient.

According to Rennert et al. (2022), "the net benefit of a climate policy is the difference between the economic cost of the emission reduction (the mitigation costs), and the value of damages that are prevented by that emission reduction (climate benefits, among others)." Therefore, SC-CO2 is commonly used in cost-benefit analyses to guide decisions related to public policies that have carbon emissions reduction benefits. Examples include more than 60 regulations in the United States affecting household appliances, vehicles, and power plants; carbon capture and storage tax credits; zero-emission credit payments for nuclear generators and power sector planning; among others (Rennert, et al., 2022).

According to Rennert et al. (2022):

> "The SC-CO2 is estimated using integrated assessment models (IAMs) that integrate simplified representations of climate system and global economy to estimate the economic effects of an incremental pulse of CO2 emissions. These models generally follow a four step process in which (1) projections of population and gross domestic product (GDP) inform a CO2 emissions pathway; (2) the CO2 emissions path drives a climate model that projects the atmospheric greenhouse gas concentrations, temperature changes and other physical variables such as sea level rise, (3) the resulting climate change impacts are monetized and aggregated as economic damage, and (4) economic discounting combines all future damages into a single present value."

The variables used to analyze SC-CO2 are treated probabilistically and are shaped by both empirical data and informed expert opinion or judgment in applying that data. The climate change impacts are represented by "damage functions" that relate climate change factors, such as global surface temperature change, to economic impacts in dollars. Based on such an approach, Rennert et al. (2022) provided the following statistical mean estimates of SC-CO2 for a range of near-term discount rates (DR) applied to the cost estimate of future damages:

- 1.5% DR - $308 (US 2020) per tCO2
- 2% DR - $185 per tCO2
- 2.5% DR - $118 per tCO2
- 3% DR - $80 per tCO2

The authors' preferred the mean SC-CO2 of $185 per metric ton of CO2 ($44 to $413 per tCO2 for 5% - 95% confidence range) because it "uses a 2% near term risk-free discount rate, which reflects the recent literature on real interests rates, which have declined substantially over recent decades." In a recent update that built on the work of Rennert et al. (2022), the US Environmental Protection Agency (EPA) issued the following estimates for SC-C02, CH4, and N2O at a 2% discount rate: $190/tCO2, $1,600/tCH4, and $54,000/tN2O.[11]

In these analyses, the discount rate is also treated as a variable with uncertainty because it is influenced by uncertain future market conditions addressed by algorithms included in the IAM. Hence, the discount rate associated with a particular SC-CO2 estimate is referenced to its "near term" value applied in the IAM for a given modeling scenario. The probabilistic range of the SC-CO2 estimates are large and not well constrained due to the many uncertainties involved in predicting the magnitude, extent, and cost of future climate impact damages. Further, the authors report that the estimate of SC-CO2 is most sensitive to the choice of discount rate; updated damage functions were reported as having the second largest effect on their results relative to prior estimates of SC-CO2.

[11] U.S. EPA, Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, September 2022, https://www.epa.gov/environmental-economics/scghg, last accessed 11/5/2023

The four damage sectors represented in their model's damage functions varied substantially in their individual contributions to the magnitude and uncertainty of the SC-CO2 estimate. The four damage sectors included in the Greenhouse Gas Impact Value Estimator (GIVE) IAM used by Rennert et al. (2022) were:

- *Temperature Mortality* – This damage sector has the largest contribution to the estimated SC-CO2 with a mean partial SC-CO2 of $90/tCO2 ($39-$165 per tCO2 for 5%-95% probability range)
- *Agricultural Impacts* – This damage sector has the second largest and similar contribution to the SC-CO2 with a mean partial SC-CO2 of $84/tCO2 ($23-$363 per tCO2 for 5%-95% probability range)
- *Sea Level Rise* – This damage sector has a relatively small contribution with a mean partial SC-CO2 of $2 per tCO2 ($0-$4 per tCO2 for 5%-95% probability range)
- *Energy Costs* (for residential and commercial buildings) – This damage sector also has a relatively small contribution with a mean partial SC-CO2 of $9 per tCO2 ($4-$15 per tCO2 for 5%-95% probability range). The relatively small value was attributed to the increase demand for cooling being offset by decreased heating demand and future technological progress.

The authors claimed that the above partial SC-CO2 estimates are consistent with other recent empirical work. The authors also acknowledged that other categories of climate damage sectors are not included, such as biodiversity, labor productivity, conflict, and migration. If included in the IAM, these would serve to increase SC-CO2. They also note that accounting for adaptation responses could offset some of these effects with a tendency to lower the estimated SC-CO2.

Given that the *Temperature Mortality* and *Agricultural Impacts* damage sectors have the greatest influence on the modeled SC-CO2 (second to the discount rate used) and account for 94% of its estimated value at the preferred 2% short-term discount rate, it is worth considering how these impacts were assessed and monetized. The purpose of this deeper dive into damage functions is not to critically review them but rather to better understand how they contribute to the SC-CO2 and ultimately define the significance of concern with the future effects or impact cost of climate change.

The *temperature mortality impacts* were reported to rely on results of Cromar, et al. (2022) which are based on expert analysis of peer-reviewed literature addressing temperature relationships to various health outcomes, including "112 studies for cardiovascular, 164 for infectious diseases, 78 for general/respiratory, and 90 studies for all other health endpoints." This work considered both the increased mortality risk at high temperatures and reduced risk at cooler temperature resulting in a net change in mortality risk per degree Celsius global average temperature change for each of 10 regions. The summary result of this work is described as follows (Cromar et al., 2022):

> "Effect estimates and associated uncertainties varied by global region, but net increases in mortality risk associated with increased average annual temperatures (ranging from 0.1% to 1.1% per 1°C) were estimated for all global regions."

The incremental change in mortality associated with global climate average temperature change is then monetized by assigning a statistical value of life following EPA's 1990 value of $4.8 million adjusted to $10.05 million in 2020 dollars (Rennert et al., 2022). Because assigning a dollar value to life is subject to many intangibles and there are large uncertainties in predicting future deaths as they relate to climate change, it would seem appropriate to also report the cumulative number of predicted deaths caused or avoided for each region in which they are modeled to occur using a particular damage function within a particular IAM. A similar recommendation is made by Cromar et al. 2022: "The ideal output for a health damage function is counts of health events (e.g., deaths), as opposed to monetary estimates (e.g., dollars), to allow users to apply different approaches to valuing the cost of those health impacts."

The *agricultural impacts* are reported to be based on the study by Moore et al. (2017) which estimated damages based on a two-step process involving (1) analyzing other studies on the effects of temperature, rainfall, and atmospheric CO2 fertilization on crop yields, and (2) using a model to estimate economic welfare consequences of crop yield "shocks" coupled with algorithms to account for trade patterns and adjustments to supply and demand across 16 regions of the world. It was found that global temperature increases had a net negative impact on crop yield to varying degrees for four major grain crops studied. It also found that the negative effect of temperature increase is partially offset or mitigated by adaptation (e.g., use of different crop varieties, crop switching, etc.) and by the increased yield with increasing atmospheric CO2 concentration (which varied from about 9% to 12% for C4 and C3 photosynthesis grain crops, respectively). From these steps, damage functions were developed for each of the 16 regions and compared to prior damage functions showing a relative increase in regions modeled to experience crop yield reductions and a decrease in those that would see net increases in crop yield due to global warming. The authors summarized the significance of their study as follows (Moore et al., 2017):

> "Here we show that the current science of climate change impacts on agriculture, combined with up-to-date economic modeling, implies larger damages to the sector than currently represented in models used to calculate the SCC. In contrast to existing regional damage functions, which show benefits in every region up to at least 3 °C of warming, we find potential for welfare declines even at much lower levels of warming. Though the range of possible effects of climate change on yields is substantial, our finding that the SCC should be increased is robust to this variation, as well as to uncertainties relating to the discount rate, economic modeling, and extrapolation of the damage function."

The IAM used by Rennert et al. (2022) then employed the agricultural damage functions of Moore et al. (2017) using a sampling scheme to assess future agricultural impacts and costs to contribute to the estimated SC-CO2. Interestingly, Moore et al. (2017) used a discount rate of 3% in assessing the partial SC-CO2 for agricultural impacts whereas Rennert et al. (2022) favored the use of a 2% discount rate resulting in a greater agricultural impact contribution and higher overall SC-CO2 estimate.

However, consideration of adaptation by use of agri-science technology innovations can result in an over-estimate of climate impacts to food production. For example, many existing agricultural innovations may help cost-effectively overcome some of the climate change threats to agriculture and food crop production.[12] To the extent such technologies are effectively implemented, it would tend to reduce the estimated social cost of carbon if included in modeled agricultural damage impact functions.

To contrast with the above assessment of SC-CO2, other studies using different IAM models and assumptions can lead to vastly different estimates of an appropriate SC-CO2 and, consequently, an overall global warming limit as a target for climate policy that differs substantially from the 1.5ºC target and 2ºC cap promoted in the Paris Agreement. For example, Lomborg (2021) evaluated the cost-benefits of various policy scenarios associated with a range of global warming temperature targets using a well-recognized IAM called the Dynamic Integrated Climate Change (DICE) model (Nordhaus, 2018). He employed a short-term discount rate of 3%, which was higher than the 2% value used by Rennert et al. (2022), but equal to that used by Moore et al. (2017). The DICE IAM also used older damage functions that differed from the updated damage functions used in the GIVE IAM as reported by Rennert et al. (2022) and discussed above.

With the above-noted analytical differences, Lomborg's analysis is summarized in Table 1. These findings form the basis of Lomborg's recommendation that an optimal climate policy should align with limiting global warming to about 3.5ºC (6.3ºF) temperature rise by 2100, which is consistent with implementing policy actions to produce carbon emission reductions over time equivalent to that of implementing a market-based carbon tax (based on SC-CO2) valued at $36/tCO2 initially and gradually increasing to $270/tCO2 by 2100. This finding has been criticized for its use of a high discount rate that under-estimates the present value of predicted future

[12] https://www.geospatialworld.net/prime/five-key-trends-to-watch-out-for-in-agritech/?utm_medium=email&utm_source=rasa_io&utm_campaign=newsletter, last accessed 2/13/2023

economic impacts of global warming, among other concerns. However, Lomborg's analysis does raise relevant and practical considerations toward forming a rational basis for climate policy development. And, his recommended carbon tax approach is similar to that recommended by National Academies of Science, Engineering, and Medicine (NASEM, 2021) as one of the key measures recommended for US federal climate policy. The NASEM climate policy recommendations will be addressed later.

Lomborg promotes a climate policy approach that: (1) implements a global carbon tax as a market-based solution to drive CO2 emission reductions and innovation to avoid the worst climate change damage; (2) emphasizes investment in adaptation (e.g., improved water management, improved resiliency of buildings and low-lying coastal communities, improved food crop varieties, etc.) as a simple and reliable means to cope with and mitigate expected future regionally-varying impacts of global warming; and (3) invests in research to develop alternative low-to-zero emission fuel sources and to develop safe geoengineering strategies as a "back-up plan" should a coordinated global effort fail to materialize or produce the desired effects to adequately limit global warming and its impacts.

TABLE 1. Economic Analysis of Climate Policy Scenarios (based on Lomborg, 2021)

Climate Policy Scenarios[1]	Climate Temperature Rise Outcome by 2100	Climate Change Impact Cost[2] 2010 US$ (500-yr cumulative)	Climate Policy Cost[2] 2010 US$ (500-yr cumulative)	Net Cost Outcome, 2010 US$ (500-yr cumulative)
No new policy c. 2010 (status quo)	7.4ºF (4.1ºC)	$140 trillion	$0	$140 trillion
Policy equivalent to $36/ton CO2 tax increasing gradually to $270/ton by 2100	6.3ºF (3.5ºC)	$87 trillion	$21 trillion	**$108 trillion (optimum lowest net cost)**
Intermediate scenario	5.3ºF (2.9ºC)	$67 trillion	$65 trillion	$132 trillion
Intermediate scenario	4.1ºF (2.3ºC)	$45 trillion	$130 trillion	$175 trillion
Policy equivalent to a $500/ton CO2 tax initiated immediately [3]	3.9ºF (2.2ºC)	$40 trillion	$177 trillion	$217 trillion

TABLE NOTES:

1. The climate policy scenarios are listed in order of least aggressive to most aggressive. According to Lomborg (2021), climate policy scenarios attempting to limit global temperature rise to less than 3.9ºF (2.2ºC) in accord with the Paris Agreement's goals were not included because it is likely impossible to reach with realistic technologies. Furthermore, such goals also appear to be well beyond the range of an optimal outcome according to Lomborg (2021).
2. Climate change impact costs and policy costs are based on using the "DICE" IAM model per Nordhaus (2018). Reductions in climate change impact cost (3rd column) come with increasing cost of climate policy (4th column) and result in a trend of diminishing returns in terms of net cost (5th column) for climate policy scenarios (1st column) and associated climate temperature rise limits (2nd column) that go beyond the optimum policy and temperature rise target yielding the least net cost (2nd row).
3. Implementing a $500/ton CO2 tax based on the SC-CO2 (bottom row) would have multiple modeled or expected impacts on cost of living and quality of life. For example, one impact (among many) would be increasing the cost of gasoline by an additional $4.50/gallon. While this would quickly curtail emissions, the overall negative impacts on society (particularly those most vulnerable) would be intolerable and perhaps even unconscionable according to Lomborg (2021).

An underlying premise of Lomborg's approach is that addressing climate change in a way that promotes prosperity by policy that optimizes cost-benefits and moderates impacts on economic growth, particularly for poorer countries, will have broad-reaching public welfare benefits, including an improved ability to adapt to climate change. He provides evidence from several examples of improved public welfare outcomes for countries that have realized these co-benefits of prosperity and have successfully adapted to past challenges. Lomborg's work also is aimed at dispelling common misrepresentations about global warming that tend to incite an apocalyptic and fear-driven public response, which leads to potentially inefficient public policy in reaction to the scientific realities and uncertainties of climate change and its future impacts. Toward that end, and in addition to numerous examples that Lomborg provides to address common mispresentations of climate change impacts, Lomborg quotes a 2014 IPCC report that speaks to the matter:

> "For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers [such as] changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development." (IPCC, 2014c – see reference in Lomborg, 2021)

However, IEA (2021) gives a very different view in its proposed plan to achieve world-wide net zero emissions (NZE) by 2050:

> "Reducing global carbon dioxide (CO2) emissions to net zero by 2050 is consistent with efforts to limit the long-term increase in average global temperatures to 1.5 °C. This calls for nothing less than a complete transformation of how we produce, transport and consume energy." (p.13)

The complete transformation required by the IEA's NZE by 2050 plan paints a picture of a net increase in global GDP in pursuing a multi-sector transformation to NZE by 2050. Based on the data presented and various coordinated strategies employed (including investment in and reliance on development and implementation of innovative clean energy and carbon capture technologies not currently available), the envisioned global transformation pathway is estimated to require roughly $2 to $3 trillion (USD) in global decarbonization investment per year through 2050 (i.e., ~ $75 trillion in total). This policy cost estimate is considerably less than Lomberg's estimates, even for his consideration of less aggressive climate change goals and associated policy actions (see Table 1).

A brief description of the economic aspects and aspirations of the IEA's plan is as follows (IEA, 2021):

> **"Economy:** In our Net-Zero Emissions by 2050 Scenario (NZE), global CO2 emissions reach net zero by 2050 and investment rises across electricity, low-emissions fuels, infrastructure and end-use sectors. Clean energy employment increases by 14 million to 2030, but employment in oil, gas and coal declines by around 5 million. There are varying results for different regions, with job gains not always occurring in the same place, or matching the same skill set, as job losses. The increase in jobs and investment stimulates economic output, resulting in a net increase in global GDP to 2030. But oil and gas revenues in producer economies are 80% lower in 2050 than in recent years and tax revenues from retail oil and gas sales in importing countries are 90% lower." (p.151)

However, the evidence provided in IEA (2021) to support the above claim of net economic benefit by way of net increase in global GDP is apparently very uncertain:

> "The macroeconomic effects of the NZE are very uncertain. They depend on a host of factors including: how government expenditure is financed; benefits from improvements to health; changes in consumer bills; broad impact of changes in consumer behaviour; and potential for productivity spill-overs from accelerated energy innovation. Nonetheless, impacts are likely to be lower than assessments of the cost of climate change damages (OECD, 2015). It is also likely that a coordinated, orderly transition can be executed without major global systemic financial impacts, but this will require close attention from governments, financial regulators and the corporate sector." (p.157)

Despite the different targets used to form climate change policy recommendations and very different policy approaches[13] with each claimed to be cost-effective or optimal (even though mutually exclusive in that regard), both of the above assessments rely on the assumption of an ideal, multi-lateral, world-wide, unified commitment by essentially all governments and all major sectors of and stakeholders in the world's and each nation's economy. However, the IEA's NZE by 2050 plan does consider the scenario of "low international cooperation" which was estimated to delay achieving the global NZE goal by several decades beyond 2050.

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[13] The Lomborg (2021) approach is primarily market-based through a globally-adopted carbon tax and the IEA (2021) NZE by 2050 plan is more heavily based on a variety of regulatory actions affecting decarbonization of various sectors of the economy, including a role for CO2 tax to offset proposed declining fossil fuel use and lost tax revenue, in a coordinated fashion by national and local governments.

1.5 Summary & Discussion

In summary, the magnitude of global warming and the understanding of its major contributing causes and impacts are reasonably well constrained by robust scientific data. It is clearly appropriate to seriously consider climate change and to take effective action. The more difficult questions are largely political and economic in nature: What is "effective action"? Who pays and how?

In general, the mechanism for funding climate change policies and actions will always and eventually be paid for by the consumer as is the case for other similar policies that intend to mitigate real but uncertain risk, like natural disaster mitigation through stronger building codes and existing building retrofits to reduce vulnerability (e.g., Crandell, 2007). Thus, the concern with "who pays" and "how" must consider an equitable distribution of the cost burden of a policy intending to address climate change with uncertain future benefits and consequences in terms of incrementally mitigated impacts that have considerable regional variation.

The issue of equitable funding for and content of climate policy is challenging at any level of government. The world's nations and constituents have vastly different socio-economic and demographic situations, capabilities, and vulnerabilities; have contributed relatively little or much to climate change based on their socio-economic history; and may suffer disproportionately small or large impacts from climate change and the cost burden of climate policies. It may be for this reason that the Paris Agreement (addressed next) has set a goal or target to limit climate change, but relies completely on individual national declared contributions (NDCs) and compliance with those promises to meet its goals.[14]

[14] As of 2020, 80% of the promised carbon emission reductions are those promised by the United States, European Union (EU), China, and Mexico (Lomborg 2021, p113). According to Lomborg (2021, p117) in citing a "best-case" estimate offered by the UN organizers of the Paris Agreement in 2015, a total reduction of 64 Gt CO_2 emissions through 2030 (representing the effect of actually realizing the national commitments made by signatories to the agreement) translates to an estimated reduction in global temperature of a mere 0.03ºC (0.05ºF) in 2100.

PART 2: Climate Policy

2.1 Global Climate Policy

From the context established in the previous section, global climate policies have emerged over the past several decades. Only two of the most recent and relevant global policies are briefly reviewed in this section: The Paris Agreement and The Glasgow Pact. From there, various plans to implement these global, high-level policies at the global, national, or local level are reviewed.

2.1.1 Paris Agreement (COP 21)

The Paris Agreement effectively replaced prior global climate agreements in Rio de Janeiro in 1992 and Kyoto in 1997. According the UN, the Paris Agreement is described as follows:[15]

> "The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels.
>
> To achieve this long-term temperature goal, countries aim to **reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century**. The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations into a common cause to **undertake ambitious efforts to combat climate change and adapt to its effects**. Implementation of the Paris Agreement requires economic and social transformation, based on the best available science. The Paris Agreement works on a 5-year cycle of increasingly ambitious climate action carried out by countries. By 2020, countries submit their plans for climate action known as **nationally determined contributions (NDCs)**. In the NDCs, countries communicate actions they will take to reduce their Greenhouse Gas emissions in order to reach the goals of the Paris Agreement. Countries also communicate in the NDCs actions they will take to build resilience to adapt to the impacts of rising temperatures."

Continuing, some of the key statements and provisions of the Paris Agreement are as follows:

> "Recognizing the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge,"
>
> "Recognizing that Parties may be affected not only by climate change, but also by the impacts of the measures taken in response to it,"
>
> "This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
>
>> (a) Holding the increase in the **global average temperature** to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
>>
>> (b) Increasing the **ability to adapt** to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and
>>
>> (c) Making **finance flows** consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."

[15] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, last accessed 12/7/2022

> “Parties aim to **reach global peaking of greenhouse gas emissions as soon as possible**, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century”
>
> “**Accelerating, encouraging and enabling innovation** is critical for an effective, long-term global response to climate change and promoting economic growth and sustainable development.”
>
> “Parties shall cooperate in taking measures, as appropriate, **to enhance climate change education, training, public awareness, public participation and public access to information**, recognizing the importance of these steps with respect to enhancing actions under this Agreement.”
>
> “The Conference of the Parties serving as the meeting of the Parties to this Agreement shall **periodically take stock of the implementation of this Agreement** to assess the collective progress towards achieving the purpose of this Agreement and its long-term goals (referred to as the "global stocktake"). It shall do so in a comprehensive and facilitative manner, considering mitigation, adaptation and the means of implementation and support, and in the light of equity and the best available science.”

2.1.2 Glasgow Climate Pact (COP 26)

In 2021, the 26th meeting of the UN Climate Change Conference of the Parties (COP26) established the Glasgow Climate Pact to build on and further modified the Paris Agreement (COP21). It is motivated by “the urgency of enhancing ambition and action in relation to mitigation, adaptation and finance in this critical decade to address the gaps in the implementation of the goals of the Paris Agreement.” [16]

The following statement addresses some of the salient outcomes of that meeting:[17]

> “The UN Climate Change Conference in Glasgow (COP26) brought together 120 world leaders and over 40,000 registered participants, including 22,274 party delegates, 14.124 observers and 3.886 media representatives. For two weeks, the world was riveted on all facets of climate change — the science, the solutions, the political will to act, and clear indications of action… Countries reaffirmed the Paris Agreement goal of limiting the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5 °C… They recognized that the impacts of climate change will be much lower at a temperature increase of 1.5 °C compared with 2 °C… Glasgow also established a work programme to define a global goal on adaptation, which will identify collective needs and solutions to the climate crisis already affecting many countries. ”

2.2 Global Climate Policy Implementation Plans

The global policies addressed in the previous section rely on the development of plans that address the broadly generalized objectives and, particularly, the stated goal to limit global average temperature rise to well below 2°C with efforts to pursue a limit of 1.5°C. These high-level goals will not be achieved without a more detailed plan to chart a pathway to achieve them. Such plans are developed at two levels or in two ways: (1) model global plans and (2) nationally declared contributions, which form the bases for detailed national plans and policies. Several representative global, national, and local plans (which all have similarities but vary in details) are reviewed in this section, including some specific plans for the building sector.

2.2.1 IEA Net Zero Emissions (NZE) by 2050

The IEA’s net zero emissions (NZE) by 2050 plan offers a comprehensive and detailed global roadmap outlining a pathway to achieve global net zero emissions (NZE) by 2050 in a manner consistent with the goals of the Paris Agreement (IEA, 2021). The key elements or “pillars” of this plan are described as follows:

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[16] https://unfccc.int/sites/default/files/resource/cma3_auv_2_cover%2520decision.pdf, last accessed 12/7/2022

[17] https://www.un.org/en/climatechange/cop26, last accessed 8/2/2022

> "Achieving the rapid reduction in CO2 emissions over the next 30 years in the NZE requires a broad range of policy approaches and technologies (Figure 2.12). The key pillars of decarbonisation of the global energy system are energy efficiency, behavioural changes, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy and CCUS [Carbon Capture, Sequestration and Utilization]." (p.64)

The plan envisions transformation of major economic sectors (electricity, buildings, transport, and industry) through a rapid phasing out of fossil fuel-based technologies and phasing in of renewable energy and related technologies. It envisions an economy where fossil fuels fall from supplying 80% to just over 20% of the world's energy demand by 2050. Implementation of conventional and market-ready technologies are the focus through 2030 with a shift to newer and innovative technologies from 2030 to 2050. Both energy supply and demand-side strategies are employed.

For example, by 2050 most of the world's energy needs would be provided by nuclear, bioenergy, hydro, solar, wind and other renewables. The largest two contributors being solar and wind. To stabilize the future electric grid with variable renewable power sources from wind and solar, a combination of demand management and energy storage technologies are envisioned.

To achieve the rapid pace of global decarbonization, key policy or action milestones are mapped at various points in time for each of the major economic sectors to correspond with the path to NZE by 2050. A selection of these milestones are summarized in Table 2.

The NZE by 2050 plan also maps some more specific actions and milestones for each sector, including buildings:

> "The NZE pathway for the buildings sector requires a step change improvement in the energy efficiency and flexibility of the stock and a complete shift away from fossil fuels. To achieve this, more than 85% of buildings need to comply with zero-carbon-ready building energy codes by 2050 (Box 3.4). This means that mandatory zero-carbon-ready building energy codes for all new buildings need to be introduced in all regions by 2030, and that retrofits need to be carried out in most existing buildings by 2050 to enable them to meet zero-carbon-ready building energy codes.
>
> Retrofit rates increase from less than 1% per year today to about 2.5% per year by 2030 in advanced economies: this means that around 10 million dwellings are retrofitted every year. In emerging market and developing economies, building lifetimes are typically lower than in advanced economies, meaning that retrofit rates by 2030 in the NZE are lower, at around 2% per year. This requires the retrofitting of 20 million dwellings per year on average to 2030. To achieve savings at the lowest cost and to minimise disruption, retrofits need to be comprehensive and one-off." (p.143)

TABLE 2. Summary of Key Milestones in the IEA (2021) Net Zero Emissions (NZE) by 2050 Plan[1]

Year	Buildings	Electric & Heat	Industry[2]	Transport
2021	--	No new unabated coal plants approved for development	No new oil, gas, or coal development	--
2025	No new sales of fossil fuel boilers	--	--	--
2030	All new buildings are zero-carbon-ready	1,020 GW annual solar and wind additions & Phase-out of unabated coal in advanced economies	Most new clean technologies in heavy industry demonstrated at scale	60% of global car sales are electric
2035	Most appliances and cooling systems "best in class"	Overall net-zero emissions electricity in advanced economies	All industrial electric motor sales are best in class	50% of heavy truck sales are electric & no new ICE car sales
2040	50% of existing buildings retrofitted to zero-carbon-ready levels [3]	Net-zero emissions electricity globally & Phase out of all unabated coal and oil power plants	~ 90% of existing capacity in heavy industries reaches end of investment cycle	50% of fuels used in aviation are low-emissions
2045	50% of heating demand met by heat pumps	--		--
2050	More than 85% of buildings are zero-carbon-ready	Almost 70% of electricity generation globally from solar PV and wind	More than 90% of heavy industrial production is low-emissions	Maritime shipping reaches 15% of 2020 emissions by use of low-carbon fuels

TABLE NOTES:
1. Not shown are: 2030 – 150 Mt low-carbon hydrogen & 850 GW electrolizers; 2035 – 4 Gt CO2 captured; 2045 – 435 Mt low-carbon hydrogen & 3,000 GW electrolizers; 2050 – 7.6 Gt CO2 captured.
2. Where referenced, heavy industry includes chemicals, concrete, steel, and others.
3. Addressing resiliency of existing buildings does not appear in the roadmap; however, it is presumed that zero-carbon-ready retrofits should be done in combination with resiliency improvements for vulnerable buildings (e.g., those at high risk of damage due to existing and changing natural hazards such as severe wind and chronic flooding).

Electrification and energy efficiency improvements account for about 70% of total building emission reductions through 2050. Building electrification (e.g., transition to heat pumps and electric appliances) accounts for almost half of the direct CO2 emission reductions for buildings. The electrification benefits are necessarily coupled with changes to the "electric & heat" sectors (see Table 2). About one-third of the necessary CO2 emission reductions for buildings come from improved energy efficiency. Other mitigation measures include behavioral changes and avoided demand (by regulated or voluntary means) as well as bioenergy and other renewables. The plan also calls for transition to 100% use of the most efficient lighting and electric appliance technologies available by 2035.

More specifically, the plan calls for major improvements to building thermal envelope efficiency to reduced heating and cooling demand together with a major shift to use of heat-pump technology for heating and cooling (away from natural gas and other direct fossil fuel sources):

> "Building envelope improvements in zero-carbon-ready retrofit and new buildings account for the majority of heating and cooling energy intensity reductions in the NZE, but heating and cooling technology also makes a significant contribution. Space heating is transformed in the NZE, with homes heated by natural gas falling from nearly 30% of the total today to less than 0.5% in 2050, while homes using electricity for heating rise from nearly 20% of the total today to 35% in 2030 and about 55% in 2050 (Figure 3.29). High efficiency electric heat pumps become the primary technology choice for space heating in the NZE, with worldwide heat pump installations per month rising from 1.5 million today to around 5 million by 2030 and 10 million by 2050. Hybrid heat pumps are also used in some of the coldest climates, but meet no more than 5% of heating demand in 2050." (p.145)

It also acknowledges financial realities and challenges in the NZE by 2050 plan's implementation:

> "Governments will need to find ways to make new zero-carbon-ready buildings and retrofits affordable and attractive to owners and occupants by overcoming financial barriers, addressing split incentive barriers and minimising disruption to building use. Building energy performance certificates, green lease agreements, green bond financing and pay-as-you save models could all play a part.
>
> Making zero-carbon-ready building retrofits a central pillar of economic recovery strategies in the early 2020s is a no-regrets action to jumpstart progress towards a zero-emissions building sector**. Foregoing the opportunity to make energy use in buildings more efficient would drive up electricity demand linked to electrification of energy use in the buildings sector and make decarbonising the energy system significantly more difficult and more costly.**" (p. 148)

The plan makes it clear that electrification of buildings must be coupled with and not done separate from improving energy efficiency of buildings, such as making significant improvements to building envelopes. Otherwise, decarbonizing the energy system would be made significantly more difficult and costly because of increased energy demand of buildings beyond that required to make the plan work. For more helpful information on IEA building energy efficiency opportunities, including building envelope performance improvements and tracking progress, refer to the IEA's website.[18]

Chapter 4 of the NZE by 2050 plan provides a thorough discussion of its wider implications, including benefits and potential consequences to be managed, such as affordability for economically disadvantaged consumers. Among the many topics addressed, the future manufacturing of building products (according to the NZE plan) is addressed and touches on lowering industrial/manufacturing emissions and methods to incentivize the market to purchase lower embodied carbon materials:

> "In heavy industrial sectors – steel, cement and chemicals – most deep emissions reduction technologies are not available on the market today. In the NZE, material producers soon demonstrate near-zero emission processes, aided by government risk-sharing mechanisms, and start to adapt their existing production assets. For multinational companies, this includes developing technology transfer strategies to roll-out processes across plants. International co-operation would help to ensure a level playing field for all. Within countries, efforts focus on industrial hubs in order to accelerate emissions reductions across multiple industrial sectors by promoting economies of scale for new infrastructure (such as CO2 transport and storage) and supplies of low-emissions energy.
>
> Materials producers work with governments in the NZE to create an international certification system for near-zero emission materials to differentiate them from conventional ones. This would enable buyers of materials such as vehicle manufacturers and construction companies to enter into commercial agreements to purchase near-zero emissions materials at a price premium. In most cases, the premium would result in only a modest impact on the final price of the product price given that materials generally account for a small portion of manufacturing costs (Material Economics, 2019)." (p. 166).

[18] www.iea.org/topics/buildings, last accessed 11/5/2023

Regarding energy security, the NZE by 2050 plan recognizes the continued importance of energy efficiency, even in a fully developed NZE economy:

> "**Improving energy efficiency remains the central measure for increasing energy security – even with rapid growth in low emissions electricity generation, the safest energy supplies are those that are not needed.**" (p.175)

During the writing of this report, the IEA released its latest "Renewables 2022" report.[19] In that report, due to significant uptake of solar PV caused by various factors including disruption of fossil fuel supplies and price increases making renewables more competitive, the IEA revised its prior forecast upward by 30% yet again for estimated future contributions of solar energy to meet primary energy demand. The major countries accelerating installed renewable power capacity are China, the EU, the US, and India. Now, solar PV and other variable renewables (i.e., subject to weather-related power production variation) are forecasted by the IEA to "become the largest source of global electricity generation by 2025, surpassing coal…reaching 38% [of the global power supply] by 2027…Meanwhile, the growth of dispatchable renewables [i.e., on demand, flexible power] including hydropower, bioenergy, geothermal and concentrated solar power remains limited despite their critical role in integrating wind and solar PV into global electricity systems. " It is for this reason that many transition plans to a net zero emissions economy envision continued use of nuclear and cleaner fossil fuel technologies to provide for dispatchable power demand necessary to provide for electric power supply-demand stability and balance. For intensive industrial power users, clean fuel technology like green hydrogen are currently envisioned as a prominent means to eventually or nearly completely replace fossil fuels in all sectors. **To the extent that this envisioned power supply transition occurs in the heavy industrial manufacturing sector (e.g., concrete, steel, and chemicals) then the materials manufactured by those industries will essentially become low-embodied carbon materials.**

There is also the possibility that investments in research and innovation will lead to even more disruptive energy technology breakthroughs that transform future clean energy production in ways that dwarf or complement that which can be achieved through current renewable technologies, like solar PV and wind. For example, Thorium nuclear fission reactor technologies are considered as a viable alternative to Uranium based nuclear fission with various pros and cons.[20] Again during the writing of this report, news hit the press regarding an important milestone for nuclear fusion research as a possible future source for clean and abundant zero-carbon power. But, the news article also correctly noted that this energy technology "has a long way to go."[21]

2.2.2 UNEP Global Status Report for Buildings and Construction

The United Nations Environment Programme (UNEP) global status report for buildings and construction provides an overview and tracks efforts to decarbonize buildings (UNEP, 2021). Global CO2 emissions and energy use for various sectors, including buildings, is shown in Table 3 based on data reported by UNEP (2021).

CO2 emissions from building operations in 2020 were around 8.7 gigatons, below the 9.6 gigatons in 2019 due to shift in building-related energy use patterns driven by the COVID-19 pandemic. CO2 emissions from building construction – mostly from materials manufacturing – was 3.2 gigatons in 2020, down from 3.6 gigatons in 2019 again due to the pandemic impact on new construction. Thus, the total emissions associated with buildings in 2020 was 8.7 + 3.2 = 11.9 gigatons CO2 which is 37% of overall global CO2 emissions in 2020.

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[19] https://www.iea.org/reports/renewables-2022, accessed 12/12/2022

[20] https://www.nsenergybusiness.com/news/newsmajor-pros-and-cons-of-thorium-nuclear-power-reactor-6058445/, last accessed 12/26/2022

[21] https://www.washingtonpost.com/business/2022/12/11/fusion-nuclear-energy-breakthrough/, last accessed 12/23/2022

TABLE 3. Building and construction share of global CO2 emissions and energy (2020)

<table>
<tr><th>Sector</th><th colspan="2">CO2 Emissions</th><th colspan="2">Energy Use</th></tr>
<tr><td>Residential (direct)</td><td>6%</td><td rowspan="5">37%</td><td rowspan="2">22%</td><td rowspan="5">36%</td></tr>
<tr><td>Residential (indirect)[1]</td><td>11%</td></tr>
<tr><td>Non-residential (direct)</td><td>3%</td><td rowspan="2">8%</td></tr>
<tr><td>Non-residential (indirect)[1]</td><td>7%</td></tr>
<tr><td>Building Constr. Industry (buildng materials)[2]</td><td>10%</td><td>6%</td></tr>
<tr><td>Other Constr. Industry</td><td colspan="2">10%</td><td colspan="2">6%</td></tr>
<tr><td>Other Industry</td><td colspan="2">23%</td><td colspan="2">26%</td></tr>
<tr><td>Transport</td><td colspan="2">23%</td><td colspan="2">26%</td></tr>
<tr><td>Other</td><td colspan="2">6%</td><td colspan="2">6%</td></tr>
<tr><td colspan="5">TABLE NOTES:
1. Indirect emissions are from electricity and commercial heat.
2. Building construction industry refers to the estimated portion of industry manufacturing building construction materials such as glass, concrete, steel, etc.</td></tr>
</table>

For buildings in 2020 the energy demand was 127 EJ which is 36 percent of overall world-wide energy demand in 2020. According to UNEP (2021):

> "For the past decade, the largest operational energy use in buildings globally is associated with space heating, with water heating, cooking, and appliances each coming in at a close second. Space cooling and lighting are in a distant third place." (p39)

Like the IEA's NZE by 2050 plan, the UNEP (2021) report calls for the global buildings and construction sector to become almost completely decarbonized by 2050 in order to achieve the Paris Agreement target to limit global warming to no more than 2^{o}C temperature rise in 2100. It recognizes a triple strategy of:

> "…reducing energy demand (behaviour change and energy efficiency), decarbonizing the power supply (e.g., electrification through renewable sources and increased use of other zero-carbon heating technologies), and addressing embodied carbon stored in building material."

It further expresses a need to urgently address embodied emissions of materials and construction processes by refurbishment rather than demolition of existing buildings, evaluating design choices based on whole building life cycle analsyis while seeking to minimize upfront carbon impacts (e.g., lean construction, low-carbon materials and construction processes, etc.) and future embodied carbon impacts during and at end of life (e.g., maximize potential for renovation, future adaptation, circularity, etc.) (UNEP, 2021, p16).

Regarding a life-cycle analysis of building carbon emissions and particularly embodied carbon in building materials, it states the following (UNEP, 2021):

> "A whole-life carbon perspective includes carbon emissions arising from the built environment during both the use of buildings (operational emissions) and their construction (embodied emissions). The 2021 Global Status Report for Buildings and Construction puts a spotlight on recent developments in Europe and provides a high-level summary of the latest policy and data development. The importance of embodied emissions is set to increase dramatically as more buildings are constructed and renovated to higher energy efficiency standards." [p23][22]

The UNEP (2021, pp.18-25) report also notes that "energy efficiency and energy codes in buildings are the second most frequently cited actions within all Nationally Determined Contributions…toward reducing emissions under the Paris Agreement. The most frequently cited contribution was use of renewable energy in the power sector." However, the report also notes that, while some countries are making much more progress than others toward the path to a zero emissions building stock, there are many gaps in implementing the "triple strategy". These gaps are present even though building carbon emissions reduction progress in 2020 showed it to be on track for zero emissions by 2050, but only because of the impact of the pandemic, not due to any actual permanent progress. Consequently, as a part of the effort to recover from the global pandemic, UNEP makes the call for "all countries to build back better, literally." It also calls to establish embedded links to adaptation and resilience in building and energy codes to better cope with the future climate impacts and avoid "locking" emissions in inefficient and unsafe built environments.

Finally, the UNEP (2021) report provides a snap shot of key indicators for progress toward net zero emission buildings by 2050 as summarized in Table 4. It provides additional specificity to particular actions for buildings than found in the IEA's NZE by 2050 plan addressed previously.

TABLE 4. Key Milestones for Reaching NZE Buildings per UNEP (2021)

Measure / Indicator	2020	2030	2050
Energy Intensity	6% reduction per year	4% reduction per year	3% reduction per year
Share of existing buildings net-zero ready	< 1%	20%	>85%
Avoided demand in homes by behavior modification	-	12%	14%
Stock of heat pumps	180 million	600 million	1,800 million
Dwellings with solar thermal heating	250 million	400 million	1,200 million
Appliance energy consumption	-	25% decrease from 2020 levels	40% decrease from 2020 levels
Distributed PV generation	320 TWh	2,200 TWh	7,500 TWh

The UNEP (2021) plan for building decarbonization focuses on actions for eight key categories:

- *Urban Planning* - Integrate energy efficiency in urban planning policies, develop national and local urban plans and ensure collaboration across themes;

[22] The relative contribution of **embodied carbon emissions of building materials** may become greater than the operational carbon emissions, but the absolute magnitude of the contribution of embodied carbon emissions will not necessarily increase as a result of building efficiency improvements that lower operational carbon emissions for heating and cooling. In fact, with decarbonization occurring in other sectors (e.g., industry and electric power generation) embodied emissions should be expected to decline. Thus, it will not necessarily increase in importance, but its relative percentage contribution (in comparison to building heating and cooling energy emissions) will increase. This is an important distinction that is often lost in statements regarding the significance of building material embodied carbon emissions. Such emissions will be addressed in much greater detail later in this report.

- *New Buildings* - Develop decarbonization strategies, implement mandatory building energy codes, and incentivize high performance;
- *Existing Buildings* – Develop and implement decarbonization strategies for refurbishment and retrofit, increase renovation rates and depth, and encourage investment;
- *Building Operations* – Sustain adoption of energy performance tools, systems and standards enabling evaluation, monitoring, energy management and improved operations;
- *Appliances and Systems* – Further develop, enforce and strengthen minimum energy performance requirements, prioritize energy efficiency in public procurement;
- *Materials* – Develop embodied carbon databases, raise awareness and promote material efficiency, accelerate efficiency in manufacturing to reduce embodied carbon over whole life cycle;
- *Resilience* – Develop integrated risk assessment and resilience strategies to ensure adaptation of existing buildings and integrate resiliency into new construction; and,
- *Clean Energy* – Develop clear regulatory frameworks, provide adequate financial incentives, encourage on-site renewable energy or green power procurement, accelerate access to electricity and clean cooking.

Given the presence of these model decarbonization plans (one addressing all facets of energy supply and demand, and the other focusing more specifically on the role of buildings), it is appropriate to ask: How are these plans contributing to efforts to meet the goals of the Paris Agreement at a global level? A recent UN article answers: [23]

Are we on track to reach net zero by 2050?

> "No, commitments made by governments to date fall far short of what is required. Current national climate plans – for all 193 Parties to the Paris Agreement taken together – would lead to a sizable increase of almost 14% in global greenhouse gas emissions by 2030, compared to 2010 levels. Getting to net zero requires all governments – first and foremost the biggest emitters – to significantly strengthen their Nationally Determined Contributions (NDCs) and take bold, immediate steps towards reducing emissions now. The Glasgow Climate Pact called on all countries to revisit and strengthen the 2030 targets in their NDCs by the end of 2022, to align with the Paris Agreement temperature goal."

2.2.3 IEA on Building Envelopes

The IEA recognizes that global effort to improve the energy and embodied carbon efficiency of building envelopes is "not on track" to meet global climate goals. Its website carries the following statement:[24]

> More than 110 countries lacked mandatory building energy codes or standards in 2021, meaning that over 2.4 billion m^2 of floor space were built last year without meeting any energy-related performance requirements – the equivalent of Spain's entire building stock.
>
> Building envelope design is critical in defining the service demand for heating and cooling, and to guarantee comfort, indoor environmental quality and safety. Its structure is also important in determining its embodied carbon impact.
>
> To be in step with the Net Zero Emissions by 2050 Scenario, all countries need to establish zero-carbon-ready building energy codes for both residential and non-residential buildings by 2030 at the latest, and all new buildings should meet this standard from 2030. This also requires 20% of the existing building floor area to be renovated to this level by 2030, with annual energy efficiency renovation rates jumping from less than 1% today to 2.5% by 2030 globally.

[23] https://www.un.org/en/climatechange/net-zero-coalition, last accessed 12/7/2022

[24] https://www.iea.org/reports/building-envelopes, last accessed 2/11/2023

The IEA report goes on to say:

> Building envelope performance improvements are critical to getting on track with the majority of the Net Zero Scenario milestones in heating and cooling intensity (energy use per total m^2). To align with the Net Zero Scenario, the final energy intensity of space heating and cooling need to fall considerably, by at least 40% and 30% respectively in 2030 compared to today. Progress in space cooling efficiency (from both improved envelope performance and air-conditioning equipment) is particularly needed due to growing demand.

Furthermore:

> Constructed floor space worldwide has increased by about 60% since 2000, to reach about 240 billion m^2 in 2021, of which nearly 80% is residential. At the same time, however, average energy use per m^2 has declined by only around 20%, meaning advances in energy efficiency have only partially offset floor area growth.
>
> In addition to the lack of building energy codes in certain countries, the average retrofit rate of the building stock is currently around 1% per year, with retrofits generally delivering average energy intensity reductions of less than 15%. To get on track with the Net Zero Scenario, however, retrofit rates must jump to at least 2.5% by 2030, and retrofits need to be deep retrofits.
>
> By 2030 all new buildings and retrofits are zero-carbon-ready buildings under the Net Zero Scenario.

The IEA report also acknowledges the following regarding embodied carbon emissions attributed to building materials:

> A number of international initiatives are uniting countries, private-sector organisations and cities to reduce embodied carbon, such as WorldGBC's Bringing Embodied Carbon Upfront, within which 80 building and construction value chain stakeholders endorse a 40% reduction in construction-related emissions per m^2 of new floor area by 2030.
>
> The Rocky Mountain Institute launched the Embodied Carbon Initiative to "change how builders build, increasing corporate investment in embodied carbon, and enacting policies to create greater demand for, and adoption of, low-embodied-carbon products".
>
> In 2021 steel, cement and aluminium manufacturing for building construction accounted for 6% of global energy and process-related emissions. Steel and cement manufacturing made up 95% of that share, as new building envelopes required nearly 2 Mt of cement and 0.5 Mt of steel – twice as much as in 2000.

The IEA report also calls for globally improved energy code adoption and enforcement.

2.3 Localized Climate Policy & Implementation Strategies

The goals of the Paris Agreement or any plan to address global climate change must ultimately be localized (ICLEI USA, 2017). The high-level global implementation plans discussed above may serve as models for national plans together with carbon emission reduction commitments that nations make when signing-on to the Paris Agreement. Some countries are more aligned with these global model plans (and the Paris Agreement goals) than others and some are now striving to become even more aggressive. A few examples are reviewed in this section, including the US. A recent IPCC (2022) report on the status of global climate mitigation, including an assessment of progress and continuing challenges as influenced by global and localized policies and actions (or inactions), makes the following general observation regarding urgency and scale of implementation required to meet the Paris Agreement goals:

> Since the IPCC's Fifth Assessment Report (AR5), important changes that have emerged include the specific objectives established in the Paris Agreement of 2015 (for temperature, adaptation and finance), rising climate impacts, and higher levels of societal awareness and support for climate action (high confidence). Meeting the

> long-term temperature goal in the Paris Agreement, however, implies a rapid inflection in GHG emission trends and accelerating decline towards 'net zero'. This is implausible without urgent and ambitious action at all scales.

2.3.1 European Union (EU)

The Council of the EU reached agreement on a proposal that all new buildings should be zero-emission buildings by 2030 and that existing buildings be transformed to zero-emission buildings by 2050.[25] The approach is design to rapidly phase-in the transition for all publicly-owned buildings by 2028 and all new buildings by 2030 with some exceptions possible such as historic buildings, churches, and buildings for defense purposes. Designing new buildings to "optimize their solar energy generation potential" is also targeted on an even more rapid pace to achieve goals for all buildings by 2029.

For existing buildings, the approach employs the increasingly common approach of "minimum energy efficiency performance standards" that rely on energy use intensity (EUI) targets for existing buildings (i.e., energy per m^2 of building floor area). These EUI targets or thresholds for minimum performance are also phased in over time. By 2030 all non-residential buildings would need to meet a threshold set at the 85th percentile of energy use intensity of the existing building stock which focuses on mitigating the worst-performing 15th percentile of the non-residential building stock. The target then shifts to a 75th percentile threshold for the non-residential building stock by 2034. For residential buildings, minimum energy performance standards would follow a "national trajectory" to progressively renovate existing buildings to attain a zero-emission residential building stock by 2050.

EU member states agreed to issue "national building renovation plans" to roadmap the pathway to achieve the goals of the Council of the EU's agreement. The aim is to put the EU on a "path to climate neutrality by 2050" citing that "The proposal is particularly important because buildings account for 40% of energy consumed and 36% of energy-related direct and indirect greenhouse gas emissions in the EU." There was no mention of any justification based on estimated cost of this policy in relation to the cost savings of incrementally reduced climate impacts. This same concern carries forth to other reviewed national and local climate policies and implementation strategies. As noted earlier, the climate goals of the Paris Agreement also were not based on such economic considerations weighing policy cost verses avoided cost of future climate impacts. Instead, national and local policies appear to take the Paris Agreement goals at face value and considered to be sufficiently justified without further thought other than to perhaps to consider least cost paths to compliance with its goals.

Meanwhile, some EU countries have been implementing building decarbonization strategies based on life-cycle analysis (LCA). For example, according to UNEP (2021):

> Netherlands – Since 2017 has required all new residential and office buildings greater than 100 m^2 in floor area to report embodied carbon emissions based on a simplified, national calculation method for LCA. Since 2018, all CO2 emission impacts have been monetized to implement a "mandatory environmental impact cap" for new buildings.
>
> France – Based on building regulations established in 2021, maximum thresholds of carbon emission intensity (i.e., kg CO2e per m^2 per year) have been set for both operational energy and embodied carbon emissions in materials. The thresholds decrease over time and differ for different building types (e.g., apartments vs. houses). For example, the initial 2022 thresholds are set at about 750 and 650 kg CO2e/m^2/yr for apartments and houses, respectively. They are scheduled to decrease in three steps to achieve a cumulative reduction in carbon emissions intensity of about 50% by 2031. A dynamic life-cycle carbon emissions calculation approach is used that accounts for near term emissions having a greater climate impact than those later in the building's life cycle.

Finland, Sweden, and Belgium have instituted or are developing similar strategies based on LCA and include supporting data such as Belgium's national environmental product declaration (EPD) database. Germany,

[25] Press Release, 25 October 2022, www.consilium.europa.eu, last accessed 11/3/22

Switzerland, and the United Kingdom have instituted LCA requirements for public buildings and projects (UNEP, 2021).

2.3.2 United States (US)

The US first joined the Paris Agreement in 2015 under the Obama administration. The following describes the US National Declared Contribution (NDC) as also illustrated in Figure 5: [26]

> "In the U.S. NDC, submitted to the UNFCCC in March 2015, the federal government laid out its goal to achieve an economy-wide target of reducing its greenhouse gas emissions 26% below 2005 levels by 2025 — with a reach goal of reducing emissions by 28%. This target covers all greenhouse gases included in the 2014 Inventory of United States Greenhouse Gas Emissions and Sinks, along with all IPCC sectors, and would put the country on a path to achieve a 17% reduction by 2020."

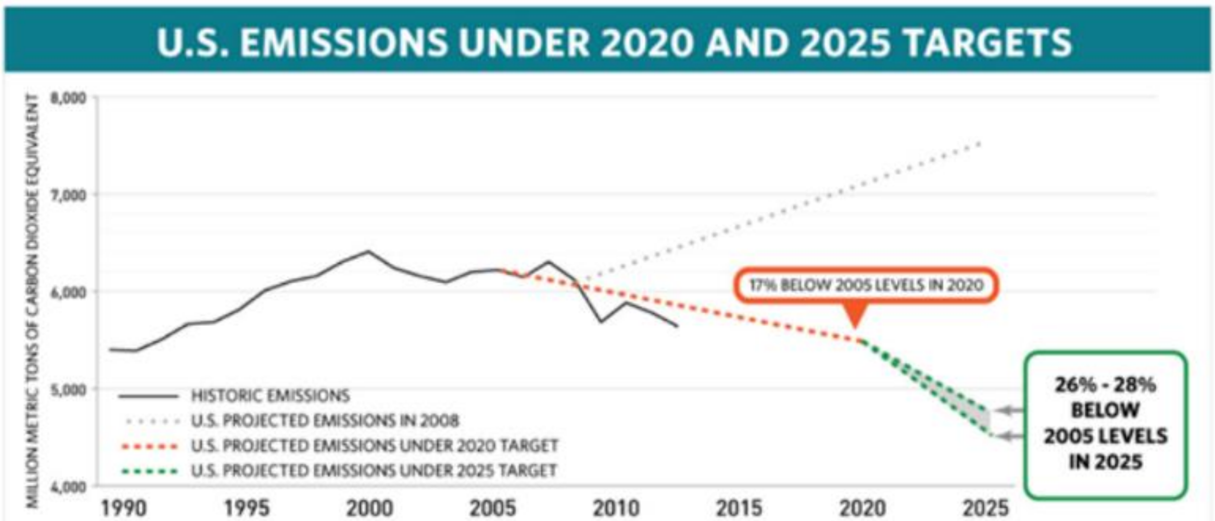

Figure 5. 2015 U.S. NDC projected reduction of CO2 equivalent emissions.
Source: ICLEI USA, 2017

The US later departed from the Paris Agreement during the Trump administration. However, on April 22, 2021, under the Biden administration, the US rejoined the Paris Agreement. The current NDC of the United States (US NDC) and the NDCs of other signatory countries of the Paris Agreement can be found at the website administered by the United Nations Framework Convention on Climate Change (UNFCCC). [27]

The 2021 US NDC includes significantly increased near term carbon emission reduction targets as mentioned below and shown in Figure 6:

> Climate change is an existential threat and demands bold action. Solutions exist today to reduce emissions rapidly while supporting economic growth and improving quality of life. Addressing the climate crisis requires scaling the many solutions we already have, while investing in innovation to improve and broaden the set of solutions, enabling multiple pathways to reach global net zero emissions.
>
> After a careful process involving analysis and consultation across the United States federal government and with leaders in state, local, and tribal governments, **the United States is setting an economy-wide target of reducing its net greenhouse gas emissions by 50-52 percent below 2005 levels in 2030.** The National Climate Advisor developed this NDC in consultation with the Special Presidential Envoy for Climate, and it was approved by President Joseph R. Biden Jr.

[26] https://icleiusa.org/localizing-the-paris-agreement/, last accessed 12/13/2022)
[27] https://unfccc.int/NDCREG, last accessed 11/6/2023

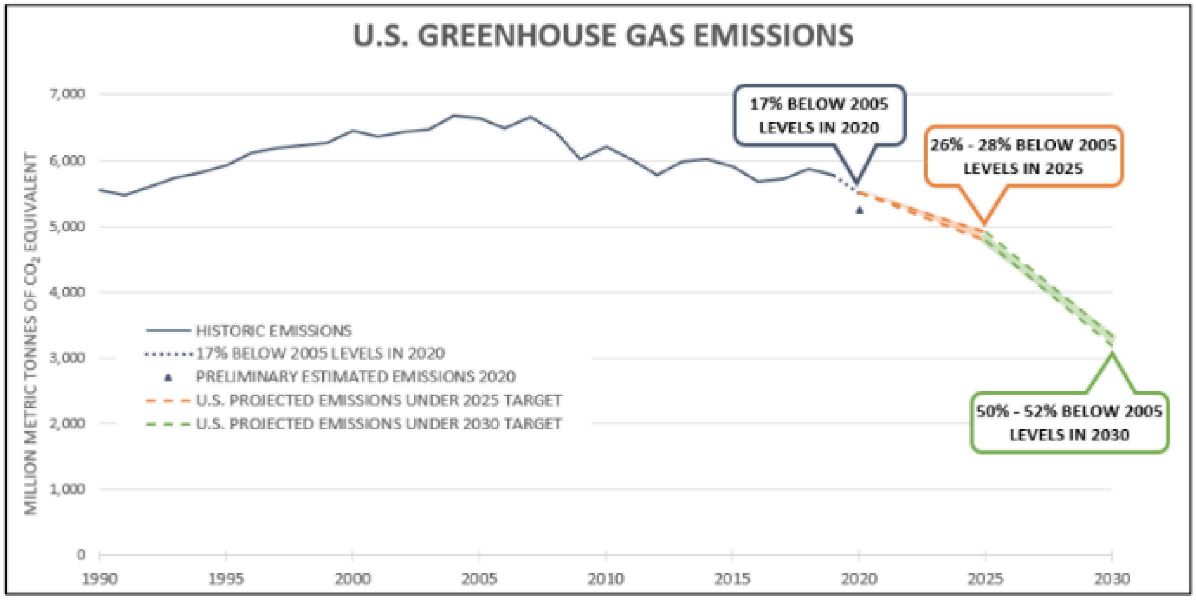

Figure 6. US GHG historic emissions and projected targets per the 2021 US NDC
Note: The baseline 2005 U.S. emissions = 6,625 million metric tons CO2e as published in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (http://www.epa.gov).

Even though the 2021 US emissions are an increase of 7% from the 2020 emissions during the pandemic, the 2021 US NDC acknowledges the following regarding its commitment to the Paris Agreement:

> "Based on preliminary estimates, the United States is expected to have met and surpassed its 2020 target of net economy-wide emissions reductions in the range of 17 percent below 2005 levels and is broadly on track to achieve 26-28 percent emissions reductions below 2005 levels in 2025. The 2030 target represents increased ambition made possible in part through advances in technology and resulting market responses."

The 2021 US NDC acknowledges that there are multiple plans or paths and technology combinations to reach the proposed carbon emission reductions. In the following excerpt, the 2021 US NDC also makes an economic cost-benefit statement that does not cost-justify the proposed policy and instead appeals to the cost-ineffectiveness of doing nothing:

> "There are multiple paths to reach this goal, and the United States federal and subnational governments have many tools available to work with civil society and the private sector, mobilizing investment to meet these goals while supporting a strong economy. The solutions are affordable, and the cost of inaction far outweighs the cost of action in economic and humanitarian terms."

According to Lomborg (2021, p225), the Biden policy's effect on future global warming, even if the policy is sustained until 2100, will serve to reduce the expected global temperature rise of 4.1ºC by a mere 0.04ºC (0.07ºF) based on the UN standard climate model.

Key features of the 2021 US NDC are excerpted and explained as follows:

> "…conducted a detailed analysis to underpin this 2030 target, reviewing a range of pathways for each sector of the economy that produces CO2 and non-CO2 greenhouse gases: electricity, transportation, buildings, industry, and the land sector. Technology availability, current costs and available savings, and future cost reductions were considered, as well as the role of enabling infrastructure. Standards, incentives, programs, and support for innovation were all weighed in the analysis."

“Each policy considered for reducing emissions is also an opportunity to improve equity and support good jobs in the United States.”

“Electricity: The United States has set a goal to reach 100 percent carbon pollution-free electricity by 2035, which could be achieved through multiple cost-effective technology and investment pathways, each resulting in meaningful emissions reductions in this decade.”

Transportation: The largest sources of emissions from transportation are light-duty vehicles like SUVs, pickup trucks, and cars, followed by heavy trucks, aircraft, rail, and ships. These transportation modes are highly dependent on fossil fuels, with more than 90 percent of transportation energy use coming from petroleum. Transportation provides essential access to services and economic opportunities, but has historically contributed to racial and environmental inequities in the United States. There are many opportunities to reduce greenhouse gas emissions from transportation while also saving money for households, improving environmental quality and health in communities, and providing more choices for moving people and goods. Policies that can contribute to emissions reduction pathways consistent with the NDC include: tailpipe emissions and efficiency standards; incentives for zero emission personal vehicles; funding for charging infrastructure to support multi-unit dwellings, public charging, and long-distance travel; and research, development, demonstration, and deployment efforts to support advances in very low carbon new-generation renewable fuels for applications like aviation, and other cutting-edge transportation technologies across modes. Investment in a wider array of transportation infrastructure will also make more choices available to travelers, including transit, rail, biking, and pedestrian improvements to reduce the need for vehicle miles traveled.

Buildings: Building sector emissions come from electricity use, as well as fossil fuels burned on site for heating air and water and for cooking. There are many options to avoid these emissions while reducing energy cost burden for families and improving health and resilience in communities. The emissions reduction pathways for buildings consider ongoing government support for energy efficiency and efficient electric heating and cooking in buildings via funding for retrofit programs, wider use of heat pumps and induction stoves, and adoption of modern energy codes for new buildings. The United States will also invest in new technologies to reduce emissions associated with construction, including for high-performance electrified buildings.

Industry: Emissions in the heavy industry sector come from energy use, including onsite fuel burning as well as electricity, and direct emissions resulting from industrial processes. The United States government will support research, development, demonstration, commercialization, and deployment of very low- and zero-carbon industrial processes and products. For example, the United States will incentivize carbon capture as well as new sources of hydrogen – produced from renewable energy, nuclear energy, or waste – to power industrial facilities. In addition, the United States government will use its procurement power to support early markets for these very low and zero-carbon industrial goods.

Agriculture and lands: America’s vast lands provide opportunities to both reduce emissions, and sequester more carbon dioxide. The United States will support scaling of climate smart agricultural practices (including, for example, cover crops), reforestation, rotational grazing, and nutrient management practices. In addition, federal and state governments will invest in forest protection and forest management, and engage in intensive efforts to reduce the scope and intensity of catastrophic wildfires, and to restore fire-damaged forest lands. Alongside these efforts, the United States will support nature based coastal resilience projects including pre-disaster planning as well as efforts to increase sequestration in waterways and oceans by pursuing “blue carbon.”

Non-CO2 Greenhouse Gas Emissions: The United States will implement the American Innovation and Manufacturing (AIM) Act to phase down the use of hydrofluorocarbons. To address methane, the United States will update standards and invest in plugging leaks from wells and mines and across the natural gas distribution infrastructure. In addition, it will offer programs and incentives to improve agricultural productivity through practices and technologies that also reduce agricultural methane and N2O emissions, such as improved manure management and improved cropland nutrient management.

The 2021 US NDC makes the following observations regarding progress and expected future benefits:

> In the United States, the amount of energy used per unit of economic growth (energy intensity) has declined steadily for many years, while the amount of CO2 emissions associated with energy consumption (carbon intensity) has generally declined since 2008.
>
> In 2020, United States renewable generation reached a new record of 761 million megawatthours (MWh) – approximately 19 percent of the total United States electricity use. This was more than double the renewable generation in 2010, with more than 90 percent of the increase in renewables over the past decade coming from wind and solar generation. Total carbon-free generation in 2020 represented approximately 39 percent of total United States electricity generation.
>
> As noted above, this NDC exceeds the pace required for a straight-line path to achieve net-zero emissions, economy-wide, by no later than 2050. This NDC would therefore contribute substantially towards achieving the ultimate objective of the UNFCCC of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, and within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Finally, the following clause included in the 2021 US NDC reinforces the work of organizations at the state and local government level:

> A whole-of-government approach on climate action at the federal level will play an important role in achieving our target in 2030, building upon and benefiting from a long history of leadership on climate ambition and innovation from state, local, and tribal governments. Strong and predictable policy frameworks support private investment in innovation and deployment of carbon pollution-free technology and infrastructure, spurring markets that drive continued progress. All levels of government and the private sector will partner to drive and implement this NDC and create a more equitable, resilient, zero carbon future for the American people.

2.3.3 State Climate Policies in the US

In the midst of the changing federal landscape and policies on climate change leading up to the US rejoining the Paris Agreement in 2021, various cities, towns, counties, and regional authorities either began or continued action in accordance with the Paris Agreement and the original 2015 US NDC (ICLEI USA, 2017). It is noteworthy that several local communities in the US had already instituted ambitious goals for decarbonization as shown in Figure 7. ICLEI USA, an organization providing services and resources to help communities develop sustainability plans, offered several decarbonization strategies for various economic sectors that could be influenced by local political jurisdictions. These sectors included energy supply, energy demand, industrial processes and product use, agriculture, land use change and forestry, waste management, and transportation. Recommended strategies and actions are similar to those discussed earlier. Some of the recommended actions specifically relevant to buildings and development projects include (ICLEI USA, 2017):

- Establish innovative financing for energy efficiency and renewables projects;
- Streamline the approval and permitting process for building-mounted solar panel systems;
- Consider leasing roof space from industrial and commercial buildings to generate residential solar energy;
- Curtail expansion of natural gas infrastructure to new service areas and advocate for state renewable energy policies such as renewable portfolio standards, net metering, and virtual power purchase agreements;
- Require municipally owned and private developed new construction to meet a transparent building rating requirement, such as LEED Gold or Platinum;
- Participate in model energy code development and retrain inspectors to ensure proper enforcement;

- Require solar generation on new construction with optimal building & PV panel orientation
- Institute a green roof or cool roof requirement or program;
- Require energy use disclosure for all buildings more than 10 years old;
- Pursue energy efficiency as the “first fuel” for meeting energy needs of existing structures by supporting efficiency programs and weatherization/efficiency retrofit programs; and,
- Environmental purchasing policies to promote growth of circular economic businesses and purchasing based on environmental impacts and lifecycle costs.

Box 2
A sampling of several cities and towns with ambitious, community-wide emissions-reduction targets, as reported through the carbon*n* Climate Registry.

Jurisdiction	Emissions reduction target
Atlanta, GA	20% by 2020 and 80% by 2040, below 2009 levels
Boulder, CO	80% by 2050, below 2017 levels
Broward County, FL	17% by 2020 and 82% by 2050, below 2005 levels
Cincinnati, OH	40% by 2028 and 84% by 2050, below 2006 levels
Hayward, CA	82% by 2050, below 2005 levels
Minneapolis, MN	30% by 2025 and 80% by 2050, below 2006 levels
Olympia, WA	45% by 2035 and 80% by 2050, below 1990 levels
Philadelphia, PA	45% by 2035, below 1990 levels
Portland, OR	40% by 2030 and 80% by 2050, below 1990 levels
Urbana, IL	25% by 2020 and 80% by 2050, below 2007 levels

Figure 7. US cities and towns implementing ambitious decarbonization targets in 2017
Source: ICLEI USA, 2017

Initiated by the governor of the State of California and a core group of philanthropic partners together with two founding States of Washington and New York, the U.S. Climate Alliance (USCA) has become a bipartisan coalition of state governors now including 24 states representing more than half of the US GDP and population. Its member States make the following commitments:[28]

> U.S. Climate Alliance states are committed to taking real, impactful, on-the-ground action that urgently addresses the climate challenge. In becoming an Alliance member, states commit to achieve the Paris Agreement’s goal of keeping temperature increases below 1.5 degrees Celsius by:
>
> - Reducing collective net GHG emissions at least 26-28 percent by 2025 and 50-52 percent by 2030, both below 2005 levels, and collectively achieving overall net-zero GHG emissions as soon as practicable, and no later than 2050.
> - Accelerating new and existing policies to reduce GHG pollution, building resilience to the impacts of climate change, and promoting clean energy deployment at the state and federal level.
> - Centering equity, environmental justice, and a just economic transition in their efforts to achieve their climate goals and create high-quality jobs.

[28] http://www.usclimatealliance.org/ , last accessed 8/2/2022

- Tracking and reporting progress to the global community in appropriate settings, including when the world convenes to take stock of the Paris Agreement.

A wave of U.S. climate leadership is answering the global call to action to combat the climate crisis. Cities, states, and communities across the U.S. are executing bold, ambitious plans to reduce national emissions, even in the absence of federal leadership. This rapidly expanding coalition is showing the world that the transition toward a transformed, clean economy generates opportunities and extensive benefits for economies, communities, and ecosystems.

The USCA has published numerous guide books to help states achieve the above commitments.[29] A brief summary of key findings and recommendations from a selection of these guides follows:

- *2022 Enabling Industrial Decarbonization* (USCA, 2022a) – This guidebook addresses one of the largest contributors to carbon emissions in the US and worldwide, accounting for 34% of total carbon emissions, yet receiving little comparative attention. The industry sector is projected to become the largest national source of GHG emissions by 2030 necessitating more than just incremental action to meet climate goals by 2050. The guide reports: "Onsite fossil fuel combustion, mostly used for process heat generation, accounts for over half of industrial direct emissions. The majority of the sector's remaining direct emissions is a result of utilizing fuels in production (e.g., feedstock fuels like natural gas used to make plastics); chemical reactions that release carbon dioxide as a byproduct during the production of chemicals, iron and steel, and cement; and natural gas system leaks." The guide also acknowledges that many states have adopted over 100 relevant policies including material embodied carbon limits through Buy Clean procurement policy and building code policy to indirectly influence industry decarbonization. It notes that the collection of policies may provide valuable perspective for national discussion. The states mentioned include Colorado, Massachusetts, Maine, California, Louisiana, Michigan, Washington, Wisconsin, Minnesota, New York, New Jersey, and Oregon. Finally, as shown in Figure 8, the guidebook "… recommends that state policymakers consider five cross-cutting strategies — or pillars — for industrial decarbonization. These pillars include: (1) efficiency; (2) electrification; (3) low-carbon fuels and feedstocks; (4) carbon capture, utilization, and storage technologies; and (5) procurement." While the first 4 pillars address physical changes to industrial processes and their energy sources to avoid or offset CO2e emissions, the fifth pillar seeks to create "opportunities to drive demand and create new markets for low-carbon industrial products." Policy options and considerations address planning, research, carbon pricing, standards, and others. "Heavy industry" subsectors addressed include chemical production, petroleum refining, iron and steel production, cement production, and glass production.[30] Light industries addressed include forest products and food & beverage processing. Figure 8 shows a diagram representing the interaction of the guidebook's strategic decarbonization pillars and policy options.

[29] For various USCA guides and resources, refer to: http://www.usclimatealliance.org/publications-1

[30] These industry decarbonization strategies also have a direct relationship to actions in the 2021 Buildings Decarbonization Roadmap (USCA, 2021a) because by reducing the carbon-emissions of industrial processes it will serve to reduce the embodied emissions associated with various materials such as steel, concrete (mainly cement), and other materials that require energy-intensive manufacturing processes. So, for example, the goal to lower the embodied carbon emissions attributed to building materials is largely served by policy that invests in and helps enable industrial decarbonization. However, the use of Buy Clean policies are cited as examples to address industrial or material embodied carbon emissions. It is noteworthy that process and material efficiency gains are considered most cost-effective yet have limitations (about 20 percent emission reductions available) that will eventually require deeper and more intensive capital investment to cause physical infrastructure transformation to occur over longer timeframes. Consequently, it is for this reason that Buy Clean policies consider a progression of moving targets for material embodied carbon levels in keeping with available technology and market capability to respond in a manner that protects consumer price stability and functionally competitive product availability.

<table>
<tr><th></th><th>Efficiency</th><th>Electrification</th><th>Low Carbon Fuels & Feedstocks</th><th>Carbon Capture</th><th>Procurement</th></tr>
<tr><td rowspan="3">Planning & Governance</td><td colspan="5">State emissions and efficiency targets</td></tr>
<tr><td colspan="5">State analysis and roadmaps</td></tr>
<tr><td colspan="5">State governance structures</td></tr>
<tr><td rowspan="2">Research, Development, Demonstration, & Deployment</td><td colspan="4">Direct investment</td><td>Pilot projects</td></tr>
<tr><td colspan="4">Tax credits</td><td>Product life cycle assessments</td></tr>
<tr><td rowspan="3">Carbon Pricing</td><td colspan="5">Regulated carbon markets</td></tr>
<tr><td colspan="5">Carbon taxes</td></tr>
<tr><td colspan="5">Border carbon adjustments</td></tr>
<tr><td rowspan="2">Incentives</td><td colspan="5">Financial incentives (incl. grants, rebates, cash)</td></tr>
<tr><td colspan="5">Financing (incl. loans, bonds, green banks)</td></tr>
<tr><td rowspan="3">Standards</td><td colspan="5">Emissions standards</td></tr>
<tr><td>Efficiency standards</td><td colspan="2">Clean heat standards</td><td rowspan="2">Carbon management standards</td><td>Clean product standards</td></tr>
<tr><td>Circularity and recycling standards</td><td colspan="2">Clean fuel standards</td><td>Embodied emissions standards</td></tr>
<tr><td rowspan="7">Supporting Policies</td><td>Strategic energy management</td><td colspan="4">Low-carbon infrastructure investment</td></tr>
<tr><td colspan="2">Technical assistance</td><td colspan="3">Low-carbon material procurement</td></tr>
<tr><td colspan="5">Labeling and certification</td></tr>
<tr><td colspan="5">Emissions disclosure and monitoring</td></tr>
<tr><td colspan="5">Equity and environmental justice</td></tr>
<tr><td colspan="5">Diverse workforce development</td></tr>
<tr><td colspan="5">Industry clustering</td></tr>
</table>

Figure 8. Matrix of state policy measures aligning with the 5 pillars for decarbonization (table column headings) of industry recommended by the U.S. Climate Alliance.
Source: USCA, 2022a

As stated in the guide: "Designing effective decarbonization policy depends on a foundation of robust energy and GHG emissions data. In the United States, the Greenhouse Gas Reporting Program (GHGRP) requires facilities emitting over 25,000 metric tons CO2e per year to report their emissions to the EPA. This threshold applies to about 7,600 electric and industrial facilities and 1,000 fuel/gas suppliers, accounting for nearly 90 percent of total national GHG emissions… Some states have developed their own compulsory disclosure schemes to meet specific policy needs." The states enacting GWG emissions reporting programs include California and Colorado, and Louisiana, New York, and Washington have proposed similar programs.

Finally, the guide acknowledges the benefits of new federal programs:

> "New federal programs and investments enabled by recent legislation offer significant opportunities for states to share information, collaborate on best practices, and implement and scale technologies to decarbonize their industries. A DOE analysis found that the combination of programs and incentives in the *Inflation Reduction Act* (IRA) and *Infrastructure Investment and Jobs Act* (IIJA) will reduce national GHG emissions by almost 1,150 MMT CO2e by 2030, with industrial emissions reductions representing the second-largest driver of the reductions."

- *2022 The Social Cost of Greenhouse Gases* (USCA, 2022b) - This publication provides an excellent review of the social cost of greenhouse gases (SC-GHG) with examples and guidance for its use for climate policy evaluation. It is similar to the prior discussion on the SC-CO2 (Rennert et al. 2022) with the major difference being that the SC-GHG includes the impacts of other greenhouse gases such as Methane (CH_4) and Nitrous Oxide (N_2O) and a different IAM model and damage functions were referenced in the USCA publication. Also, the report makes a case for considering global damage costs (not just those within the borders of a given nation) in assigning value to SC-GHG for US climate policy development and addresses other points of contention, such as an appropriate discount rate, which are often raised with regard to adopting a specific SC-GHG estimate. It relies on updated SC-GHG valuations determine by the Interagency Working Group on Social Cost of Greenhouse Gases (OMB, 2021) which pre-date the more recent work of Rennert et al. (2022) addressed earlier in this report (Section 1.4). Consequently, the reported average values for SC-GHG (2023 USD) are considerably lower than those estimated by Rennert et al. (2022) and also do not consider the preferred discount rate of 2.0%.
- *2021 Building Decarbonization Roadmap* (USCA, 2021a) – This roadmap is described as "a tool designed to summarize the highest-impact actions that states can take to decarbonize buildings." It describes building sector decarbonization as hinging on five core principles: (1) energy efficiency, (2) electrification, (3) grid-interactivity, (4) low-carbon fuels as needed, and (5) low-embodied carbon materials and reuse of carbon-intensive materials and structures where possible.

  Two key strategies for any substantive building decarbonization action are (1) fostering zero-carbon new construction and (2) establishing existing building and replacement equipment requirements. Supporting strategies include transforming the energy market, supply chain changes to support low-carbon approaches, and access to capital to address barriers to low-carbon solutions as addressed in other USCA guides. For example, decarbonization of industry (USCA, 2022a) will serve to reduce embodied carbon emissions that occur largely during raw material extraction and manufacturing and which are "assigned" to the material as embodied carbon. Thus, it could be argued that the primary policy investment related to building materials (or many other products) should be in helping industry overcome its key barriers to decarbonization (e.g., availability and cost of alternative low-carbon or renewable fuels to power high-heat manufacturing processes). This would potentially avoid costly inefficiencies of attempting to track materials and employ strategies in various regulatory instruments to account for re-assigned carbon emissions in the downstream market place.

  Greenhouse gas emissions are categorized as: (1) operating emissions from building energy consumption including both direct (on-site) emissions from burning fossil fuels (e.g., gas furnaces, appliances, and water heaters) and indirect emissions (e.g., electricity generation emissions offsite including the impact of energy lost in transmission to the site); (2) embodied emissions which represent the GHG emissions associated with manufacturing of building materials; and (3) refrigerant emissions or leakage known as "fugitive emissions" from HVAC equipment (e.g., air conditioners and heat pumps, including heat pump water heaters).

  Buildings account for about 40% of total global annual CO2 emissions including direct and indirect emissions. In the US it is reported that 60% of total annual building sector emissions are indirect emissions (e.g., electricity), 25% are direct emissions (e.g., fuel combustion on site), and about 12.5% are embodied emissions as reportedly based on a preliminary assessment of data from IEA and embodied emissions data from Architecture 2030 internal analysis.[31] Of the direct emissions from building operations, roughly 67% (two thirds) are from space heating. Water heating and cooking/other account for 19% and 13%, respectively.

[31] See Table A and Figure A in Executive Summary showing embodied emissions for all US building materials produced annually (excluding other construction material applications) is about 4% of total annual US GHG emissions or about 0.4% of total annual global GHG emissions.

As reported for materials used in infrastructure construction: “From 2008 to 2018, public infrastructure projects accounted for 32 percent of the total embodied carbon emissions from construction in the United States—over 150 million metric tons (MMT) CO2e per year.”[32]

Building decarbonization is presented as a “strong investment” with benefits including: job creation and economic development, improved health and safety, enhanced equity, increased resiliency and security, and increase value of the building stock. Various policy actions are presented including legislative, regulatory, and other actions including decarbonization planning and commitments. A menu of transformative policy concepts is provided including, but not limited to, the following:

- New construction built to a low-carbon standard with high efficiency which is typically the lowest cost energy resource by requiring less energy from onsite renewables or grid power; both prescriptive and flexible performance pathways (e.g., energy use intensity or EUI limits) should be included with accommodations for affordable housing; other features should include electric vehicle (EV) charging, on-site renewable energy provisions , demand response and load flexibility, low-embodied carbon materials, and stretch codes such as Passive House standards; enforcement and training is also considered important. California, Washington and Massachusetts, including San Jose and Seattle, are cited as examples of instituting these types of building code features;
- All electric construction (or alternative low-carbon and renewable fuels where electrification is not feasible);
- Set energy use or GHG emissions intensity limits for certain building types through mandatory building performance standards (BPS) to address the worst-performing buildings in the existing building stock; currently four cities (St. Louis, New York, Reno, and Boulder) and the state of Washington have a BPS in place. New York City’s approach is the only one based on CO2e emissions intensity; the BPS can decouple on-site direct energy emissions (e.g., gas, diesel, propane) and electricity indirect emissions such that emissions intensities can be separately adjusted to encourage electrification. BPS necessitates building energy benchmarking and disclosure policies, although benchmarking can come first to inform the market and future policy. Several cities (Boulder, Washington DC, New York City, Reno, and St. Louis) and the state of Washington have adopted BPS provisions including benchmarking for certain existing building types and sizes;
- Higher efficiency standards for HVAC equipment, appliances, and lighting (although this may experience the barrier of federally mandated equipment minimum efficiencies unless pursued perhaps through the authority of air quality or health and safety laws rather than building code or energy efficiency laws);
- Establish energy efficient resource standards (EERS) on the basis of total energy or avoided GHG emissions rather than separately addressing gas and electric such that utility incentives are aligned;
- Building performance benchmarking, measurement, disclosure, and transparency to arm decision-makers with the knowledge to reduce emissions;
- Consumer awareness of clean efficient options and incentives available in the market;
- Provide leadership by taking decarbonization action on public buildings;
- Provide financial mechanisms to motivate market actors and develop markets for low-carbon building technologies; and,

[32] See Table A and Figure A in Executive Summary showing embodied emissions for all US non-building construction materials produced annually is about 2% of total annual US GHG emissions or about 0.2% of total annual global GHG emissions.

- Pursue low-embodied carbon materials and low-GWP refrigerants as operational emissions decline in relative significance to total emissions.[33] Examples state policies include California's Buy Clean Act, Marin County, California's low-embodied carbon concrete code, and the AIM Act authorizing the EPA to regulate a group of 20 HFCs used for refrigerants.

- *2021 Governors' Climate Resiliency Playbook* (USCA, 2021b) – Climate resiliency addresses the ability to cope with the future effects or risks (e.g., hazard, exposure, and vulnerability) exacerbated or incrementally worsened by climate change caused by anthropogenic GHG emissions. Consequently, it is associated with the need for adaptation in a way that promotes resiliency in an equitable and effective manner. This guide outlines 12 steps to resilience as a model for state and local implementation. Some of the resiliency strategies directly overlap with decarbonization strategies like improved building envelope performance to reduce operational emissions while also making the building more resilient to extreme cold or heat, especially during periods where power supply is interrupted by extreme weather.

The USCA website also features fact sheets describing its member states' various policies, actions, and impacts toward meeting or exceeding their obligations to the alliance.[34] In general, the member states' actions are consistent with the direction and types of policy measures represented in the guidebook publications of the U.S. Climate Alliance (a few of which were reviewed above). Consequently, they are generally consistent with the 2021 US NDC and the goals of the Paris Agreement.

2.3.4 NASEM Plan for US Federal Climate Policy

The National Academies of Sciences, Engineering, and Medicine (NASEM) has produced an interim report to guide federal climate policy and accelerate decarbonization of the US energy system in view of the climate science, the Paris Agreement, and the 2021 US NDC (NASEM, 2021):

> Against this backdrop, the National Academies of Sciences, Engineering, and Medicine appointed an ad hoc consensus committee to assess the technological, policy, and social dimensions to accelerate the deep decarbonization of the U.S. economy and recommend research and policy actions in the near to midterm. This interim report focuses on the first 10 years of a 30-year effort—a comprehensive report covering the final two decades will follow in a year. In this interim report, the committee identifies technological actions required during the 2020s to put the United States on a trajectory to net zero by midcentury while still maintaining optionality. Most importantly, the interim report provides a manual for the federal policies needed to enable these technological actions and to build a non-emitting energy system that will strengthen the U.S. economy, promote equity and inclusion, and support communities, businesses, and workers.

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[33] Regarding embodied carbon in materials, the USCA (2021a) guide states the following:

> "For a typical building, embodied carbon may equal 10 to 15 years of operating emissions; with contemporary, high-efficiency buildings, it can equal 50 years of operating emissions. Low-embodied-carbon strategies address the life cycle carbon emissions associated with building materials, from resource extraction to end-of-life. Solutions include embodied carbon limits in new buildings, waste handling requirements, financial instruments (e.g., low-embodied-carbon loans or incentives), and more. Design decisions that minimize the amount of material needed and limit the over-specification of materials can also substantially lower the amount of embodied carbon associated with a project.
>
> Products that sequester carbon in the material itself (e.g., low-emissions concrete) may also represent an important emerging strategy and could make net-negative-carbon buildings possible in the future. At the same time, while many people think of using low-carbon or carbon-sequestering products as the primary method for decreasing embodied carbon, a much wider array of strategies is available. Policies can generally achieve earlier and more impact by focusing on pathways such as refurbishing buildings or finding ways to avoid the need for new construction entirely.
>
> Reducing embodied carbon reduces the acoustic, PM2.5, and health harm caused by machinery and dust, manufacturing, and road transport. It can also lead to less area destroyed by resource extraction, more job creation, and less congested landfills. Particular low-embodied-carbon strategies can also provide their own specific benefits. For example, mass timber, a low-carbon alternative to certain steel and cement applications, is safer during fires than these other materials can be. It is also often faster to assemble on-site, which shortens construction schedules and saves costs. Some concrete admixtures can reduce the amount of carbon-intensive cement needed while improving the product's workability and strength."

[34] To access the USCA's fact sheets on member states' actions, refer to: http://www.usclimatealliance.org/state-climate-energy-policies

The NASEM report addresses following over-arching and inter-related goals:

Technological Goals
- Invest in energy efficiency and productivity.
- Electrify energy services in transportation, buildings, and industry.
- Produce carbon-free electricity.
- Plan, permit, and build critical infrastructure.
- Expand the innovation toolkit.

Socioeconomic Goals
- Strengthen the U.S. economy.
- Promote equity and inclusion.
- Support communities, businesses, and workers.
- Maximize cost-effectiveness.

Regarding the "maximize cost-effectiveness" socioeconomic goal, it is noteworthy that the report's cost-effectiveness objective is not to find an optimal policy goal to limit global warming (as pre-determined by the Paris Agreement and the 2021 US NDC – also without consideration of cost-benefit optimization – see the earlier discussion on the social cost of carbon in Section 1.4 of this report). Instead, the NASEM report states that it seeks a "least-cost" path to a pre-determined objective (that is itself not cost optimized) while at the same time acknowledging the importance of cost-effectiveness to society:

> "This goal begins with an objective to be accomplished—in this case, achieving a net-zero economy by 2050—and finding the least-cost (or most cost-effective) path to accomplish it. Here, the cost of a particular policy is the material consumption that households must give up, including any changes in taxes or government services, to achieve net-zero emissions. A policy's cost-effectiveness measures how this cost compares to the least-cost alternative that achieves the same net-zero outcome and associated benefits. Cost-effectiveness is important because society has multiple objectives, including material well-being. If the country can avoid spending more than necessary in order to achieve net-zero emissions, additional resources are available for other aspirations. However, cost-effectiveness analysis ignores how costs and benefits are distributed within an economy. A U.S. net-zero policy will necessarily need to balance cost-effectiveness with equity and other goals."

The technical goals are summarized as follows (NASEM, 2021):

> **Invest in energy efficiency and productivity.** Over the next 10 years, energy used for space conditioning and plug loads would be reduced in existing buildings by 3 percent per year and total energy use by new buildings reduced by 50 percent. The rate of increase of industrial energy productivity (dollars of economic output per unit of energy consumed) would be increased from a recent pace of 1 percent per year to 3 percent per year. Note that energy efficiency in transportation, buildings, and industry overlaps with electrification, because switching to electric heat pumps and motors also significantly increases the efficiency of heating and transportation relative to fossil-fueled boilers and internal combustion engines. Further, electrification provides opportunities to install broadband and smart grid technologies that enable demand-side management and grid optimization. Also, improvements in efficiency and productivity help to reduce the power loads for equipment, which can reduce the cost of capital and operations lowering hurdles for electrification in these sectors.
>
> **Electrify energy services in transportation, buildings, and industry.** The most significant actions to accomplish this goal are as follows: reach zero-emissions vehicles as approximately 50 percent of new vehicle sales across all classes by 2030 (light, medium, and heavy); increase the share of electric heat pumps for heating and hot water to 25 percent of residential and 15 percent of commercial buildings, replacing fossil furnaces and boilers; initiate policies for new construction to be all electric in all practical climate zones; and transition low- to moderate-temperature process heat sources to low-carbon electrical power (e.g., by replacing or supplementing conventional units with electric boilers, heat pumps, or noncontact thermal sources such as infrared or microwave) totaling approximately 10 GW of capacity.

Produce carbon-free electricity. During the 2020s, the nation would need to roughly double the share of electricity generated by non-carbon-emitting sources to roughly 75 percent by 2030. Until 2025, this would require an average pace of wind and solar installation that each year matches or exceeds the record historical yearly deployment of these technologies and accelerates to an even faster pace from 2025 to 2030. Emitting coal plants would continue to retire at the current or an accelerated pace. Existing nuclear plants would be preserved wherever it is possible to continue safe operations. Emitting gas-fired generation would decline 10 to 30 percent by 2030 and total capacity would be roughly flat. Some new gas-fired capacity in certain regions could be built during the 2020s to replace aging assets, including coal, because it is more economical than coal regardless of age and can be used to replace aging assets and where coal retirements require replacement capacity for reliability purposes, and where new gas capacity is prepared to retire by 2050 or retrofit to combust hydrogen or be equipped with carbon capture.

Plan, permit, and build critical infrastructure. Build or upgrade electrical transmission facilities to increase overall transmission capacity (as measured in GW-miles) by as much as 60 percent by 2030 to interconnect and harness low-cost wind and solar power across the country. Accelerate the build-out of the nation's electric vehicle (EV) recharging network, including at least 3 million Level 2 chargers and 120,000 DC fast chargers by 2030. This infrastructure should be a mix of private and public ownership and operation, including fleet operators. Plan and initiate a national CO2 transport and storage network to ensure that CO2 can be captured at point sources across the country, including in industry, power generation, and low-carbon fuels production (including hydrogen).

Expand the innovation toolkit. The committee proposes a tripling of federal investment in clean energy RD&D to provide new technological options, to reduce costs of existing options, and to better understand how to manage a socially just energy transition. Innovations that would fundamentally enhance the net-zero transition include next-generation energy systems for transportation, buildings, and industry; improved energy storage and firm low-carbon electricity generation options to complement variable renewable electricity; low-cost zero-carbon fuels including hydrogen from the electrolysis of water or biomass gasification; lower-cost carbon capture and use technologies; and lower-cost direct air capture. Progress is needed in particular on net-zero options for aviation, marine transport, and the production of steel, cement, and bulk chemicals. As important will be innovations in how federal policies and programs support RD&D, particularly for technologies in the demonstration and deployment stages.

Please note that some regulatory reform will be necessary to achieve many of the above technological goals. In particular, timely siting and permitting of the new electricity transmission infrastructure is likely to prove difficult or impossible without regulatory reform. Also, the above goals reflect the committee's judgment that a net zero energy system able to meet the nation's projected business-as-usual demand for energy services will be much easier to achieve than one requiring dramatic reductions in demand for energy services. Thus, the goals do not include greatly reduced mobility or home size.

Toward the above goals, a suite of policy actions were developed and presented in detail, including a cost assessment for needed private sector investment and federal government funding. While the policies focus on actions needed in the next 10-year horizon (2020s), they are intended to set the stage for future policy actions that ultimately serve the goal of attaining a net-zero emissions economy by 2050. A sampling of some of the recommended federal policy actions are as follows:

- Federal funding for Executive and Congressional branches to administer adherence to the US CO2 and GHG emissions budget (including emissions disciplinary action for missing the target);
- Economy-wide price on carbon (social cost of carbon) established by Congress starting at $40/tCO2 and rising 5% per year for a total of ~$2 trillion in tax revenue from 2020 to 2030. The price level is not designed to alone directly achieve net-zero emissions. Hence, it is coordinated with other more focused regulatory policy actions that follow below;
- Establish various governmental entities, such as tasks forces and an independent national transition corporation, to equitably navigate social impacts of the net zero transition and provide funding to areas of need in an equitable manner; including involvement of regional and state entities to administer grants that are guided by environmental justice principles (see the NASEM report for various policy details);

- Set clean energy standards to transition electricity generation to 75% zero-emissions by 2030 and then to 100% net zero by 2050;
- Set standards for all vehicles and strengthen Corporate Average Fuel Economy (CAFE) standards. The standard for zero-emission vehicles (ZEV) ramps to 50% of sales for light-duty vehicles and 30% of heavy-duty vehicles by 2030;
- Set standards for zero-emission appliances including hot water, heating, and cooling; ramp up to 100% all electric in 2050;
- Enact three near-term actions on new and existing building energy efficiency (two by DOE related to efficiency, carbon-neutral new and existing buildings, and carbon benchmarking standards and one by GSA related to emissions cap for new and existing federal buildings, prioritizing high-reduction low-cost actions);
- Enact five federal actions to advance clean electricity markets, and to improve their regulation, design, and functioning (including EV charging network and broadband for advanced metering in separate actions);
- Establish an environmental product declaration (EPD) library to create an accounting and reporting infrastructure to support the development of a comprehensive Buy Clean policy;
- Plan and assess requirements for CO2 transport and geologic storage in reservoirs with fair public input;
- Establish education and training for a diversified net-zero workforce;
- Revitalize clean energy manufacturing through subsidies and loans and eliminate support for fossil technology exports;
- Increase clean energy and net-zero transition research, development, and demonstration that integrates equity indicators; and,
- Increase funds for low-income households for energy expenses, home electrification, and weatherization (including separate appropriations for electrification of tribal lands).

Regarding the carbon pricing policy recommendation listed above, the NASEM report states the following (NASEM, 2021, p.12):

> The committee proposes an **economy-wide price on carbon beginning at $40/t CO2 and rising by 5 percent per year**. The advantages of an economy-wide price on carbon are that it would unlock innovation in every corner of the energy economy, send appropriate signals to myriad public and private decision makers, and encourage a cost-effective route to net zero. However, assuming that the country implements a carbon price before key trade competitors, a mechanism that levels the playing field for domestic firms and avoids emissions leakage will be necessary. Also, because the direct impacts of an economy-wide price on carbon would fall disproportionately on people with the lowest incomes and the fewest choices, it should be augmented by rebates and by funding programs that promote a fair and just transition. The proposed carbon price is deliberately set at a level that would not by itself cause a 30-year transition to net zero because of concerns about equity, fairness, and competitiveness. For example, the committee was not confident that it could design a package of policies that would address competitiveness and mitigate unfair impacts of a carbon price that starts at or climbs rapidly to $100/tCO2.

While acknowledging the simplicity and potential effectiveness of a policy approach that relies exclusively on a social cost of carbon tax, it advises that a partial reliance on SC-CO2 coupled with additional government interventions are necessary for a number of reasons including the following (NASEM, 2021, pp.38-39):

> An economy-wide price on carbon tends to be the most cost-effective option in this narrow sense, but cannot by itself address a host of important issues that will inevitably arise, including the need to protect historically disadvantaged communities, communities adversely affected by the energy transition, and U.S. manufacturing

> that competes in a global transition. For example, if the United States begins the transition before some of its economic competitors without such protections in place, both domestic manufacturing and CO2 emissions may simply shift overseas.
> …
> Last, a high carbon price would likely be required to drive the economy to net-zero emissions using carbon pricing alone. Based on existing studies, it is unclear whether competitiveness and equity concerns can be convincingly addressed at such high prices. Therefore, the committee chose to limit the carbon price and turn to other policies, with some loss of cost-effectiveness, in order to manage these concerns.

Interestingly, the additional government interventions mentioned above are themselves funded by taxes, so it must be assumed that the authors' felt that the existing US tax code provides a more socially equitable means of distributing the cost of climate policy than would be achieved by a carbon tax alone or variants of a properly implemented carbon tax. Not much information is provided regarding the analysis supporting this conclusion other than to say that it is "unclear" based on existing studies. However, the matter of a carbon tax and its appropriate implementation has been given at least some bi-partisan consideration in the US Congress as a viable means to both promote and fund decarbonization.[35]

The NASEM report identifies and describes five critical actions for the first 10 years (NASEM, 2021, p71-79):

1. Invest in energy efficiency and productivity.

- increased fuel efficiency of on- and off-road vehicles
- **increased efficiency of building enclosures, appliances, and equipment ; including use of on-site renewable energy and maximum 20% purchased off-site renewable energy; work toward passive house energy standards of 5-60 kBtu/ft^2/yr (depending on building type and climate); reduce peak loads through load shifting in both new and existing buildings; achieve a 30% reduction in overall energy demand by 2030**
- enhanced energy productivity in manufacturing and other industrial processes, including power generation
- materials efficiency (e.g., recycling and reuse)
- deliver 25% reductions in industry sector energy use by various efficiency measures
- **decrease embodied energy in products and building materials by a minimum 30 percent, particularly for high-carbon-intensive building and infrastructure materials**

2. Electrify energy services in buildings, transportation, and industry sectors in tandem with decarbonization of electricity generation.

- **For buildings, the primary electrification action is to switch to high-efficiency heat pumps** (25% of current residences or 25-30 million households by 2030 and 15% of commercial buildings). Focus on stock turnover and new builds in Climate Zones 1-5, planning for 100 percent of sales by 2030. Also, switch to heat-pump water heaters when existing stock reaches end-of-life, ramping up to 100 percent of new sales by 2030.
- For transportation, focus on electric vehicles with 50 percent of new vehicle sales and 15 percent of fleet vehicles by 2030. Also, expand opportunities for renewable transportation fuels to prepare for 2030 and beyond.
- **For Industry, advance proportion of electric for process heat production**, use of heat pumps, and other electric heating technologies for low-temperature heat applications, including electric boilers, etc.

3. Produce carbon-free electricity.

- **Double the share of carbon-free electricity generation from 37% today to 75% by 2030**
- At least double wind power generation by 2030 and approximately quadruple solar power generation by 2030 to supply 50% of electricity generation (up from 10 percent in 2020)

[35] Patnaik, S. and Kennedy, K., "Why the US should establish a carbon price either through reconciliation or other legislation," Brookings Institute, October 7, 2021. https://www.brookings.edu/research-commentary/ (last accessed 11/6/2023)

- Manage or accelerate retirement of coal-fired power plants
- Preserve Nuclear power and employ small modular reactors by late 2020s
- Moderate decline in gas-fired power plants to maintain reliability as coal retires while avoiding new commitments to natural gas pipeline infrastructure.
- Deploy energy storage capacity through 2030 to integrate with variable wind and solar power among other benefits

4. Plan, permit, and build critical infrastructure and repurpose existing energy infrastructure.

- Policy actions include expanding EV-charging network, long-distance electricity transmission to support corridors for wind and solar deployment, expand automation and controls to enable greater demand response for EV charging, space and water heating loads, etc.
- For actions related to fuels (e.g., hydrogen infrastructure) and industry (e.g., hydrogen applications), and carbon capture, utilization and sequestration (CCUS), refer to the NASEM (2021) report.

5. Expand the innovation toolkit through significant investment in RD&D in the areas of electricity generation, industry, energy storage, net-zero carbon fuels, CCUS, and other needs.

For buildings, the following specific actions are recommended based on emissions data shown in Figures 9 and 10 after re-assigning originating sources of emissions by attributing them to end-use sectors, such as buildings, as indirect emissions (NASEM, 2021, p93-94):

> Building demand reduction presents the largest opportunity to reduce energy demand, as critical to decarbonization as reducing emissions from energy supply. Commercial and residential buildings use 39 percent of total U.S. energy and are responsible for over 35 percent of total U.S. greenhouse gas emissions (EPA, 2020). The built environment can significantly reduce its energy demand, its share of electricity demand, and its embodied carbon. To enable intelligent policy and investment in demand reduction in the building sector, emissions from residential and commercial buildings should be considered together (Figure 2.3.1a) and should consider all associated electricity energy use and emissions (2.3.1b), as well as the embodied carbon in their use of steel, concrete, aluminum, and plastics (2.3.1c). Improvements in the built environment can dramatically reduce energy demand while optimizing asynchronous energy supply (often via thermal storage) and providing measurable gains for productivity, health, and environmental quality.
>
> As evident in the benchmarking data from Seattle displayed in Figure 2.3.2, the worst performing buildings use 2.5–8 times more fossil fuel and electricity than the best performing ones. Demand reductions of 40 percent are easily achievable by 2030, and 80 percent reductions in building energy use intensity (EUI) are achievable by 2050 in the United States, combining new and retrofit construction. Moreover, these massive reductions in demand are some of the most cost-effective investments for decarbonization (McKinsey and Company, 2013).

More importantly, re-assigning originating sources of emissions to buildings and building materials creates inefficiencies and a potential “double-counting” problem with policies aimed broadly at decarbonization. For example, policies aimed at originating sources of fossil fuel combustion (e.g., electric power generation, transportation, and industry) which are the primary sources of emissions are potentially duplicated by policies that are aimed at downstream assignment of those same emissions in a re-attribution accounting scheme. While there are certainly actions that can and should be taken at downstream end-uses to minimize upstream GHG emissions in the current primary energy supply situation, those should be secondary to an emphasis on policy and efficient use of available funds directly aimed at addressing challenges and needs at the level of the originating sources of emissions.

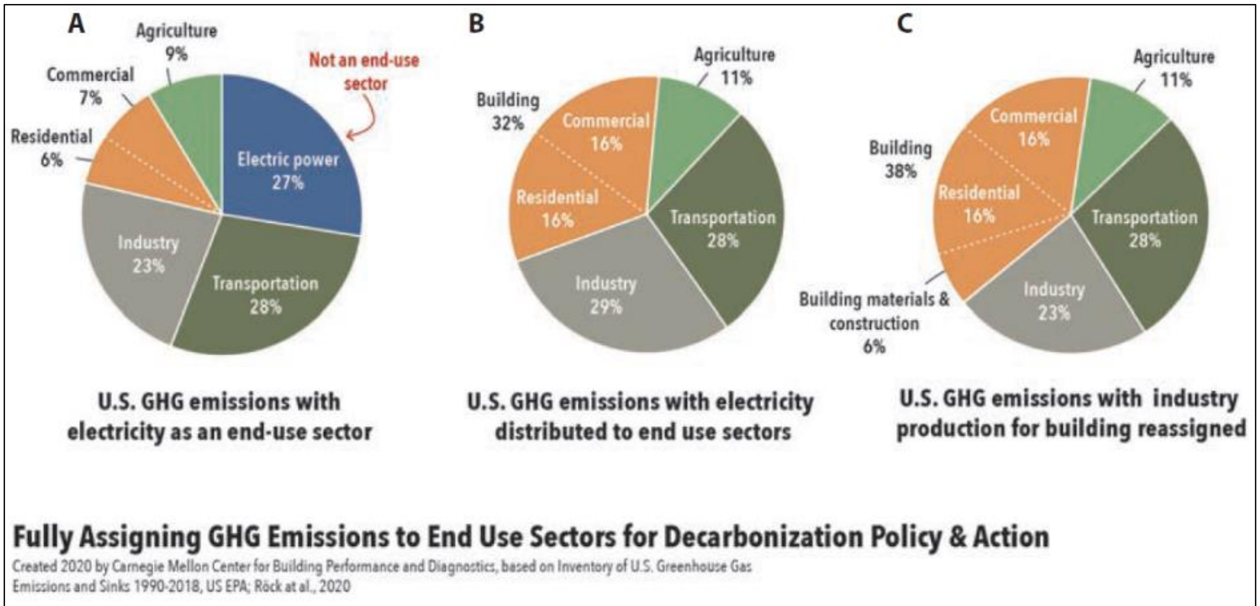

FIGURE 2.3.1a,b,c Collecting all building-related GHG emissions reveals that 38 percent of the environmental challenge is in building construction and operations.
SOURCE: Data from Carnegie Mellon Center for Building Performance and Diagnostics (2020).

Figure 9. Re-assignment of US sector emissions to end-use sectors based on 2018 data.
Source: NASEM (2021)

FIGURE 2.3.2 Variation in source energy use intensity (EUI) in five building types.
SOURCE: Committee generated using data from Sullivan (2019).

Figure 10. Range in Energy Use Intensity (EUI) of Buildings based on Seattle, WA data.
Source: NASEM (2021)

In Part 3 of this report, it will be clearly shown that about 80% of the US energy consumption and over 90% of US CO2 emissions (or about 73% of total gross US GHG emissions) are associated with the combustion of fossil fuels. And, the vast majority of these fossil fuel combustion emissions are associated with electricity generation (coal and natural gas), industry (mostly natural gas and some petroleum), and transportation (petroleum). Buildings are in a distant fourth place when the re-assignment of source emissions are not double counted (e.g., the same emissions originating from and assigned to electricity generation and industry from primarily fossil fuel combustion are not duplicated by also assigning them to residential and commercial buildings). If not carefully understood, the re-attribution of emissions can obscure the relative importance and effectiveness of different policy-making decisions and investments to decarbonize.

It is worth noting that the IPCC (2022, p.65) report presents a somewhat different breakdown and re-assignment (see Figure 11) of sector emissions at the global level:

> In 2019, 34% (20 GtCO2-eq) of global GHG emissions came from the energy sector, 24% (14 GtCO2-eq) from industry, 22% (13 GtCO2-eq) from agriculture, forestry and other land use (AFOLU), 15% (8.7 GtCO2-eq) from transport, and 5.6% (3.3 GtCO2-eq) from buildings. Once indirect emissions from energy use are considered, the relative shares of industry and buildings emissions rise to 34% and 16%, respectively.

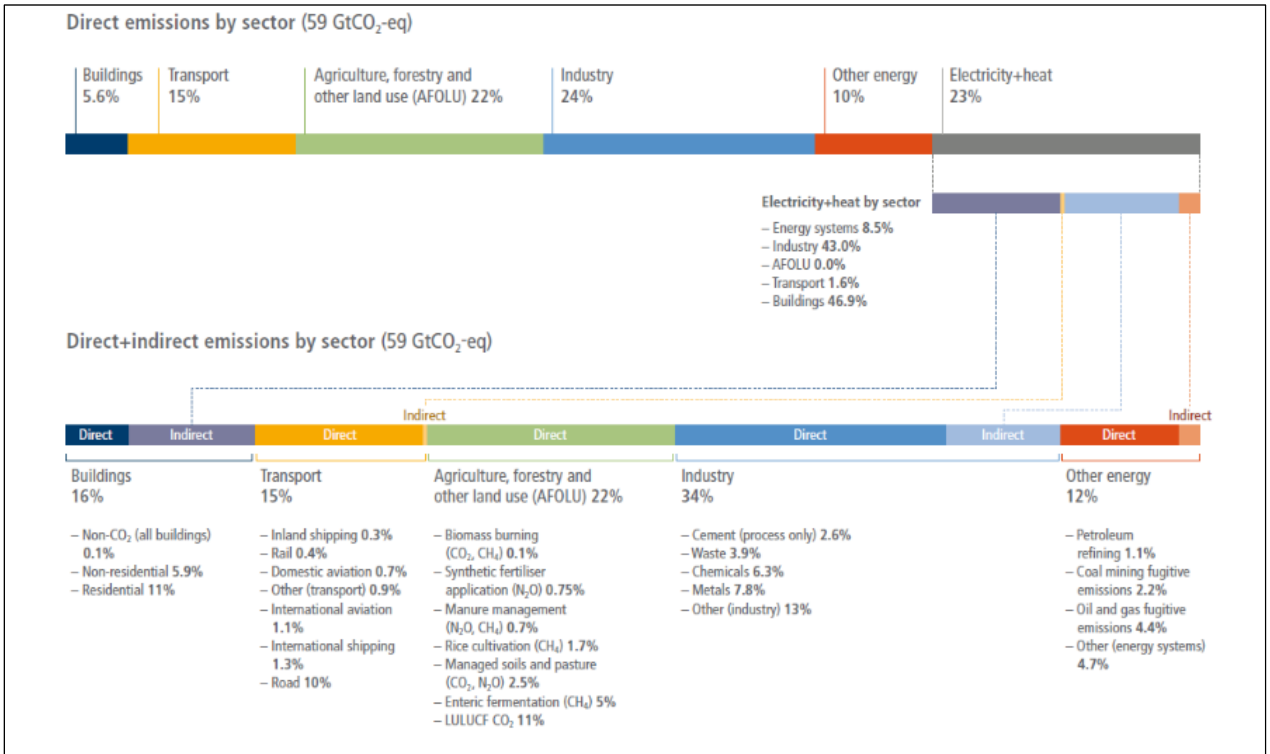

Figure TS.6 | Total anthropogenic direct and indirect GHG emissions for the year 2019 (in GtCO2-eq) by sector and subsector. Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions – as used here – refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). Note that cement refers to process emissions only, as a lack of data prevents the full reallocation of indirect emissions to this sector. More comprehensive conceptualisations of indirect emissions including all products and services (scope 3 reporting) are discussed in Section 2.3. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100-year time horizon (GWP100) from the IPCC Sixth Assessment Report. Percentages may not add up to 100 across categories due to rounding at the second significant digit. {Figure 2.12, 2.3}

Figure 11. Re-assignment of global direct emissions by sector to end-use sectors
Source: IPCC (2022)

The main difference between the re-assignment of emissions to buildings in the US (Figure 9) in comparison to the global re-assignment of emissions (Figure 11) is due to the difference in the assignment of indirect electricity emissions to buildings (i.e., 47% shown in Figure 11 globally and about 70% shown in Figure 9 for the US). This is confirmed for the US later in Tables 6 and 7 based on EPA (2022).

The NASEM report follows with six overarching goals and objectives for building energy demand reduction and decarbonization (NASEM, 2021, pp.94-96):[36]

1. **Invest in demand reduction to improve quality of life**, provide U.S. jobs, and reduce inequities. Current U.S. codes, standards, RD&D, and investments in building demand reduction significantly lag behind peer

[36] The CO2 savings reported for each investment reflect current grid and fuel emissions levels (based on 2020 data included in the 2021 NASEM report).

nations. The development of national standards and the removal of market barriers can lead to significant reductions in energy use from key building technologies through their natural replacement cycle. Such standards, which would likely be enforced at a local or state level, are further discussed in Chapter 4.

2. **Make strategic investments in building efficiency and fuel switching** to meet near-term building energy and carbon goals, as outlined in (Ungar and Nadel, 2019):

    - *Appliance and equipment efficiency*: 5.6 quads, 210 MMtCO2/yr reductions. Next generation Energy Star standards and replacements for low-income homeowners offer 70 percent energy savings from a dozen products: residential water heaters, central air conditioners/heat pumps, showerheads, clothes dryers, refrigerators, faucets, and furnaces, as well as commercial/industrial fans, electric motors, transformers, air compressors, and packaged unitary air conditioners and heat pumps.
    - *Net-zero emissions in new homes and commercial buildings*: 5.7 quads, 265 MMtCO2/yr reductions. Standards and low-income homeowner incentives offer 70 percent energy savings relative to reference-case efficiency levels, with the remaining 30 percent coming from on-site or off-site carbon-free energy systems.
    - *Smart homes and commercial buildings—new and existing*: 3.2 quads, 125 MMtCO2/yr reductions. Weatherization Assistance Program (WAP) training and employment for smart controls, access to real-time information, and smart algorithms will optimize energy savings for automation systems in both residential and commercial buildings (Elliott et al., 2012).
    - *District and combined heat, cooling, and power—new and existing*: 4 quads, 150 MtCO2/yr reductions. Co- or poly-generation of power, heating, hot water, and cooling with district energy systems can reduce emissions by 150 million metric tons of CO2 each year (MMtCO2/yr) by installing new combined heat and power (CHP) plants with a total capacity of 40 GW by 2020 (Park et al., 2019). As long as there is sufficient waste heat from industry and power generation (including increases in waste-to-power), district energy systems offer substantial efficiencies in mixed-use communities in heating dominated climates and offer resiliency for hospitals, schools, and community spaces.
    - *Existing home and commercial building envelope retrofits*: 3.8 quads, 125 M MtCO2/yr reductions. WAP training and employment for retrofits that improve air tightness, envelope insulation, and window quality to meet ENERGY STAR can reduce energy use by 20–30 percent and improve comfort and health (Belzer et al., 2007; Liaukus, 2014). All commercial buildings undergoing major retrofits should achieve 50 percent reductions in demand (Shonder, 2014).
    - *Electrification of space heating and water heating in existing homes and commercial buildings:* 0.9 quads (after measures above), 76 MMtCO2/yr reductions. Industry standards and incentives can accelerate the deployment of high-efficiency heat pumps that use electricity from low- or no-carbon generation, including on-site photovoltaics that can offer a level of resiliency.

3. **Reduce embodied carbon emissions.** As buildings become more efficient, the embodied carbon in building materials becomes as critical as operational carbon. The embodied carbon emissions from all new buildings, infrastructures, and associated materials should be reduced by 50 percent by 2030 and eliminated by 2050.[37]

4. **Electrify the built environment and integrate it with the grid.** Buildings have a role in electricity generation, storage, and carbon sequestration as well. Buildings and communities play a significant role in decarbonizing energy supply through the following:

    - Electrification of the built environment with the lowest conditioning, process, plug and parasitic loads through conservation, passive conditioning, and energy cascades;
    - Peak load shaving and demand flexibility;
    - District and building CHP for 150 MMtCO2/yr;

[37] As addressed later, significant reductions of embodied carbon emissions associated with building materials will require, in the long-run, overcoming significant challenges in addressing industry emissions from fossil fuel combustion, particularly for high-temperature, energy-intensive processes. Low-carbon and renewable energy sources are needed and, to the degree achieved and implemented, would inherently minimize embodied carbon emissions of a myriad of manufactured products, including building materials.

- Site- and building-integrated photovoltaics and solar thermal, where cost-effective;
- Thermal energy storage (water, ice, phase change materials);
- Geothermal, aqua-thermal, and ground-coupled HVAC; and
- Site-generated electricity and off-peak electricity storage.

5. **Enhance the carbon sequestration ability of buildings and infrastructures through a series of innovations:**

    - Increasing the use of wood construction from sustainably harvested forests (SFC) to reduce or replace steel, aluminum, and concrete;
    - Encapsulating CO2 into aggregate and/or the sand that makes up 85 percent of concrete to sequester up to 1,200 pounds of CO2 per cubic yard of concrete and allow buildings to be carbon negative; and
    - Restoring indigenous landscapes through green roofs and the reforestation of urban, suburban, and rural communities.

6. **Adopt the New Buildings Institute's five foundations of Zero-Carbon Building Policy:** [1] energy efficiency, [2] renewable energy, [3] grid integration and storage, [4] building electrification, and [5] embodied carbon. A net-zero carbon or a net-negative carbon built environment is key for the decarbonization of the United States. Energy Use Intensities should be driven by code to achieve passive house standards of less than 25 to 50 kBTU/sqft per year depending on building type. This should be followed by integrating site and community renewable energy sources with effective grid integration and energy storage, wherever cost effective. These actions should fully anticipate the elimination of fossil fuels and combustion in buildings, with building electrification as a linchpin solution for decarbonization of the United States. Last, the built environment offers a path to carbon sequestration, with sustainably managed forests and the use of carbon sequestering materials. The optimum mix of investments in design for deep efficiencies, electrification with site and community generation, and reduced carbon in building material production or even carbon sequestering material can ensure that the building sector achieves net positive in carbon sequestration (Webster et al., 2020).

In closing, it appears that several the policy and funding recommendations of the NASEM (2021) report have influenced the provisions of and funding amounts for decarbonization in recent US legislation, including the *Infrastructure Investment and Jobs Act* (IIJA) and the *Inflation Reduction Act* (IRA).

PART 3: Status of US Energy Use and GHG Emissions

3.1 Overview

At the beginning of this paper climate change and its association with global GHG emissions, particularly CO2 emissions from fossil fuel combustion, was reviewed and established. In this section we turn to focus on energy use and CO2 and other GHG emissions for the United States (US), including its various energy sources and economic sectors to which those emissions may be re-assigned in various accounting or attribution methodologies.

US energy use in 2021 is shown in Figure 12. From Figure 12, the approximate percentage use of different energy sources is as follows (with fossil fuel combustion accounting for nearly 80% of energy consumption and about 12% from renewable energy sources):

Petroleum – 36% **Natural Gas – 32%** **Coal – 11%** Nuclear – 8.4%

Biomass – 5.0% Wind – 3.4% Hydro – 2.3% Solar – 1.5% Geothermal – 0.2%

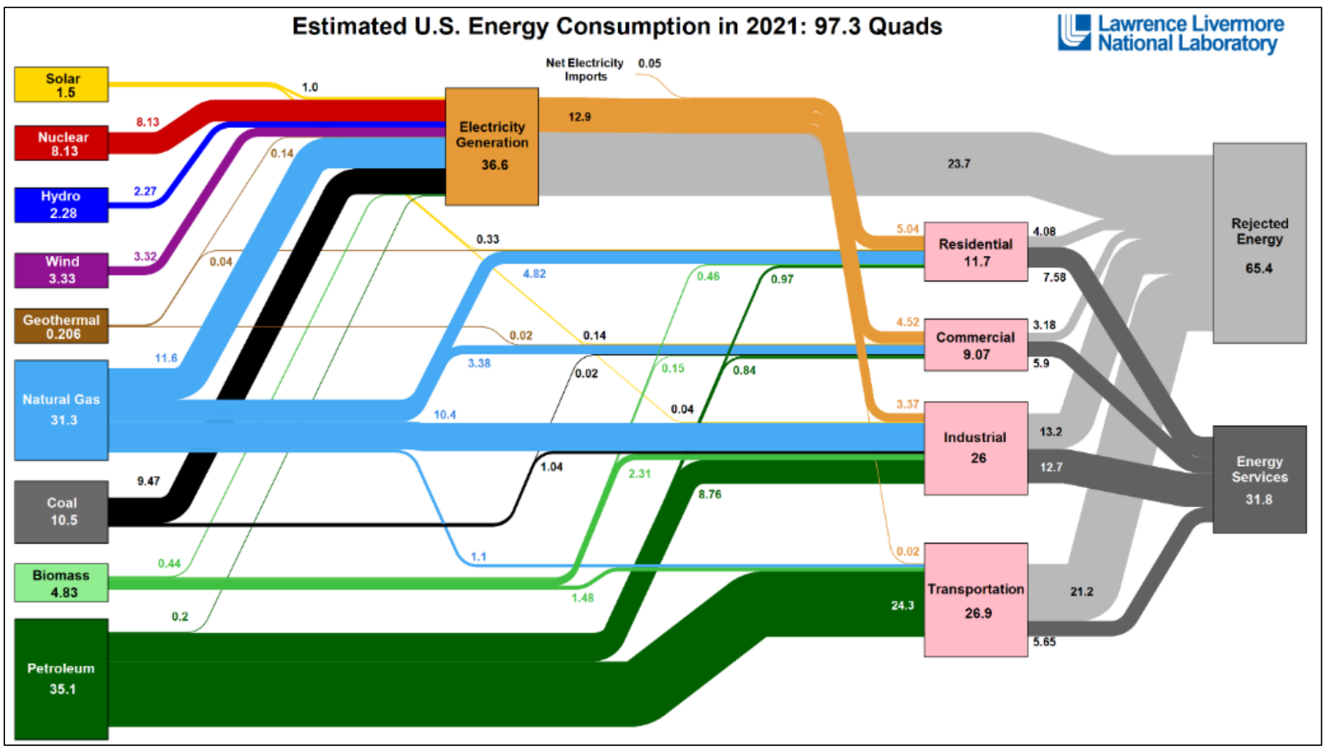

Figure 12. Flow Chart for US Energy Consumption in 2021

Source: LLNL & U.S. Department of Energy, https://www.energy.gov/energysaver/articles/annual-energy-and-carbon-flow-charts-detail-us-energy-use-sources-and

NOTE: 1 Quad equals 1 quadrillion (10^{15}) BTU. British Thermal Units (BTUs) are a common unit of measurement for energy. One BTU is equivalent to the amount of heat it takes to raise 1 pound (~1 pint) of water by 1 degree Fahrenheit. 3,412 BTUs is equivalent to 1 kilowatt-hour (kWh) of electric energy, which is the amount of energy it takes to light an efficient LED lightbulb for a week. Therefore, 1 quadrillion (10^{15}) BTUs equals 293,100,000,000 kWh (the amount of electricity equivalent to typical annual electricity use of about 25,000,000 homes or about 8 billion gallons of gasoline. Multiply those figures by 97.3 to understand the magnitude of US annual energy use in all economic sectors (transportation, industry, buildings, etc.)

It is noteworthy that 80% of US total energy consumption (all sectors) comes from fossil fuel combustion: petroleum (mostly for transportation), natural gas (split roughly 50/50 between buildings and industrial), and coal (mostly for electricity in buildings and some for industrial applications). Combined renewable energy sources account for about 12.4% of total US energy consumption in 2021, even with a substantial increase in wind and solar sources in recent years.

As a significant observation, about 67% (65.4 Quads) of the US energy use results in waste or "rejected" energy due to inefficiencies, primarily in the generation and distribution of electricity (e.g., gas turbine heat loss, coal-fired furnace heat loss, and electric distribution line losses), inefficiencies in internal combustion engines used for transportation (e.g., waste heat instead of mechanical power), and inefficiencies in industrial fuel combustion (i.e., process heating for things like steel, cement, gypsum, glass, and plastics manufacturing). This speaks to the significant role that energy efficiency can continue to play across various economic sectors in reducing energy use and associated carbon emissions.

With regard to US CO2 emissions in 2021, refer to Figure 13 where the referenced LLNL website source mentions the following:

> The carbon flow chart [shows] that national carbon dioxide (CO_2) emissions increased from 4,555 to 4,863 million metric tons, indicative of a 7% increase. This increase is especially notable because, between 2019 and 2020, there was an 11% decrease in carbon dioxide emissions. This increase is a combined result of the increase in coal for electric coal generation and increases in the petroleum-based transportation sector.

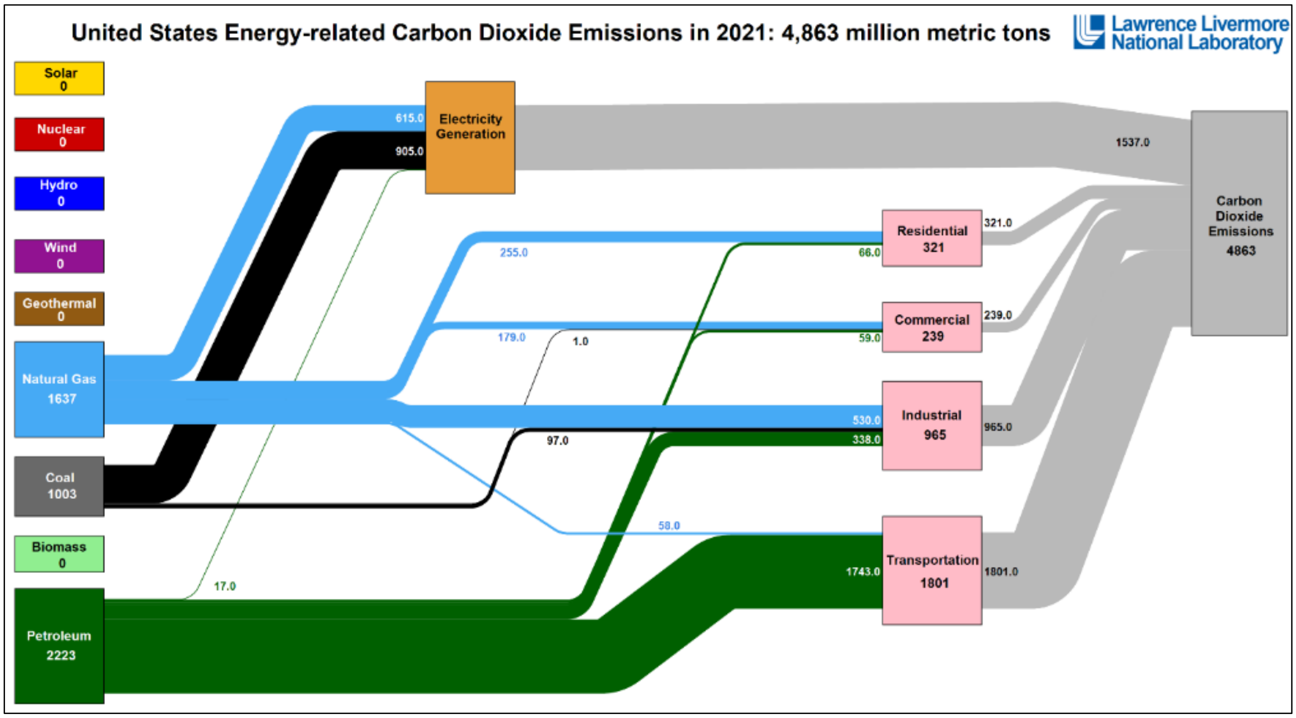

Figure 13. Flow chart for U.S. Energy-related Carbon Dioxide Emissions in 2021
Source: LLNL & U.S. Department of Energy,
https://www.energy.gov/energysaver/articles/annual-energy-and-carbon-flow-charts-detail-us-energy-use-sources-and

According to the US EPA's draft "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021", key preliminary findings regarding US GHG emissions (including CO2 from fossil fuel combustion and also other GHG sinks and emissions from other sources) are as follows:[38]

[38] https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks#:~:text=Key%20findings%20from%20the%20DRAFT,sequestration%20from%20the%20land%20sector, last accessed 2/26/2023

- **In 2021, US GHG emissions totaled 6,347.7 million metric tons of carbon dioxide equivalents (6.348 GtCO2e)**, or 5,593.5 million metric tons of carbon dioxide equivalents (5.594 GtCO2e) after accounting for sequestration from the land sector.
- **Emissions increased from 2020 to 2021 by 6.8 percent** (after accounting for sequestration from the land sector), driven largely by an increase in CO2 emissions from fossil fuel combustion due to economic activity rebounding after the COVID-19 pandemic. However, the 2021 GHG emissions in 2021 were 16.3 percent below 2005 levels.

The 2021 US total GHG emissions of 6.348 GtCO2e (which represents a 16.3% reduction from 2005 levels) appears to be slightly lagging behind the intent of the 2021 US NDC submitted to the UN for the Paris Agreement which promised CO2e emissions reductions below 2005 levels of 17% by 2020, 26% by 2025, and 50% by 2030. While the years from 2005 to 2021 saw an average of 1% per year reduction in US total GHG emissions, the 4 years from 2022 to 2025 will need to accelerate to a 2.5% per year pace if the US 2021 NDC promise to the UN is to be met.

Based on the above 2021 data, the ratio of US total CO2 emissions to US total GHG (CO2e) emissions (not including sinks) is 4.863 GtCO2 / 6.348 GtCO2e = 0.77 or 77%. As shown in the NASEM (2021) data that follows, the ratio in 2019 for the US was larger at about 5 GtCO2 / 6 GtCO2e = 0.83 or 83%. As also shown in the data that follows, the global ratio of CO2 to CO2e emissions in 2019 was 37 GtCO2 / 55 GtCO2e = 0.67.

The NASEM (2021) report aptly summarized the status of US GHG emissions in 2019 as follows[39]:

> Global anthropogenic emissions of all greenhouse gases (GHGs) amounted to 55 Gt CO2e/y in 2019, the majority as CO2 (37 Gt CO2/y) and the rest as methane, N_2O, and fluorinated gases. Corresponding emissions for the United States were 6 Gt CO2e/y of all GHGs and 5 Gt CO2/y. Ninety percent of global CO2 emissions is caused by fossil fuel combustion (Friedlingstein et al., 2019). The majority of methane and N_2O emissions are agricultural, but approximately one-third of methane emissions represent natural gas that escapes from oil, gas, and coal operations, or that escapes in transportation or storage before being combusted by an end-user (Saunois et al., 2020). Fluorinated gases primarily escape during industrial use and the production and aging of refrigeration and cooling systems. The United States also possesses a large CO2 sink from its managed forests of approximately 0.7 Gt CO2/y, which approximately offsets the nation's agricultural emissions (EPA, 2020). Thus, reducing U.S. net emissions to zero over 30 years means that net emissions must be reduced by an average of approximately 0.2 Gt CO2e/y. (p34)

The US total GHG emissions based on the NASEM (2019) data are about 11% of total global GHG emissions (i.e., 6 Gt CO2e/55 Gt Co2e = 0.11 or 11%). However, in Figure 11 of Part 2, the IPCC (2022) reports total 2020 global GHG emissions to be 59 GtCO2e and this value will be adopted for the purposes of this report as it appears to represent gross emissions without including carbon sinks.

Finally, in Figure 13 it appears that no emissions are associated with renewable energy sources but it is likely that they have embodied emissions associated with the manufacturing of materials to build them, some operational emissions to maintain them, and additional emissions associated with end-of-life. For example, the concern with embodied emissions in the manufacturing of electric vehicle (EV) batteries is similar whereby it somewhat offsets the operational emission reduction benefits of an EV relative to an internal combustion engine (ICE) vehicle depending on the mix of renewables in the electric power grid used to charge EVs and the fuel efficiency of the ICE vehicle. While not the focus of this report (or the data of Figure 13), the emissions associated with renewable energy sources should be considered to be non-zero.

[39] Anthropogenic sources result from energy-related activities (e.g., combustion of fossil fuels in the electric utility and transportation sectors), agriculture, land-use change, waste management and treatment activities, and various industrial processes. https://www.epa.gov/report-environment/greenhouse-gases

3.2 Inventory of US Greenhouse Gas Emissions and Sinks, 1990-2020

The US Environmental Protection Agency (EPA) prepares an inventory of anthropogenic US greenhouse gas emissions and sinks (EPA, 2022) in collaboration with hundreds of experts representing more than a dozen US government agencies, academic institutions, industry associations, consultants and environmental organizations. The EPA also collects GHG emissions data through its Greenhouse Gas Reporting Program.[40] The inventory report is submitted annually to the United Nations (UN) in accordance with the UN Framework Convention on Climate Change (UNFCCC).[41] The reported overall trends in total US emissions are shown in Table 5 and Figure 14. The uncertainty in total emissions is reported to be about +/- 5%. For data relevant to 2021, refer to the previous section which reported preliminary values from a draft EPA report including that year.

TABLE 5. Recent Trends in US GHG Emissions and Sinks (MMT CO2e)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	5,122.5	6,137.6	5,251.8	5,211.0	5,376.7	5,259.1	4,715.7
CH_4[a]	780.8	697.5	657.6	663.8	671.1	668.8	650.4
N_2O[a]	450.5	453.3	449.2	444.6	457.7	456.8	426.1
HFCs	46.5	127.4	168.3	171.1	171.0	175.9	178.8
PFCs	24.3	6.7	4.4	4.2	4.8	4.6	4.4
SF_6	28.8	11.8	6.0	5.9	5.7	5.9	5.4
NF_3	+	0.5	0.6	0.6	0.6	0.6	0.6
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Emissions[a]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change/CO_2[b]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[c]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

TABLE NOTE: Refer to Table ES-2 in EPA (2022) for complete table notes. LULUCF refers to GHG fluxes from the Land Use, Land-Use-Change, and Forestry (LULUCF) sector, which are included in net emission and excluded from the gross emission values. The EPA (2022) reports gross emissions unless otherwise noted.

[40] https://www.epa.gov/ghgreporting , last accessed 11/6/2023

[41] https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements , last accessed 11/6/2023

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (EPA, 2022)

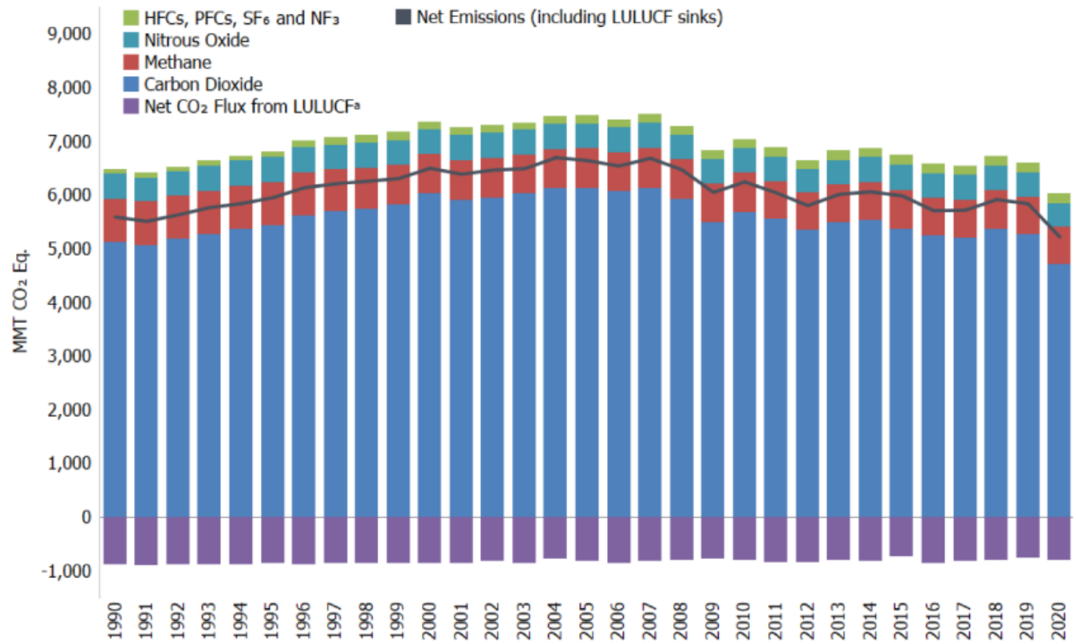

Figure 14. US GHG Emissions and Sinks by Gas
Source: U.S. EPA (2022)

EPA (2022) acknowledges that the sharp decline in emissions from 2019 to 2020 is largely due to the impacts of the COVID-19 pandemic on travel and economic activity. However, it also reflects a continued shift from coal to less carbon intensive natural gas and renewables for the electric power sector in the US. In 2020, the GHG emissions by gas (weighted by the GWP of each type of GHG) are shown in Figure 15 which indicates that CO2 emissions (mainly from fossil fuel combustion for transportation and power generation) account for about 79% of the GWP of all US GHG emissions.

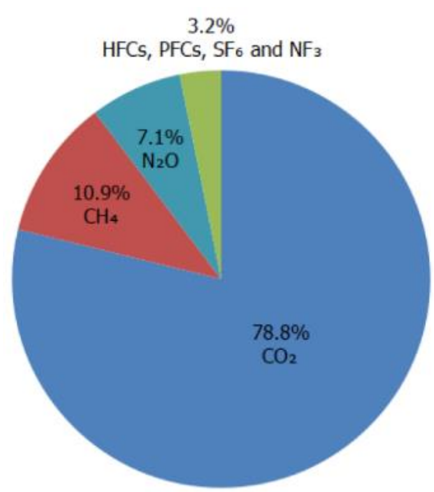

Figure 15. 2020 U.S. GHG Emissions by Gas (based on MMT CO2e)
Source: U.S. EPA (2022)

Focusing on CO2 emissions, fossil fuel combustion in the US accounted for about 92 percent of the total CO2 emissions mainly for transportation and electric power generation. Figure 16 shows fossil fuel combustion accounting for 4,343 MMT CO2 emissions whereas other non-energy uses and industrial uses of fossil carbon accounting for the remaining 8 percent. Note that the figure's bar chart is compressed for the fossil fuel combustion amount, distorting the perception of its orders of magnitude greater contribution than the other emission sources listed in Figure 16. **For example, the CO2e emissions from non-energy use of fuels (e.g., feedstock for manufacturing) is less than 3% of the emissions from fossil fuel combustion for energy (truncated top bar of chart in Figure 16).**

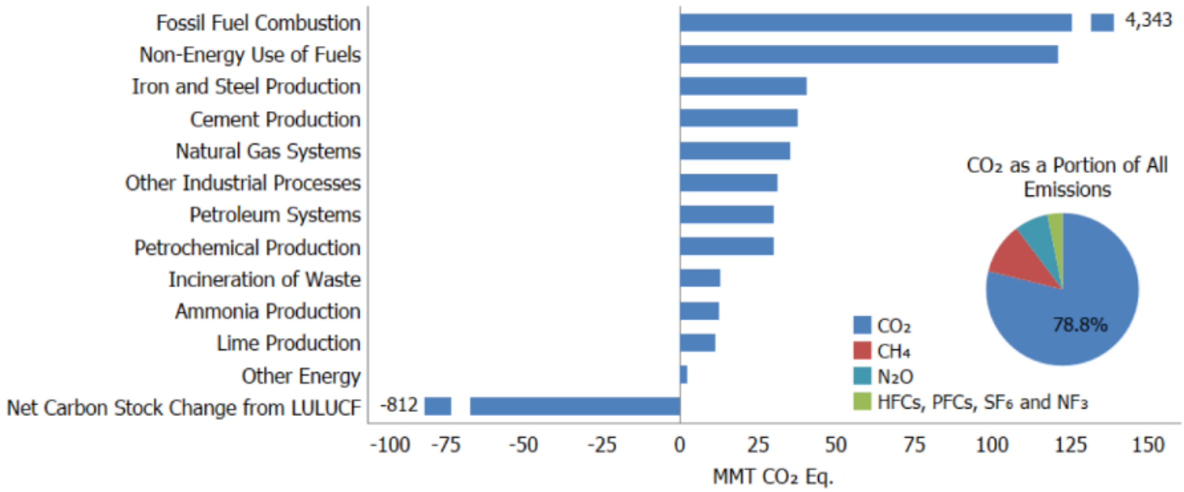

Figure 16. 2020 Sources of CO2e emissions
Source: U.S. EPA (2022)

According to EPA (2022), the five major fuel-consuming economic sectors are transportation, electric power, industrial, residential buildings, and commercial buildings. The CO2e emissions from fossil fuel combustion for each of these sectors by fuel type is shown in Figure 17. It is notable that coal (which has twice the carbon intensity of natural gas – see Figure 18) still accounts for more than one-half of the electric power sector's emissions in 2020. **The transportation and electric power sectors account for 72% of the CO2e emissions from fossil fuel combustion across all sectors shown in Figure 17.**

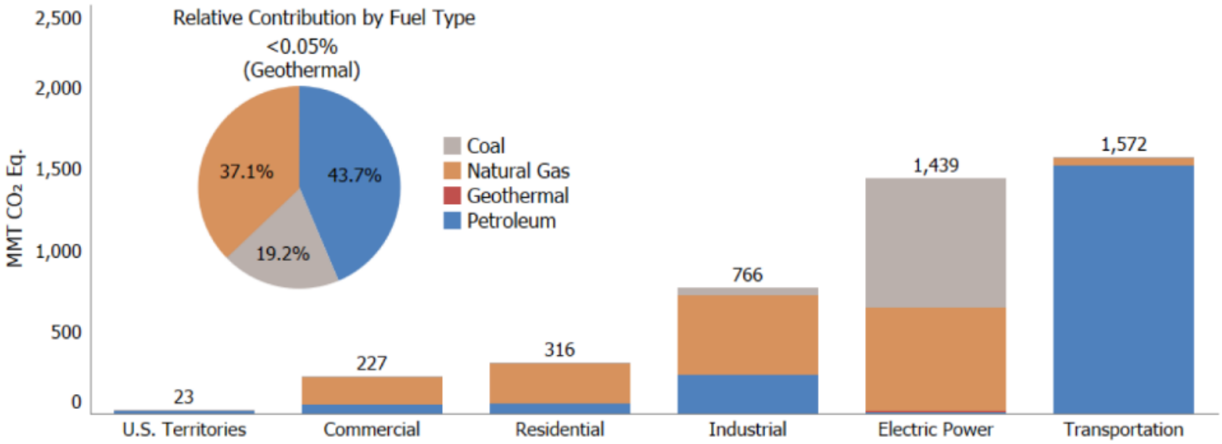

Figure 17. 2020 US CO2e emissions from Fossil Fuel Combustion (4,343 MMT CO2 total)
Source: U.S. EPA (2022)

FOSSIL FUELS	lb CO_2/MMBtu
Coal (Anthracite)	228.6
Coal (Bituminous)	205.7
Coal (Lignite)	215.4
Coal (Subbituminous)	214.3
Diesel Fuel and Heating Oil	161.3
Gasoline (Without Ethanol)	157.2
Propane	139.0
Natural Gas	117.0

Figure 18. CO2 Emissions Intensity (lbs CO2 per MMBtu) for Fossil Fuel Sources
Source: *ASHRAE Journal*, November 2022

The same CO2e emissions can be reported differently by re-assigning and attributing the off-site (indirect) electric power emissions to end use sectors as shown in Figure 19.

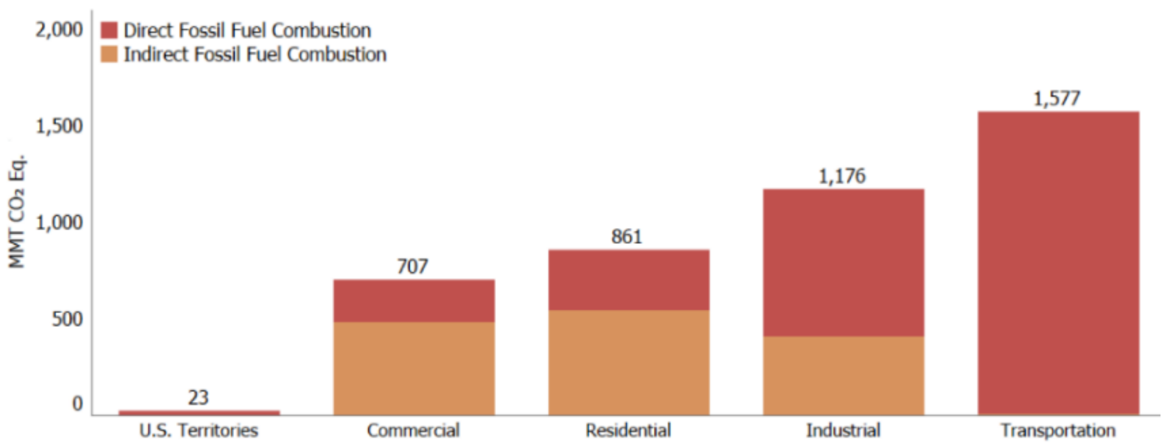

Figure 19. 2020 US CO2 Emissions from Fossil Fuel Combustion (4,343 MMT CO2 total) Re-assigned to End Uses
Source: U.S. EPA (2022)

The re-attribution of emissions in Figure 19 to end use sectors can lead to a misunderstanding of the originating source of emissions and an appropriate balance for policy solutions, particularly for the industrial and buildings sectors. **With regard to CO2 emissions from combustion of fossil fuels (which is about 73% of the total gross US GHG emissions), the primary source of the emissions is from electric power generation (shown as indirect fossil fuel combustion in Figure 19) and transportation which together account for 72% of all fossil fuel combustion CO2 emissions (and more than 50% of total gross US GHG emissions) as more clearly shown in Figure 17**. However, this reality is not meant to divert attention away from addressing the direct fossil fuel combustion contributions of buildings and industry as shown in both Figures 17 and 19. It does mean to draw attention to the need to focus attention on alternative renewable or low-carbon fuels to replace uses of coal, natural gas, and petroleum in the transportation, electric power, industrial, and buildings sectors. Success at this direct “root cause” level will inherently translate to other decarbonization benefits, such as lower embodied carbon emissions attributed to materials produced in the industry sector (including building materials, vehicle materials, and essentially all consumer goods produced in the US). Therefore, with a proper focus on the originating sources of emissions and solutions (e.g., process energy efficiency and use of alternative renewable and low-carbon energy sources), the end use sectors should focus on efficient use of energy and material resources (and coordinated fuel switching or electrification) which will serve to multiply the impact and rate of transition to alternative sources of energy. Also, these suggestions for policy emphasis also are not meant to distract from other non-energy sources of GHG emissions that occur in the industry sector[42] or elsewhere as they have been and should continue to be reduced by appropriately focused policy to spawn or spur innovative technology solutions and emission reduction improvements in the production and use of valuable goods for the US economy and welfare.

According to Figure 19 with the fossil fuel combustion CO2 emissions of Figure 17 re-assigned to end-uses rather than originating sources, transportation still accounted for 1,577 MMT CO2e emissions representing 36.2% of US CO2e emissions from fossil fuel combustion in 2020 (with 38% of that amount attributed to passenger vehicles followed by 26.3% for freight trucks and 18.9% for light-duty trucks). While transportation emissions have increased since 1990 due to various factors (e.g., population growth, economic growth, low fuel prices over much of the period, etc.), improvements in new vehicle fuel economy since 2005 has slowed the rate of increase of CO2e emissions. Since the 1970s, fuel efficiency of vehicles has moved from a national average of under 13 mpg to now almost 25 mpg. Without these vehicle efficiency improvements, US CO2e emissions would be dramatically worse. While vehicle fuel efficiency remains an important part of decarbonization in the US and the world in the short term, electrification of transportation, development of alternative clean fuels, and cleaning the electric power grid for charging of electric vehicles remain important long term decarbonization strategies. Because the transportation sector is not the focus of this report, it will not be further addressed.

According to EPA (2022), electricity generators used 31.2% of US energy from fossil fuels and emitted 33.1% of the CO2 from fossil fuel combustion in 2020. The electric power sector is the largest consumer of coal in the US, accounting for 91% of all coal consumed in the U.S. Coal-fired power generation in the US has declined from 54.2% in 1990 to 19.9% in 2020. In 2020, natural gas power generation accounted for 39.5% (up from 10.7% in 1990). Wind and solar accounted for 11.1% (up from 0.1% in 1990). Consequently, CO2 emissions from fossil fuel combustion in the electric power sector have declined by 20.9% since 1990 and the carbon intensity (CO2e per QBtu input) has similarly decreased. For a representation of electric power generation and emission trends, see Figure 20.

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[42] According to EPA (2022): This end-use sector [Industry] also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 and CO_2 emissions from coal mining, byproduct CO_2 emissions from cement manufacture, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

IPPU [Industrial Process and Product Use] activities are responsible for 3.5, 0.1, and 5.5 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases including HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 6.3 percent of U.S. greenhouse gas emissions in 2020.

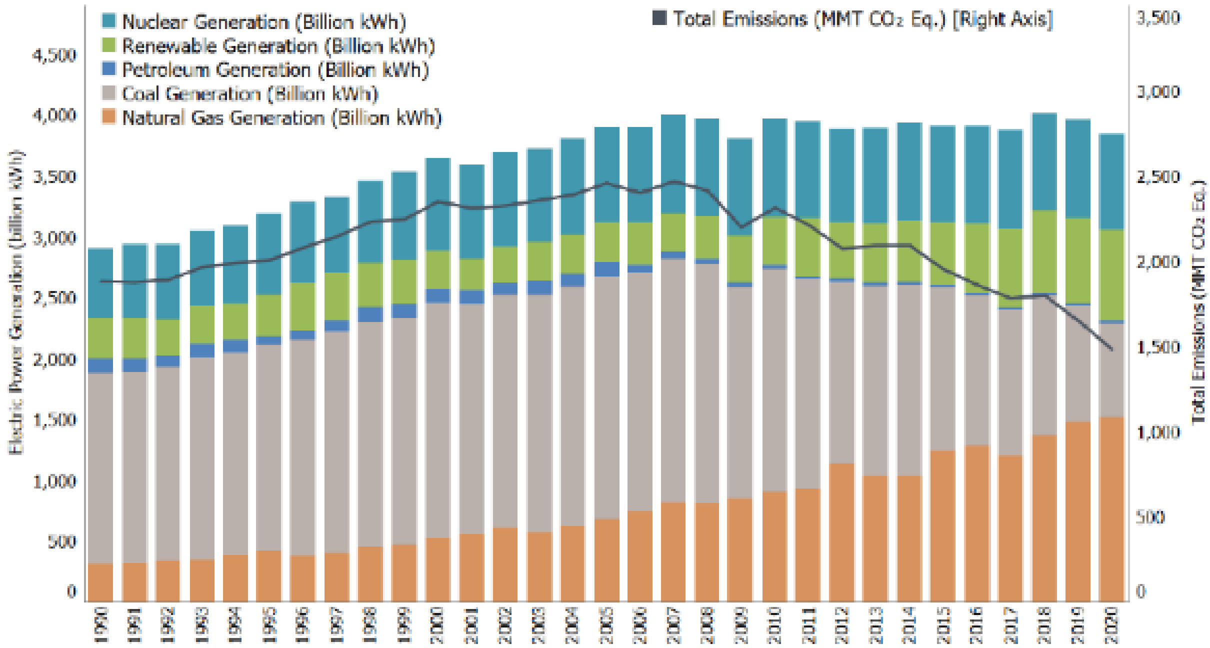

Figure 20. Electric Power Generation (Billion kWh) and Emissions (MMT CO2e)
Source: U.S. EPA (2022)

According to EPA (2022) and the re-assignment of emissions in Figure 19, the industrial end-use sector is the second largest sector, accounting for 27.1% of total US CO2e emissions from fossil fuel combustion (although about 17.6% in terms of direct emissions in accordance with Figure 17). About 65% of these emissions are from direct (on-site) fossil fuel combustion to produce steam and heat for industrial processes. The remainder results from use of electricity for motors, electric furnaces, ovens, and various other applications (i.e., indirect electric power emissions). Total direct and indirect emissions from the industrial sector have declined 22% since 1990 as a result of structural changes in the US economy (i.e., shifting from a manufacturing-based to a service-based economy), efficiency improvements, and fuel switching (e.g., coal to natural gas). For example, the iron and steel industrial sector have seen a 64% decrease in CO2e emissions from 1990 to 2020 due to restructuring, technology improvements, and increased scrap steel use. The industrial sector will be addressed in greater detail later since its emissions are re-assigned as embodied emissions attributed all manufactured goods, including building materials.

According to EPA (2022) and the re-assignment of emissions in Figure 19, the residential and commercial building end-use sectors account for 19.8 and 16.3 percent of total US CO2e emissions from fossil fuels in 2020, respectively (although about 7.3% and 5.2% in terms of direct emissions in accordance with Figure 17). Indirect emissions from electric power usage accounted for 63.3% and 67.9% (about two-thirds) of the total of direct and indirect emissions for residential and commercial buildings, respectively. Electric power usage was associated with lighting, heating, cooling, and operating appliances. The remaining emissions (about one-third) were due to direct (on-site) combustion of natural gas and petroleum for heating and cooking.

It should be noted that year-to-year variation in heating and cooling degree days and other factors can impact year-to-year changes in national averaged annual emissions from building operation. Since 1990, total direct and indirect emissions from the residential and commercial sectors have decreased by 7.6 and 7.7%, respectively. Some of this decrease could be attributed to the warming climate as demonstrated in Figure 21 which shows the trend of decreasing annual average heating-degree-days (HDD) and increasing cooling-degree-days (CDD) for the US. These warming climate trends in the US have the effect of increasing cooling energy demand and a decrease in heating energy demand. The net effect, however, is a decrease in overall annual building energy use because US normal cooling-degree-days (1,514 CDD) is less than half that of the normal heating-degree-days (3,916 HDD).

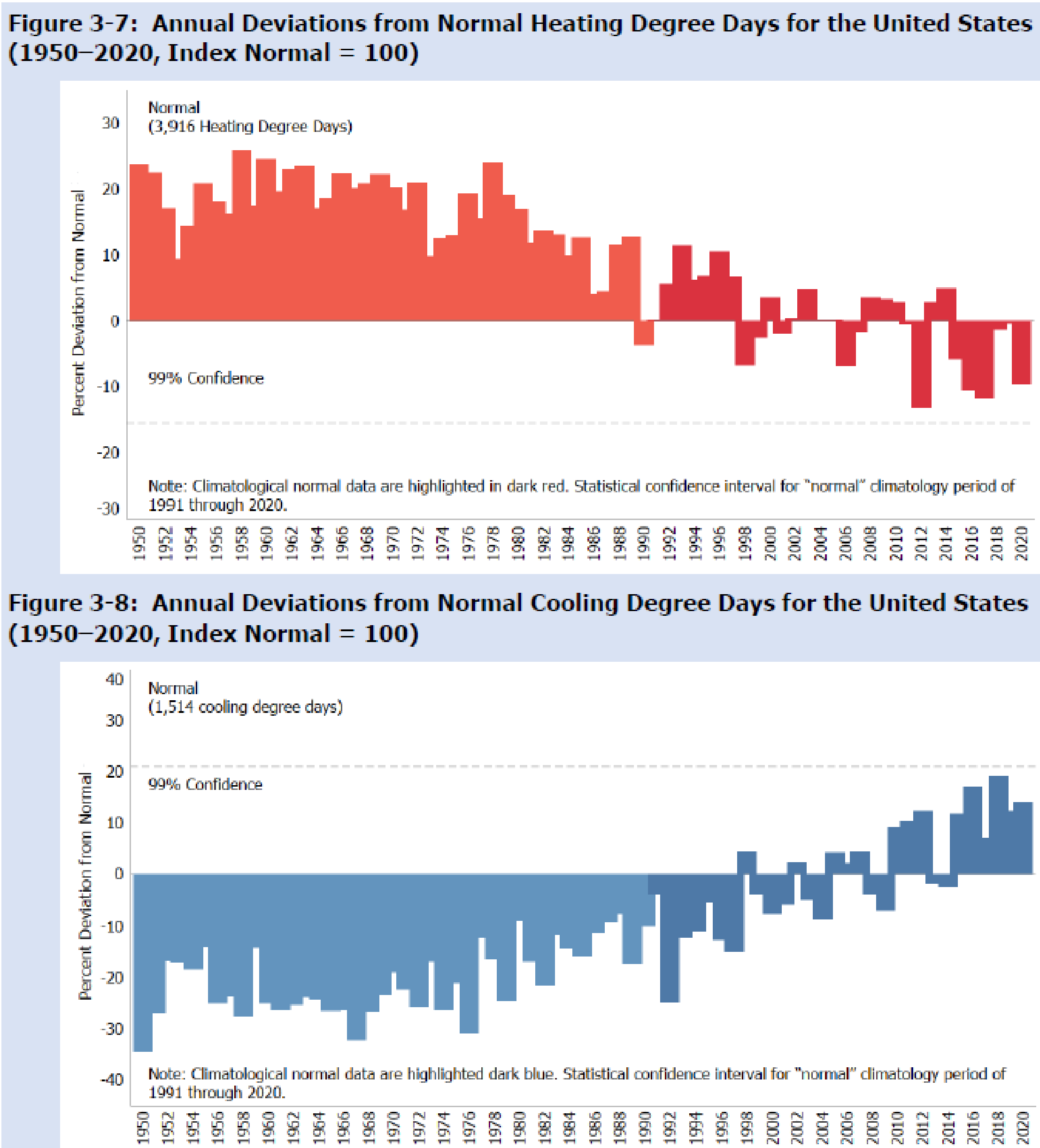

Figure 21. Average annual HDD and CDD trends in U.S.
Source: U.S. EPA (2022)

In 2020, 78.8 percent of US energy use was attributed to fossil fuel combustion and the remaining 21.2 percent came from other energy sources as shown in Figure 22.

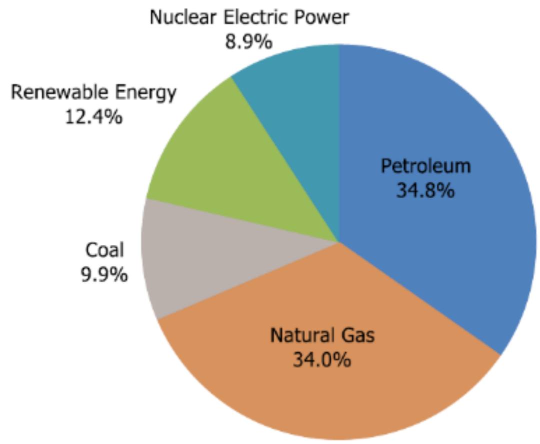

Figure 22. 2020 Percent U.S. Energy Consumption by Energy Source
Source: U.S. EPA (2022)

NOTE: The 12.4% renewable energy portion is made up of the following sources: wind (26%), hydroelectric (22%), wood (18%), biofuels (17%), solar (11%), biomass waste (4%) and geothermal (2%). Biomass sources (wood, biofuels, and biomass waste) account for 39% of renewable energy.

Total GHG emissions (including all GHG emissions, not just fossil fuel combustion CO2e emissions) are directly allocated to economic sectors as shown in Figure 23 and further detailed in Table 6. It is worth noting that in this attribution of emissions, only direct emissions within each sector are considered (i.e., indirect emissions as a result of use of off-site electricity generation are attributed to the electric power industry and not to various end-use sectors). With this allocation in mind, transportation, electric power, and industry are the three most significant contributors with nearly equal shares of GHG emissions.

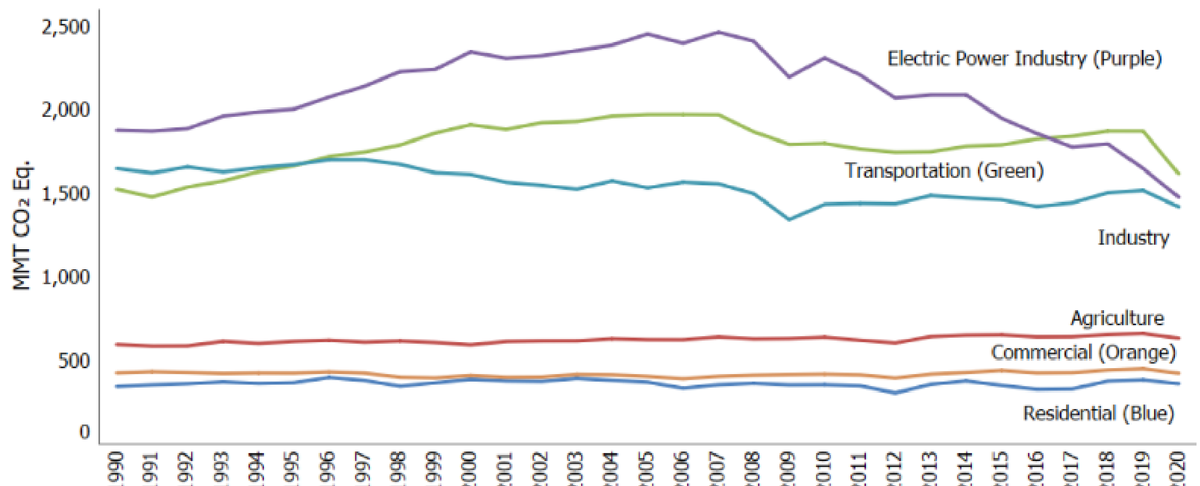

Figure 23. US GHG Emissions Allocated to Economic Sectors
Source: U.S. EPA (2022)
NOTE: LULUCF emissions and removals are excluded and also emissions from U.S. territories.

TABLE 6. US GHG Emissions Allocated to Economic Sectors (MMT CO2e)

Economic Sectors	1990	2005	2016	2017	2018	2019	2020
Transportation	1,526.4	1,975.5	1,828.0	1,845.2	1,874.7	1,874.3	1,627.6
Electric Power Industry	1,880.5	2,456.7	1,860.5	1,780.6	1,799.8	1,651.0	1,482.2
Industry	1,652.4	1,536.2	1,424.4	1,446.7	1,507.6	1,521.7	1,426.2
Agriculture	596.8	626.3	643.4	644.4	657.9	663.9	635.1
Commercial	427.1	405.4	426.9	428.5	444.2	452.1	425.3
Residential	345.1	371.0	327.8	329.9	377.4	384.2	362.0
U.S. Territories	25.1	63.7	26.8	25.8	25.8	24.6	23.0
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[a]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

Based on Figure 16, US GHG emissions from fossil fuel combustion was 4,343 GtCO2e in 2020. From Table 6, the US total gross emissions was 5,981 GtCO2e. **Thus, the combustion of fossil fuels in the uses represents 73% of the US total gross GHG emissions (or about 4,343/5,222 x 100% = 83% if compared to net emissions).**

Also, based on Figure 11 in Part 2, the total global GHG emissions in 2019 was approximately 59 GtCO2e as serves as a proxy for 2020 for the purposes of this report (more recent global data was not completed at the time of this writing). **Therefore, it is estimated that total US GHG emissions of 5.981 GtCO2e in 2020 are about 10.1% of total global GHG emissions (and 11% if based on the 2019 data of Table 6).**

When emissions from the electric power sector are distributed to end-use sectors as shown in Figure 24 and Table 7, industrial and transportation sectors account for 30.3 and 27.3 percent of US GHG emissions in 2020. The residential and commercial sectors account for the next largest contribution of 15.4 percent each. When combined for about 31 percent, building sector emissions are similar in magnitude to emissions of the industry and transportation sectors. But, bear in mind, as shown previously these emissions are still primarily attributed to the combustion of fossil fuels, no matter how they may be re-allocated to end use sectors downstream from the origination of the sources of energy.

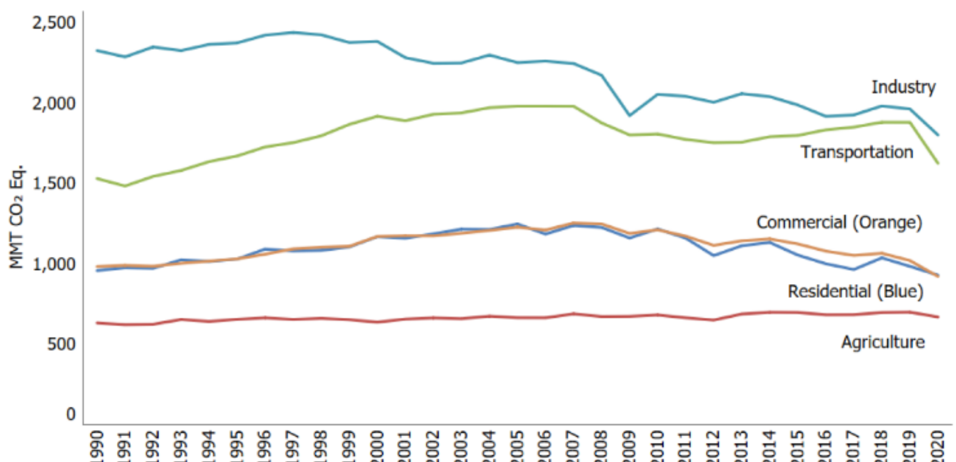

Figure 24. US GHG Emissions with Electricity-Related Emissions Re-Assigned to Economic End Use Sectors

Source: U.S. EPA (2022)

NOTE: LULUCF emissions and removals are excluded and also emissions from U.S. territories.

TABLE 7. US GHG Emissions with Electricity-Related Emissions Re-Assigned

Economic Sectors	1990	2005	2016	2017	2018	2019	2020
Industry	2,326.5	2,251.6	1,917.5	1,926.4	1,983.1	1,964.7	1,813.7
Transportation	1,529.6	1,980.3	1,832.4	1,849.6	1,879.5	1,879.1	1,632.4
Residential	957.6	1,247.2	999.9	964.3	1,036.7	984.1	923.1
Commercial	982.7	1,227.4	1,078.6	1,051.7	1,065.3	1,020.1	919.7
Agriculture	631.9	664.6	682.6	683.2	697.1	699.1	669.5
U.S. Territories	25.1	63.7	26.8	25.8	25.8	24.6	23.0
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[a]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

Source: U.S. EPA (2022)

It is useful to look at US energy use and GHG emissions using normalized metrics to better represent effects of population change and changes in productivity such that emissions are characterized on a more functional basis such as emissions or energy use per capita or per dollar of gross domestic product (GDP). Figure 25 shows such normalized trends with 1990 serving as the baseline year. The graph shows that, despite population increases and a significant increase in GDP, energy productivity (energy used per dollar of productive output) and, consequently, emissions per capita and per GDP have significantly improved through various structural changes, efficiency improvements, and fuel switching actions in the economy. For this reason, the total gross emissions data in Table 6 and Table 7 show a peak in 2005 and a gradual decrease (1.4% annual rate) since 2005 (not considering the more significant decline in 2020 mostly due to the COVID-19 pandemic).

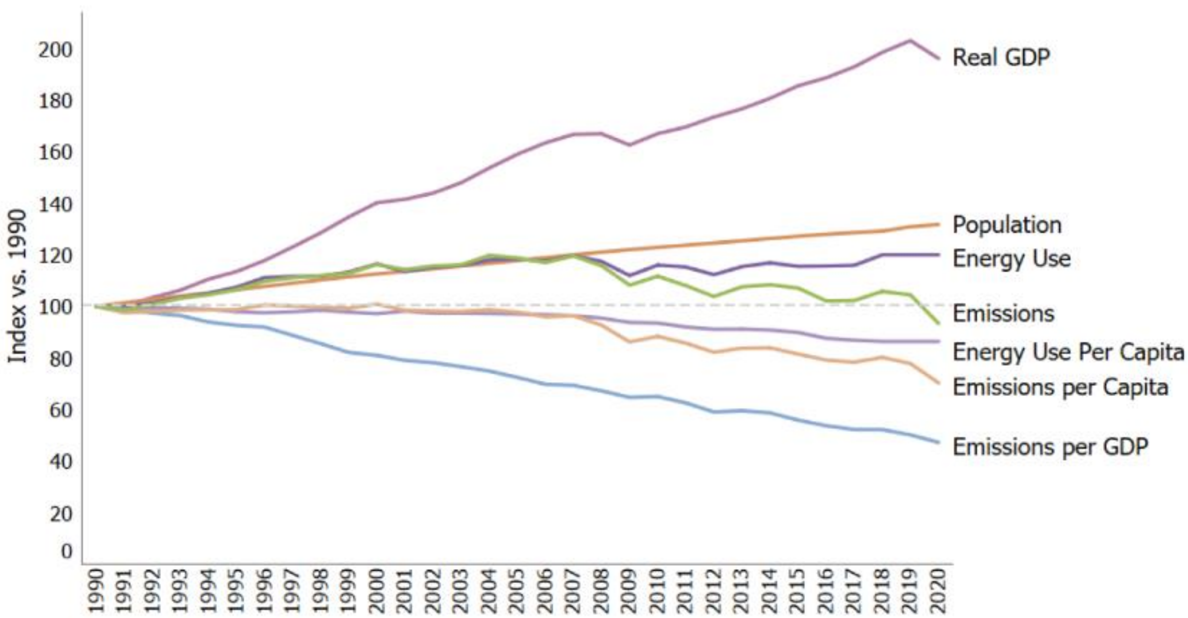

Figure 25. Indexed U.S. GHG Emissions per Capita and per Dollar of Gross Domestic Product (GDP)
Source: U.S. EPA (2022)

In addition, it is very helpful to consider key categories of contributors to emissions or removals (sequestration) as shown in Figure 26. This "key category analysis" can help identify priority sources or sink categories to focus efforts to improve the inventory quality and to reduce net emissions. Much more information on the trends and status of US GHG emissions can be found in the EPA (2022) report. This emissions inventory ranking approach is very relevant and necessary to properly focus policy actions, market response, and investments to effectively and efficiently address GHG emissions and their effect on climate change.

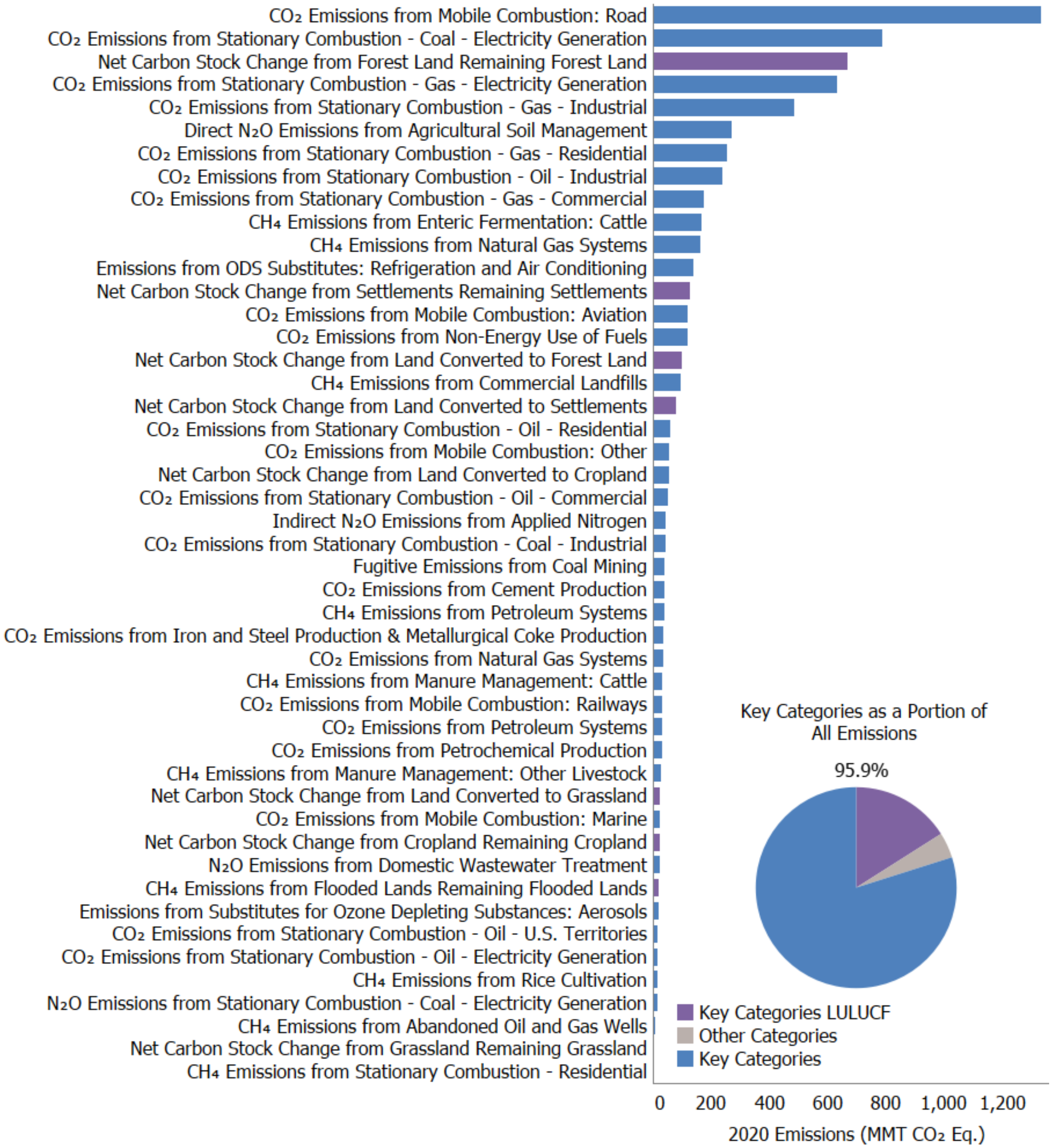

Figure 26. 2020 Key Categories for US CO2e Emissions from Fossil Fuel Combustion
Source: U.S. EPA (2022)

The following are some examples of possible policy actions to align with the top-ranking key categories identified in Figure 26:

- *"CO2 Emissions from Mobile Combustion: **Road**"* – use more efficient gas vehicles and more electric vehicles as the electric grid transitions to a larger supply of electricity from renewable resources.
- *"CO2 emissions from Stationary Combustion – **Coal - Electricity Generation**"* – Retire existing coal plants and replace with natural gas (cleaner fuel than coal) and nuclear power to provide a stable and dispatchable low-carbon power to support reliable use of renewable electric energy (wind and solar) for base demand.

- *"CO2 Emissions from Stationary Combustion –* ***Gas/Oil – Industrial****"* – transition to clean electric power where feasible and transition from fossil fuels (e.g., natural gas) to high energy intensity renewable or low-carbon fuels suitable for high-heat industrial processes with research, development, and deployment (RD&D) support as needed to facilitate and enable industry transition (i.e., combustion fuel switching, not feedstock switching).
- *"CO2 Emissions from Stationary Combustion –* ***Gas – Residential/Commercial****"* – Improve minimum efficiency of gas furnaces and electrify residential and commercial buildings with heat-pump technology where feasible and in coordination with cleaning of the electric grid (see above); retain use of gas for emergency heat back-up in colder climates and for cooking (particularly restaurants) and convert to alternative renewable or low-carbon fuels space conditioning and cooking as they become deployed (see similar recommendation above for stationary combustion for industrial processes).

The above items draw only from the top 10 end uses of primary fossil fuels as ranked in Figure 26 that generate more than two-thirds of the considered emission sources by end use. In each of those areas energy efficiency and fuel switching (to renewable or lower-carbon fuels) play a leading role. These changes also would have multiplied decarbonization impacts throughout many other sectors of the economy, including transportation and various manufactured products such as building materials. As one moves further down the ranking of Figure 26, the returns begin to significantly diminish. But, there may also be low-cost and practical improvements that could be considered for the lower-ranking end uses on a case-by-case basis. It should be recognized that many of the above concepts are included in the various policy development or guidance documents reviewed earlier.

Finally, the same type of ranking done above for the dominant source of GHG emissions (i.e., fossil fuel combustion) also can be applied to Industrial Process and Product Use (IPPU) emissions as shown in Figure 27. IPPU includes GHG emissions occurring from non-energy industrial processes and from the use of GHGs in products. While important and representing about 35% or 46% of industry GHG emissions depending on the allocation method used (i.e., whether or not electric power generation emissions are re-allocated to industry and other end use sectors)[43], the IPPU GHG emissions attributed to industry rank significantly lower in magnitude in comparison to those associated with top ranking fossil fuel combustion emission categories as show in Figure 26 for all end use economic sectors, including electricity generation.

[43] The 46% of total direct GHG emissions of industry attributed to IPPU emissions is derived from data in Figure 17 and Table 6 considering direct fossil fuel combustion emissions of 766 MMtCO2e (Figure 17) and total direct industry emissions of 1426.2 MMtCO2e (Table 6) as follows: (1 – 766/1426.2)x100% = 46%. Similarly, the 65% of total direct and indirect GHG emissions of industry attributed to IPPU emissions is derived from Figure 19 and Table 7 considering the direct and indirect fossil fuel combustion emissions of 1,176 MMtCO2e (Figure 19) and the total direct and indirect industry emissions of 1,813.7 MMtCO2e (Table 7) as follows: (1 – 1,176/1,813.7)x100% = 35%.

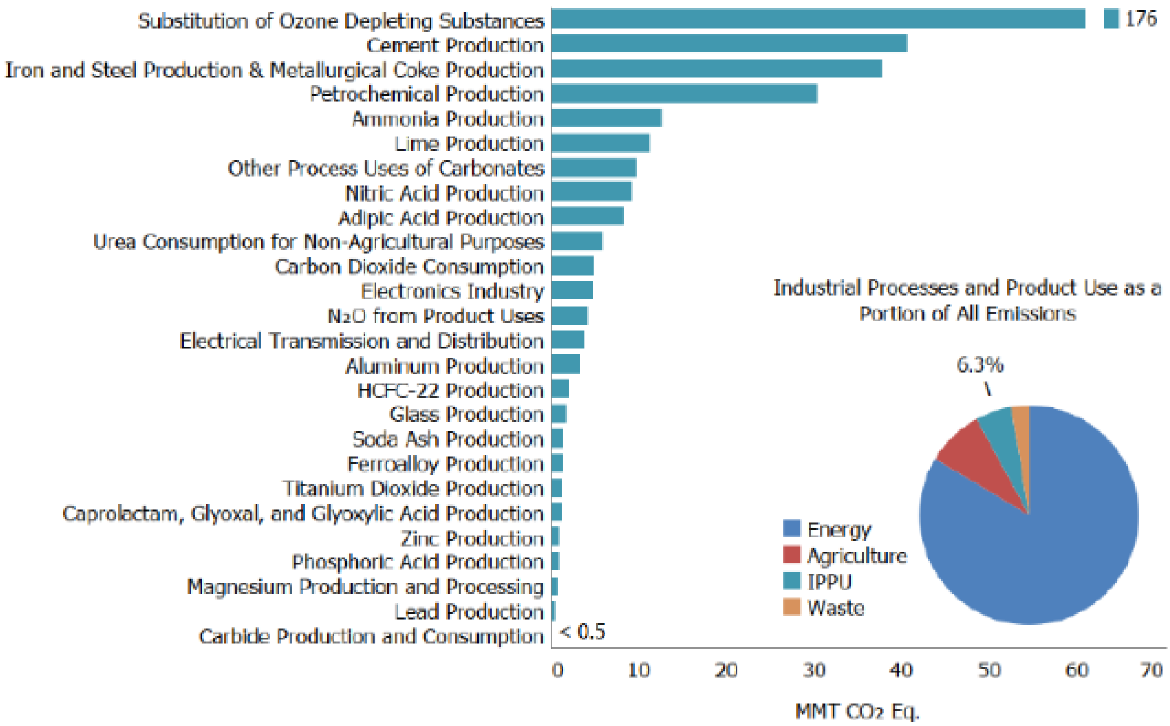

Figure 27. 2020 Key Categories for US Non-Energy CO2e Emissions from Industrial Processes and Product Use (IPPU)
Source: U.S. EPA (2022)

3.3 Decarbonization and Carbon Emissions by Industry Sub-Sectors

As mentioned and briefly reviewed earlier in this report, the U.S. Climate Alliance publishes a variety of guides to assist state policy actions related to various decarbonization efforts. One of the latest guides addresses the industry sector (USCA, 2022a). The following provides some additional detail regarding the status of industry sector carbon emissions and potential decarbonization actions. These emissions are essentially the same emissions that are attributed to various manufactured materials and products as embodied carbon emissions. Therefore, addressing embodied carbon emissions of materials and products must ultimately be aimed at the challenges the industry sector is faced with in advancing decarbonization efforts, such as switching to renewable and low-carbon fuels for the high-energy/high-heat manufacturing process required to manufacture many key materials and products, including building and construction materials.

As shown in Table 8, the total GHG emissions in 2018 of all manufacturing or industry sectors was 1,165 MMT CO2e. The share for each industry sub-sector is illustrated in Figure 28.[44] As mentioned in the previous section, industry emissions are the basis for the GHG emissions that are attributed as embodied GHG emissions of materials in all consumed goods and products (including building materials) sold and used throughout the economy. Therefore, the decarbonization of industry is foundational to reducing embodied carbon emissions for all materials, including building materials. But, a primary and fundamental challenge (accounting for about two-thirds of US industry total GHG emissions) is providing competitive alternative renewable or low-carbon fuels or electrified processes, particularly those that are capable of replacing fossil fuel combustion for high-heat industrial processes.

[44] The US total industry GHG emissions of 1.165 GtCO2e in 2018 represent about 2.4% of the global total GHG emissions of 48.9 GtCO2e in 2018 (https://www.wri.org/data/world-greenhouse-gas-emissions-2018) of which 31.3 GtCO2 (64%) of GHG emissions are attributed to fossil fuels (https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions). It also represents about 17 percent of the US total gross 6.677 GtCO2e emissions in 2018 (https://www.epa.gov/sites/default/files/2020-04/documents/us-ghg-inventory-1990-2018-data-highlights.pdf). The total net U.S. GHG emissions (subtracting U.S. carbon "sinks") was reported to be 5.903 GtCO2e for 2018.

TABLE 8. 2018 US Industry Subsector Carbon Footprints (CO2e or GHG Emissions)

	Total GHG Emissions (MMT CO_2e)				Onsite GHG Emissions (MMT CO_2e)			
	Total	*% Total Mfg.*	Offsite Total	Onsite Total	Onsite Generation	Process Energy	Process Emissions	Nonprocess Energy
Chemicals	332	*28%*	90	242	96	71	71	5
Refining	244	*21%*	33	211	63	148	0	1
Iron & Steel	100	*9%*	29	71	3	22	45	2
Cement	66	*6%*	5	61	0	22	39	0
Glass	15	*1%*	6	9	0	7	1	0
Forest Products	80	*7%*	36	44	31	11	0	3
Food & Beverage	96	*8%*	51	45	27	13	0	5
All Manufacturing	1,165	-	385	780	234	336	180	30

Source: USCA, 2022a (based on U.S. DOE, *Manufacturing Energy and Carbon Footprints (2018 MECS),* 2021 and https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2018-mecs)

NOTE: This table does not include GHG emissions of 232 MMT CO2e for "All Other Manufacturing" as shown in Figure 28 below.

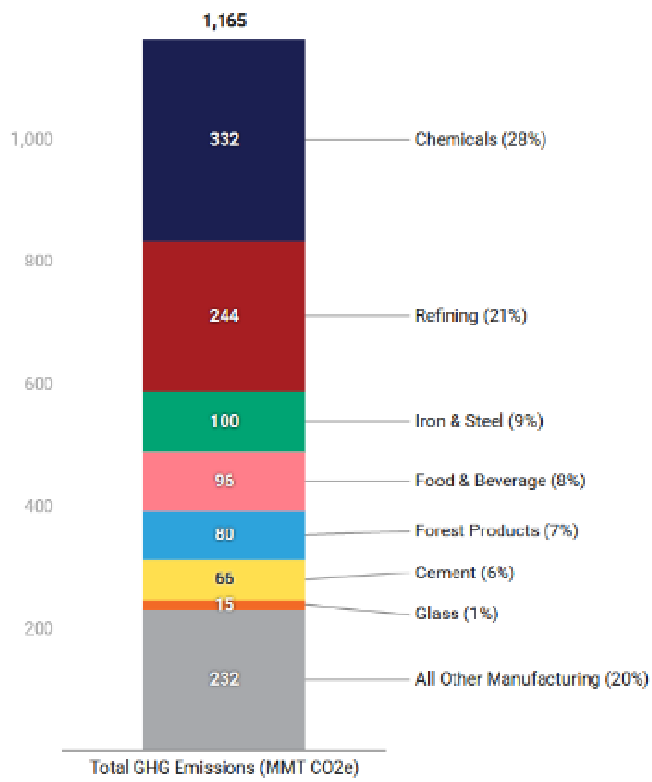

Figure 28. Share of U.S. Industry GHG emissions in 2018 by industry sub-sectors.
Source: USCA, 2022a

A breakdown of GHG emission sources within each industry subsector is shown in Figure 29.

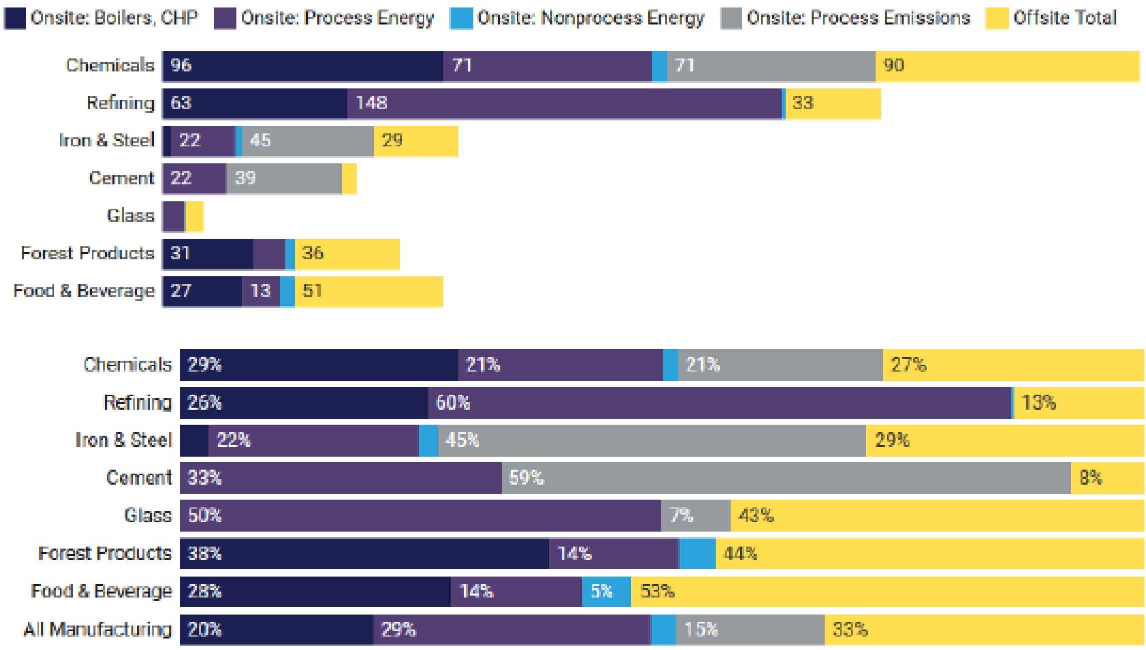

Figure 29. Breakdown of GHG emissions sources within each industry subsector.
Source: USCA, 2022a
NOTE: Values are in MMT CO2e; CHP = combined heat and power generation

The following notes convey significant observations and facts regarding each industry subsector as documented in the USCA (2022a) report:

Chemical Industry Sub-sector:

- Represents 28% of total US industry CO2e emissions or about 0.68% of total global CO2e emissions
- $768 billion/yr (25% of U.S. GDP)
- 70,000 products and 750,000 end users
- 11,000 manufacturers and 590,000 skilled workers
- Supply chain networks involve more than 96% of manufactured goods
- Decarbonizing chemical industry can have impacts across multiple sectors.
- The largest proportion of chemical manufacturing occurs in Texas and Louisiana with Indiana, Florida, California, and other states in a distant second place.
- Fuel uses: 45% natural gas, 40% hydrocarbon gas liquids (HGLs), 7% electricity, 2% coal, 6% others
- Attribution by manufactured goods:
    - Petrochemicals 32% [goods derived from petroleum or natural gas including ethylene (plastics precursor), methanol (precursor to formaldehyde and other chemicals), and carbon black (rubber additive) account for most].
    - Hydrogen Production 22% (for ammonia and methanol – large volume commodity chemicals)
    - Ammonia 20% (primarily used for fertilizer)
    - Nitric Acid 5% (primarily used for fertilizer and as feedstock for Adipic acid)
    - Adipic Acid 5% (major constituent of nylon)
    - Fluorinated Chemicals 2%

    - Other Chemicals 14%

- Several recommendations to transition to lower-carbon and renewable fuel feedstocks, transition processes to use of renewable electricity (e.g., electrolysis for hydrogen production), use of low-carbon hydrogen for heat-intensive processes, increasing energy and material efficiency, and use of carbon capture.
- Several chemical companies have established GHG reduction goals ranging from ambitious to modest, with a few targeting carbon neutrality. Technologies considered include use of industrial heat pumps, electric cracker technology, and others. Several roadmaps to transition the chemicals industry are referenced.

Petroleum Refining Industry Sub-sector:

- Represents 21% of total US industry CO2e emissions or about 0.50% of total global CO2e emissions
- 18 million barrels of oil per day refined in 2021 (mostly in Texas followed by Louisiana and California)
- U.S. consumption of 20.5 million barrels per day in 2019
- Refined into chemical feedstocks, transport fuels, industrial fuels, and other products
- Transportation sector consumed 70% and manufacturing processes consumed 24% as feedstock and fuels.
- Fuel uses: Other (65%), Natural Gas (30%), Net Electricity (5%), Other (1%)
- Process heating accounts for 142 MMT CO2e or 58% of the refining industry's emissions
- Options to decarbonize include energy efficiency, material efficiency, alternative feedstocks (e.g., biomass), and carbon dioxide capture and reuse (e.g., combine with hydrogen as a feedstock for many chemicals).
- Most corporate commitments currently rely on offsets (e.g., offsite soil carbon sequestration and purchased renewable energy credits) and do not address direct reductions of onsite GHG emissions. Some are embracing low-carbon renewable fuels and increased efficiency through energy and material management. Several roadmaps to transition the refining industry are referenced.

Iron & Steel Industry Sub-sector:

- Represents 9% of total US industry CO2e emissions or about 0.20% of total global CO2e emissions
- 87 million tons of crude steel were produced in 2021 and 25 million tons were imported.
- Steel plants employ 81,000 while iron and steel foundries employ another 64,000 with the majority of production in Indiana, Ohio, Pennsylvania, Illinois, Texas, and Michigan.
- 33% of production by three companies attributed to process using blast oxygen furnace (BOF) which uses coal and pig iron
- 67% of production by 50 companies attributed to use of electric arc furnace (EAF) which uses syngas, direct reduced iron (DRI) and recycled iron scrap and is less carbon intensive than the BOF process.
- Construction accounts for most steel consumption followed by transportation, machinery and equipment, appliances, energy, and other applications.
- Fuel uses: Natural gas (35%), Coal (21%), Coke & Breeze (18%), Net Electricity (15%), Other (11%)
- Most decarbonization efforts focus on transitioning from BOF to EAF steel-making processes and improving EAF by use of more DRI coupled with low-carbon, electrolytic hydrogen. Several large iron and steel manufacturers have set goals and made significant efforts to improving energy efficiency. Two large companies have set targets to reduce emissions by 25 percent by 2030 or to achieve net-

zero GHG emissions by 2050. Strategies being planned or pursued include use of natural gas instead of coal in BOFs; use of green and blue hydrogen, carbon capture, and electrification; increased use of scrap (circularity and recyclability); and others. Again, several roadmaps to transition the iron and steel industry are referenced.

Cement Industry Sub-sector:

- Represents 6% of total US industry CO2e emissions or about 0.13% of total global CO2e emissions
- 89 million metric tons of cement, valued at $12.7 billion, produced at 96 plants in U.S. in 2020.
- Cement industry employs 12,500 across 34 cement producing states (45% of production in Texas, Missouri, California, and Florida).
- Up to 75% of cement use is attributed to ready-mix concrete producers, 10 percent by concrete product manufacturers, and the remainder by contractors and others.
- 90% of cement produced is Portland cement.
- The U.S. is the fourth largest producer of cement in the world after China, India, and Vietnam.
- Fuel sources: Coal (36%), Other (30%), Natural Gas (20%), Net Electricity (13%), Other (1%)
- Most emissions for cement production come from process emissions (release of CO2 during calcination – 60% of the 66 MMT CO2e/yr) and pyro-process heating of limestone using electricity and thermal fuels to produce clinker (40 percent).
- The carbon intensity of cement produced from clinker is about 0.8 tonne CO2e per tonne of cement.
- IEA recommends reducing carbon intensity by 3 percent per year through reductions in clinker-to-cement ratio (e.g., greater use of blended cements) and deploying carbon capture technologies.
- Several large cement companies have established sustainability targets and made significant effort to improve operations. The largest cement manufacturer in the U.S. and the world, Lafarge Holcim, has established net-zero goals by 2050. Again, several roadmaps to transition the cement industry are referenced.

Glass Industry Sub-sector:

- Represents 1.3% of total US industry CO2e emissions or about 0.03% of total global CO2e emissions
- 16.5 million tons per year of glass products made in U.S., valued at $27.6 billion, with most production occurring in North Carolina, Texas, Ohio, California, and Pennsylvania and otherwise dispersed across several states.
- Glass industry employs more than 93,000
- The majority of glass produced is for containers, followed by flat glass and glass wool (e.g., insulation).
- Most emissions are from process heating (47%) and offsite electricity (40%) resulting from natural gas combustion used for high temperature heating in batch processing with large furnaces.
- Several glass companies have established sustainability goals and made significant efforts to decarbonizing through energy efficiency. One large company has set goals to reach carbon neutrality by 2049. Such actions can be encourage by creating markets for low embodied carbon glass such as the maximum carbon intensity of 1.43 tonnes of CO2e per tonne of flat glass established in California's Buy Clean policy for public works projects. Other state policies, such as in Colorado, Delaware, Oregon, New York, and Louisiana can encourage electrification of furnaces and general energy efficiency. A couple roadmaps to transition the glass industry are referenced.

Forest Products Sub-sector:

- Represents 7% of total US industry CO2e emissions or about 0.16% of total global CO2e emissions
  - *NOTE: Net carbon storage in U.S. forests and sequestration by carbon durably stored in an end use life cycle (e.g., wood-based building products for building construction and disposed in landfill at end of life for slow decomposition) are not accounted for as an emissions offset in the above values.*
- $300 billion in products produced a year in lumber and pulp & paper sectors (on par with the plastics and automotive industries)
- Employs 950,000 workers
- Over 22,000 manufacturing facilities producing about 17,000 wood products (such as lumber and furniture) and 5,000 products for pulp and paper applications.
- 97% of reported emissions come from the pulp and paper sub-sector with most plants located in the southeastern and eastern portions of the U.S.
- 45% of forest products sector emissions are for CHP/cogeneration and process heating (using natural gas and other energy sources) with 41% coming from offsite electricity.
- The industry has made several advances since 2005 to reduce GHG emissions by 24% (e.g., improved energy efficiency, low-carbon fuels, renewable bioenergy from leftover materials). Other emissions such as nitrogen oxides and sulfur dioxide have been even more significantly reduced by these efforts. However, natural gas still accounts for 28% and electricity 9% of energy use produced by CHP technologies supplying power to local utilities at avoided cost. Also, over two-thirds of paper consumed in the U.S. in 2021 was recovered through recycling. Individual companies and the industry as a whole have set sustainability goals to reduce Scope 1 and 2 GHG emissions intensity by 50% by 2030 from a 2005 baseline and a relevant goal for Scope 3 emissions by 2025, further advancing the circular value chain, and driving water stewardship while advancing more resilient forests. Several roadmaps to transition the pulp and paper industry are provided, including one by the American Forest & Paper Association.

Food and Beverage Industry Sub-sector:

- Represents 8% of total US industry CO2e emissions or about 0.20% of total global CO2e emissions
- $359 billion/yr in manufacturing of food and beverages in complex supply chain over the U.S.
- 31,400 companies and 36,000 processing plants employing 1.7 million workers.
- Emissions are mainly from offsite electricity usage (28% of energy used) and natural gas (57% of energy used).
- The top five food manufacturing companies in the U.S. by sales have established emission reduction targets including some with net zero goals by 2050. Common approaches include sustainable agriculture practices, carbon offsets, reduced waste packaging, supply chain management, and other measures. But, overlooked are opportunities for enhanced energy efficiency and process electrification. Several states have a variety of policies affecting decarbonization of the industry. A few decarbonization roadmaps are referenced to transition the food and beverage industry.

According to a more recent report by the US Department of Energy to provide an industrial decarbonization roadmap (DOE, 2022), the energy-related CO2 emissions of industry in 2020 are shown in Figures 30 and 31. In 2020, approximately 1,360 million metric tons of atmospheric CO2 emissions were attributed to the US industry sector, representing about 30% of the total US energy-related CO2 emissions. CO2 comprised 62% of the CO2 equivalent (CO2e) industrial sector GHG emissions, with the balance attributed to methane (22%), nitrous oxide (15%), and fluorinated gases (2%). A large portion of the non-CO2 industrial emissions is attributed to the agricultural sector. Excluding the agricultural sector, energy-related CO2 emissions (e.g., fossil fuel combustion) made up 80% of the of the industrial sector GHG emissions which was the focus of the DOE report. The other GHG emissions were considered appropriate for additional research on emission reduction pathways.

CO2 emissions for the US cement industry in 2015 are shown separately in Figure 32 because they were aggregated with lime in Figures 30 and 31. For cement, the majority of CO2 emissions are non-energy process related due to calcination. The 2015 US cement industry CO2 emissions are about 5% of the total US industry CO2 emissions in 2020 (acknowledging the different year basis of the data reported) and is reasonably consistent with data reported above by USCA (2022a).

As shown in Figure 33, process heating energy use was the largest contributor to the industrial sector energy use, comprising 51% of the total energy use. Furthermore, Figure 34 shows that much of the process heat energy use occurred for applications requiring temperatures of less than 300ºC which is suitable for non-fossil fuel combustion alternatives. Higher temperature process heating applications are more challenging to address without alternative low-carbon fuels with an energy intensity similar to natural gas.

Based on a much more detailed analysis of the various industry subsectors than summarized in this report, the DOE (2023) industry decarbonization roadmap was developed to reduce CO2 emissions as shown in Figure 35. It relied on four pillars as shown in Figure 36.

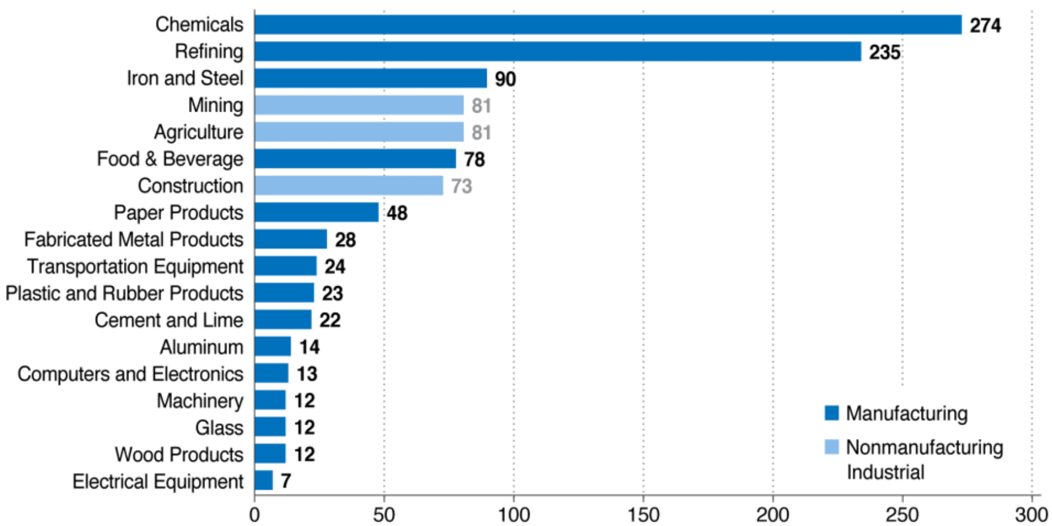

Figure 30. Energy-related CO2 emissions breakdown by industrial subsector in 2020, million MT CO2
Source: DOE (2022)

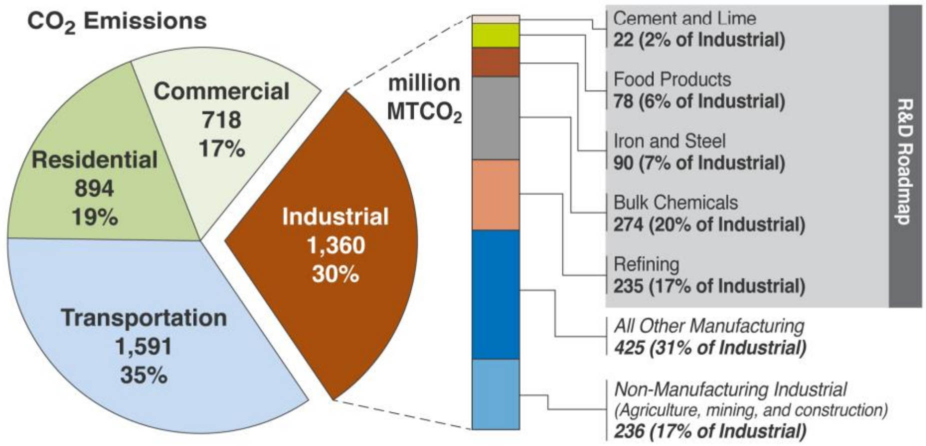

Figure 31. US primary energy-related CO2 emissions by end use sector and industrial subsectors in 2020.
Source: DOE (2022)

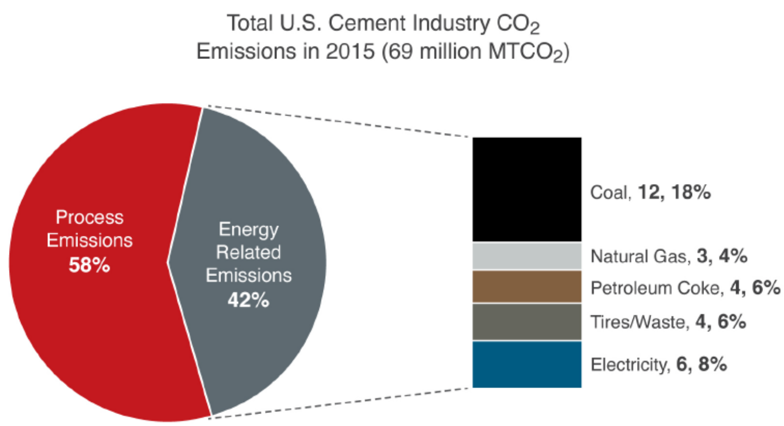

Figure 32. Sources of CO2 emissions in the US cement industry in 2015 (based on USGS 2015 energy use data)
Source: DOE (2022)

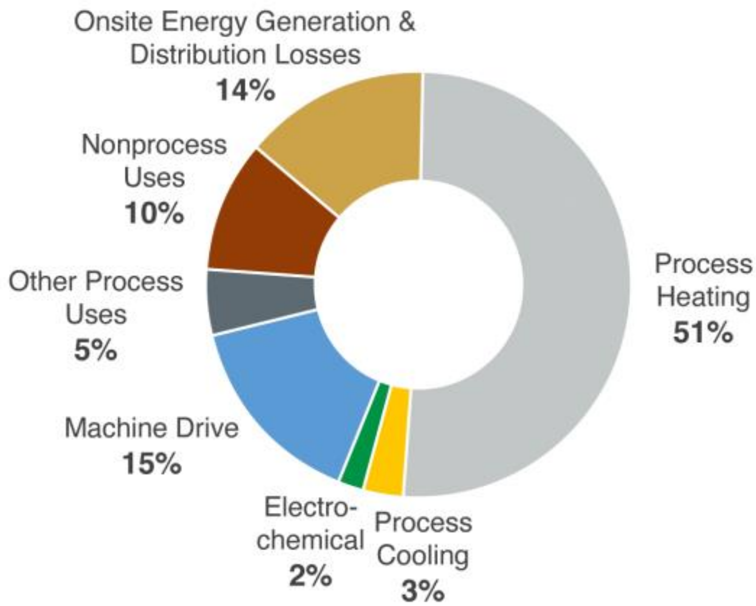

Figure 33. Energy use at US manufacturing facilities in 2018 by end use.
Source: DOE (2022)

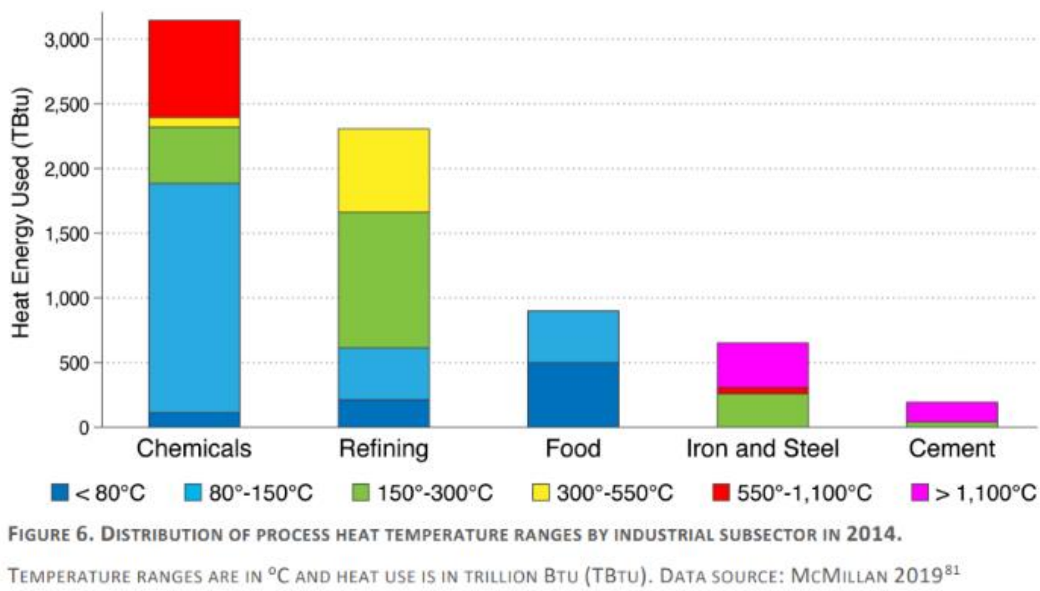

Figure 34. Process heating temperature ranges by industrial subsector in 2014.
Source: DOE (2022)

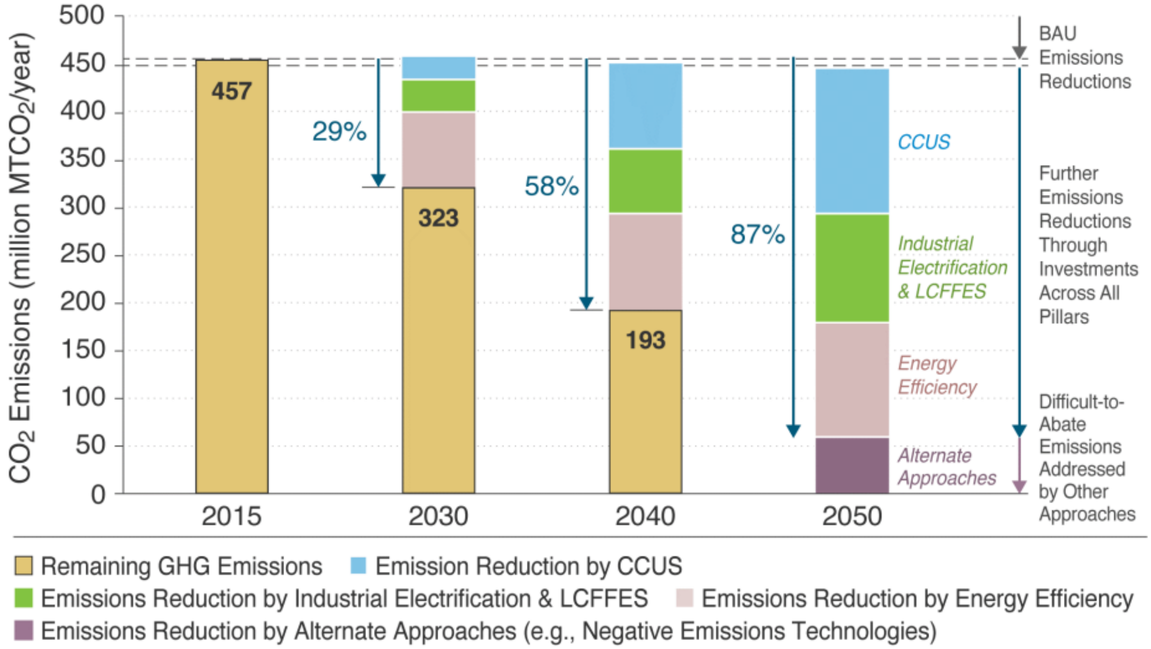

Figure 35. CO2 emissions reduction potential through the application of decarbonization pillars

Source: DOE (2022)

NOTE: CCUS = carbon capture, utilization, and storage; LCFFES = low-carbon fuels, feedstocks, and energy sources. It is important that the DOE industrial decarbonization roadmap does not require elimination of carbon-based feedstock or exclusive use of low-carbon feedstocks for materials manufacturing.

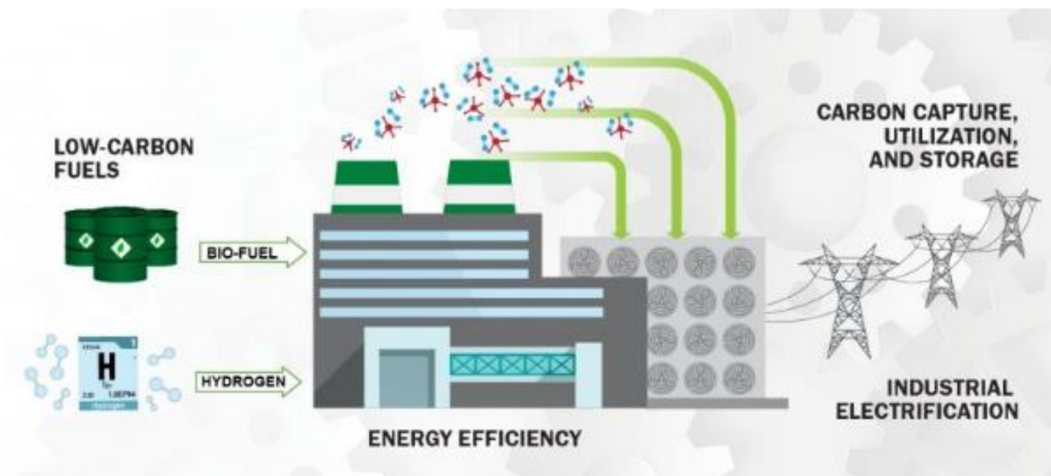

Figure 36. Four pillars of the DOE (2023) industrial decarbonization road map: low-carbon fuels, energy efficiency, carbon capture, and electrification.[45]

[45] https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap, last accessed 11/15/2023

PART 4: Decarbonization of US Buildings

4.1 General

Decarbonization involves actions that reduce CO2 emissions and other GHG emissions. Part 4 of this report is devoted to the topic of decarbonization of buildings in the US. First, common reasons used to justify the case for building decarbonization are considered (Section 4.2). Next, the foundational role of energy efficiency is explored (Section 4.3). Then, an overview of fundamental concepts of building decarbonization are reviewed (Section 4.4). Sections 4.5 through 4.8 focus on different aspects of building materials, including embodied carbon emissions and the importance of a "total carbon" approach for the evaluation of building insulation materials. Embodied carbon is an area of particular interest that has seen a dramatic surge in data, policies, guides, calculator tools, and other instruments for market transformation. Finally, Section 4.9 addresses whole building and building assembly life cycle analysis applications.

4.2 The Case for Building Decarbonization

The movement toward aggressive decarbonization of buildings and the growing surge of local city, state, and federal policies is driven by a heightened concern with global climate change (see Parts 1 and 2). Some examples of perceptions and arguments used to justify urgent pursuit of building decarbonization include:

> We're on a path to blow right past 1.5 degrees Centigrade.
> *"For our economic and national security, and for the future of all life on earth, lawmakers must act without delay."*
> (https://www.nrdc.org/stories/how-you-can-stop-global-warming , last accessed 8/2/2022)
>
> Rising global temperatures are causing climate-related natural disasters, and one of the biggest culprits is in plain sight: Buildings. In total, buildings account for about 40% of annual fossil fuel carbon-dioxide emissions (CO2), leading to increases in flooding, fires, hurricanes, and billions of dollars in annual damage. It's a global emergency of our own making. And if we don't take action now, we'll help to accelerate global warming—irreversibly changing life as we know it. (https://blueprintforbetter.org/articles/architectures-carbon-problem/ , last accessed 1/7/2023)
>
> The building sector is not on track to reach net-zero emissions by 2050. Federal RD&D investments have been disproportionately low, while national strategies that address the key hurdles of decarbonizing the building sector have been lacking. (https://itif.org/publications/2022/08/22/priorities-for-department-energy-building-rdd-portfolio/ , last accessed 1/7/2023)
>
> "We have improved operational energy efficiencies and made progress towards the widespread electrification of buildings… However, this is not enough. In order to avoid the catastrophic impacts of climate change and to have any chance of reaching the decarbonization targets set by the Paris Agreement, we have to do more. We have to tackle embodied carbon, which encompasses the greenhouse gas emissions associated with materials over the full life cycle of buildings…In order to prevent global temperatures from exceeding 1.5°C, global net anthropogenic CO_2 emissions must decline by about 45% from 2010 levels by 2030 and reach net zero by 2050. This means that we have until 2030 to radically decarbonize the building industry." (AIA-CLF Embodied Carbon Toolkit for Architects, https://carbonleadershipforum.org/clf-architect-toolkit/ , last accessed 10/24/2023)
>
> "The SE 2050 Commitment Program is being developed in response to the SE 2050 Challenge which states: ***All structural engineers shall understand, reduce and ultimately eliminate embodied carbon in their projects by 2050.*** It's well documented that we must be a carbon neutral society by 2050 if we are to avoid irreversible detrimental impacts to our environment." (Structural Engineers 2050 Commitment Program, American Society of Civil Engineers – Structural Engineering Institute, https://se2050.org/what-is-se-2050-overview/ , last accessed 1/7/2023)
>
> "As Denver works to reduce operational emissions in buildings over time, the importance of embodied carbon grows… As Denver achieves the goal of all new buildings and homes meeting net zero energy by 2030, the operational carbon emissions will significantly decline. By 2040, when Denver meets its goal for all buildings and homes achieving net-zero by 2040, operational carbon emissions will disappear, and embodied carbon will become 100% of the emissions… Based on the key findings comparing embodied carbon to operational carbon,

> emissions by building type and sector, and emissions from material type, embodied carbon increasingly impacts the health of our environment." (City and County of Denver, 2021)
>
> "As global construction continues to rise, and existing building operations become more efficient, embodied carbon will become an increasingly significant issue—accounting for approximately 50% of global building-sector emissions between now and 2050. This growing problem will account for a significant amount of our remaining carbon budget for keeping global warming below 1.5°C, and it needs to be addressed by policymakers and practitioners now to drive the most impact…Embodied carbon is critical to mitigating global climate change, because most of these emissions typically occur up front, at the start of a building's life cycle. Architecture 2030 reports that "unlike operational carbon emissions, which can be reduced over time with building energy efficiency renovations and the use of renewable energy, embodied carbon emissions are locked in place as soon as a building is built. It is critical that we get a handle on embodied carbon now if we hope to phase out fossil fuel emissions by the year 2050…**It is imperative that practitioners employ the strategies and solutions available today to accelerate the adoption of low-embodied-carbon construction.** These changes are necessary to deliver the unprecedented action required to meet the goal of the Paris Climate Agreement and limit global warming to 1.5°C." (RMI, 2021)
>
> "Success in decarbonizing the built environment will depend on an organizations exercising their power of decision to set requirements on embodied emissions while also taking accountability for embodied emissions. This is important because a decision made related to the embodied emissions impact of materials in buildings is irreversible once a product is made, purchased and delivered. The products lifetime emissions are essentially spent at installation showcasing that embodied emissions are highly influenceable if understood and prioritized before purchase." (Brightworks/WAP, 2021, p4)
>
> "As buildings become more energy efficient, a resulting larger *relative* percentage of a building's total CO2e impact will be the upfront embodied carbon. As part of the design and renovate process, AEC professionals have the ability to influence and reduce carbon impacts in the built environment. Recognizing the role that embodied carbon plays relative to the total CO2e is key to identifying how the AEC industry can help mitigate the climate crisis by reducing its carbon footprint… The AEC industry yields significant influence over the planning, design, construction, and operations of the built environment. Notably, the building sector is one of the biggest contributors to GHG emissions, which cause global warming. Given this influence, the AEC industry is poised to adopt more sustainable practices and lead cross-industry decarbonization efforts to reduce its impact on climate change." (https://redshift.autodesk.com/articles/what-is-embodied-carbon , accessed 12/14/2022)

The American Institute of Architects (AIA) and Carbon Leadership Forum's (CLF) embodied carbon guide brings additional concerns with construction sector emissions related to building materials as follows:[46]

> Building materials are one of the highest-risk industries for modern slavery in the world. According to the International Labor Organization, the construction industry ranks as the second-highest sector in terms of risk of forced labor (after domestic labor) with exploitation occurring at the construction site as well in the material supply chain.
>
> In order to address modern slavery in construction materials, supply chains must be better tracked and better understood. Tackling embodied carbon requires a similar approach: better supply chain transparency and traceability. This will be a challenge because the construction sector is "the largest industrial sector in the world, the most disaggregated, and the least modernized." But scrutinizing supply chains will allow us to both address greenhouse gas emissions and human rights violations hidden in construction material supply chains around the world.

The commonly-cited reasons for aggressive, rapid decarbonization of buildings and building materials are all very similar and are summarized as follows:

[46] https://carbonleadershipforum.org/clf-architect-toolkit/, last accessed 2/5/2023

- As building energy efficiency improves and the electric grid becomes cleaner, the importance and impact of embodied carbon emissions associated with building materials increases.
- Buildings account for about 40% of total global GHG emissions (28% for building operations and 11% for building materials & construction).
- Floor space of buildings is expected to globally double over the next several decades and embodied emissions from those new buildings will amount to 49% of emissions from that new construction over the same time period (the remaining 51% of emissions due to building operations).
- Net zero emissions construction is needed by 2050 and a minimum 40 percent reduction in current emissions by 2030 to reach the 1.5ºC global temperature rise limit of the Paris Agreement and avoid the worst impacts of climate change.
- There are material choices now that, for many buildings, can result in them becoming a net carbon sink for the life of the structure resulting in net-zero emissions (e.g., shift to biogenic materials such as wood, wood fiber, and similar plant-based building materials and components, including insulation).
- Embodied carbon of buildings of any type can be significantly reduced with attention to material selection and specification with cost increases of not more than 1% of total construction cost.

Some of the statements and statistics summarized above appear to lack appropriate context or clarity in the presentation of relevant data. Consider the following as one example where the claim is made that 100% of emissions will be from embodied carbon as building operational carbon is reduced to zero in the future.

> Figure [37] shows a building stock analysis of the ratio of operational carbon and embodied carbon in Denver, Colorado over 40 years (City and County of Denver 2021). As building codes head to netzero energy and we consider decarbonization of heating through electrification, the operational carbon becomes a smaller percentage of the overall emissions from a building. In the example of Denver, the embodied carbon emissions are estimated to make up 27% of all emissions from buildings built in 2030 compared to annual operational emissions for all buildings in 2030. If Denver were to achieve its goal of all buildings to be net-zero energy by 2040, 100% of emissions will be from embodied carbon. (Esram and Hu, 2021)

While true in a relative sense, it is says nothing about the actual role or significance of the small magnitude of emissions associated with building materials as illustrated by Figure 37. Decreasing building operational emissions by improved energy efficiency, electrification, and the transition to a cleaner electric grid has very little impact on the actual magnitude (not relative percentages) of embodied carbon emissions attributed to materials used in buildings. Figure 37 demonstrates that, where the operational carbon emissions of buildings are successfully reduced over time, the magnitude of embodied carbon emissions associated the building materials in the building stock do not change. Annual operational carbon emissions of buildings are at least an order of magnitude greater than the annual contribution of material embodied carbon emissions associated with production of new building materials. It also shows that material embodied carbon emissions are relatively small in comparison to the benefits of energy efficiency and clean electric energy toward the reduction of large annual operational emissions of the building stock. This topic will be more thoroughly investigated and explored later in Section 4.8 and 4.9 from a “total carbon” perspective, particularly for insulation materials and their use in building envelope assemblies.

Decarbonization policy that prioritizes and focuses on energy efficiency, electrification, and cleaning the electric grid have by far the greatest decarbonization value for the climate and also will serve to help decarbonize materials to the extent industry also electrifies and improves in process energy efficiency. Industry decarbonization was addressed in Section 3.3, relates directly to the embodied carbon of materials, and must be carefully coordinated with decarbonization actions or policies intended to affect downstream applications of materials.

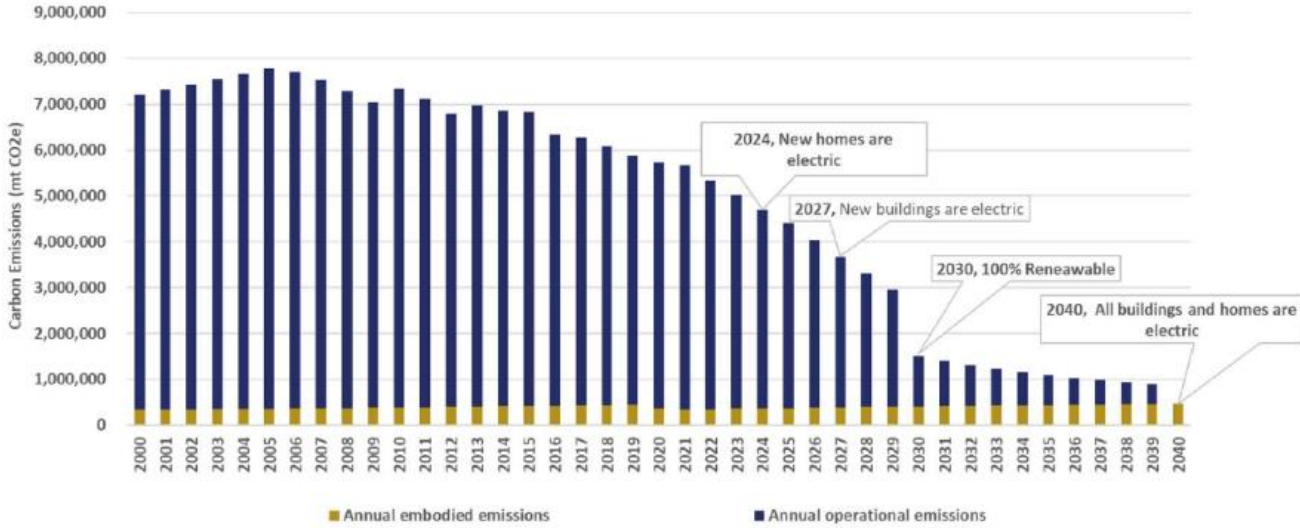

Figure 37. Embodied carbon and operational emissions for all Denver area buildings by year
Source: City and County of Denver, 2021

In addition, it is often stated that building materials and construction account for 11% of global CO2e emissions. While true, this global statistic is not accurate when applied to US building materials. It does not account for the fact that decarbonization improvements in the US industry sector have actually resulted in significantly reduced GHG emissions impacts relative the rest of the world (which tends to use more coal and less efficient processes for material manufacturing). And, many companies within the US industry sector have plans to continue significant reductions in GHG emissions. The topic of industry emissions (which are attributed to materials as embodied emissions) and associated data was addressed in Part 3 of this report. The following discussion applies that data specifically to US building and construction materials in relation to total US GHG emissions and total global GHG emissions. The comparison to total global GHG emissions provides a meaningful basis for assessing the significance of material embodied emissions to global climate change. The climate problem is necessarily global in scale because all emissions are ultimately mixed into the Earth's atmosphere as part of a global carbon cycle that affects climate change as shown in Part 1 of this report.

In 2019, the U.S. building materials & construction sector accounted for about 6% of total US GHG emissions (NASEM, 2021). Furthermore, the total gross US GHG emissions of 5.98 GtCO2e in 2020 was about 10% of the world's total gross GHG emissions of 59 GtCO2e (NASEM, 2021). This value is conservative when compared to the 12% of global total GHG emissions reported for all of North America according to IPCC (2022). **Therefore, US GHG emissions attributed to emissions generated from the manufacturing of building and construction materials is estimated to be about 6% x 10% = 0.6% of the total global GHG emissions or 0.6% x 59 GtCO2e = 0.354 GtCO2e (or 354 MMtCO2e).**

Furthermore, public infrastructure projects accounted for 32% of total embodied GHG emissions from construction in the US according to USCA (2021a):

> "From 2008 to 2018, public infrastructure projects accounted for 32 percent of the total embodied carbon emissions from construction in the United States—over 150 million metric tons (MMT) CO2e per year."

Therefore, about 68% of the emissions reported above for building and construction materials are attributed to just building materials. Consequently, the contribution of **US building and construction materials to total global GHG emissions is about 0.4% (i.e., 0.6% x 68% = 0.4%).**

For US new home construction, a recent study (RMI, 2023) estimates annual embodied GHG emissions of as much as 55 million tCO2e (0.055 GtCO2e) which appears to include biogenic carbon storage of wood-based materials commonly used for US home construction. **Based on total US GHG emissions of about 6**

GtCO2e/yr, the embodied GHG emissions represented by US new home construction is about 0.9% of total annual US GHG emissions (i.e., 0.055/6 x 100% = 0.9%). Based on total global GHG emissions of about 59 GtCO2e/yr, the embodied GHG emissions in US new home construction is about 0.09% of total annual global GHG emissions.

Consistent with the above estimates of overall US building material contributions to global and US GHG emissions, **the US concrete industry has estimated that their industry contributes about 0.17% to the total annual global GHG emissions.**[47] This concrete estimate is reasonably consistent with data presented in Parts 2 and 3 of this report, including DOE (2022) and EPA (2022). Concrete is by far the most significant embodied carbon contributor for US infrastructure, buildings, and other applications. Also according to NBI (2021), about 51% of concrete consumption is used for buildings in the US. **Therefore, annual US concrete usage for building applications accounts for about 0.09% (less than one-tenth of a percent) of total global GHG emissions.** Other building materials and products manufactured in the US will be considered in a later section of this report in an attempt to similarly quantify and aggregate their contributions to total US and global GHG emissions.

The realities of the above data and the small contributions to global GHG emissions should not be taken to mean that improvements to reduce building material embodied carbon emissions are completely inconsequential and should not be pursued where practical and feasible. Material embodied carbon necessarily requires a focus on the industry sector where materials are produced and material embodied emissions originate. See Section 3.3 of this report for data to help focus appropriate policy emphasis on key categories of emissions associated with material production in the industry sector. In building industry applications of materials downstream from the materials manufacturing industry, any additional actions related to material embodied carbon must be carefully coordinated to avoid redundant actions that may bring costly and unintended consequences. Such actions must be careful to not have significant impacts on other functional performance attributes of buildings (such as safety, durability, resiliency, and energy efficiency).

Finally, building insulation materials have a crucial role in energy efficiency as a foundation for building decarbonization. Therefore, insulation materials should not be judged merely on their embodied carbon footprint and separate from significant GHG emission reduction benefits that are directly associated with and realized during the material's use. As addressed in later sections of this report, a "total carbon" approach should be used to evaluate both the carbon footprint (embodied carbon) and carbon handprint (operational carbon savings), particularly for insulation materials used in building thermal envelope assemblies. Various insulation materials have different properties and multi-functional capabilities that can also be used to optimize building assembly total carbon, resource efficiency, and other factors required for performance and building code compliance.

4.3 The Foundational Role of Energy Efficiency

Many believe that the traditional energy efficiency focus of energy codes and standards has approached or even reached a point of diminishing returns. To some degree, this viewpoint depends on the position of whether or not social cost of carbon (SC-CO2) should be included as a "hidden cost" of combusted fossil fuels used to supply operational energy to buildings (see Section 1.4 for information on the SC-CO2). If it were not for significant advances in energy efficiency of newer buildings, the amount of energy use and carbon emissions associated with the US existing building stock and annual new building construction would be much greater than it is today. More importantly, improved energy efficiency for new and existing buildings will continue to play a crucial role in decarbonizing the US electricity system by saving billions of dollars in cost as the US electric grid and power generation system transitions to cleaner primary energy sources and as more buildings electrify by using heat pump technologies (ACEEE, 2023a; ACEEE, 2023b).

[47] Based on unpublished Portland Cement Association data presented at ACEE webinar, 2022.

In a recent report by ACEEE (2022), the broad and beneficial impact of energy efficiency was evaluated and quantified. The report describes energy efficiency as “getting the maximum use from energy consumed”. Yet, it also recognizes that characterizing energy efficiency across many economic sectors, including buildings, is a “complex task”. Key findings from the study are excerpted as follows:

> By getting twice the economic output from our energy than in 1980, efficiency drives U.S. economic competitiveness and allows for less energy to drive economic growth.
>
> Without the energy efficiency investments made since 1980, energy consumption and emissions would have been 60% higher, and consumers would be paying nearly $800 billion more per year in energy costs. Though energy efficiency’s benefits go beyond energy and cost savings; their benefits also include a cleaner environment and improved public health.
>
> Six key energy efficiency policies and programs (vehicle fuel economy standards, appliance and equipment efficiency standards, utility sector energy efficiency programs, ENERGY STAR, building energy codes, and federal research, development, and deployment) reduced total U.S. energy consumption by roughly 29 quads in 2021, equal to roughly 30% of total U.S. energy consumption in that same year, or the energy use of the entire transportation sector.
>
> Energy efficiency is the foundation of deep decarbonization and is one of the best-established and most-implemented examples of a distributed, zero-carbon resource. Energy efficiency, together with grid integration technologies, also plays an important role in shaping electricity demand to match supply, making it an important resource in the transition to a renewable energy-powered electric grid.

Regarding the untapped potential remaining for energy efficiency improvements, the ACEEE (2022) report states the following:

> There is enormous remaining potential for existing energy efficiency technologies, but new technologies that enable greater control, connectivity, and higher levels of system optimization are also evolving, yielding even more impressive outcomes. Getting to the next level of energy efficiency deployments will require extensive policy, programmatic support, and sustained commitment.
>
> While several cities and states have enacted building performance standards for existing buildings, many have not yet taken that step. Similarly, the majority of states have not yet adopted the most recent international commercial or residential energy codes. Furthermore, the U.S. market for Zero Net Energy Buildings is growing rapidly, but it still constitutes only a small fraction of the building market.
>
> Investment in energy efficiency over the past decades has shifted our economic, social, and environmental trajectory. However, investments are not keeping pace. Additionally, trends toward increasing size and number of buildings and devices, and increasing vehicle miles traveled, may lead to significant increases in energy use without accelerated energy efficiency.
>
> Incremental investments in energy efficiency across buildings, transportation, and industry sectors in North America increased after years of stalled investment. However, we must raise our ambitions to support energy efficiency – advancing on tried-and-true policies that unlock private capital, drive innovation, and ensure energy efficiency is accessible for all while preparing for energy efficiency’s future.

The ACEEE (2022) report on energy efficiency summarizes the 2019 US economic, population, and energy use situation as follows:

- The U.S. constitutes roughly 4% of the world’s population;
- accounted for 24% of global gross domestic product (GDP);
- consumed about 17% of the worldwide energy demand (US – 97.33 quadrillion Btu);
- produced 12% of worldwide GHG emissions (US – 5,269 MMT CO2);

- in 2020, the U.S. had energy expenditures of $1.01 trillion (4.8% of US GDP) down from $1.22 trillion in 2019 (5.7% of GDP) which corresponds to a doubling of energy productivity (GDP divided by energy expenditures) since the 1970s;
- consequently, energy consumption and carbon emission would be 60% and 78% greater, respectively, without the energy efficiency investments over the past several decades avoiding 3,810 MMT CO2 emissions that would have otherwise occurred in 2021; and,
- over the past 21 years, per capita energy consumption has consistently decreased for a total of 16% reduction thanks to energy efficiency investments that offset the impact of a 46% increase in population and 41% increase of vehicle miles driven since 1980.

The ACEEE (2022) report also indicates that 6 key energy efficiency policies accounted for 30% (or about one-half) of the avoided energy demand (and associated emissions) in 2021 as shown in Figure 38.

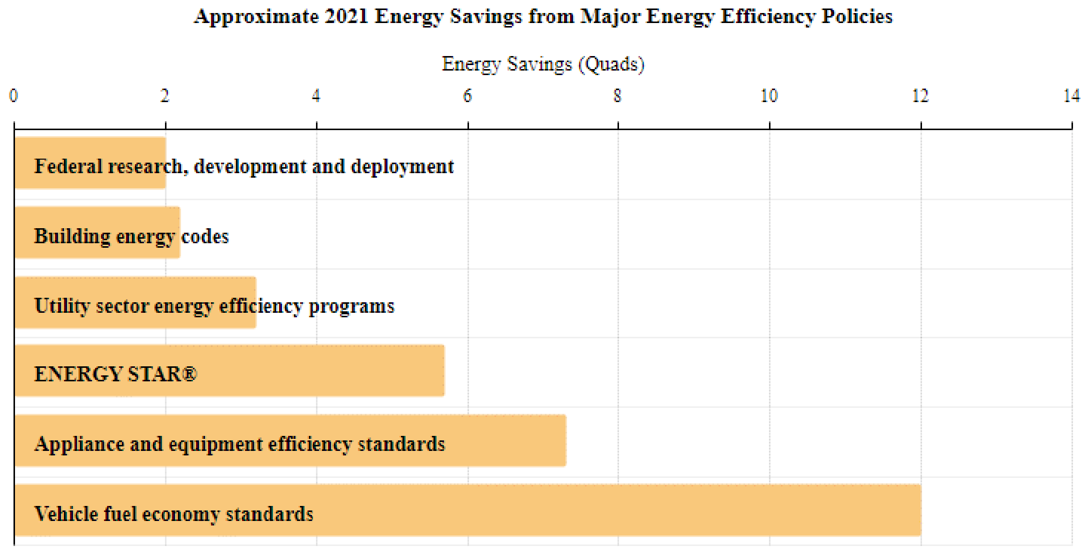

Figure 38. Approximate annual energy savings in 2021 from major US energy efficiency policies
Source: ACEEE (2022)

Among other benefits specifically associated with the four policies shown in Figure 38 that have direct or indirect influence on building energy efficiency, the report indicated the following (ACEEE, 2022):

- Energy efficiency improvements have driven down household energy expenditures by 16% since 2005.
- Energy consumption of average new appliances (1980-2018) have improved by more than 40% for heat pumps, AC, refrigerators, and clothes dryers (whereas market average new gas furnaces show a relatively sluggish improvement of 20%).
- Commercial building energy use intensity (EUI) has decreased from about 250 kBtu/sf (1995) to about 185 kBtu/sf (2021) – a 26% improvement – due mainly to lighting and space heating efficiency improvements; this also is accompanied with a significant increase in annual building EUI benchmarking under EPA's Energy Star® Portfolio Manager along with a steady climb in Energy Star ® and LEED certified commercial buildings.
- Annual Energy Star® rated homes also have steadily increased and have reached a cumulative 2.35 million homes in 2021.

- Continually improved model energy conservation codes (i.e., IECC and ASHRAE 90.1) over the past 40 years have the potential to reduce new building energy use by 45% (relative to 1975) if the latest 2021 IECC or ASHRAE 90.1-2022 standard is adopted and effectively enforced.
- The uptake of zero net buildings has continued to grow in recent years with now over 20,000 housing units per year and just over 600 commercial buildings per year.
- Finally, over 30 US jurisdictions have passed or committed to pass building performance standards by 2024 which focus mainly on improving the existing building stock.

Furthermore, the ACEEE (2022) report noted that two-thirds or 25.8 million of low-income households in the US experienced a high energy burden in 2017 (i.e., >6% of household income on energy expenses) and roughly one-third were severely energy burdened (i.e., >10% of household income on energy expenses). Thus, energy efficiency is an important consideration for all market segments, especially those most vulnerable to high energy expenses.

Development and use of cleaner energy sources coupled with more efficient use of energy are the primary means to minimize anthropogenic GHG contributions to global warming for all US sectors, including buildings. Energy efficiency and renewable energy are known as the "two pillars" of a sustainable energy strategy (ACEEE, 2007; Crandell, 2019a) as illustrated in Figure 39. Of the two pillars, energy efficiency is properly understood to be "the least cost approach to U.S. environmental stewardship".[48] Others also recognize that in the pursuit of a decarbonized economy by 2050, "energy efficiency remains the priority for reducing energy consumption, along with increased use of renewable energy sources in order to reduce GHG emissions and dependency on fossil fuels." (Lawrence and Costas, 2023).

Figure 39. Twin Pillars of a Sustainable Energy Strategy.
Source: Crandell, 2019a

But, where these two pillars of decarbonization are not individually protected such that energy conservation and renewable "clean" power or electrification are considered tradeable in US energy codes and standards, counter-productive and hidden cross-subsidies appear in the market that erode the effectiveness of both pillars (Crandell, 2019b). This problem is illustrated in Figure 40 where energy efficiency measures are traded-off to subsidize the cost of renewable energy measures. The benefits of the renewable energy resource used to displace fossil fuel energy sources are then completely or partially eroded by increased energy consumption by the building because of weakened measures for energy efficiency. Furthermore, the problem may be exacerbated when the trade-off of a building's energy efficiency measures is made by use of purchased off-site renewable energy credits without robust accountability. Consequently, the purchased off-site renewable energy

[48] Alliance to Save Energy, "Doubling Energy Productivity", www.awe.org, last accessed 11/7/22

credits used to weaken building energy efficiency in this trade-off or "green-washing" scheme may not actually result in any new renewable energy infrastructure being placed into service despite green energy marketing claims to the contrary (Gillenwater, Lu, and Fischlein, 2014).

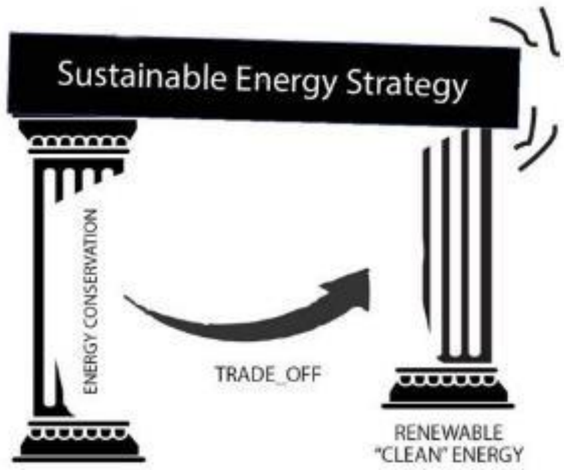

Figure 40. Trade-off of energy conservation to subsidize building
Source: Crandell, 2019b

Trading-off energy efficiency measures (such as insulation) to either subsidize the cost of purchasing renewable energy systems or electrification in US energy codes and standards for buildings (or other policies) will tend to result in increased energy demand for the life of the structure. It diminishes or erodes the benefits of increased renewable energy production and building electrification. This trade-off approach is founded on a faulty assumption that renewable energy production and energy conservation (of current fossil energy use and limited available renewable resources) are equivalent such that the trade-off has a so-called "neutral energy" impact. But, this faulty assumption relies on a very narrow view of energy merely from the perspective of the units of energy (e.g., Btu, kWh, etc.). Such units do not differentiate between the sources of energy used (i.e., fossil vs. renewable). This trade-off subsidy essentially sacrifices a reliable investment in energy efficiency and undermines a sustainable energy strategy for decarbonization.

A recent study of US building sector decarbonization scenarios to 2050 by the Lawrence Berkley Laboratory (LBL) agrees with these two pillars in the sense that they are energy efficiency and electrification with continued investment in renewable electric energy sources (Langevin et al., 2023). The investment in energy efficiency is a necessary component to support and protect the investment in electrification while the electric grid is transitioning to greater reliance on variable renewable sources (e.g., wind and solar). These two pillars are dependent on each other in a sustainable and attainable strategy.

Some of the key findings of the LBL study are shown in Figures 41 through 44 based on LBL's website summary of Langevin et al. (2023).[49] In short, a near term focus on improved energy efficiency is critical to ensuring long term success in achieving decarbonized electrification of the building sector by 2050 (see Figures 41, 42, and 43). The near term investment in energy efficiency improvements of buildings (particularly envelope and heating/cooling equipment efficiency) can also save over $100 billion per year in electric power system costs by 2050 in meeting future building electricity demand (see Figure 44).

[49] https://buildings2050.lbl.gov/, last accessed 11/15/2023

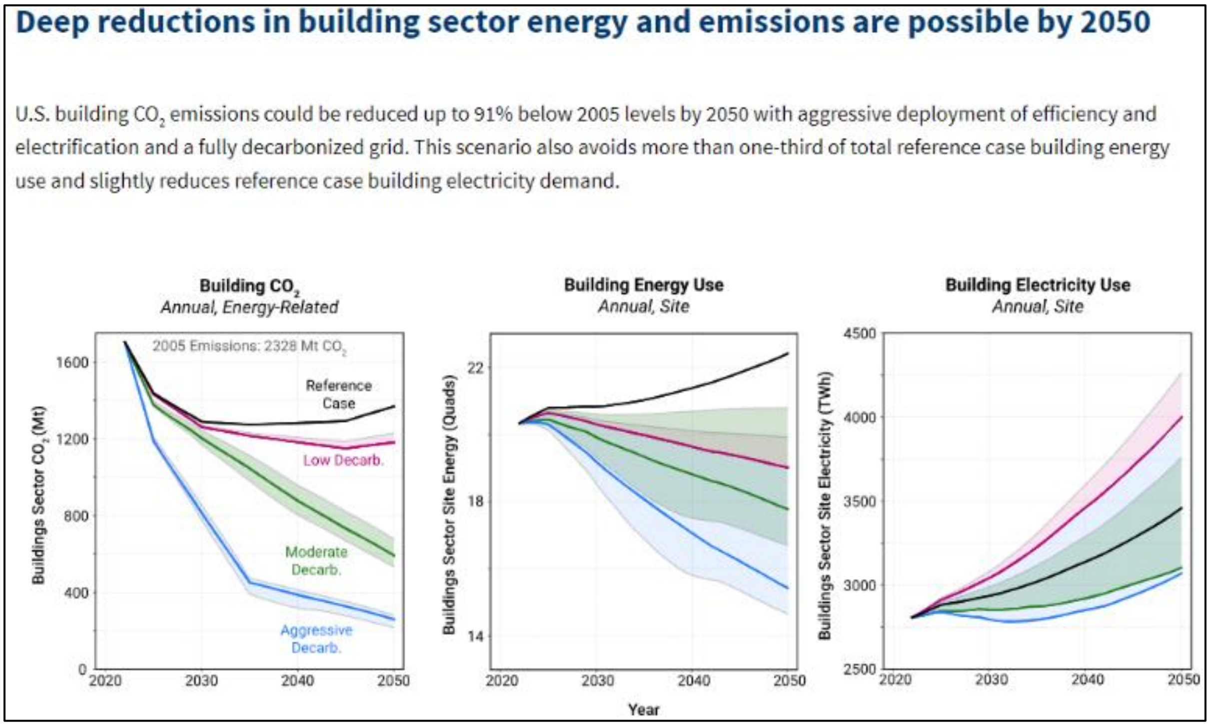

Figure 41. Scenarios for building sector decarbonization from 2022 – 2050.
Source: https://buildings2050.lbl.gov/ based on Langevin et al. (2023)

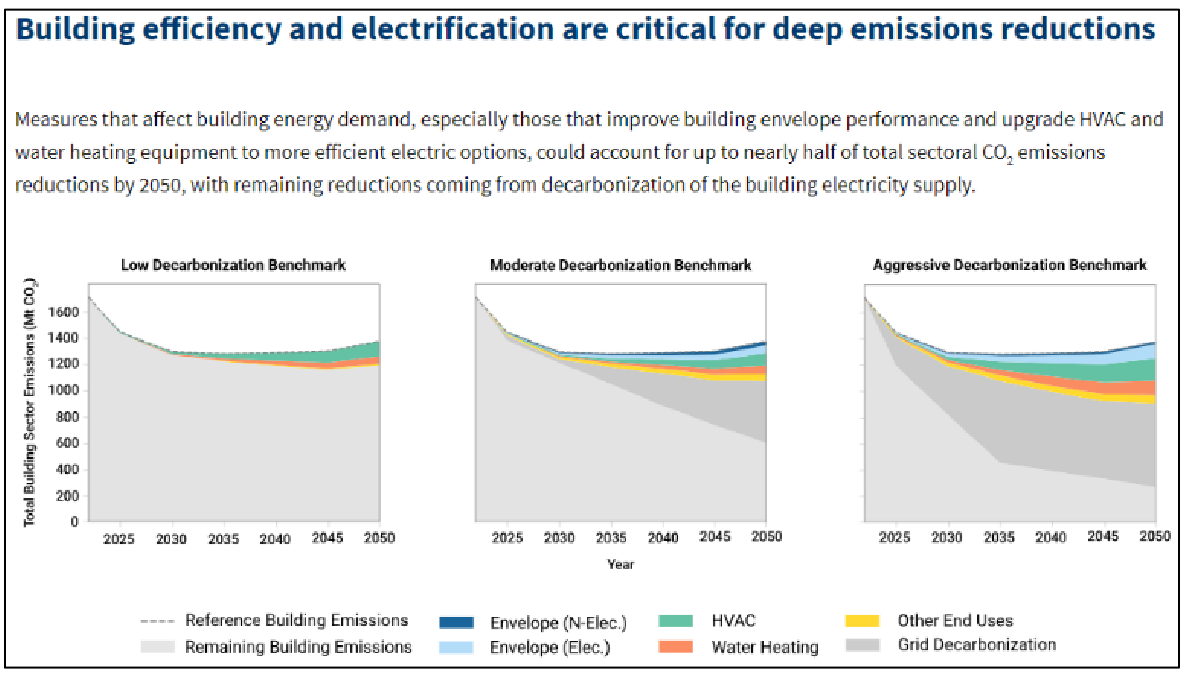

Figure 42. Emissions reduction wedges showing importance of energy efficiency
Source: https://buildings2050.lbl.gov/ based on Langevin et al. (2023)

Efficiency reduces emissions now and enables electrification impacts later

Building electrification with grid decarbonization is an essential long-term component of building sector decarbonization, delivering nearly twice as much emissions reductions as building efficiency from 2030–2050. Prioritizing efficiency in the near-term, however, delivers significant CO_2 reductions by 2030 and hedges against a slower pace of end-use electrification. Building efficiency and demand flexibility also facilitate electrification at all scales of the electricity system (from behind-the-meter and distribution through transmission and generation).

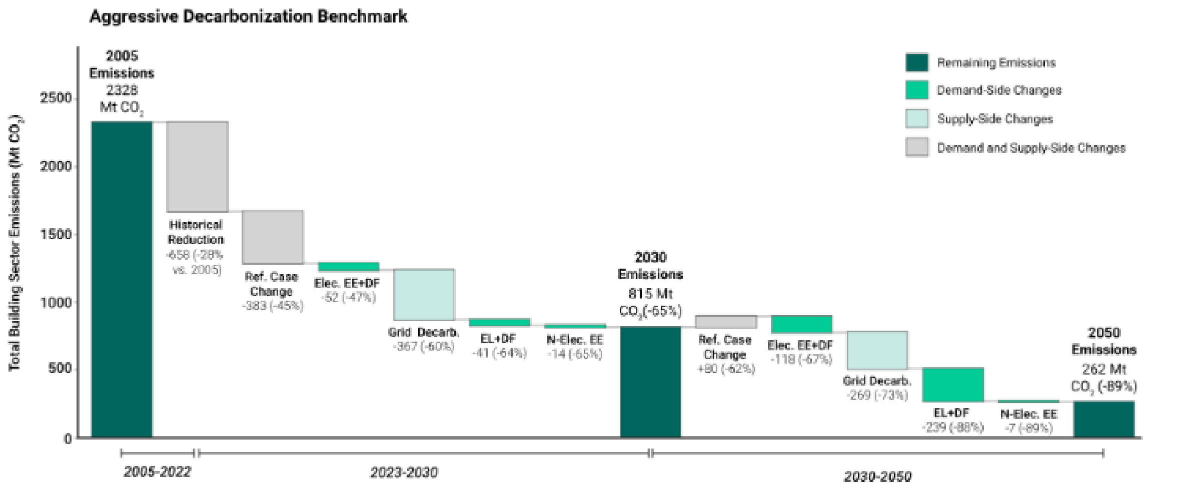

Figure 43. Reductions in building sector emissions made possible by investment in energy efficiency first to enable longer term decarbonization of the electric grid as buildings also electrify.
Source: https://buildings2050.lbl.gov/ based on Langevin et al. (2023)

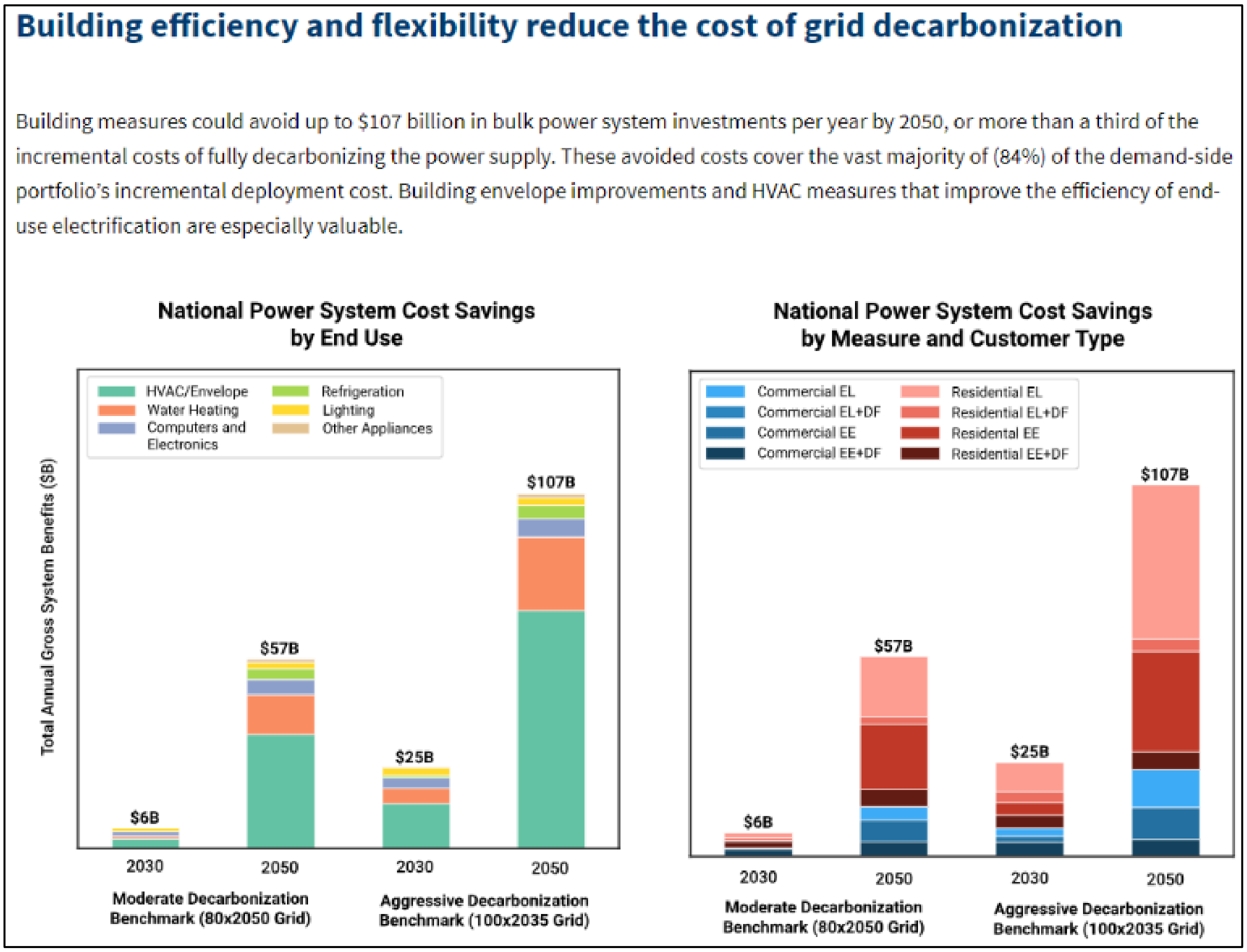

Figure 44. Estimate of electric power system avoided costs per year
Source: https://buildings2050.lbl.gov/ based on Langevin et al. (2023)
NOTE: EL = electrification; EE = energy efficiency; and DF = demand flexibility

US building energy efficiency will remain important well beyond the time-frame of the present optimistic goal to achieve a zero carbon economy by 2050. This reality is evidenced in Figure 45 which shows a realistic future transition scenario where direct and indirect fossil energy consumption will continue and grow in magnitude through 2054 at which time a "turning point" is predicted. The curve of cumulative CO2e savings will remain negative until 2054 and contribute significant annual CO2e emissions which are most effectively mitigated by continued pursuit of and emphasis on energy efficiency. Also, additional energy efficiency improvements can decrease the time to the crossing point where cumulative CO2e emissions savings become positive (e.g. no net contribution of GHG to global emissions). The graphic of Figure 45 was provided with limited commentary and the observations provided here are based on this author's interpretation.

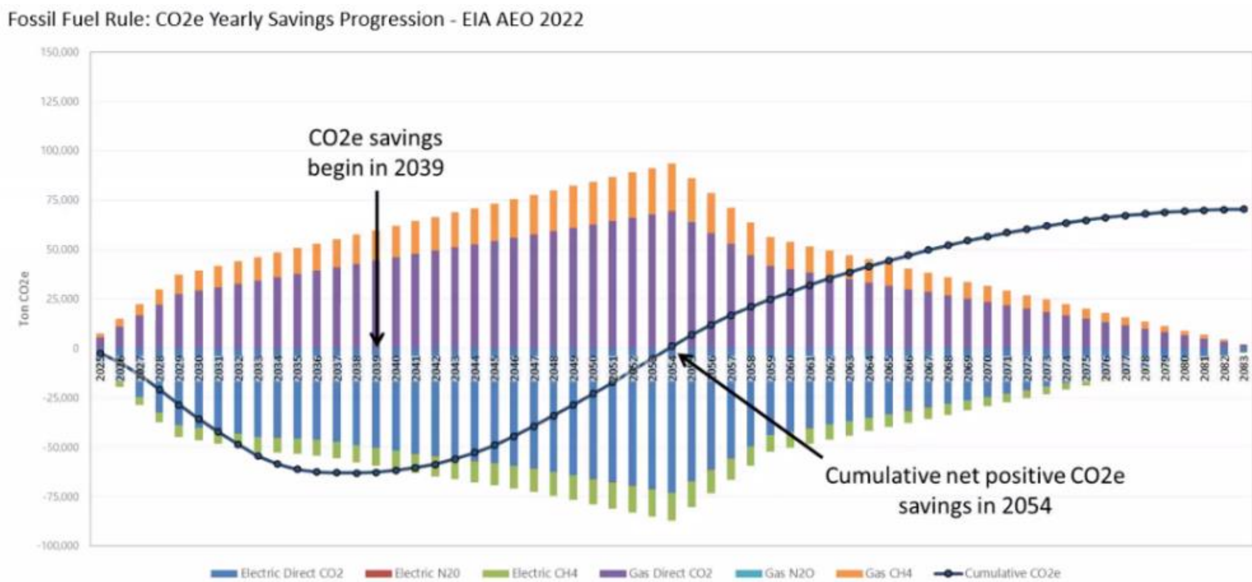

Figure 45. Fossil Fuel Rule: CO2e Yearly Savings Progression – EIA Annual Energy Outlook (AEO) 2022
Source: "Clean Energy Federal Buildings Rule, SNOPR Public Meeting, 01052023", U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 1/5/2023 (unpublished powerpoint presentation)

Finally, consistent with Figure 45, the US EIA (2021) energy use projections in Figure 46 indicate that US residential and commercial building populations will continue to grow in the future resulting in significant energy demand increases if not otherwise moderated by a continued emphasis on energy efficiency improvements. The increased energy demand, if not mitigated will cause continued significant GHG emissions from fossil energy sources and cause delays and difficulties (e.g., peak demand increases) in the transition to renewable energy sources, especially as buildings increasingly electrify for heating (Buonocore, et al., 2022). This concern is emphasized by others in making the case for building energy efficiency as an important part of the path for building decarbonization (Hamilton, 2023).

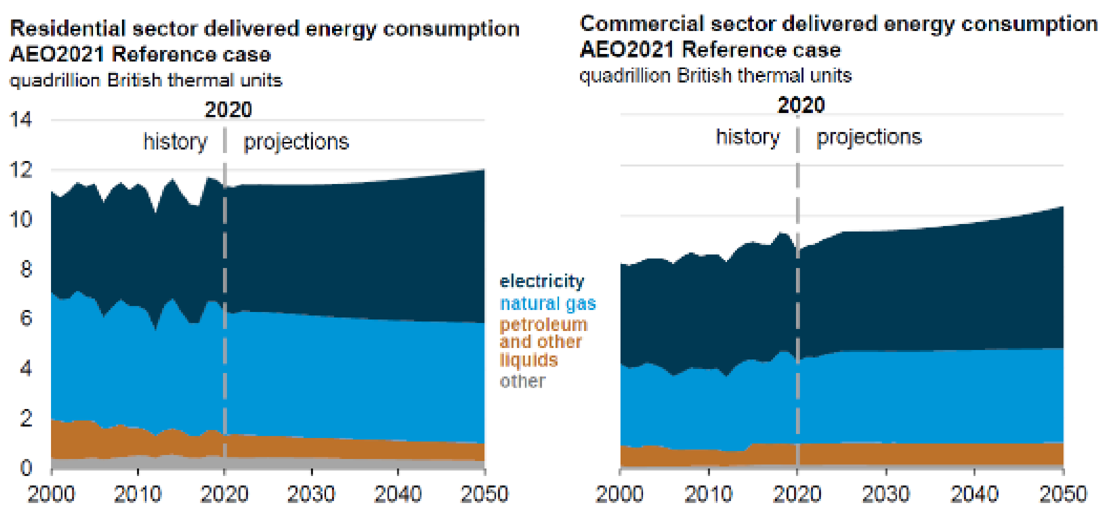

Figure 46. Residential and commercial building sector energy use history and projections.
Source: U.S. EIA, AEO2021, www.eia.gov/aeo

4.4 Fundamentals of Building Decarbonization

4.4.1 General

GHG emissions associated with buildings fall into two categories:

1. **Operational emissions** are primarily related to fossil energy use either directly (e.g., fossil fuel combustion in HVAC equipment and appliances) or indirectly (e.g., use of electricity that has at least some portion of supply generated by fossil fuel combustion); and

2. **Embodied emissions** (or attributed material emissions) which are the industrial sector emissions associated with the manufacturing of building materials including extraction of raw materials, transport, and processing into final products that then leave the "gate" of the plant for transportation and distribution to an end use such as a building project where additional emissions occur with handling and installation of materials during construction; embodied carbon emissions also include emissions associated with building use and end-of-life as well as potential for reuse and recycling as shown in Figure 47.

As described by the City and County of Denver (2021):

> A building's life cycle GHG emissions are comprised of operational carbon and embodied carbon. Operational carbon emissions results from the on-site electricity and natural gas (gas) consumption required to operate buildings and homes. Embodied carbon is generated from the materials used to build structures and includes material extraction, manufacturing, transportation, building construction, maintenance, demolition or deconstruction, and disposal. Refer to [Figure 47]."

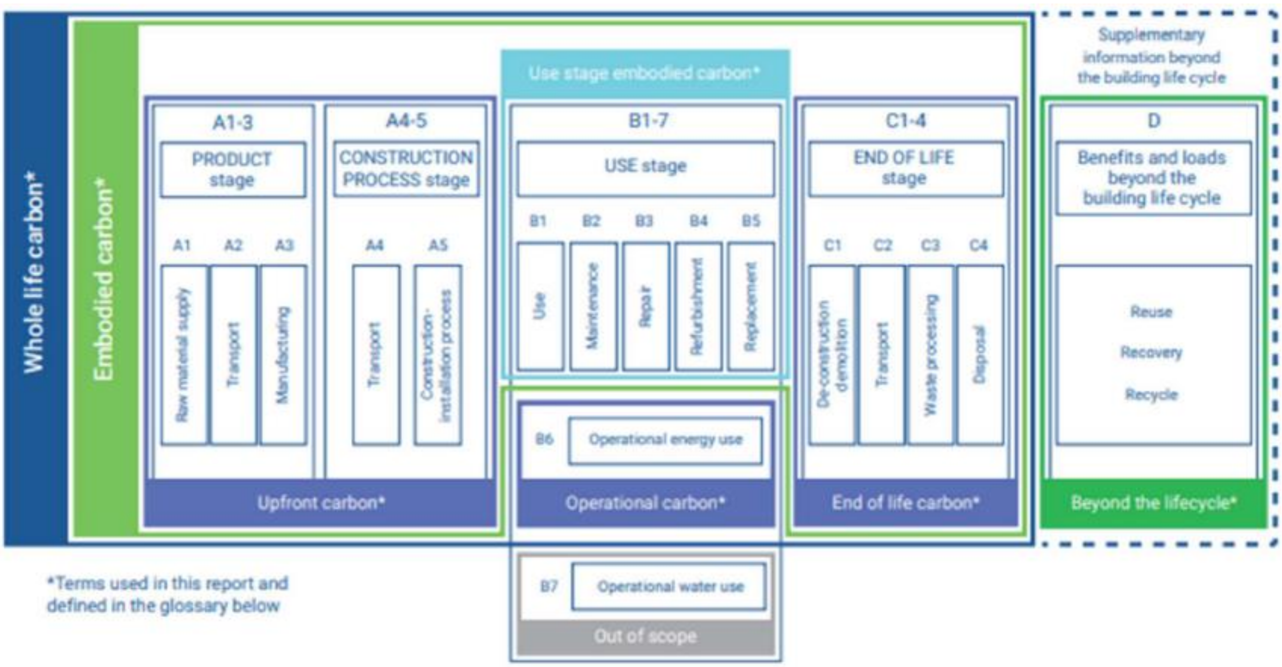

Figure 47. Life cycle stages of a building or any of its constituent materials, products, and systems.
Source: City and County of Denver (2021)

The life-cycle stages shown in Figure 47 are based on EN and ISO standards that will be discussed later. Operational or use stage carbon emissions encompass Stages B1-B7. Embodied GHG emissions can occur in association with the building and its constituent materials and products within any stage except Stages B6 and B7 (although the energy supplied for building operations also has embodied emissions associated with its extraction, refinement, and distribution to the site). For accounting of material embodied emissions, Stage B6 is excluded because its associated emissions are captured under separate analysis, such as a whole-building lifecycle analysis (WB-LCA) which includes emissions associated with the operational energy use of the buildings. Whole building energy modeling and energy-to-GHG conversion factors are used for to evaluate operational lifecycle GHG emissions. The energy-to-GHG conversion factors are based on the current and assumed future mix of fossil and renewable energy sources used to power the building.

It should be noted that Stage B6 is excluded from material environmental product declarations (EPDs). But, Stage B6 represents the use stage for insulation materials where significant operational GHG emission savings occur as a result of insulation applications to building thermal envelopes. As mentioned earlier in this report, the use stage benefits of insulation materials should not be separated from the consideration of the GHG emissions that occur in other life-cycle stages. Operational energy savings and GHG emission savings are the primary function of all building insulation materials as will be addressed later in Sections 4.8 and 4.9.

Estimated and reported material embodied GHG emissions may address different portions or scopes of the overall lifecycle shown in Figure 47. Where only addressing emissions that occur during Stage A1-A3, the embodied emissions are commonly called “cradle-to-gate” emissions. Where they include Stages A1-A5, they are called “upfront” emissions. Where the complete lifecycle is considered (Stages A1 through C4 and also D, but excluding B6) the quantified embodied carbon emissions are characterized as “whole life carbon” or “cradle-to-grave” emissions. Stage D is considered supplementary and addresses material “paths” beyond the lifecycle of a building material or other original end use. These paths include reuse, recovery, and recycling of materials at the end of life of their original application. These actions incur additional emissions associated with activities like demolition, recovery, and recycling. These Stage D pathways may offset some emissions that would otherwise be incurred with the use of completely new materials or construction of a completely new building.

Evaluated and reported embodied GHG emissions of materials (even at a whole building scale) can be associated with different levels of scope completeness in terms of the lifecycle stages included from Figure 47. Consequently, the level of completeness in accounting for GHG emissions can have significant design decision-making or policy effectiveness implications related to the goal of building decarbonization. In addition, policies that focus on a single material property (like global warming potential as reported in EPDs and used in “Buy Clean” policies) as a basis for material selection and specification can have significant unintended consequences. A couple of examples follow.

First, insulation materials have different properties and uses that determine their effectiveness in saving energy in end use. These differences are not represented by the functional units used to represent GWP values published in material EPDs. Insulation materials use a functional unit for GWP of kgCO2e/m2-RSI. The R-value or RSI (R-value in SI units) is based solely on the material thermal resistance property and not the effective R-value in end use as part of a building thermal envelope assembly. For example, continuous insulation minimizes building thermal bridges caused by the structural materials of a building whereas cavity insulation is thermally bridged by building structural members resulting in a 15% to 60% reduction in the effective thermal property used as the basis for “functional units” in EPD reporting of GWP. Therefore, insulation material selection based solely on compared GWP and functional units reported in EPDs will completely miss this important end use distinction that has significant influence on operational carbon emissions and energy use of a building. This problem can be overcome only by comparison of insulation materials at the level of a building envelope assembly (at a minimum) or whole building life cycle analysis using a “total carbon” approach. In particular, the whole building or assembly analysis would need to account for the assembly thermal performance (i.e., U-factor) including the presence of thermal bridges in specific assembly applications to accurately account for differences in operational energy and carbon emission savings attributed to different insulation applications, even for materials of like kind and function.

Second, where a particular insulation product has multi-functional capabilities, its own GWP (embodied GHG emissions) value will not capture GHG emission savings when the product’s multi-functional capabilities are optimally integrated into the design of a building assembly or overall building system. For example, a recent case study of an efficiently designed single-family home demonstrates this concern in a simple manner (Pages-Ruiz, 2022). The foam plastic insulating sheathing (FPIS) continuous insulation (ci) material specified was able to support several inter-related design functions resulting in cost, energy, material resource, and overall GHG emission savings as follows:

- FPIS ci was used resulting in improved energy and operational carbon savings due to reduced thermal bridging for essentially the same insulation material R-value in the original design.
- The FPIS ci served as siding backer and additional fastening of the interior gypsum wallboard allowed it to serve a multi-functional purpose as code-compliant wall bracing which eliminated the cost and upfront embodied GHG emissions associated with a separate exterior structural sheathing material.
- Additional cost and carbon emission savings also where made possible by specifying a FPIS ci product that also could serve as the wall's code required water-resistive barrier and air-barrier, thereby eliminating another material layer and its cost and upfront GHG emissions (although not done on this particular project).
- The exterior continuous insulation was continued down the exterior wall assembly to include the foundation slab perimeter such that a code-compliant frost-protected shallow foundation could be used to eliminate many cubic yards of concrete and minimize foundation excavation (reducing construction cost and the embodied GHG emissions attributed to the foundation by more than 2 metric tons of CO2e) while delivering better than code-minimum energy efficiency.
- In summary, operational energy and GHG emissions were reduced through improved energy efficiency of the walls and foundation by the use of FPIS ci; embodied GHG emissions were reduced by use of FPIS ci as a multifunction sheathing material on above-grade walls together with a multi-functional use of interior gypsum wallboard as wall bracing; multi-functional use of FPIS ci on the foundation resulted in significantly reduced concrete usage, excavation, and overall embodied GHG emissions of the foundation; with these multifunctional applications of FPIS ci, the first cost of the overall building was reduced by several thousand dollars.

In the above real-life building design and construction example, if the insulation materials used in the project had been selected or excluded purely on the basis of material GWP functional units (even among a like category of materials such as thermal insulation), then much of the energy, GHG emissions, and cost savings would not have been realized. Instead, the project would have become a major missed opportunity to cost-effectively achieve significant decarbonization benefits while also making the home more affordable with higher than code-minimum energy efficiency. A material-based decarbonization policy strategy, like "Buy Clean" procurement policies or "material specification codes" (both of which are addressed later), can become counter-productive to the intended goal if the concerns and opportunities discussed and demonstrated above are effectively ignored or dis-incentivized by such policies. This is particularly true for multi-functional applications of building materials like many foam plastic insulations.

4.4.2 Sources of Building GHG Emissions

Ultimately, most of GHG emissions associated with embodied and operational carbon emissions come from combustion of fossil fuels, either in the manufacturing of materials (industry sector) or associated with the operational energy use of a building (building sector) as confirmed by various data sources reviewed in Part 3 of this report.

Operational GHG Emissions

Specific sources of building operational GHG emissions (Stages B1-B7 of Figure 47 and mainly focusing on Stage B6) include the following:

- Heating (direct fossil fuel combustion on site or indirect off-site combustion of fossil fuels for electricity generation)
- Cooling (off-site combustion of fossil fuels for electricity generation)
- Hot Water (same as heating depending on whether electricity or fuel-combustion is used)
- Lighting (same as cooling)
- Appliances (same as heating depending on electric or gas)
- Miscellaneous equipment and plug loads (mostly electricity and same as cooling)

Energy efficiency comes into play by reducing and limiting the energy demand caused by those sources of operational carbon emissions. For example, an improved building envelope (better insulation, better windows, and lower air leakage rate) results in less heating and cooling energy use. For the building envelope, the climate zone (magnitude of seasonal heating vs. cooling loads) also makes a significant difference in the importance of its efficiency. Use of higher efficiency HVAC equipment, appliances, lighting (e.g., LED high-efficacy bulbs), and automated controls also significantly reduce and help manage energy use and associated operational GHG emissions. Other efficient building design factors include building orientation, shape, shading, use of natural lighting, and configuration of conditioned space area to building envelope shell area.

Electrification of buildings (e.g., eliminating on-site fossil fuel combustion equipment and replacing with electric equipment like heat pumps) can result in operational energy savings depending on various factors, but its primary purpose is for GHG emission savings. The decarbonization benefits of electrification increase as the electric grid becomes increasingly supplied by renewable or low-carbon sources (e.g., wind, solar, hydro, nuclear, etc.) and fossil fuel electric power plants are gradually retired or at a minimum switched from coal to natural gas or other low-carbon sources like nuclear.

At this point, it is worth noting that as buildings are increasingly electrified, peak electric demand will increase and shift to peak in winter rather than peak in summer (Buonocore, et al., 2022). Consequently, energy efficiency is crucial to decarbonization of electric power generation (ACEEE 2023a; ACEEE 2023b) in addition to automated control of building systems, building load management strategies, and renewable electric energy storage. Energy efficiency is also important to building resiliency and the ability to manage load for a period of time during electricity outage or for control of peak demand on the electric supply grid. Building energy efficiency also is important to limit the amount of new renewable resources needed to cover the energy demand of a growing population without requiring a massive buildout of renewable energy and seasonal energy storage (Buonocore, et al., 2022). Refer to the earlier discussion on the foundational role of energy efficiency in Section 4.3.

According to Buonocore, et al. (2022) and in agreement with concerns raised in NASEM (2021):

> "Building electrification is essential to many full-economy decarbonization pathways. However, current decarbonization modeling in the United States (U.S.) does not incorporate seasonal fluctuations in building energy demand, seasonal fluctuations in electricity demand of electrified buildings, or the ramifications of this extra demand for electricity generation. Here, we examine historical energy data in the U.S. to evaluate current seasonal fluctuation in total energy demand and management of seasonal fluctuations. We then model additional electricity demand under different building electrification scenarios and the necessary increases in wind or solar PV to meet this demand. We found that U.S. monthly average total building energy consumption varies by a factor of 1.6×—lowest in May and highest in January. This is largely managed by fossil fuel systems with long-term storage capability. **All of our building electrification scenarios resulted in substantial increases in**

> **winter electrical demand, enough to switch the grid from summer to winter peaking. Meeting this peak with renewables would require a 28× increase in January wind generation, or a 303×increase in January solar, with excess generation in other months. Highly efficient building electrification can shrink this winter peak—requiring 4.5×more generation from wind and 36×more from solar."** [**bold** emphasis added] [50]

Embodied GHG Emissions

Building material embodied GHG emissions primarily occur upstream of a building project during the manufacturing of building materials in the manufacturing industry sector (see Section 3.3). The majority of these emissions are associated with fossil fuel combustion in the manufacturing of materials, and to varying degrees other process or non-energy related emissions depending on the particular material. Building material embodied GHG emissions accounting methods attribute these emissions to the materials as a means to document these upstream emissions. So, at the downstream building design and material specification stages, the materials themselves are considered to represent the sources of embodied carbon emissions that occurred upstream of a given building project.

Building material embodied GHG emissions become embodied in a whole building or building assembly as follows (City and County of Denver, 2021):

> Upfront carbon, the emissions generated before the building is used…Upfront carbon, contributes the most to a building's embodied carbon emission total, and these sources have the greatest opportunity to be reduced, refer to [Figure 48].
>
> - Foundation: footings and retaining walls.
> - Structure: framing, reinforcement, slabs, and decking.
> - Enclosure: cladding, fenestration, insulation, and roofing.
> - Additional assemblies: interior furnishings (equipment, fixtures, furniture), building systems (electrical, mechanical, and plumbing), and site work (excavation, exterior paving, and shoring and formwork).
>
> Most emissions are generated from the production of the following structural elements:
>
> - Concrete
> - Steel
> - Wood
>
> The second-largest source of embodied carbon in buildings is from the building's enclosures.
> Some life-cycle assessment (LCA) studies [51] suggest that aluminum curtainwall and foam insulation are the greatest enclosure contributors to carbon."

[50] https://www.nature.com/articles/s41598-022-15628-2, last accessed 1/29/2023

[51] Refer to BuildingGreen Inc. (2018)

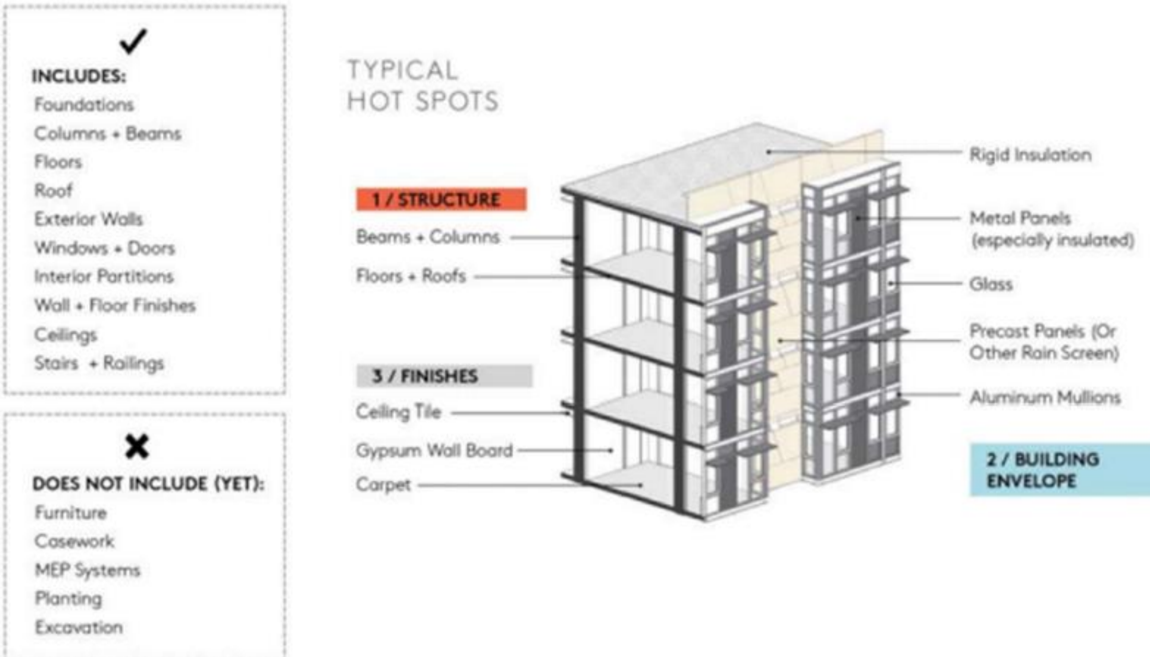

Figure 48. Illustration of building embodied carbon emission typical "hot spots"

Source: City and County of Denver (2021) and Building Green Inc. (2020)

According to Building Green Inc. (2018):[52]

> "Structural systems bear the bulk of the embodied carbon footprint of buildings, but the enclosure is also significant, representing up to 15% of the global warming impact of a typical commercial office building, according to Duncan Cox, associate at Thornton Tomasetti. (This number varies considerably by building type, he emphasized.)"
>
> Cox said that, based on WBLCA studies he's conducted over the years, the carbon hot spots in the enclosure tend to be aluminum curtainwall and foam insulation (the latter because of high-embodied-carbon blowing agents—see Avoiding the Global Warming Impact of Insulation). "When you start playing around with window-to-wall ratios, you can have quite a big impact" because of curtainwall's footprint, he said. The embodied carbon of curtainwall (not to mention the aluminum shading systems that often come with it) is just one more reason to minimize its use, since it has operational energy impacts as well (see Rethinking the All-Glass Building).
>
> On opaque walls, cladding choices can also make a big difference (see Cladding: More Than Just a Pretty Façade). Brad Benke, AIA, at LMN Architects, recently conducted an LCA considering different wall systems. "If you only have time to do one thing, hire a good engineer and work to reduce the structural load," he said, but his firm has invested in in-house LCA studies for the envelope…With that goal in mind, Benke looked at ten different wall systems, comparing their embodied impacts, then conducted a secondary study looking at five functionally equivalent brick wall types. The winner? Thin brick on metal studs had the lowest embodied carbon among the options, showing a 58% reduction from the baseline building (thin brick with precast concrete). The best part is that this lower-embodied-carbon wall, to a casual observer, looks and functions just the same.

According to City and County of Denver (2021):

> **Varying perspectives on embodied carbon contributions.** The Concrete Sustainability Hub of Massachusetts Institute of Technology wrote, "The operational phase of a building, however, makes the largest contribution to the

[52] **NOTE:** As with many similar documents referenced in this report, reference is made to foam insulation as having "high-embodied-carbon blowing agents". However, significant reductions in embodied carbon of blowing agents used for foam plastics have occurred in recent years as documented in Section 4.7.4 of this report. Therefore, conclusions drawn regarding the significant of foam plastic insulation embodied carbon are outdated in many recent studies. Refer to newer evaluations in Section 4.8 of this report.

> life cycle impacts of a structure and can overshadow the embodied emissions."[xi] And "When the GWP [Global Warming Potential] for the total life cycle is calculated, it becomes clear that the embodied emissions are a small fraction of the life cycle emissions..." [xii] While the World Green Building Council[xiii], the International Living Future Institute[xiv], and Building Green[xv] note that operational and embodied emissions may contribute equally to a building's overall emissions today, embodied carbon emissions are expected to be more significant over the next several years and may represent up to 90 percent of a building's total emissions by 2050. The baseline assumptions (i.e., grid makeup, etc.) from which each organization builds its calculations heavily influence the role of embodied carbon contributions.

The above concern is reflected in the following characterization of embodied vs. operational GHG emission impacts expected in the future for Denver's building population (City and County of Denver, 2021):

> "While Denver expects operational emissions to decrease over time, embodied carbon emissions are likely to grow if there is no intervention. Unlike operational emissions, embodied carbon emissions are "irreversible" and are emitted once a building's materials are made and the building is constructed. Even in the case of net zero energy new construction, the construction materials themselves have contributed such high emissions in their extraction and refining, that the building is essentially emitting for decades…"

In conducting "hot spot" assessments for whole-building GHG emission footprint reductions (upfront emissions), some studies and embodied GHG emissions accounting tools consider wood and other plant-based or biomass materials to be net carbon sink or a carbon-sequestering material. The concern with embodied GHG emissions in general and the interest in considering the use of carbon-sequestering materials like wood and other plant-based building materials (e.g., cellulose insulation, wood fiberboard insulation, straw, hemp-crete, bamboo, etc.) is primarily because GHG emissions associated with building materials occur prior to construction and its climate impact is "locked in" before a building is completed and operated. Thus, it has an immediate and "upfront" CO2e emissions climate impact whereas operational impacts (or their avoidance) occur over time and depend on various assumptions or scenarios related to future energy sources. These assumptions govern the relative role or magnitude and timing of climate impacts from operational vs. upfront embodied GHG emissions impacts of building materials.

Even the atmospheric carbon stored or sequestered in wood and other bio-based materials ends up returned to the atmosphere at the end-of-life of those materials and during the process of eventual decomposition after disposal or incineration (or a recycled use or use as bio-fuel). However, if the sequestered biogenic carbon in wood and other plant-based materials are stored in a building for 75 years or more, the impact to the climate is significantly delayed and, in the meantime, may allow for other climate mitigation actions to "catch-up" and reduce the net emission of CO2e emissions into the atmosphere. Given the uncertainties involved, the treatment of carbon-sequestering building materials in carbon accounting standards, methodologies, and tools is controversial and unsettled without means to properly and consistently account for the time-effects of carbon emissions on climate response (RMI, 2023).

Regarding this matter of wood and plant-based carbon sequestration in building embodied carbon accounting, the BuildingGreen Inc. (2018) guide reports the following:

> You may have heard (including from BuildingGreen) that building with wood instead of concrete or steel has major carbon benefits. It seems to make sense, since wood products sequester carbon, while concrete and steel are made by burning fossil fuels. Interest in building with mass timber structural products like cross-laminated timber (CLT) has skyrocketed, in part because of the presumed lower embodied carbon impacts. But a few scientists are asking everyone to slow down, contending that LCAs have grossly overestimated the benefits of wood.
>
> First of all, LCAs mostly give wood a free pass when it comes to the state of the forest after harvesting. But a lot of carbon in forests is stored in the soil and below it, and it's unclear how much carbon and methane (a more potent greenhouse gas) is released when harvesting … and how much that depends on how the wood is harvested.

> Second, there is the question of whether trees are being grown and replaced in such a way that we can truly assume carbon neutrality from forestry. As an example, for Douglas fir in the Pacific Northwest, a harvest cycle of 40 to 45 years is standard in business-as-usual (BAU) forestry practices, according to Mark Harmon, Ph.D., professor at Oregon State University. Harmon coauthored a recent paper implicating the Oregon timber industry as the largest source of carbon emissions in the state. The study found that an 80-year harvest cycle would be more beneficial for carbon storage in the forest because the longer time period allows the trees to build to their optimum volume before harvesting. Harmon compares a forest to a “leaky bucket”: “There is carbon pouring into the bucket [from absorbing CO2] but always carbon flowing out” as well from harvesting, decomposition, and fires, he explained. “The thing that determines how leaky it is, is related to how long the ‘water’ [carbon] stays in the bucket. … A 45-year forest is a much leakier bucket than a 90-year one” because carbon is leaving it much more quickly. At 75 to 100 years of age, though, Douglas fir stops growing so quickly, meaning carbon storage slows, so it makes the most sense to harvest the trees then. Also, as this example shows, there is the issue of regional differences. Douglas fir reaches its optimum volume at a different age than, say, southern yellow pine.
>
> Once the wood is harvested, it requires significant energy to be kiln-dried; most of this energy comes from burning waste wood, which is given a free pass as “carbon neutral” by the U.S. Environmental Protection Agency. But a contentious 2010 report commissioned by the Commonwealth of Massachusetts calls that carbon neutrality into question, saying that the carbon footprint of burning woody biomass depends on a number of factors, including forestry practices, and stating that in some cases burning wood is worse than burning fossil fuels.
>
> There’s also the fact that wood products continue to sequester carbon as long as they are in use, but the length of use is all over the map. Harmon’s group assumed a useful life of 30 years, while others argue for 60 or even 100. And what happens when the wood is ultimately disposed of? It’s not clear how quickly wood products decay and emit methane in landfills. This dispute is reflected in WBLCA tools, with Athena Impact Estimator assuming relative stability and Tally assuming quicker releases. (Currently, neither Athena nor Tally gives wood initial “credit” for sequestering carbon in a whole-building LCA, although in the upcoming new version of Tally, this will be optional.)

The ISE (2020) guide addresses the nature of embodied carbon emissions associated with wood materials with the following observations:

> Carbon dioxide is removed from the atmosphere as trees grow — via photosynthesis, known as ‘sequestration’. The carbon element of this CO2 is temporarily stored within timber until it is released at end of life in the form of a greenhouse gas (CO2 or CH4), for example by burning or decomposition of the timber. An example of this is illustrated in Figure 2.5 [**Figure 49**].
>
> Here we propose that carbon sequestration — part of Module A1 for timber products — should always be considered in an embodied carbon calculation, provided that the timber originates from a sustainably managed forest with FSC or PEFC (or equivalent) certification. However, in line with RICS guidance5, whether the sequestration value is added to the total reported embodied carbon value depends on the scope of calculation:
>
> - Modules A1–A5: do not include sequestration within the A1–A5 total value but report it separately alongside the A1–A5 total (Figure 2.8)
> - Modules A–C: include sequestration within the total A–C value reported (Fig. 2.8)
>
> Emissions in Stage C account for the sequestered carbon released back into the atmosphere at the end of life of the product. Unless reuse of the component can be guaranteed, these end of life (Modules C3 and C4) emissions will either balance or exceed (depending on end of life scenario) the carbon sequestration in Module A1. It is therefore extremely important to implement design measures to maximise the lifespan of timber elements to ensure the sequestered carbon is locked up for as long as possible before being released.
>
> The rationale behind not including carbon sequestration within the total A1–A5 value, but reporting it separately alongside is:
>
> - Including sequestration in the A1–A5 total would typically result in a negative value for A1–A5 embodied carbon (i.e. showing a net extraction of carbon emissions from the atmosphere). This could

allow engineers to show that less efficient use of timber results in lower, i.e. a greater negative value of, embodied carbon. This must be avoided to prevent unnecessary use of resources
- We should not ignore the fact that carbon sequestration happens, therefore we should show it

In the absence of product specific data, carbon sequestered can be assumed as -1.64kgCOe per kg of timber.

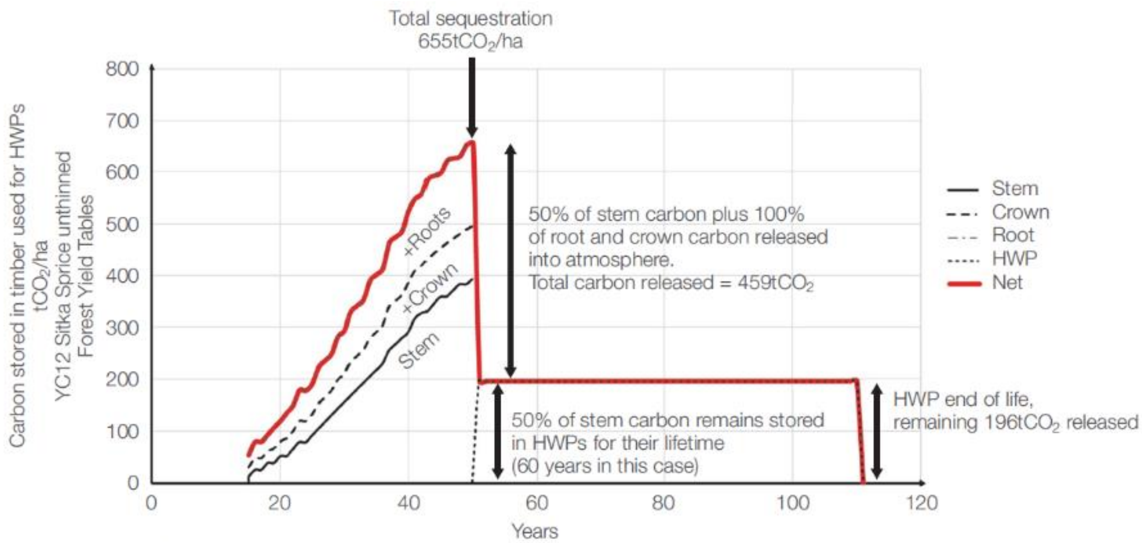

Figure 49. Example of carbon sequestration of harvested wood products showing initial carbon capture (forest growth), harvesting-related emissions, storage during useful life, and final emissions at end of life.
Source: ISE 2020 (Figure 2.5)

Regardless, some studies and material carbon emission tools and databases do attribute the upfront carbon storage (sequestration) for wood and bio-based materials as being nearly 100% effective for a WB-LCA that is limited in scope to just upfront (A1-A5) or cradle-to-gate (A1-A3) life-cycle stages.

For example, a study by Magwood et al. (2021) of cradle-to-gate (Stage A1-A3, Figure 47) embodied GHG emissions intensity of a sample of Canadian wood-frame homes showed results varying from -84 kgCO2e/m^2 (representing net carbon storage) to 758 kgCO2e/m^2 (representing a high amount of net carbon emissions) based on consideration of various levels of material carbon emission intensities. The study characterized the significance of home construction material carbon emissions (MCE) as follows:

> "Three existing studies on MCE indicate that the emissions associated with building materials are quite substantial. Based on these studies, a typical low-rise residential building in North America has an average MCE footprint of approximately 250 kg CO2e per square meter of floor area. (International Energy Agency, 2018; Simonen et al., 2017; Magwood, 2019).[53] If this average is accurate and it is applied to the total additional annual average of 56.33 million m^2 (Natural Resources Canada, 2020) of new low rise (Part 9 of the NBC) built in Canada each year, the MCE of Canadian homes would be 14.1 Mt CO2e/year. This is equivalent to the annual emissions from 3.1 million Canadian vehicles (Natural Resources Canada, 2014) or 3.6 coal-fired power plants (Israël & Flanagan, 2016) (figure 2). The housing sector does not account for or address these emissions."

[53] Low-rise residential buildings average 150-400 kg of GHGs per square metre of floor area (25-75 tonnes for a 2,000 square foot home). – Appendix A on the MCE[2] tool

The results of the Magwood et al. (2021) study were summarized as follows:

> The results indicate the significant impact of MCE and material selection on the carbon footprint of new homes and the potential to significantly reduce or eliminate it without changing the design or performance of the home. Insulation, exterior cladding and concrete were identified as the material categories with the highest impact on overall MCE. [Operational Carbon Emissions] OCE varied based on the carbon intensity of the local electric grid which can change the OCE contribution by a factor of 8 to more than 20. The cleaner electric grids all resulted in OCE of less than 1 tCO2e/yr/home on average whereas the more emissions-intensive grids resulted in OCE of 7.7 to 23 tCO2e/yr/home.
>
> Regarding insulation, each step up on the NBC's energy code tiers resulted in an increased thickness of insulation and increased MCE for carbon emitting insulations or decreases in overall MCE for carbon storing insulations. The increase of MCE of 93 kgCO2e/m^2 between Tier 3 and Tier 5 for high carbon intensity insulations is regarded as a cautionary warning that the pursuit of energy efficiency should be coupled with consideration of material emissions.
>
> Across all housing archetypes in all regions, the mean [Material Carbon Intensity] MCI for High Carbon Material (HCM) models was 556 kg CO2e/m^2, over half a tonne per square meter of living space. Additionally, the average MCI result for Mid-range Carbon Material (MCM) buildings was 146 kg CO2e/m^2, a significant improvement but not a result compatible with Canada's emissions targets.
>
> The results of incorporating more insulation in a home has a linear effect on the total MCE. The use of insulation materials that have net GHG emissions, including all petrochemical- and mineral-based products, will drive the MCE of the building higher as more of the material is added to achieve improved operational performance. The use of insulation materials that have net carbon storage will drive the MCE of the building lower as operational efficiency improves, and was the key factor leading to the climate-positive results for the BAM and BPM models. [Table 9] lists the average MCI changes caused by NBC energy performance Tier shifts across all archetypes and regions.

In conclusion, the Magwood et al. (2021) study states:

> Achieving net-zero emissions in the Canadian housing sector is possible, but as this study makes clear it will require seriously addressing MCE by embracing low-carbon and carbon-storing materials and designs, while recalibrating efforts on the operational side by concentrating on total GHG metrics rather than energy use metrics. Together, these efforts could predictably lead to a zero-emission housing sector in Canada.
>
> A concerted effort to develop the supply chains and scale up the technological advancements of carbon-storing building materials—insulation materials in particular—would accelerate the elimination of all MCEs from the homebuilding sector in a timeframe well within Canada's 2050 net-zero goals.

TABLE 9. Average increase in building material carbon intensity (MCI, kg CO2e/m^2) based increasing energy efficiency Tiers in the Canadian energy code and different material tiers based on selected material embodied GHG emissions.

Increase in average MCI by Tier			
Material Tier	Tier 3 to 4 increase in kg CO_2e/m^2	Tier 4 to 5 increase in kg CO_2e/m^2	Tier 3 to 5 increase in kg CO_2e/m^2
High carbon material selection (HCM)	37.7 ↑	55.2 ↑	92.9 ↑
Mid-range carbon material selection (MCM)	3.9 ↑	5.8 ↑	9.7 ↑
Best available carbon material selection (BAM)	-5.1 ↓	-7.8 ↓	-12.9 ↓
Best possible carbon material selection (BPM)	-3.9 ↓	-3.4 ↓	-7.3 ↓

Source: Table 8 from Magwood, et al. (2021)

The building materials used in the Magwood et al. (2021) study for the different material selection tiers shown above in Table 9 were described as follows (refer to Magwood et al. (2021) for additional details):

High Carbon Insulation Material (HCM) Selections:

Sub-slab:	XPS foam board / OC Foamular 250, R 5/inch
Fnd Wall:	XPS foam board / OC Foamular 250, R 5/inch
Ext. Wall CAVITY:	Spray polyurethane foam - Closed Cell (HFC), SPFA, R 6.6/inch
Ext. Wall Continuous:	XPS foam board / OC Foamular 250, R 5/inch
Roof/Ceiling:	Spray polyurethane foam - Closed Cell (HFC), SPFA, R 6.6/inch

Moderate Carbon Insulation Material (MCM) Selections:

Sub-slab:	Mineral wool board - heavy density, NAIMA, R 4.2/inch
Fnd Wall:	EPS FOAM ICF, R-23 (ICF foundation wall)
Ext. Wall CAVITY:	Mineral wool batt, Rockwool / Safe'n'Sound, ComfortBatt / R 3.8/inch
Ext. Wall Continuous:	Mineral wool board - AVERAGE
Roof/Ceiling:	Mineral wool loose fill, NAIMA, R 3/inch

Best Available Insulation Material (BAM) Selections:

Sub-slab:	EPS foam board (EPSIA), R 4.6/inch, Type IX, 25 psi (Type 3, 140 kPa)
Fnd Wall:	Cellulose – AVERAGE
Ext. Wall CAVITY:	Cellulose – AVERAGE
Ext. Wall Continuous:	Wood fiber board - AVERAGE
Roof/Ceiling:	Cellulose - Roof Insulation - AVERAGE

Best Possible Insulation Material (BPM) Selections:

Sub-slab:	Foam glass aggregate - AVERAGE
Fnd Wall:	Hempcrete -- AVERAGE
Ext. Wall CAVITY:	WOOD FRAME with STRAW BALE INFILL - 14" R-46, Double 2x4 @ 30" o/c
Ext. Wall Continuous:	n/a
Roof/Ceiling:	Straw Bale / Wheat & rye straw / R 3.3/inch

Consequently, the recommendation to pursue best available material (BAM) solutions would entail using insulation materials like cellulose cavity insulation and wood fiberboard continuous insulation for all above-grade insulations and also for the interior side of basement walls. This would effectively exclude materials like foam plastics, fiberglass, and mineral fiber for most or all building envelope applications. Because the study considered only life-cycle stages (A1-A3) in a “cradle-to-gate” analysis using the EMC2 embodied emissions tool and database, the full carbon sequestering benefit of wood materials was counted without considering end-of-life carbon impacts. For this reason, the HCM and MCM insulation materials selected that were non-bio-based materials accounted for a much higher relative portion of the buildings estimated embodied carbon. The study also made other recommendations such as development and use of a Carbon Use Intensity (CUI) to account for stored and operational carbon emissions with a strategy to balance the time differences of the emissions.

The Magwood et al. (2021) study also was used as a basis for the City of Nelson’s (BC Canada) Material Carbon Emissions Guide (City of Nelson, 2022) which focused on materials as shown in Figure 50 based on a relative (percentage) level of significance to reducing embodied carbon emissions from a selection of surveyed wood frame homes in Canada and use of a high-carbon emissions materials as a baseline.

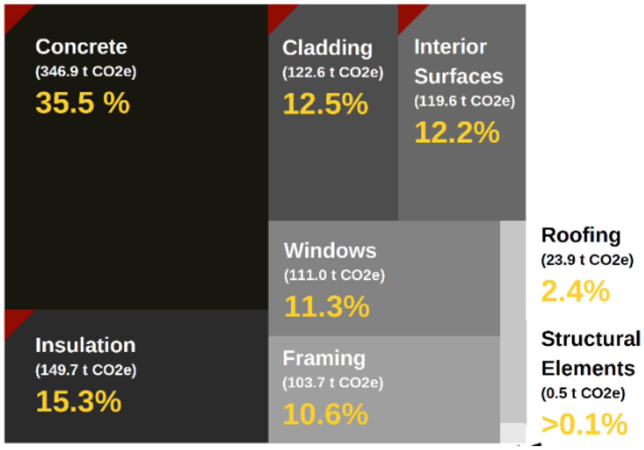

Figure 50. Importance of building material carbon emissions based on percentage of carbon emissions associated with materials in sampled homes.

Source: City of Nelson, 2022

NOTE: *Wood and plant-based materials were considered as carbon sinks and so are not included in the tally for this graphic which is based on Magwood et al. (2021).*

As mentioned earlier in Part 4, it is not the relative amount of emissions (see Figure 50) that is important, but the absolute amount in comparison to total global emissions that is important because that determines the impact related to the objective of addressing climate change. Furthermore, for insulation materials and other building thermal envelope materials the consideration of both operational and embodied carbon emissions may be best addressed objectively by incorporation of social cost of carbon (see Section 1.4) into the cost-benefit analysis methodologies used by US model energy codes and standards such as ASHRAE 90.1 and the IECC. Refer to Section 4.8.6 for more information.

To evaluate Vancouver's housing construction and the ability to attain the City's goal of reducing embodied carbon emission by 40 percent by 2030, various case studies were conducted using the BEAM analysis tool with results like those shown in Figure 51 (City of Vancouver, 2022). Using what was classified as "best available" materials it was determined that the goal was reachable with currently available products that increasingly draw from bio-based materials like cellulose and wood fiberboard insulation products.

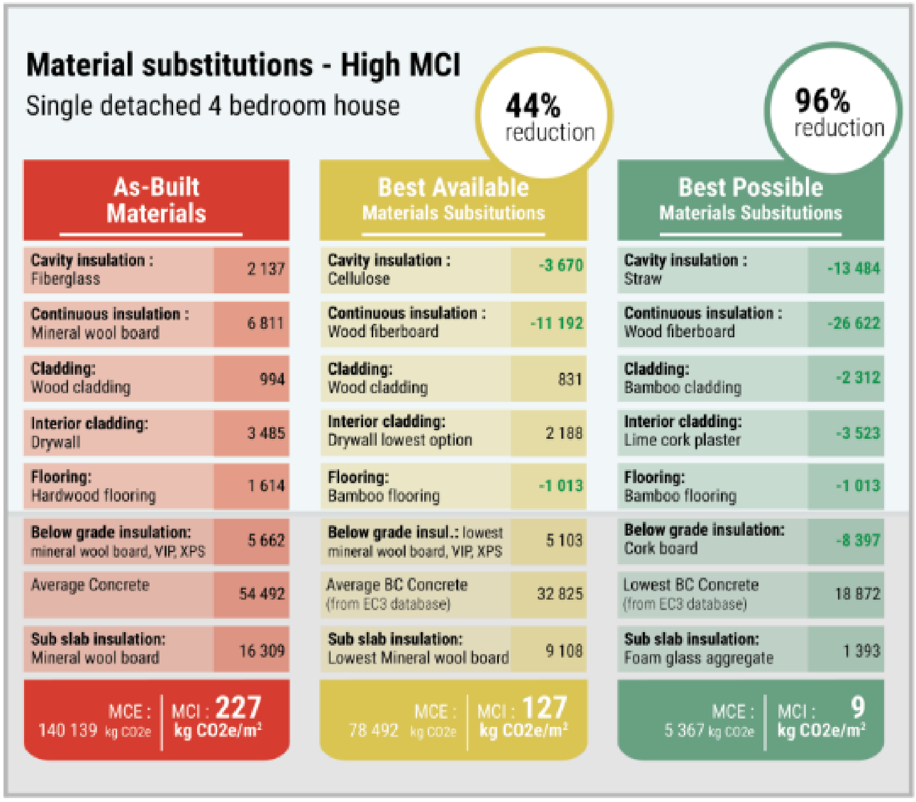

Figure 51. Example case study analysis of material substitutions in a whole-building embodied carbon analysis for the City of Vancouver.
Source: City of Vancouver (2022) as published by Builders for Climate Action

Data from various sources regarding embodied carbon emissions associated with specific products or classes of products and materials will be addressed in a later section and related to their significance to global GHG emissions.

4.5 Environmental Product Declarations (EPDs) & Product Category Rules (PCRs)

Environmental product declarations (EPDs) and their associated Product Category Rules (PCRs) serve as the foundation for data necessary to evaluate embodied GHG emissions or global warming potential (GWP) of materials and products used in buildings and any other application. For example, the material carbon emission (MCE) and building material carbon intensity (MCI) data shown in Figures 50 and 51 of the previous section were derived from building plan material take-offs and GWP data from various EPDs included in a database or analysis tool to facilitate the accounting process. EPD data for each building material of interest is necessary for a whole-building approach to embodied GHG emissions accounting.[54] The veracity of such an analyses of embodied GHG emissions is dependent on the accuracy, scope, completeness, consistency, and the temporal and regional relevance and availability of EPDs for products specified for a given project, among other factors.

According to NBI (2022):

> **Environmental Product Declarations** (EPDs) are a summary of a product lifecycle analysis and disclose the impacts of materials, including the material's carbon dioxide equivalent (CO2e), as represented as global warming potential (GWP). Other environmental impacts or attributes are also disclosed. Type I EPDs are third-party

[54] **NOTE:** A whole-building embodied carbon analysis lacks the full scope of a whole-building lifecycle analysis, which includes a building's operational GHG emissions as will be addressed in Sections 4.8 and 4.9.

verified based on ISO 14024; Type II EPDs are self-declarations based on ISO 14021; and Type III EPDs are third-party verified product data based on lifecycle impacts based on ISO 14025.

Global warming potential (GWP) is the most common metric for measuring and evaluating materials' greenhouse gas emissions over a product or building's lifecycle, also called embodied carbon.

Lifecycle assessment (LCA) is an independently verified study of a product or building. Product-level LCAs must be done in accordance with ISO 14040 and ISO 14044 for incorporation in a product's environmental product declaration.

Whole building LCA (WB LCA) evaluates all the products and materials used in a building, or scope, to determine the carbon emissions associated with the materials.

According to the Embodied Carbon Toolkit for Architects (AIA/CLF, 2021), there are three types of EPDs:[55]

- **Industry-wide EPDs** (IW-EPD) represent typical manufacturing impacts for a range of products for a group of manufacturers. Industry-wide EPDs provide the least-specific data on a product's embodied carbon footprint and cannot be used to compare products. However, they are helpful in understanding the typical impact of the specific products typified in the scope of an IW-EPD.
- **Product-specific EPDs** represent the impacts for a specific product and manufacturer across multiple facilities.
- **Facility-specific EPDs** are product-specific EPDs in which the environmental impacts can be attributed to a single manufacturer and manufacturing facility. This type of EPD was introduced by the Buy Clean California Act in 2017.

While various standards exist to define the general development of EPDs as noted later below, PCRs are needed to define specific requirements for development of EPDs within a given material or product category, such as insulation materials.

According to NBI (2022):

Product Category Rules (PCRs) define product categories and are necessary to develop a Type III EPD based on ISO 21930:2017. The PCR lays out impacts that the manufacturer must include and guidelines for measuring those impacts. They must be updated every 5-years to remain current.

And, according to the Carbon Leadership Forum (CLF) Embodied Carbon Policy Toolkit (CLF, 2021):

The development of a product category rule is led by a **program operator**. A program operator is a company, industry sector or trade association, public agency, or independent body that manages the development and publication of a PCR and resulting EPDs. Examples of North American program operators include ASTM, NSF, UL Environment, SCS Global Services, and Sustainable Minds.

Examples of EPD program operators and links to their versions of PCRs used to evaluate and certify EPDs in accordance with relevant ISO and EN standards (listed later below) include:

- UL Solutions - https://www.ul.com/offerings/product-category-rules-pcrs
- ICC-ES - https://icc-es.org/environmental-program/environmental-product-declarations/
- Sustainable Minds - http://www.sustainableminds.com/transparency-products/transparency-reports

[55] EPDs also are classified based on their use for two communication purposes: Business-to-business (B2B) or Business-to-consumer (B2C). B2B EPDs are most common and cover resource extraction to the manufacturing plant gate ready for shipment (i.e., cradle-to-gate) and may also include scenarios for other life cycle stages. B2C EPDs must cover all stages of the life cycle, must include ancillary materials used for installation and maintenance, and must include replacement over assumed building service live.

UL is the program operator for the PCR applied to insulation materials in North America – Part B: Building Envelope Thermal Insulation EPD Requirements (UL 10010-1) which is currently undergoing review and updating with input from the insulation industry and other interested stakeholders (UL, 2018).

EPDs are often considered as a means to compare carbon emissions intensity of materials for policy and building design decision-making purposes. Several guides and policies that make use of EPDs will be reviewed in later sections. However, there are many caveats and cautions associated with use of EPDs for this purpose as mentioned in an earlier section. According to the CLF's Material Baseline Report (Carlisle, et al., 2021):

> These declarations can be used to track supply chain-specific product data and compare products if the products are functionally equivalent and have aligned scopes.
>
> The CLF Baselines represent a rough estimate of a product category's carbon footprint. However, in order to make material comparisons, it is incumbent upon a user to assure that the products, materials, or assemblies are functionally equivalent — i.e., that they serve the same purpose and meet the same performance standards within the building design.

The CLF's Embodied Carbon Policy Toolkit (CLF, 2021) provides the following critically important guidance on using EPDs for comparison of materials and products:

> Comparisons between EPDs should only be made if (1) their impacts were calculated using the same methodologies and (2) the products being compared are functionally equivalent. The environmental performance of two different materials (e.g. concrete and wood) cannot be compared using EPDs and require a WB-LCA to properly analyze and compare provided the WB-LCA includes full scope.
>
> **Functionally equivalent** products have the same unit (such as 'one metric ton of steel') and technical performance. Technical performance characteristics vary by product category and use. For example, performance characteristics of structural concrete include criteria like strength, cure time, and durability, whereas carpet criteria may include things like use (commercial vs. residential) and durability (density, etc.).
>
> Note that functional equivalence is a process that involves judgment and assumptions, and must be done with care. Once the functional equivalence of the products being compared is established, it is also key to ensure that the EPDs have the same:
>
>> **Methodology**: EPDs should follow the same PCR.
>> **System boundaries**: EPDs must include identical life cycle stages. Life cycle stage reporting varies (see Figure [47]) and the reported stages must be the same (i.e. cradle-to-gate analysis cannot be compared to cradle-to-grave, etc.)
>> **Upstream data**: Life cycle inventory datasets for transportation and electricity generation should be aligned.

Various ISO and EN standards governing life cycle analysis of materials and systems, including their relationship to the development EPDs and PCRs and important qualifications in making appropriate material EPD comparisons (beyond those mentioned above and mentioned elsewhere in this report), are listed below. Note that some of the standards may cost several hundred dollars. For more information on the development history, content, and inter-relationships between these standards, refer to Esram and Hu (2021) and WAP (2021).

- *ISO 14040: 2006 Environmental Management—Life Cycle Assessment—Principles and Framework,* https://www.iso.org/standard/37456.html
- *ISO 14044: 2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines,*. https://www.iso.org/standard/38498.html

- ISO 14020: 2000 Environmental labels and declarations - general principles, https://www.iso.org/standard/34425.html
- ISO 14024: 2018 Environmental Labels and Declarations—Type I Environmental Labelling—Principles and Procedures, https://www.iso.org/standard/72458.html
- ISO 14021: 2016 Environmental Labels and Declarations—Self Declared Environmental Claims (Type II Environmental Labelling), https://www.iso.org/standard/66652.html
- ISO 14025: 2006 Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures, https://www.iso.org/standard/38131.html
- ISO 14027: 2017 Environmental labels and declarations – Development of product category rules, https://www.iso.org/standard/66123.html
- ISO 21930: 2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services, https://www.iso.org/standard/61694.html
- BS EN 15978:2011 Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation Method, https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

4.6 Policy, Programs, Guides, Tools, Standards, and Codes

This section is a broad sweep through activities related to the building decarbonization movement in the US. It will briefly explore examples of organizational policies, voluntary programs, governmental policies, guides, tools, standards, and codes.

4.6.1 Organizational Policies and Strategic Plans

Various building and construction industry organizations have issued position or policy statements and initiated programs regarding building decarbonization, including US-based organizations like ASHRAE, ICC, AIA, ASCE, and others. Commonly, such organizations have either endorsed the ultimate goal of reaching net-zero emission buildings by 2040 (or 2050) or have pledged to provide the necessary tools to support such a goal.

For example, ASHRAE's Position Document on Building Decarbonization[56] makes broad commitments and recommended actions toward building decarbonization. The position document appears to rely exclusively on global data and goals to establish the need and makes use of the following quote from the earlier-reviewed UNEP (2021) assessment to align with the global call to decarbonize buildings:

> " By 2030, the built environment should halve its emissions, whereby 100 percent of new buildings must be net-zero carbon in operation, with widespread energy efficiency retrofit of existing assets well underway, and embodied carbon must be reduced by at least 40 percent, with leading projects achieving at least 50 percent reductions in embodied carbon. By 2050, at the latest, all new and existing assets must be net zero across the whole life cycle, including operational and embodied emissions."

ASHRAE's press release dated July 12, 2022, provided the following summary of ASHRAE's position document:[57]

> By 2030, the global built environment must at least halve its 2015 greenhouse gas (GHG) emissions, whereby:
>
> - all new buildings are net-zero GHG emissions in operation,
> - widespread energy efficiency retrofit of existing assets are well underway, and

[56] https://www.ashrae.org/file%20library/about/position%20documents/pd_buildingdecarbonization_2022.pdf, last accessed 1/29/2023

[57] https://www.ashrae.org/about/news/2022/ashrae-commits-to-broad-building-decarbonization-initiatives-in-new-position-document, last accessed 1/29/2023

- embodied carbon of new construction is reduced by at least 40 percent.

Additional positions and recommendations include the following:

- Increasing stringency and enforcement of energy codes are critical for decarbonization.
- Whole Building Life Cycle Assessment must be considered in future building codes to reduce embodied and operational GHG emissions related to buildings and their HVAC&R systems.
- Building Performance Standards (BPS) should be considered as a policy tool for existing building decarbonization.
- Decarbonization policies must contemplate and mitigate impacts on disadvantaged communities and less-developed nations.
- Building decarbonization strategies and policies must consider healthy, safe, and comfortable environments; environmental and social impacts; sustainability; resilience; and economics.
- Promote research and development of heat pump technology.
- Support the development, update, and adoption of relevant standards and guidelines that facilitate the whole life reduction of GHG emissions from new and existing buildings.
- Encourage greater collaboration and the development of standards and guidelines among the energy, transportation and building sectors to improve secure building-grid integration, data communication, and optimization of energy performance (generation, use and storage).
- Work in partnership with industry to increase the capacity and opportunities for a skilled workforce supporting building decarbonization.

In the same press release, ASHRAE also announced its newly formed Task Force for Building Decarbonization (TFBD) with intentions to create six guides and corresponding training courses.[58] In addition, ASHRAE has initiated new standards activities and updates of existing standards to address building decarbonization. Such standards activities will be addressed later.

Similarly, in September of 2022 the International Code Council, Inc. (ICC) completed its strategy statement on decarbonization of the built environment, including recommended solutions that the ICC envisions.[59] The ICC's strategy document was preceded by a March 2021 energy efficiency and sustainability commitment by ICC.[60,61] In its October 20, 2022 press release, ICC made the following statements and claims:[62]

> The report recognizes the significant impact of buildings on the environment and the need for a coordinated set of solutions to support the achievement of energy and greenhouse gas (GHG) reduction goals set by governments…The report also calls for expanded activities that support a coordinated approach across the International Codes (I-Codes), standards and other solutions. As part of the process outlined within the Code Council's energy efficiency and greenhouse gas reduction framework, Leading the Way to Energy Efficiency: A Path Forward on Energy and Sustainability to Confront a Changing Climate, the Code Council is currently undertaking an internal road mapping effort and will leverage its Energy and Carbon Advisory Council and a to-be-formed Ad Hoc Committee on Decarbonization to make recommendations on the organization and format of a comprehensive approach.
>
> "The Code Council is prepared to deliver the tools that communities need to realize their climate-related goals. Collaboration is essential to support consistency and limit confusion as the industry navigates new priorities. Our collaboration with ASHRAE on a standard to support evaluation of carbon across the life cycle of a building is just

[58] https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization, last accessed 1/29/2023

[59] https://www.iccsafe.org/wp-content/uploads/22-1876_COMM_92011_Decarbonization_Strategy_FINAL_emb.pdf, last accessed 1/29/2023

[60] https://www.iccsafe.org/wp-content/uploads/ICC_Leading_Way_to_Energy_Efficiency.pdf, last accessed 1/29/2023

[61] https://www.iccsafe.org/products-and-services/codes-standards/energy/, last accessed 1/29/2023

[62] https://www.iccsafe.org/about/periodicals-and-newsroom/international-code-council-charts-path-to-support-building-decarbonization-efforts/, last accessed 1/29/2023

one example of the type of solutions needed," said Dominic Sims, CBO, Chief Executive Officer of the International Code Council.

Through existing codes, standards and other solutions, the Code Council has already made significant contributions to reducing the climate impacts of buildings:

- The International Energy Conservation Code (IECC) has improved energy savings by nearly 40 percent since 2006 and provided over 700 million metric tons (MMT) of carbon reduction since the 2009 edition. Zero energy appendices appear in the 2021 edition and the 2024 and future editions will deliver even more energy savings.
- The hazard resistance provisions of the codes reduce the need for rebuilding, saving 1.5 MMT of GHG emissions annually.
- The International Green Construction Code (IgCC) includes requirements for measuring the climate impacts of materials through environmental product declarations (EPDs) and life-cycle analysis.
- Off-site construction standards (ICC/MBI Standards 1200 and 1205) support more efficient construction processes.
- The ICC Evaluation Service (ICC-ES) is an EPD program operator and will continue to assist manufacturers and jurisdictions in determining the impacts of building materials.

Regarding the one point above about energy savings and carbon emissions savings of the IECC, the stated values appear not to be actual savings and are instead based on a presumed 100% adoption by all US states with perfect enforcement. Thus, they represent ideal or potential savings, not actual savings.

The ICC's Decarbonization of the Built Environment document makes the following recommendations, among others:

- Co-develop the Standard on Measurement and Verification of Carbon in Construction, Materials, and Operations with ASHRAE.
- Continue support of the International Green Construction Code (IgCC) as a coordinated approach to GHG reductions across the design, construction, and operations of buildings.
- Expand the development of environmental product declarations (EPDs) for materials and products used by the construction industry alongside the conduct of evaluations of the performance of materials and products with lower environmental impacts.
- Continue development of the International Fuel Gas Code (IFGC) to assure the safe use of natural gas and explore updates necessary to address the safe deployment of emerging fuels.
- Continue development of the International Energy Conservation Code (IECC) under the revised scope and intent to continue energy use reduction as approved by the Board in Leading the Way to Energy Efficiency: A Path Forward on Energy and Sustainability to Confront a Changing Climate.

Other major building industry organizations, such as the American Institute of Architects (AIA) and the American Society of Civil Engineers – Structural Engineering Institute (ASCE-SEI), also have made commitments and have developed voluntary programs to support building decarbonization which will be addressed in the next section.

4.6.2 Voluntary Programs

Representative voluntary programs that focus on or emphasize decarbonization of buildings, particularly the reduction of embodied GHG emissions, include the following:

- AIA's "Architecture 2030" and "Blueprint for Better" programs[63,64]
- ASCE-SEI's "SE 2050" program[65]
- Leadership in Energy and Environmental Design (LEED)[66]
- Living Buildings Challenge[67]
- Passive House Institute US (PHIUS)[68]

Programs which focus primarily on energy efficiency and, consequently, decarbonization through reduction of operational GHG emissions without requirements for reducing embodied GHG emissions include the following:

- US Department of Energy (DOE): Zero Energy Ready Home (ZERH) Program[69]
- EPA - Energy Star Program[70]

It is noteworthy that the new 45L tax credits being implemented through the *Inflation Reduction Act* (IRA) will result in a $5,000 tax credit for new energy efficient homes complying with DOE's ZERH program and $2,500 tax credit for those complying with EPA's Energy Star program.

The AIA's "Blueprint for Better" program is primarily a political action activity within the organization with the following description of its purpose which includes reducing and eventually eliminating embodied carbon in buildings in response to what it describes as "architecture's carbon problem":

> Human activity is warming our climate to dangerous levels, and carbon is the primary culprit. Buildings contribute about 40% of that carbon. The harm that results affects us all but doesn't impact us all equally. As authors of that environment, architects are crucial to addressing and mitigating the damage.
>
> This campaign is a call to action. AIA, the largest design organization in the world, is asking architects, design professionals, civic leaders, and the public in every community to join our efforts. Help us transform the day-to-day practice of architecture to achieve a zero-carbon, resilient, healthy, just, and equitable built environment.

The AIA's "Architecture 2030" program has been active for almost two decades and describes its mission as follows:

> Architecture 2030's mission is to rapidly transform the built environment from the major emitter of greenhouse gases to a central solution to the climate crisis. For nearly two decades, we've provided the leadership and designed the actions needed to achieve the CO_2 emissions reductions for a high probability of limiting planetary warming to 1.5°C. Our action plan has two primary objectives:
>
> - Achieve a dramatic reduction in the energy consumption and CO_2 emissions of the built environment by 2030, and a complete phase-out of fossil fuel CO_2 emissions by 2040; and,

[63] https://architecture2030.org/, last accessed 1/30/2023
[64] https://blueprintforbetter.org/articles/architectures-carbon-problem/, last accessed 1/30/2023
[65] https://se2050.org/what-is-se-2050-overview/, last accessed 1/29/2023
[66] https://www.usgbc.org/leed, last accessed 1/30/2023
[67] https://living-future.org/lbc/, last accessed 1/30/2023
[68] https://www.phius.org/, last accessed 1/30/2023
[69] https://www.energy.gov/eere/buildings/zero-energy-ready-home-program, last accessed 1/30/2023
[70] https://www.energystar.gov/partner_resources/residential_new/homes_prog_reqs/national_page, last accessed 1/30/2023

- Advance the development of sustainable, resilient, equitable, and zero-carbon buildings communities and cities.

> We empower the building and industrial sectors to achieve these goals through: Design & Planning, Education, Policy, and Collaboration.
>
> Building on nearly two decades of success, we're responding to the urgency of this moment with a range of initiatives to catalyze action and accelerate results. These feature a whole-sector approach to the built environment, including a focus on embodied carbon and materials, local government codes and policies that rapidly scale solutions, "how-to" conferences, and major international sector actions and collaborations.
> In the course of transforming the built environment, significant market opportunities will emerge and help to drive this urgent transition. Our research illustrates that low- to no-carbon techniques and applications can be implemented at no incremental cost, as the evolving regulatory environment increasingly mandates their adoption.
>
> The stakeholders leading in climate action now will be best positioned to capitalize on and lead the transition.

In 2020, 318 architecture firms submitted building project portfolios to the Architectural 2030 program with the primary metric reported being energy use intensity (EUI), which is an index of operational energy use).[71] However, 239 or 1% of the projects submitted did report embodied carbon estimates in 2020. About 4% or 775 projects reported renewable options (such as PV or use of RECs). Various embodied carbon tools were used in the reported projects with "Build Carbon Neutral" and "Tally" being the most popular. Other tools used much less frequently included "OneClick", "Athena", and "EC3". Such tools will be addressed in a later section of this report.

The AIA 2030 program has teamed with the Carbon Leadership Forum (CLF) to develop a building embodied carbon guide series to help architects meet the program goals by reducing and eventually eliminating carbon emissions by 2050. The features of this guide series will be addressed later.

According to ASCE-SEI, the SE 2050 program began in 2019, is described as follows, and has over 100 signatory design firms participating:[72]

> SE 2050 stands for the Structural Engineers 2050 Commitment Program that is in response to the SE 2050 Challenge issued in 2019 by the Carbon Leadership Forum (CLF) and the SE 2050 Commitment Program developed by the Sustainability Committee of the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE). This site is dedicated to the SE 2050 Commitment Program or the SE 2050 Commitment for short. This comprehensive program has been designed to ensure substantive embodied carbon reductions in the design and construction of structural systems by the collective structural engineering profession.
>
> The SE 2050 Commitment Program is being developed in response to the SE 2050 Challenge which states:
>
> > ***All structural engineers shall understand, reduce and ultimately eliminate embodied carbon in their projects by 2050.***
>
> It's well documented that we must be a carbon neutral society by 2050 if we are to avoid irreversible detrimental impacts to our environment.

The SE 2050 and Architecture 2030 programs work somewhat like the US NDC and UN climate framework whereby signatory design firms submit a commitment letter and then report activity or progress toward those commitments on an annual basis.

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[71] https://content.aia.org/sites/default/files/2022-04/2020_By_the_Numbers_AIA_2030_Commitment_Final.pdf, last accessed 1/30/2023

[72] https://se2050.org/signatory-firms/, last accessed 1/29/2023

The LEED (Leadership in Energy and Environmental Design) building certification program by the US Green Building Council (USGBC) has been in existence since 1998 and, since that time, has certified over 100,000 buildings.[73] Its program goals and emphasis are described as follows [bold added for emphasis]:

> LEED is a holistic system that doesn't simply focus on one element of a building such as energy, water or health, rather it looks at the big picture factoring in all of the critical elements that work together to create the best building possible. The goal of LEED is to create better buildings that:
>
> - Reduce contribution to global climate change
> - Enhance individual human health
> - Protect and restore water resources
> - Protect and enhance biodiversity and ecosystem services
> - Promote sustainable and regenerative material cycles
> - Enhance community quality of life
>
> Of all LEED credits, 35% of the credits in LEED are related to climate change, 20% of the credits directly impact human health, 15% of the credits impact water resources, 10% of the credits affect biodiversity, 10% of the credits relate to the green economy, 5% of the credits impact community and 5% of the credits impact natural resources. **In LEED v4.1, a majority of the LEED credits are related to operational and embodied carbon.**

With regard to embodied carbon emissions, LEED gives credits ranging from use of materials with EPDs to whole building reduction of embodied carbon emissions by 5 or more percentage points relative to a comparable building baseline.

4.6.3 Federal, State, and Local Policies

Within the recent past, several organizations have arisen to assist in policy development and implementation in various US States and also abroad. Examples include:

- Carbon Leadership Forum (CLF) Embodied Carbon Policy Toolkit (U.S. and Canada) [74]
- City Policy Framework for Dramatically Reducing Embodied Carbon (international)[75]
- Zero Carbon Building Accelerator (international)[76]

The policy actions recommended affect all facets of building, development, and infrastructure, including zoning laws, new and existing building construction and materials specification, government purchasing regulations (i.e., Buy Clean procurement policies), tax incentives or penalties, financing mechanisms, and others. Buy Clean policies have received the greatest attention in recent policy activities in the US in some states and cities and in the Federal government. According to NBI (2022):

> **Buy Clean** policies (also referred to as embodied carbon procurement) are the most common type of policy addressing greenhouse gas emissions in individual construction materials. The procurement policy approach incorporates low-carbon construction purchasing requirements for any project receiving jurisdiction funds. Policy components include disclosure (GWP), incentives (bid bonus), and standards (GWP limits.) The Buy Clean approach can be applied at the federal, state, or local level and even used by private building owners.

[73] https://www.usgbc.org/leed, last accessed 11/20/2023

[74] Carbon Leadership Forum, *Embodied Carbon Policy Toolkit,* November 2021. https://carbonleadershipforum.org/clf-policy-toolkit/

[75] https://www.embodiedcarbonpolicies.com/, last accessed 1/31/2023 (developed by Carbon Neutral Cities Alliance, One Click LCA, and Architecture 2030).

[76] https://buildingefficiencyaccelerator.org/, last accessed 1/31/2023

Material specification regulations are similar to Buy Clean policies in that they set embodied carbon emission benchmarks for construction materials in locally adopted building codes or other regulatory instruments. The benchmarks are set to eliminate the worst-performing materials (or manufacturers) in terms of their embodied carbon emissions (e.g., kg CO2e per kg of material or other measure of material quantity such as unit area or volume of material or function). All of these regulations rely on the local availability of EPD data for the regulated materials. Where not available, some rely on prescriptive limitations (e.g., a concrete with a particular mix that is considered to be of acceptably low embodied carbon emissions intensity).

Another active policy area in the US is aimed at existing buildings through what is called "Building Performance Standards" (BPS). They have been defined as follows: [77,78]

> **Building Performance Standards (BPS)** – A policy that requires building owners to meet performance targets by actively improving their buildings over time. These can include energy or emissions targets building must meet to improve energy efficiency and reduce climate impacts.
>
> Building performance standards (BPS) are an emerging and increasingly important policy tool for jurisdictions looking to reduce the operational greenhouse gas (GHG) emissions of their built environment to meet their climate commitments. Unlike construction and energy codes, which only affect buildings at distinct events in their life cycle, such as new construction or major renovation, BPS aim to regulate and reduce the climate impact of existing buildings by establishing increasingly stringent targets that require buildings to improve performance throughout their lifetimes.

According to the Carbon Leadership Forum (CLF, 2021a) and the map of Figure 52 accessed at the time of this writing documents, about 44 local, state, or federal embodied carbon policies existing or under legislative consideration in the U.S. Most of these policies are in the category of Buy Clean or material specification policies which set benchmarked limits on embodied carbon emissions (e.g., GWP) for certain materials in new construction or for existing buildings and rely on the use of EPDs for compliance.

Figure 52. U.S. Embodied Carbon Policy Tracker Map
Source: https://carbonleadershipforum.org/clf-policy-toolkit/#map, last accessed 1/10/2023

[77] McGowan, M. 2022. "Building a Foundation for Building Decarbonization," ASHRAE Journal, March 2022, www.ashrae.org

[78] https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization, last accessed 2/3/2023
Building Performance Standards: A Technical Resource Guide, ASHRAE & U.S. DOE, 2023

The Carbon Leadership Forum provides the following summary of policy actions in 2022:[79]

International Policy Action
Embodied carbon has gained attention on an **international** scale. In 2022, the United Nations Industrial Deep Decarbonisation Initiative announced a global coalition of governments committing to a Green Procurement Pledge to fight climate change by increasing demand for low-carbon industrial materials. Corporations have also committed to take action by creating markets for emerging clean technologies through the First Movers Coalition. The Coalition focuses on steel and aluminum (amongst other areas like shipping and trucking), with a new addition of the cement and concrete sector announced at COP 27 that took place in November 2022. Another announcement from COP 27 was that 158 ratifying countries to the Paris Agreement have included energy efficiency and building decarbonization in their national commitments.

Federal Policy Action
On the **federal** level, building off President Biden's commitments in 2021 around clean manufacturing, we have seen significant actions supporting these efforts from the first days of 2022. In January, President Biden's 2021 Executive Order on Federal Sustainability established the federal Buy Clean Taskforce. The Taskforce aims to increase federal purchasing of low-carbon construction materials while supporting American manufacturing companies. Federal agencies took action in the months following this announcement:

- General Services Agency announced its Buy Clean program requiring low-carbon concrete and asphalt to be used in large public projects and requiring Environmental Product Declarations (EPDs).
- Department of Transportation announced a pilot program to increase the use and transparency of EPDs and procure low-carbon materials for their infrastructure projects.
- Federal Highway Administration awarded $7.1 million in grants to 35 projects across the US as part of their Climate Challenge to quantify emissions of sustainable pavements.
- In August 2022, the passage of the Inflation Reduction Act allocated a total of $369 billion to finance climate change solutions from various levels. Specific to embodied carbon reductions, the law allocates $4.5 billion to the Environmental Protection Agency, Department of Transportation, and General Services Agency to procure climate-friendly construction materials for federally funded projects. Examples of funding relating to embodied carbon include:
- Develop a low-embodied carbon labeling system for construction materials and increase EPD development and standardization.
- Using and procuring low-carbon materials for federal buildings.
- Research on emerging technologies related to building materials.
- Funding transportation projects using lower embodied carbon materials.

Additionally, in September 2022, the White House announced the Federal Buy Clean Initiative stating that the federal government will prioritize purchasing lower greenhouse gas emission steel, concrete, asphalt, and flat glass. They will convene states to partner on Buy Clean policies, launch pilot programs to advance clean construction materials, and increase data transparency through supplier reporting. In October, the White House published a fact sheet that cited the CLF's Regional Hubs, the CLF Embodied Carbon Educational Series, our published data and research, the SE2050 and MEP2040 commitments and companies, and highlighted many partners working in this space.

State and Regional Policy Action
In addition to the action on the federal level around embodied carbon, there has been progress on the **state and regional** levels as well. A few examples include:

- Oregon's Buy Clean bill was signed into law in March 2022 and will require the Oregon Department of Transportation to establish a framework for reducing greenhouse gas emissions related to the construction and maintenance of their projects.

[79] https://carbonleadershipforum.org/policy-2022-review/, last accessed 1/31/2023

- California's AB 2446 designates state agencies to develop a framework for measuring and then reducing the average carbon intensity of residential construction materials.
- Washington State's Buy Clean Buy Fair Pilot Study was completed in 2022 which developed a reporting database to collect environmental and labor information from state construction projects.
- The Pacific Coast Collaborative Low Carbon Construction Taskforce announced at COP26 began convening in Spring 2022 to identify opportunities for regional alignment and action around embodied carbon.

Local Policy Action
Furthermore, we are seeing embodied carbon measures included in an increasing number of city and county climate action plans. See the CLF Policy Tracker for more info.

- The City of Vancouver's Whole Building Life Cycle Assessment zoning requirement became part of their Building By-Law which goes into effect in 2023.
- New York City's Executive Order 23 includes requirements for using low-carbon concrete on capital projects and concrete sidewalks, submitting EPDs to the EC3 tool, using low-emission vehicles and equipment, performing Life Cycle Analysis, and developing action plans that incorporate embodied carbon.
- The City of Denver accepted two proposed amendments to its building code that address embodied carbon, specifically requiring EPDs and setting limits for concrete and steel.
- San Francisco's Construction and Demolition Law went into effect in January 2022. It sets debris recovery requirements for all projects in the City to be recycled or reused with no waste to landfill.

What's Ahead?
2023 is set up to be yet another year of unprecedented action on embodied carbon policy. The US federal government, joined now by a growing set of international partners, will take bold action to reduce embodied in their building and infrastructure portfolio while providing funding, technical assistance, and other programs to states, cities, and companies across the country to implement reductions. Policies led by states, cities, and provinces will continue to lead the way and set precedent for legislative action by integrating embodied carbon across urban planning and building regulations as well as innovative incentive programs. Stay in touch with our policy team and reach out to tell us about new policies for the CLF Policy Tracker!

The Carbon Leadership Forum also has published a report providing a more detailed assessment of EPD requirements in Buy Clean and other procurement policies related to various building products (CLF, 2021b).

Various procurement policies or Buy Clean policies have been reviewed (Lewis, et al., 2021). As one example of a Buy Clean provision refer to Table 10.

TABLE 10. GWP limits for materials addressed in the Buy Clean California Act

Eligible Material	Subcategory	Proposed GWP limit
Structural Steel	Hot-Rolled Structural Sections (unfabricated)	1,080 kg CO2e / metric ton
	Hollow Structural Sections (unfabricated)	1,710 kg CO2e / metric ton
	Plate (unfabricated)	1,590 kg CO2e / metric ton
Concrete Reinforcing Steel	Rebar (unfabricated)	920 kg CO2e / metric ton
Flat Glass		1,430 kg CO2e / metric ton
Mineral Wool Board Insulation	Light Density	3.33 kg CO2e / m2 RSI-1
	Heavy density	8.16 kg CO2e / m2 RSI-1

Source: https://carbonleadershipforum.org/buy-clean-california-limits/, last accessed 1/10/2023

According to Esram and Hu (2021) the U.S. federal Buy Clean provision is described as follows:

> **U.S. General Services Administration's (GSA) Office of Federal High-Performance Green Buildings** issued "Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies" in February 2021 (GSA 2021). These recommendations include a material-based approach for all projects and a whole-building life-cycle assessment approach for larger projects over $3.095 million. The material-based approach requires "environmental product declarations for 75% of materials used (by cost or weight), and that their emissions fall in the best performing 80% of global warming potential (GWP)[7] among functionally equivalent products as demonstrated by environmental product declarations (EPDs)."[8] The whole-building approach requires "designing a building in such a way that life-cycle carbon assessments show that the selected design results in a 20% carbon reduction, compared to a baseline building."[9] With a robust backdrop of community pressure and regulatory threats, well designed, voluntary initiatives in environmental governance can effectively motivate private firms to act proactively; however, such initiatives have only modest effects and are unlikely to substitute for regulations (Coglianese and Nash 2016).

Esram an Hu (2021) also describes the following material specification provision which at the time was the only codified version of such a policy in the U.S.:

> **Marin County in California** is the first and the only jurisdiction that has adopted an embodied carbon provision in its building codes (Marin County, California 2021). Chapter 19.07 of Title 19 in the Marin County Building Code sets maximum embodied carbon limits (ranging from 260 to 675 kg CO_2e/m^3) for concrete of various compressive strength levels. It also allows the total embodied carbon of all concrete mix designs to be calculated and evaluated at the project level. The Marin County code also grants exemptions for circumstances that make it a hardship or infeasible to meet the requirements.

At the time of this writing, several other states are considering similar material specification provisions for concrete. For example, the following is a description of actions being considered in the State of Maryland:[80]

> "Initiated in 2019, the Buy Clean California Act requires contractors who bid on state infrastructure projects to disclose greenhouse gas emissions data for certain materials with an environmental product declaration (EDP). These materials include steel, glass, and concrete. Several other states and jurisdictions have now adopted this practice including Colorado; Oregon; Hawaii; New York State; Marin County, California; Austin, Texas; and

[80] Maryland Green Building Council. 2022. Findings and Recommendations on Section 13 of the Maryland Climate Solutions Now Act 2022, December 2022.

> Portland, Oregon. In 2021 the General Services Administration (GSA) began the Federal Buy Clean Initiative, which promotes the development of low-carbon construction materials and supports job growth in clean US manufacturing. In 2022, the GSA released amended requirements that tie concrete compressive strength to a maximum global warming potential (GWP) limit. GSA has collaborated with the EPD Program Operators including the National Ready Mixed Concrete and ASTM International to develop these requirements.
>
> A significant challenge for the State of Maryland is that currently no in-state concrete manufacturers have developed EPDs for their mixes. Most concrete producers already have the knowledge and experience manufacturing low carbon concrete mixes that have less Portland cement and high supplementary cementitious materials (SCM) content. EPDs do, however, allow for a quantitative comparison of mixes and their global warming potential measuring seven climate impact indicators, one significant category being GWP. GWP is significant as it is a direct measurement of embodied carbon, in a kilogram CO2 equivalent.
>
> Adding EPDs to the procurement process could increase the cost of concrete for the State but is likely to significantly increase costs for concrete suppliers, particularly small businesses. A recent survey found the first cost of a new single EPD was approximately $15,000. The actual cost may be significantly higher because the real cost is not producing the EPD, but rather supplying low carbon concrete. Low carbon concrete with an EPD will cost the State more than concrete currently being used. EPDs can be tracked through Lifecycle Assessment (LCA) databases like OneClick and the Embodied Carbon in Construction Calculator (EC3 Tool), which includes over 24,000 concrete EPDs available for products manufactured in the USA and Canada. The EPDs are searchable and sortable by strength, location, manufacturer, plant, mix ID and most are concrete mix and batching plant specific."

The Maryland Green Building Council's report goes on to discuss "incentives" to lower carbon emissions of purchased concrete for state projects. However, the only incentive mentioned is providing funding support for smaller suppliers to develop EPDs, which are very scarce in Maryland. The presumption is that the larger suppliers can better absorb the cost. It also speaks of setting performance standards – which are really cut-off limits for allowable concrete suppliers or mix designs. It does acknowledge that this could have other market and cost impacts and construction impacts, such as the loss of flexibility to adjust concrete mix design for site conditions that can result in construction delays or performance trade-offs. It discusses setting carbon-reduction targets for specific state-funded projects. Education of suppliers and users is discussed as well as policy tools to consider like the CLF's Embodied Carbon Policy Toolkit. Finally, it discusses funding for a Maryland-specific EPD database.

The Maryland Green Building Council's report also addresses a material specification approach like that in adopted by Marin County California:

> In 2019, the Marin County, California Board of Supervisors adopted requirements for performance specifications and provide samples of specification sections. Marin County developed their performance thresholds through an involved stakeholder process, resulting in four pathways of compliance. Two of the pathways are 'cement limiting' mainly directed for use by small scale projects (i.e., residential) while the other two pathways are a performance metric, tying the embodied carbon limits to the compressive strength of the mix. Refer to Table 19.07.050 [Table 11] of the Marin County Low Carbon Concrete Code below.
>
> For jurisdictions interested in adopting a similar ordinance, the Marin County site includes a link to a 'Code Amendment Toolkit'3. Additionally, their sample non-residential specification section includes compliance forms and multiple paths for compliance.4 Marin's Development and Adoption Process highlights the considerations, challenges, and studies they conducted to develop their policy.

TABLE 11. Marin County, California, Concrete Embodied Carbon Limits

	Cement limits for use with any compliance method 19.07.050.2 through 19.07.050.5	**Embodied Carbon limits** for use with any compliance method 19.07.050.2 through 19.07.050.5
Minimum specified compressive strength f'c, psi (1)	Maximum ordinary Portland cement content, lbs/yd³ (2)	Maximum embodied carbon kg CO_2e/m^3, per EPD
up to 2500	362	260
3000	410	289
4000	456	313
5000	503	338
6000	531	356
7000	594	394
7001 and higher	657	433
up to 3000 light weight	512	578
4000 light weight	571	626
5000 light weight	629	675

Notes
(1) For concrete strengths between the stated values, use linear interpolation to determine cement and/or embodied carbon limits.
(2) Portland cement of any type per ASTM C150.

From this example, it is clear that states like Maryland are reviewing their own EPD and construction materials environment and studying existing policy examples to replicate. Where EPDs are scarce, prescriptive solutions (like specified concrete mix design or type) are being considered. Where EPD data is available and benchmarks can be set, performance-based material carbon emission limits are established to exclude the worst-performing product producers (or force them to improve their product or processes). The latest example of a new concrete emissions law is from New Jersey where it claims that concrete is responsible for 7% of global carbon emissions. But, in reality, the contribution of the entire US concrete industry is actually about 0.17% of total global GHG emissions and 1.7% of total US GHG emissions as shown earlier in Part 4 (to be revisited again later in Section 4.7). The New Jersey law also provides tax credits for assessment of alternative concrete mix designs based on GWP.[81,82]

Another example of local policy action is from Washington DC:[83]

> By 2026, all new buildings and substantial renovations in D.C. will have to be net-zero construction, meaning they produce as much energy as they consume, under legislation passed unanimously by the D.C. Council Tuesday. The legislation, which also bans most natural gas use in new buildings, now heads to Mayor Muriel Bowser.
>
> At the same time, the Council passed separate climate legislation committing to making the entire city carbon neutral by 2045.
>
> The Climate Commitment Act, which also passed unanimously, for the first time codifies in D.C. law the city's greenhouse gas reduction goals. The bill also speeds up the timeframe for ditching fossil fuels, committing to going carbon neutral five years earlier than the previous goal of 2050. Shorter term goals in the legislation include a 60% cut in carbon emissions by 2030, and District government-owned buildings going carbon neutral by 2040.
>
> The clean building legislation, just four pages long, does not itself create the new net-zero building codes, but rather instructs the mayor to do so by no later than Dec. 31, 2026. Buildings will be prohibited from using "on-site fuel combustion" (aka, burning natural gas) for furnaces or water heaters. There is an exemption to the fuel combustion ban for backup power generators in "buildings that are essential to protecting public health and safety."

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[81] https://www.smartcitiesdive.com/news/new-jersey-law-low-carbon-concrete-incentives/641701/?utm_medium=email&utm_source=rasa_io&utm_campaign=newsletter, last accessed 2/11/2023
[82] https://legiscan.com/NJ/text/S287/id/2692968, last accessed 2/11/2023
[83] https://dcist.com/story/22/07/14/dc-natural-gas-ban-net-zero-carbon-new-construction/, last accessed 8/2/2022

Also, the states of Maryland, New York, and Massachusetts have passed recent legislation to restrict and transition away from the use of on-site combustion of fossil fuels for building heating.[84]

The Institute for Market Transformation (IMT) has reviewed and compared numerous BPS policies (similar to the NYC Law 97) as enacted by 44 states and cities over the past 12 years or so.[85] These policies including benchmarking and transparency provisions and, in some cases like NYC, also specific criteria or targets for performance improvements of a certain portion of the commercial building stock.

As part of its unfolding strategy to engage in building decarbonization policy support, on January 30, 2023 the International Code Council (ICC) released a new Building Performance Standards Guide as a coordinating resource as states and local governments consider BPS policies for new and existing buildings.[86] It discusses the benefits of BPS, reviews various examples of state and local PBS policies, and makes recommendations for alignment of BPS with energy codes for new buildings such that compliance is coordinated once a new building becomes an existing building at occupancy. The latter concern is in part due to BPS policies often being implemented by different agencies than those responsible for new building construction. A similar guide on BPS policy development has also become available through ASHRAE shortly after publication of the ICC's guide and it covers similar content.[87] It describes the four key components of a BPS:

> There are four key components of a BPS policy: 1) the scope of the policy in terms of the buildings that it covers, 2) the metrics used to measure performance, 3) the associated performance targets, and 4) the compliance time frame and implementation mechanisms.

The ASHRAE BPS guide recognizes the uptake of BPS at state and local levels and reviews their variation in application among other factors, such as choice of metric, which should be considered in the implementation of a localized BPS policy. Some excerpts are as follows:

> As of December 2022, BPS policies were fully approved and adopted as local ordinances or laws in eight U.S. cities, one county, and three states, as well as at the federal level through the Federal Building Performance Standard (The White House 2022a), which applies to certain federally owned facilities. BPS policies were also being considered for implementation in more than 20 additional jurisdictions as part of the National Building Performance Standards Coalition (The White House 2022b).
>
> …
>
> Because BPS focus primarily on a building's energy-consuming operations, the regulation of carbon emissions, generally expressed as carbon dioxide equivalent, or CO2e, would be primarily measured based on operational carbon and exclude embodied carbon in building materials. Over time, as embodied carbon is better understood and categorized, this may change.
>
> …
>
> A BPS performance target denotes a specific level of performance that a building must meet to comply with the policy. For example, a BPS policy that uses greenhouse gas intensity (GHGI) as a metric may set a performance target of 8.5 kilograms of carbon dioxide equivalent per square foot per year (kg CO2e/ft^2/yr) for office buildings. Office buildings reporting at or below 8.5 kg CO2e/ft^2/yr would be in compliance, whereas office buildings reporting above 8.5 kg CO2e/ft^2/yr would not. Performance targets in BPS may vary by building type, size, or other parameters, and may also vary over time.
>
> …
>
> For example, ASHRAE/IES Standard 100 (ASHRAE 2018b) provides site energy use targets (electricity and fossil fuel) for 53 building activity types across 17 climate zones. Figure 3.2 [Figure 53] shows an excerpt of the site EUI targets for different building types from the standard, including multiple subcategories of offices. If using this standard for target setting, the jurisdiction could adopt targets for either all or a subset of the building categories included in the standard. Prior experience with target-setting analyses using data obtained from Standard 100, the

[84] https://www.aceee.org/blog-post/2022/08/three-states-enact-integrated-plans-decarbonize-buildings#:~:text=New%20York's%20law%20will%20ensure,clean%20energy%20legislation%20this%20year, last accessed 1/31/2023

[85] https://www.imt.org/resources/comparison-of-commercial-building-benchmarking-policies/, last accessed 1/31/2023

[86] https://www.iccsafe.org/content/energy-codes-and-building-performance-standards-download/, last accessed 1/31/2023

[87] https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization, last accessed 2/3/2023
Building Performance Standards: A Technical Resource Guide, ASHRAE & U.S. DOE, 2023

CBECS and the ESPM suggests that more granular categories are preferable to simple high-level categories because they provide the opportunity for more detailed target setting to differentiate buildings.

		EUIs by Building Type by Climate Zone (kBtu/ft²·yr)																
		ASHRAE Climate Zone																
No.	Commercial Building Type	1A	2A	2B	3A	3B Coast	3B Other	3C	4A	4B	4C	5A	5B	5C[a]	6A	6B	7	8
1	Admin/professional office	39	40	39	42	33	39	33	46	40	40	48	42	39	54	47	58	81
2	Bank/other financial	55	57	56	59	46	55	47	65	56	57	68	59	56	76	67	82	115
3	Government office	49	50	49	52	41	48	42	57	49	50	60	52	49	67	59	72	101
4	Medical office (nondiagnostic)	33	34	33	35	28	33	28	39	34	34	41	36	33	46	40	49	69
5	Mixed-use office	45	46	45	48	38	45	39	53	46	47	56	48	45	62	55	67	94
6	Other office	38	39	38	40	32	37	32	44	38	39	47	40	38	52	46	56	78
7	Laboratory	178	176	171	175	147	165	159	194	173	179	209	187	181	232	211	249	331
8	Distribution/shipping center	12	16	16	20	11	18	14	27	23	22	36	30	24	49	40	60	113
9	Nonrefrigerated warehouse	6	8	8	10	5	9	7	13	11	11	17	14	12	24	19	29	54
10	Convenience store	135	146	135	152	127	139	141	166	150	157	178	162	167	193	179	208	263
11	Convenience store with gas	108	118	109	122	102	112	114	133	121	126	144	130	135	156	144	168	212
12	Grocery/food market	112	122	113	127	106	116	118	138	125	131	149	135	139	161	149	174	219
13	Other food sales	34	37	34	38	32	35	36	42	38	40	45	41	42	49	45	53	66

Figure 53. Excerpt from Table 7.2a of ASHRAE/IES Standard 100 showing EUI targets[88]

As one example of BPS policy implementation, New York City Local Law 97 enacted in 2019 addresses operational carbon emissions of existing buildings in the city.[89] It includes operational carbon intensity limits that scale downward over future time periods, requires owners to report progress and compliance, and includes civil penalties for falsifying information of up to $500,000 as a misdemeanor with up to 30 days of jail time. It also includes fines such as a $268/tCO2e penalty for exceeding the law's emissions limits. Generally, covered buildings are 25,000 square foot in floor area or greater in size. The law also includes various exceptions including low-rise residential buildings (not more than three stories), city buildings, and religious buildings, among others.

It is worth noting here as a recommendation that a practicable approach to addressing existing buildings should establish triggers to improve energy efficiency and reduce emissions at a time when an existing building is already undergoing certain types of activities such as equipment replacement, alterations, and renovations. This would cost-effectively couple the expense of making improvements with normal episodes in the life cycle of building operation, maintenance, repair, and alteration. This is the approach currently under consideration for the 2024 edition of the IECC for commercial and residential buildings. This is unlike many BPS policy implementations (like NYC Local Law 97) whereby improvements are required on a locally specified timeframe to meet local climate policy goals, irrespective of opportunities to economize improvements in the existing building stock by coordinating with normal building materials, equipment, and systems lifespans for replacement.

Other related policy activities are being considered for implementation in state-adopted energy codes. For example, at the time of this writing, the State of Vermont is in the process of adding embodied carbon emissions accounting and targets or limits for insulation materials into its state-wide energy code based on the metric of GWP per square foot of building floor area (the same metric used in BPS discussed above).[90] Unfortunately, it focuses on insulation materials using solely a materials-based embodied emissions

[88] https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization, last accessed 2/3/2023
Building Performance Standards: A Technical Resource Guide, ASHRAE & U.S. DOE, 2023

[89] https://www.nyc.gov/site/sustainablebuildings/ll97/local-law-97.page, last accessed 1/31/2023

[90] https://publicservice.vermont.gov/efficiency/building-energy-standards/building-energy-standards-update, last accessed 1/31/2023

approach.[91] When such an approach is applied to insulation materials which are the very materials that reduce operational carbon emissions, it can misrepresent the significance of material choices on the overall carbon footprint (embodied) and hand print (operational emissions) of the insulation materials used in a building for energy efficiency purposes. For example, some insulation materials have multifunctional capabilities and benefits that can be used to improve the overall building performance and carbon emission reductions. However, these opportunities may be foregone if the only focus is on the upfront carbon emissions of the insulation material itself as currently proposed in Vermont. It also uses predetermined GWP values for insulation materials which do not necessarily reflect the GWP values and improvements of specific products within a given type of insulation material (see Section 4.7.4 for updated insulation material GWP values). Its accounting methodology as currently conceived also does not appear to properly account for installed (actual or effective) R-value differences of insulation materials in their end use configuration (e.g., continuous insulation vs. cavity insulation). Such omissions in a material-property-based embodied emissions approach will significantly skew the selection of materials based merely on the functional units of GWP used for insulation products. For example, a greater amount of cavity insulation material (and thus greater amount of embodied emissions) will be required to match the effective thermal performance of continuous insulation. Again, problems with this type of an approach and actual examples of consequences (or potential missed opportunities) were presented earlier in Section 4.4.1 of this report.

NBI (2022) recommends a three-stage, sequenced process to introduce and then increasingly control embodied carbon emissions in building codes for new construction in view of the infancy of the market in addressing this matter:

(1) **Disclosure** (e.g., reporting only by way of requiring a certain number or amount of products used on a project to have EPDs – thereby pressuring industry to produce EPDs)
(2) **Material targets** (e.g., prescribing material GWP limits to eliminate the upper 25% of products with greatest levels of GWP reported in EPDs)
(3) **Whole building LCA**

Finally, NBI (2023) implements the second stage (material targets) as noted above in the form of proposed US model building code changes or as amendments at the point of local jurisdiction adoption of a model building code, such as the International Building Code (IBC). It addresses essentially all major construction materials (e.g., concrete, steel, glass, gypsum board, insulation, interior finishes, roofing, etc.). In general, the approach requires that a specified product not exceed 125% of the average GWP of a material class based on an industry-wide EPD which would have the effect of eliminating approximately 30% of the products with EPDs reporting GWP greater than 125% of the industry-wide average. For an example of proposed building code language, see Figure 54. Other proposed changes include definitions to support the various building material proposals like the one shown in Figure 54. The NBI (2023) report also includes an appendix with an extensive listing of available North American industry-wide EPD data for the GWP of various building materials.

[91] https://www.efficiencyvermont.com/news-blog/whitepapers/the-high-greenhouse-as-price-tag-on-residential-building-materials, last accessed 1/31/2023

Chapter 26: Plastic

Products included in this section: insulation: Expanded polystyrene (EPS), and Polyurethane Foam Insulation (HFC and HFO)

SECTION 2603 FOAM PLASTIC INSULATION

Add new text as follows:

2603.2 Embodied CO2e of Foam Plastic Insulation Products. 50% of all insulation products, including expanded polystyrene (EPS) and polyurethane foam insulation (HFC or HFO) used in the *building*, based on cost and area, shall not exceed 125% of IW-EPD's kgCO2e/m2-RSI. Products shall have a *product-specific Type III EPD*. Documentation of the product's kgCO2e/m2-RSI and EPDs shall be verified by a *registered design professional* on the project, and a summary shall be made available to the *code official* that includes a list of each product and associated kgCO2e/ m2-RSI., per the EPD.

Exception:

1. *Reflective plastic core insulation*

Product percentage options: Foam plastic insulation EPDs have room for growth, meaning it may be hard to find complying products for all applications. However, since the majority of products are procured from the same manufacturer, a higher percentage of product categories can comply, when the products are available.

Insulation may be referred to differently per region. Other terms for rigid insulation include board, foam board, rigid, Styrofoam, or closed-cell. Other common terms for spray polyurethane foam insulation include SPF, spray foam, low or medium-density spray foam, open-cell, closed-cell, or expanding foam. These foams are only related to those with blowing agents with hydrofluorocarbons (HFC) or those with hydrofluoroolefins (HFO). Products using both blowing agents are indicated in Appendix A.

Mineral wool insulation and cellulose insulations are included in Chapter 7, Fire and Smoke Protection Features.

Insulation is an essential component of energy efficiency. However, not all insulation is the same; comparing products' upfront and lifecycle kgCO2e/m2-RSI, some insulation is more carbon intensive, based on the raw ingredients and manufacturing methods. Projects will need to balance operational carbon and embodied carbon requirements. Specifying the right insulation for the application will support a carbon-balanced project.

Figure 54. Example of proposed building code language to establish GWP limits
Source: NBI (2023)

4.6.4 Embodied Carbon Design Guides

Various policy development guides or toolkits were discussed in an earlier section of Part 4. This section addresses a selection of building decarbonization guides that are aimed at practitioners, like architects and engineers, and the practice of reducing embodied or upfront carbon emissions of buildings. Some examples include:

- Embodied Carbon Quick Guide: A Quick Reference Guide for Teams to Reduce their Project's Embodied Carbon (LFI, 2020) [92]
- AIA-CLF Embodied Carbon Toolkit for Architects (AIA/CLF, 2021) [93]

[92] International Living Future Institute, 2020. https://living-future.org/wp-content/uploads/2022/07/Embodied-Carbon-Quick-Guide.pdf

[93] https://carbonleadershipforum.org/clf-architect-toolkit/, last accessed 2/15/2023

- Carbon Smart Materials Palette [94]
- Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities (RMI, 2021)[95]
- Denver's Building Sector Embodied Carbon Emissions (City and County of Denver, 2021)[96]
- The Urgency of Embodied Carbon and What You Can Do About It (BuildingGreen, Inc., 2018)[97]
- How to Calculate Embodied Carbon (ISE, 2020)[98]

Most of the above-listed guides focus on reduction of embodied carbon of buildings. In most cases, reducing embodied carbon of buildings requires knowledge of the embodied carbon of building materials. Other recommendations relate to the matter of resource-efficient building design and building configuration such that the amount of materials used is reduced while still achieving the functional objectives of a building project, regardless of the material selections and their individual GWP. This latter recommendation is one the more cost-effective approaches to making significant embodied carbon reductions with minimal design effort, minimal risk of unintended consequences of material substitutions, and minimal demand for material GWP information and accounting. However, in some cases, the ultimate goal of these guides is not simply the practical or cost-effective reduction of carbon emissions. Many appear to be aimed at eventually eliminating all sources of building-related carbon emissions by 2050 (which aligns with the ultimate goal of the voluntary programs, regulatory policies, and decarbonization strategies reported earlier in this paper).

Some guides do recognize that operational carbon emission reductions involve continued improvement of new and existing building energy efficiency together with electrification and use of on-site renewable energy or power from an electric grid that is increasingly supplied by renewable power generation. This approach is shown below in Figure 55 based on the AIA's "Architecture 2030" program. It includes a host of actions which were addressed in the broader plans for a decarbonized energy system reviewed in earlier parts of this report.

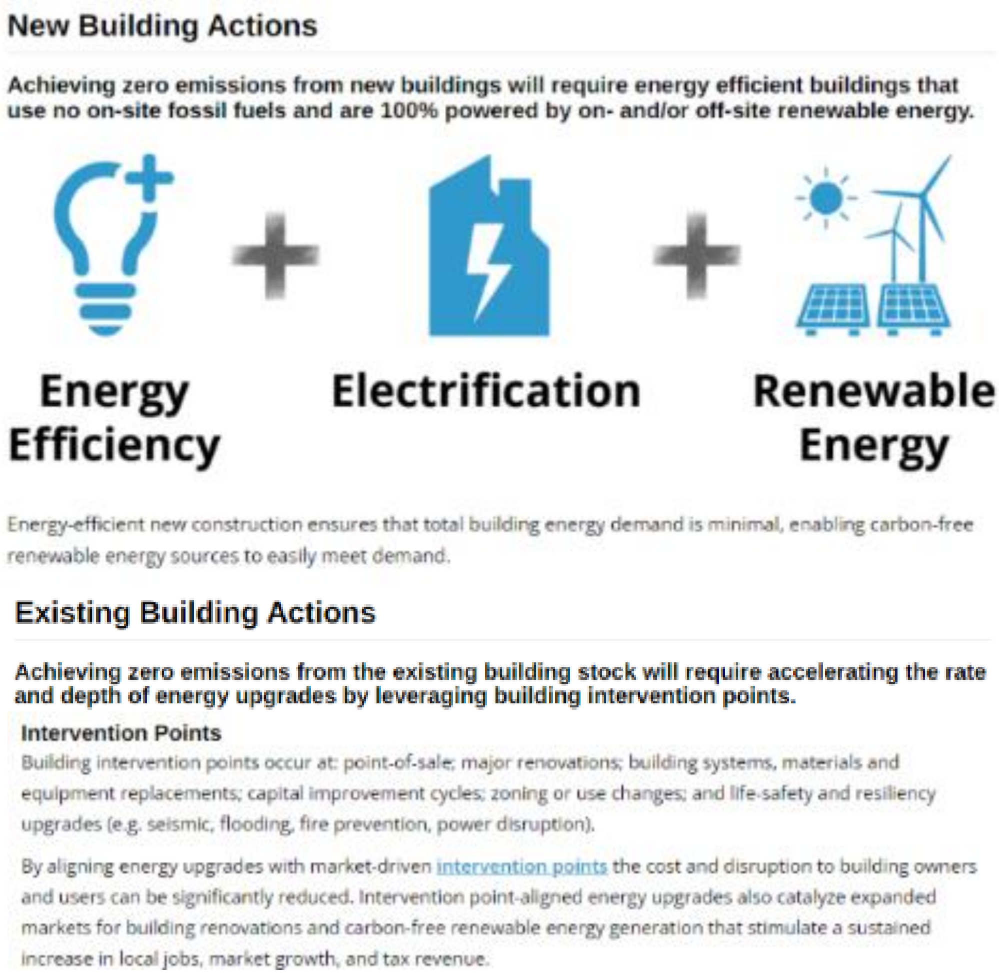
[94] https://materialspalette.org/, last accessed 2/14/2023

[95] https://rmi.org/insight/reducing-embodied-carbon-in-buildings, last accessed 2/14/2023

[96] https://www.denvergov.org/files/assets/public/climate-action/documents/hpbh/nze/denvers-building-sector-embodied-carbon-emissions-june-2021.pdf?mc_cid=a6ccfdd350&mc_eid=d4b9a8d903, last accessed 2/15/2023

[97] https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it, last accessed 2/15/2023

[98] For a 2nd edition of the ISE (2020) guide, refer to https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/, last accessed 11/10/2023; for a brief guide, refer to https://www.istructe.org/IStructE/media/Public/TSE-Archive/2020/A-brief-guide-to-calculating-embodied-carbon.pdf, last accessed 11/20/2023



New Building Actions

Achieving zero emissions from new buildings will require energy efficient buildings that use no on-site fossil fuels and are 100% powered by on- and/or off-site renewable energy.

Energy Efficiency + **Electrification** + **Renewable Energy**

Energy-efficient new construction ensures that total building energy demand is minimal, enabling carbon-free renewable energy sources to easily meet demand.

Existing Building Actions

Achieving zero emissions from the existing building stock will require accelerating the rate and depth of energy upgrades by leveraging building intervention points.

Intervention Points

Building intervention points occur at: point-of-sale; major renovations; building systems, materials and equipment replacements; capital improvement cycles; zoning or use changes; and life-safety and resiliency upgrades (e.g. seismic, flooding, fire prevention, power disruption).

By aligning energy upgrades with market-driven intervention points the cost and disruption to building owners and users can be significantly reduced. Intervention point-aligned energy upgrades also catalyze expanded markets for building renovations and carbon-free renewable energy generation that stimulate a sustained increase in local jobs, market growth, and tax revenue.

Figure 55. Operational carbon emissions reduction strategy based on AIA's "Architecture 2030" program for new and existing buildings

Source: https://architecture2030.org, accessed 8/3/2022

One of the most compact and complete collections of recommendations toward reduction of embodied carbon in buildings is found in the International Living Future Institute's Embodied Carbon Quick Guide (LFI, 2020) which provides the following checklist for building designers:

PRE-DESIGN

Include low carbon emissions in the site selection and development criteria:

- Build only on previously developed sites
- Restore any undeveloped portions of the site area with native vegetation

Conduct an inventory of the site resources:

- Identify buildings or in-situ materials with highest potential for reuse

Include strategies to reduce building material quantities in the Pre-Design package, including:

- Reduce floor area by optimizing the program and considering multiple uses for spaces
- Design for flexibility to eliminate future waste (e.g. open floor plates, moveable partitions)
- Specify a compact and efficient structure that reduces or eliminates redundancy

DESIGN

Conduct iterative embodied carbon assessments[1]:

- Conduct an initial life cycle assessment (LCA) in Schematic Design to form a baseline of the embodied carbon of the project (see TOOLS)
- Use the LCA to identify "hot spots"; materials or assemblies with highest carbon intensities
- Set a carbon reduction target for the project
- Use the LCA to test lower carbon design or material alternatives, specifically for materials of the foundation, structure, and enclosure

Select building systems and assemblies that minimize embodied carbon:

- Specify pre-fabricated assemblies that reduce material waste and construction time
- Evaluate the use of carbon-sequestering structural systems such as mass timber
- Minimize the use of interior finish materials (e.g. polishing concrete instead of carpet, open structure without drop ceilings)
- Design for deconstruction to minimize waste generated at the end of the project life (e.g. mechanical fasteners, modular design)

Specify material characteristics[2] that result in low embodied carbon, including:

- Salvaged or reclaimed materials
- Locally harvested and/or manufactured
- Manufactured using renewable energy
- Contains high recycled content
- Naturally carbon-sequestering (e.g. wood, bamboo, cork, straw, hemp)
- Sustainably harvested with third-party verification (e.g. FSC certification for wood)
- High durability with long service life

Document embodied carbon design decisions in the final Basis of Design

- Summarize the methodology used to make decisions related to embodied carbon
- Record the embodied carbon of alternatives considered, and estimated avoided impacts (measured in CO_2e)

CONSTRUCTION

Request embodied carbon data during Contracting and Procurement:

- Select products with a type III Environmental Product Declaration (EPD), as defined by the International Organization for Standardization (ISO) Standard 14025, or equivalent
- Select product alternatives with lowest documented embodied carbon value

Reduce construction waste:

- Procure materials at appropriate quantities to eliminate extras and reduce packaging
- Divert the maximum quantity of construction waste from going to the landfill (i.e. recycling)

Document the as-built embodied carbon content:

- Inventory the final material and product selections, including quantities
- Conduct a final LCA to document the total embodied carbon of the project
- Consider carbon offsets to account for the remaining embodied carbon

Source: International Living Future Institute's Embodied Carbon Quick Guide (LFI,2021)

MATERIAL GUIDANCE

Concrete

- Reduce cement content; use supplementary cementitious materials (SCMs)
- Specify local, recycled and strong aggregates
- Specify Portland limestone cement (PLC) instead of Portland cement
- Utilize appropriate mixes for each application; specify high-strength only where needed
- Select from the lowest energy kiln type; e.g. dry with preheater and precalciner
- Utilize CO_2 injection technology if applicable

Steel

- Procure steel produced in an electric arc furnace (EAF), avoid steel from a basic oxygen furnace (BOF)
- Avoid the use of hollow structural shapes and metal decking, utilize rebar only if needed
- Utilize salvage or reclaimed steel
- Specify high recycled content (90%+)

Wood

- Utilize reclaimed wood where possible
- Specify wood from certified sustainably managed forests (e.g. FSC certification)
- Specify fast-growing wood species
- Specify wood products manufactured using electricity and/or renewable energy

Insulation

- Minimize or avoid foam-based insulation products such as Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyisocyanurate (Polyiso), Structurally Insulated Panels (SIPs) and spray foam
- Use blown-in insulation in wall cavities
- Protect insulation from heat and water
- Consider natural insulation alternatives, such as wool, cork, denim or hemp

Information Source: Carbon Smart Materials Palette

See **RESOURCES** for additional guidance

TOOLS

Embodied Carbon in Construction Calculator (EC3)
https://buildingtransparency.org

Open-source materials comparison tool and EPD database that enables evaluation of embodied carbon data across material classes.

Tally
https://choosetally.com

LCA application that integrates with Autodesk® Revit® to allow comparison of design alternatives and direct reporting of environmental impacts.

Athena Impact Estimator
https://calculatelca.com/software/impact-estimator

LCA tool that allows users to create unique assemblies and envelope configurations, allowing flexibility for complex designs and existing buildings.

One Click LCA
http://www.oneclicklca.com/green-building-software

Web based LCA tool with editable baselines that permits rapid comparison of design and material alternatives. Based upon European product data.

eTool
http://etoolglobal.com

Free web based LCA tool that can either use predefined assemblies or allow the user to create their own. Based upon Australian product data.

RESOURCES

Zero Carbon Certification – International Living Future Institute (ILFI)
https://living-future.org/zero-carbon-certification

Certification system that addresses operational and embodied carbon.

Carbon Leadership Forum
http://www.carbonleadershipforum.org

Industry-academic collaboration of manufacturers, designers, builders and researchers focused on reducing embodied carbon in building materials.

Carbon Smart Materials Palette
https://materialspalette.org

Attribute-based design and material specification guidance for procuring low embodied carbon products in common material types.

Source: International Living Future Institute's Embodied Carbon Quick Guide (LFI, 2021)

According to City and County of Denver (2021), two categories of actions are recommended:

(1) Using low-embodied carbon emission material types has the potential to reduce embodied carbon emissions by up to 60 percent in an example home, see [Figure 56].

(2) Consider the following best practices (in three categories) which also implements the first recommendation in various ways:

Prevent

- Reuse and repurpose existing buildings – establish an adaptative reuse policy.
- Use salvaged building materials in new construction.
- Consider adaptive reuse during initial design to ensure that buildings can be used for different purposes over their lifetime.

Reduce and optimize.

- Understand which materials contribute the most; limit their use.
- Require transparent product documentation such as environmental product declarations
- (EPDs) to help decide which low-carbon materials to use.
- Limit the use of and replace materials with the most embodied carbon.
- Involve the structural engineers from the onset. The greatest amount of embodied carbon is emitted from the building's structural system – concrete, steel, or wood. Ensure composite design using concrete and steel are prioritized.
- Denver should require concrete containing supplemental cementitious materials like fly ash or blast-furnace slag in place of Portland cement to be included in construction specifications.
- Avoid over-engineering building designs to reduce use of concrete, wood, and steel.
- If using steel, use steel sourced from North America, which typically has a lower carbon footprint than steel manufactured overseas. Pueblo, CO plans to have the world's first solar-powered steel mill. This factory will create jobs in the local economy, while lowering the carbon emissions impact.
- Require at least 50% recycled steel content in construction specifications.
- Use Forest Stewardship Council (FSC) certified wood and salvaged wood.
- Minimize aluminum curtainwalls.
- Use alternatives to foam insulations types that have high global warming potentials.
- Consider sourcing materials that meet steel and concrete low-embodied carbon guidelines: ResponsibleSteel and Concrete Sustainability Council.

Plan.

- Consider the end-of-life use – provide salvaged materials to another project or reuse building.
- Design for Deconstruction – Design building assemblies to make building materials more easily salvageable.

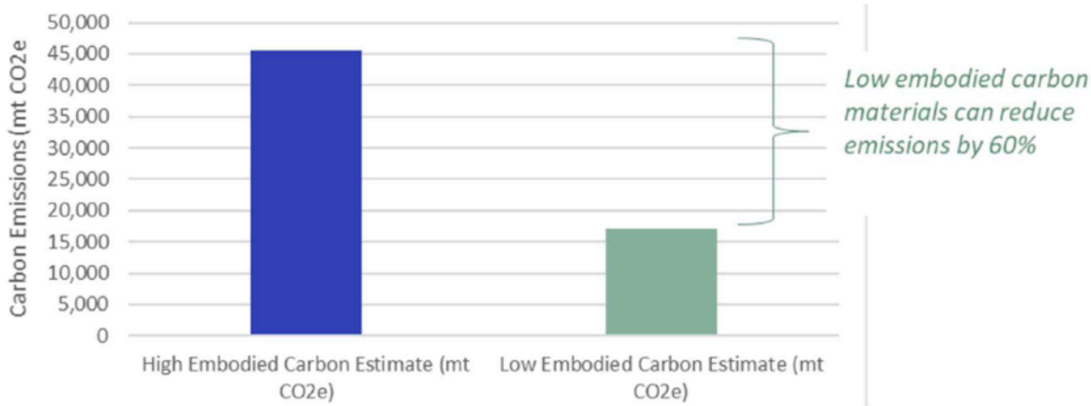
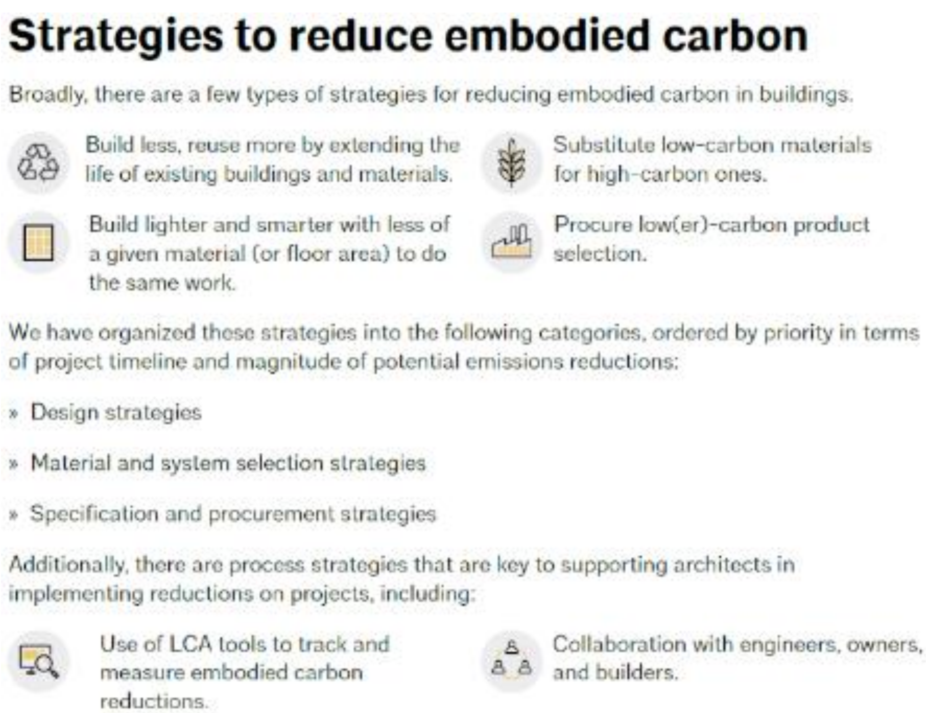


Figure 56. Embodied carbon emissions for high and low embodied CO2e materials for an example home.

The AIA/CLF (2021) architect's guide, which supports the AIA's "Architecture 2030" program, offers the recommendations shown in Figure 57 as an approach to building design focusing on embodied carbon emission reductions or avoidance:



Setting targets for reduction

Before picking which strategies to pursue, it can be helpful to set a reduction goal to align the design and construction team around.

Architects can often make large embodied carbon reductions with cost-neutral measures. A 2021 report from RMI found that case studies had embodied carbon savings of 24–46% at cost premiums of less than 1%.[1] Even greater reductions can be achieved through prioritizing design strategies early in a project to reduce embodied carbon.

Global organizations have set the following embodied carbon reductions targets to indicate which reductions need to be made on projects to reach net-zero as shown in table 1.

Organization	Target year			
	2025	2030	2040	2050
Arch 2030[2]	45%	65%	Net-zero	
LETI[3]	40%	60%	-	-
C40[4]	30%	50%	-	-
WGBC[5]	-	40%	-	Net-zero

Figure 57. Guidance for Architects to reduce building embodied carbon emissions.
Source: AIA-CLF (2021)

The AIA-CLF (2021) guide also recommends specific design strategies, material & system selection strategies, specification & procurement strategies, and design process strategies. Under the category of "material & system selection" the following strategies are recommended:

- Select carbon storage structural, envelope, insulation, & finish materials
- Select MEP systems with low-carbon refrigerants
- Choose insulation carefully
- Select Salvaged or refurbished materials
- Design for disassembly (and re-use)
- Avoid unrecyclable materials & coatings
- Select finish carefully

Under the strategy of "choose insulation carefully" the AIA/CLF (2021) guide provides the following information:

> "Selecting an insulation that balances operational and embodied carbon tradeoffs is key to achieving a total carbon balance for building. Generally, plastic/petrochemical-based insulations (rather than those nature-based materials) will have much higher embodied carbon. In particular, architects should avoid specifying HFC-containing rigid polyurethane spray foam, sealants, and XPS products that are being banned or significantly restricted in Canada and a growing number of U.S. states."

As part of the AIA's "Architecture 2030" program, a Carbon Smart Materials Palette provides building designers with the following information: [99]

> The Carbon Smart Materials Palette contains an attribute-based approach to embodied carbon reductions in the built environment. It identifies key attributes that contribute to a material's embodied carbon impact, and offers guidelines and options for emissions reductions. The Carbon Smart Materials Palette is designed to support and

[99] https://materialspalette.org/, last accessed 2/14/2023

complement Life Cycle Assessments (LCAs) and Environmental Product Declarations (EPDs), while providing highly impactful guidelines for low/no carbon material selections and specifications.

The Carbon Smart Materials Palette also provides recommendations to reduce carbon emissions impacts of "high-impact" materials that it identifies as including steel, concrete, and insulation. It also provides "carbon smart" material substitution guidance promoting the use of bio-based materials, which is summarized as follows:

BAMBO: High strength, flexible, get from sustainable growing practices

HEMPCRETE: Carbon sequestering depending on how grown and harvested (325 kg C sequestered per metric ton of hemp); has R-2.5/in (high R-value for plant-based structural material); fireproof, breathable, no VOC, good acoustics, etc.

SHEEP'S WOOL: Sequester carbon, fire resistant (Class A) and self-extinguishing and will not support flame up to 1100 ^{o}F, absorbs; 1 kg of clean wool = 1.8 kg of CO2 stored (sheep converts plant biomass capture of CO2 by photosynthesis into carbon in wool); R-4.3/in – competitive R-value.

STRAWBALE CONSTRUCTION: stores 60 times more carbon than used to grow, bale, and transport to building sites in the same region. Wheat product in US could support over two million new 2,000 sqft homes/yr. About 40% carbon by weight. Sequesters carbon, utilizes "waste" material; R-1.3/in (27in wall = R-30); cost competitive relative to other thick-wall methods; naturally fire resistant can achieve up to 2-hour fire rating if lime-plastered; best used in dry climates, but otherwise durable if kept dry.

WOOD: Similar information as above.

According to RMI (2021), there are three categories of low-embodied carbon solutions:

- **Whole-building design** (adaptive reuse, reduced square footage, more efficient structural systems, alternative building techniques, pre-fabrication, minimized construction waste)
- **One-for-one material substitutions** (direct replacement of one material with another that will meet functional requirements with a lower GWP)
  - EXAMPLE: "Choosing cellulose as an insulating material in place of a petroleum-based insulation (e.g., expanded polystyrene) can achieve the same functional need (insulation) while dramatically reducing the embodied carbon of the overall project."
  - "In some cases, insulation products can lead to near-zero or net negative (sequestering) carbon emissions."
  - When considering two materials, it's important to consider their functional performance. For insulation products, this includes their thermal properties (e.g., R-value) as well as their form factors (e.g., blown product, rigid board, batt) and other performance qualities (whether they also provide an air barrier, resist fire, repel pests, etc.).
- **Specification** (establishing a value or limit for a material characteristic that will dramatically reduce embodied carbon content)
  - E.g., specific percent reduction in GWP in a given concrete mix
  - Pros and cons – longer cure times, etc.

The RMI (2021) guide also included three wood, steel, and concrete building embodied carbon reduction case studies and came to conclusions illustrated in Figure 58:

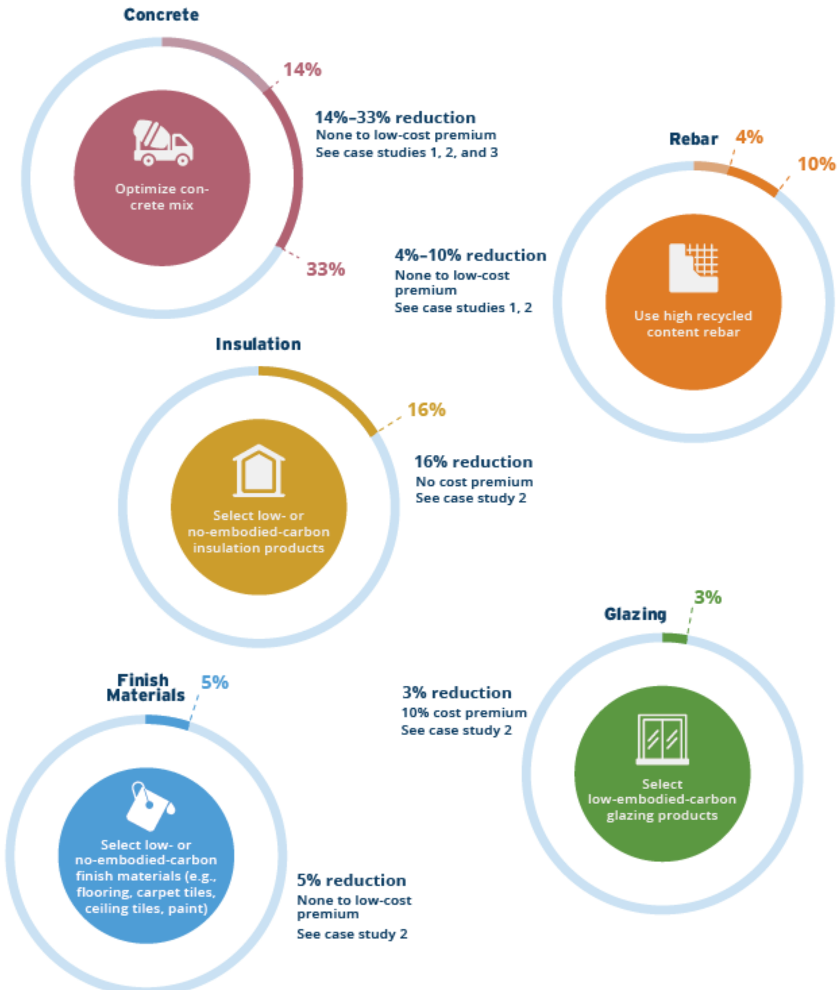


Figure 58. Case study embodied carbon emissions showing categories in which a building project's embodied carbon can be reduced at little to no cost.
Source: RMI (2021)

Finally, the "How to calculate embodied carbon" guide by the Institution of Structural Engineers (ISE, 2020) provides an straightforward and transparent methodology for accounting for the embodied carbon content of buildings and their major components. It maps the methodology and provides guidance as shown in Figure 59.

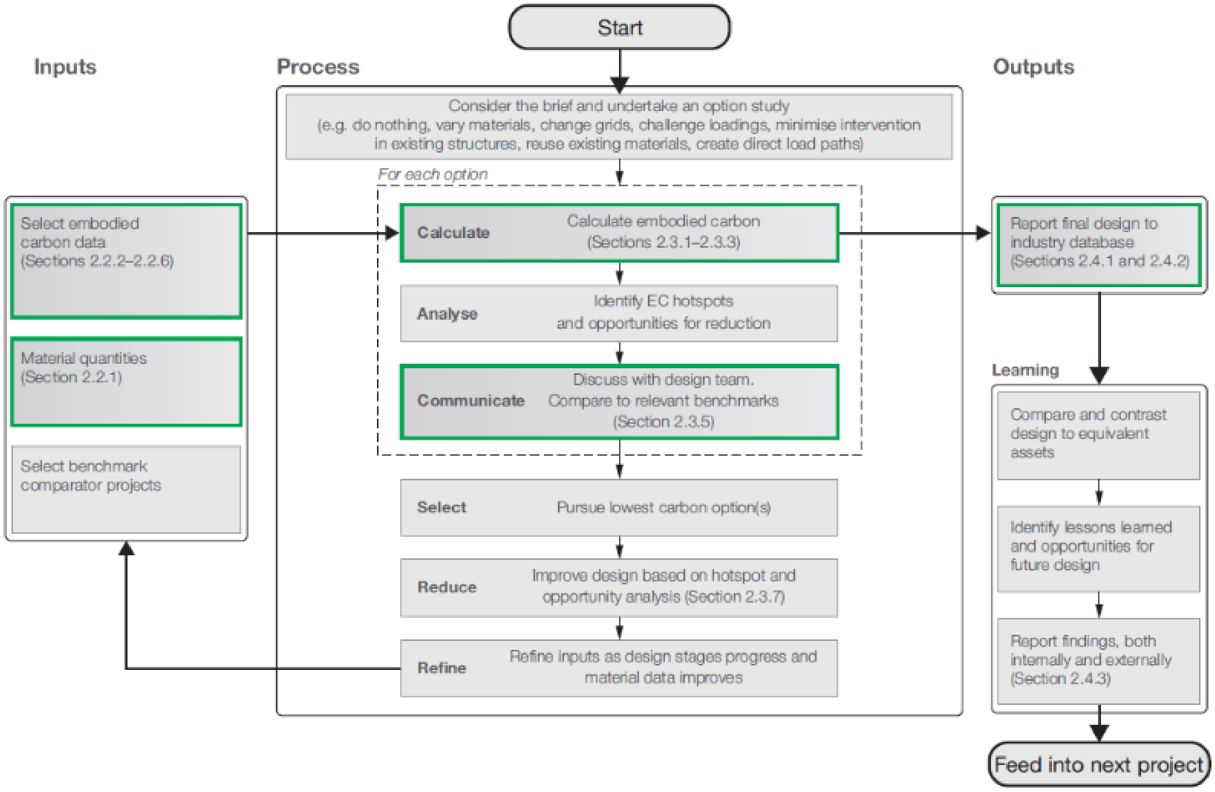


Figure 59. Overview of process for calculating embodied carbon in buildings (ISE, 2020)

4.6.5 Carbon Emissions Accounting Tools

With the heightening interest in accounting for building material embodied carbon emissions, accounting tools and various databases or inventories of materials with EPDs have been developed and updated periodically to maintain currency. These on-line or computer software or spreadsheet based tools often vary in cost, scope, and completeness. For example, some may include a whole building and whole-life-cycle scope (including accounting of embodied and operational carbon emissions) while others may just focus on cradle-to-gate (Stage A1-A3) carbon emissions. Therefore, as with EPDs and other carbon emissions data sources, such tools and their outputs and material data sources must be carefully understood to avoid misunderstanding, misuse, omissions, or errors in the consistent application of results and comparison of those results in the process of making building design and material specification decisions. It is for this reason that various standards (addressed later) are under development to establish a consistent basis and metric for evaluating building-related carbon emissions.

For a thorough analysis of various embodied carbon assessment tools and their comparative accessibility, completeness, quality assurance, standardization, and transparency, refer to Esram and Hu (2021). In their study, the authors considered the following tools (Esram and Hu, 2021):

> Table [12] compares six tools with respect to their provider, method, and database used, and the type of embodied carbon (EC) assessment that can be performed. The table also provides information on the cost and format of each tool. Each tool is discussed in detail in subsequent sections. Athena and Tally provide whole-building assessments and are mostly used by building designers and professional consultants. The other tools provide assessments at the material and/or the product level. GaBi and SimaPro are the most well-known LCA tools, with the latter being mostly used for research purpose in academia, but neither is U.S. focused. BEES is the only tool that uses the Economic I-O method and provides both LCA and LCC assessments.

TABLE 12. Tools supporting embodied carbon assessment in the U.S.

Database	Cost of use	Stand-alone versus embedded	No. of datasets	Region	Data source	Life-cycle stage
ecoinvent [a]	EUR 3,800 (USD 4,482)	Standalone, Embedded	18,000+	Global, Europe focus	Secondary [b]	A1–A3, A1–A5, A1–C4
U.S. National Renewable Energy Laboratory (NREL) LCI Database [c]	Free (companies or agencies pay to publish data)	Standalone	600+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
USDA LCA Digital Commons	Free (manufactures and agencies pay to publish data)	Standalone	300+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
NIST BEES database [d]	Free	Standalone, Embedded	Unknown	U.S. focus	Secondary	A1–A3, A1–C4
Quartz [e]	Free	Standalone	102 products	U.S. focus	Secondary (no lingered maintained)	
GaBi database	USD 3,000	Standalone, Embedded	15,000+	Global, Europe focus	Primary and Secondary	A1–A3, A1–A5, A1–C4
Athena database	Free	Standalone	200,000+ (building and construction materials specific)	U.S. and Canada focus	Secondary	A1–A5, A1–C4
Carnegie Mellon database [f]	Free	Standalone	3,500+	U.S., Canada, Germany, Spain, China	Secondary	A1–A3, A1–A5
Environmental Product Declaration (EPD) library	Free	Standalone	149 products [g]	Global	Primary	Vary
Embodied Carbon in Construction Calculator (EC3)	Free	Standalone	47,000+	Global, with a U.S. focus	Primary	A1–A3 (as of 2021)

Source: Esram and Hu, 2021

The Building Transparency website features the Embodied Carbon in Construction Calculator (EC3) tool and the Tally Life Cycle Assessment (tallyLCA) tool, both of which include EPD databases.[100] The EC3 tool focuses only on material embodied carbon emissions whereas tallyLCA is a whole building assessment tool. The Athena Sustainable Materials Institute's website features the Athena Impact Estimator for Buildings which also is a whole building life cycle assessment tool.[101] The OneClick LCA tool appears to be sponsored by a number of European interests and may use materials EPD data only applicable to Europe.[102] However, it claims to have applicability to the US such as compliance with the SE 2050 voluntary decarbonization program described earlier.

Some other carbon accounting tools including EPD databases not included in Table 12 include:

[100] http://www.buildingtransparency.org/, last accessed 2/15/2023
[101] https://calculatelca.com/, last accessed 2/15/2023
[102] https://www.oneclicklca.com/planetary/, last accessed 2/15/2023

- Builders for Climate Action - *BEAM Estimator* (assesses material's embodied carbon footprint only for stages A1-A3 and claims to be the only tool on the market that accounts for carbon storage materials)[103]
- Natural Resources Canada - *Materials Carbon Estimator* (MCE2) which is designed for Canada's home building industry and estimates both embodied and operational carbon emissions using a downloadable spreadsheet-based tool.[104]

Other resources that provide reviews and links to various tools used to measure embodied carbon of building materials include:

- AIA/CLF Embodied Carbon Toolkit for Architects (AIA-CLF, 2021) [105]
- Denver's Building Sector Embodied Carbon Emissions (City and County of Denver, 2021)[106]
- Canadian Wood Council, Carbon Calculator[107]
- Operational Carbon Embodied Carbon (OCEC) tool[108]

4.6.6 Decarbonization in US Codes and Standards

Building decarbonization concepts are increasingly making way into US model codes and standards. As mentioned, operational carbon emissions reduction have inherently been a part of energy conservation codes and standards. However, in recent editions of these codes, other features such as electrification of buildings and use of renewable energy through on-site systems or purchasing of "credits" from off-site renewable energy production or physical resources has become increasingly present. In addition, building code proposals have appeared in the latest code development hearings that attempt to establish EPD benchmarking limits for GWP of materials like steel and concrete. Future work in codes and standards is on track to become increasingly aimed at specifically addressing both material embodied and operational carbon emissions and not just energy consumption. Building code proposals for the control of material embodied GHG emissions are now in que for essentially all major building materials as discussed earlier with regard to model code change proposals by NBI (2023) with an example for insulation materials shown in Figure 54.

The following is a brief summary of the status of decarbonization-related provisions in and proposals being considered for various US codes and standards activities:

- **International Building Code (IBC)**
  - The IBC is by far the most widely used model building code in the U.S. for commercial building construction. It is adopted (and often moderately amended) by U.S. states and local jurisdictions.
  - The 2024 or prior versions of the IBC include no provisions related to decarbonization.
  - In the 2024 IBC code development cycle, a code change proposal to include **EPD-benchmarked material specification GWP limits** for steel and concrete materials based on NBI (2022) failed to gain approval by a large margin of votes. See proposal S178-22 published in the 2022 ICC Group B code hearing agenda for the IBC-Structural committee.[109]

[103] https://www.buildersforclimateaction.org/beam-estimator.html, last accessed 2/15/2023
[104] https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/material-carbon-emissions-estimator/24452, last accessed 2/15/2023
[105] https://carbonleadershipforum.org/clf-architect-toolkit/, last accessed 2/15/2023
[106] https://www.denvergov.org/files/assets/public/climate-action/documents/hpbh/nze/denvers-building-sector-embodied-carbon-emissions-june-2021.pdf?mc_cid=a6ccfdd350&mc_eid=d4b9a8d903, last accessed 2/15/2023
[107] https://cwc.ca/en/design-tools/carbon-calculator/, last accessed 3/4/2023
[108] https://passivehouseaccelerator.com/articles/now-available-beta-version-of-ocec-tool-developed-by-skylar-swinford, last accessed 11/8/2023
[109] https://www.iccsafe.org/products-and-services/i-codes/code-development-process/2021-2022-group-b/, last accessed 2/17/2023

- **Future activity in the area of embodied carbon material specification** is expected as more and more states and localities adopt Buy Clean policies or establish EPD-benchmarked material specification GWP limits for increasing numbers of building product categories.

- **International Energy Conservation Code (IECC)**
    - The IECC is the most widely used model energy code in the U.S. (with ASHRAE 90.1 included as an alternate pathway for compliance).
    - The 2024 IECC is currently under development following ICC's consensus-based standards procedures (prior editions used the ICC code development hearing process)
    - New provisions are expected that will further **promote decarbonization goals** through use of renewable energy (on-site and off-site), provide provisions for electrification readiness and electric vehicle (EV) readiness, and greatly expanded additional energy efficiency credit options including measures such as improved envelope, improved HVAC equipment efficiency, and use of load management and renewable energy measures.
    - Appendices have been included for optional adoption by jurisdictions desiring to pursue **net-zero energy performance** in commercial or residential buildings.
    - Also, advancements are expected in improved energy efficiency requirements for existing building provisions that apply to additions and certain types of alterations which trigger energy efficiency improvements (e.g., roof replacement, siding/window replacement, etc.).
    - Reliance on **federally-mandated minimum equipment efficiency** levels for gas furnaces and the requirement to use those minimum levels for energy code trade-offs remains a problem. This problem resides in the Federal rule establishing minimum HVAC equipment and appliance efficiencies as administered by DOE.[110] The rule was originally intended to solve a past market problem (inconsistent regulation across states for minimum equipment efficiencies). But, it also included a regulation mandating its use as a baseline for energy efficiency trade-offs in building design and compliance with applicable state-adopted energy codes. Consequently, this over-reaching aspect of the federal regulation has caused a conflicting problem in energy code application whereby a cross-subsidy is created. The cross-subsidy enables the energy efficiency of a building to be reduced and the resulting construction cost savings to be used to subsidize the purchase of commonly used gas furnaces that are of higher efficiency than the federal minimums. Thus, the use of a high-efficiency gas furnace in new construction may result in no net energy savings to the consumer, although it may be perceived as doing so. This cross-subsidy also works against building decarbonization and electrification goals by incentivizing the use of gas heating systems over heat pumps and creating a greater building operational energy demand resulting in increased emissions and larger-sized HVAC systems. It should be noted, however, that the Federal rule was updated with dramatically improved gas furnace minimum efficiency requirements during the writing of this report.[111] This rule update was originally due in 2016 and now will finally take effect in 2028 if not successfully challenged.
    - A **Social Cost of Carbon** value of $51/tCO2 has been included as a voluntary consideration in committee-approved procedures established for evaluating the economic justification of code change proposals intending to make incremental changes to the code. However, this value is relatively small (see prior discussions on SC-CO2) and only makes a small marginal difference in justifying energy efficiency or other code improvements that impact operational energy use and carbon emission reductions.
    - Interestingly, some **conflicted positions and odd alliances** have recently become apparent in the ICC's new consensus standard development process for the IECC. For example:
        - In updating the IECC residential provisions an alliance of electrification (decarbonization) interests and building industry interests has formed whereby trade-offs to reduce energy efficiency (e.g., weaken building envelope thermal performance) to obtain incentives for electrification (e.g., use of heat pumps instead of gas furnaces) are currently in the updated draft 2024 IECC standard. This is effectively a cross-subsidy which sacrifices efficiency for electrification.
        - Also, for the IECC commercial provisions, architects representing AIA and its Architecture 2030 program which has goals to aggressively decarbonize buildings are at the same time desiring to use purchasing of limited off-site renewable energy resources as a means to offset construction of poorly performing building envelopes with large glazing areas. This serves to increase energy

[110] U.S. Code of Federal Regulations, 10 CFR 430.32

[111] https://www.energy.gov/articles/doe-finalizes-energy-efficiency-standards-residential-furnaces-save-americans-15-billion, last accessed 11/15/2023

demand, making decarbonization of the electric grid more difficult to attain as the building population increases and its energy demand increases in the future.

- **ANSI/ASHRAE/IES 90.1-2022, Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings (I-P)**
    - ASHRAE 90.1 is similar to the IECC in scope and content.
    - Unlike the IECC, ASHRAE 90.1-2022 includes an appendix to convert annual energy use to **operational carbon emissions** when using its Appendix G simulated building performance path.
    - ASHRAE leadership has set a goal for the 90.1 standard to **achieve net-zero emissions by the 2031** edition and to include such an appendix for jurisdictional optional adoption by the end of 2023.
    - NOTE: The parallel ASHRAE 90.2 standard addresses residential low-rise construction (e.g., single family detached and attached dwelling units) and relies heavily on the RESNET 301 standard and its energy rating methodology. The 90.2 committee intends to create an informative appendix for zero energy and zero carbon in new and existing buildings in 2023. It is also considering setting criteria based on the CO2 Index of the RESNET 301 standard for general compliance. **Currently, ASHRAE 90.2 is rarely if ever used for dwelling construction compliance in the U.S.**

- **ANSI/RESNET/ICC 301-2022, Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index**[112]
    - The RESNET 301 standard primarily addresses operational energy efficiency of new homes and retrofits through its Home Energy Rating Score (HERS) methodology which relies on raters using qualified software following the ruleset in the RESNET 301 standard. The HERS is a relative rating based on comparison to a hypothetical 2006 IECC reference home.
    - It is a recognized compliance path in the IECC for residential construction with Energy Rating Index (ERI) targets established in the IECC. However, its provisions for building ventilation, operational set point temperatures (78ºF for cooling and 68ºF for heating)[113], use of a 78 AFUE gas furnace in its hypothetical reference home, and inclusion of appliances and on-site renewable energy (among other differences) is not necessarily congruent with the scope and provisions of other compliance paths in the IECC. Therefore, the ERI targets (based on HERS of RESNET 301) established in the IECC attempt to offset these inconsistencies with the prescriptive compliance path in the IECC. This concern has been a persistent matter of debate in the IECC updating process.
    - The standard incorporates means to include on-site renewable power (e.g., solar PV systems) in its HERS rating and thereby creates a cross-subsidy whereby renewable energy production can be used to trade-off building energy efficiency measures such as envelope insulation. This is similar to the problem discussed above with the IECC regarding cross-subsidies associated with the federally-mandated minimum efficiencies for HVAC equipment.
    - The standard currently includes a means of determining and reporting an **operational carbon emissions index (CO2 Index)** which is also a relative measure, like HERS, based on baseline emissions of a hypothetical 2006 IECC reference home.
    - RESNET has appointed an **Advisory Council on Embodied Carbon** to evaluate means to addressed embodied carbon emissions in the 301 standard. Its role is to investigate development of a standard to calculate the embodied carbon in homes to address questions related to scope and approach. Noted challenges include: (1) the lack of a baseline on the carbon content of building materials, (2) questions of market demand for such a rating, and (3) whether it should be addressed as a stand-alone standard or part of the RESNET Carbon Index (currently only operation carbon), or a new rating index combining both embodied and operating carbon emissions. At the time of this writing, a standards development committee (SDC 1500) has been formed and started developing a new ANSI candidate standard (RESNET/ICC 1550) to calculate the embodied carbon in residential building materials.[114]

[112] Residential Energy Services network, Inc., Oceanside, CA, https://www.resnet.us/, last accessed 2/17/2023

[113] Note that the 2021 IECC Section R302 requires a maximum of 72ºF for heating and minimum of 75ºF for cooling in determining load calculations for HVAC equipment sizing whereas RESNET 301 Section 4.4.3.2 specifies 75ºF (cooling) and 70ºF (heating) for HVAC equipment sizing purposes. Thus, the RESNET operational and equipment sizing set-point assumptions could result in significant under-estimation of actual energy use. While set-point temperatures in actual buildings is primarily driven by occupant behavior, the selection of a set-point for energy code compliance and HVAC equipment sizing has significant energy use and cost implications.

[114] https://www.resnet.us/about/standards/committees/standards-development-committee-1500/, last accessed 12/24/2023

  - Since its inception over 3.6 million homes have been rated for energy efficiency using the Home Energy Rating Score (HERS) of the RESNET 301 standard. In 2022, there were 337,962 homes rated for energy efficiency and energy code compliance using the RESNET 301 standard which is one of the alternative compliance paths in the IECC residential energy code provisions.[115]
  - The average HERS index score in 2022 was 58 which represents a home that is 42% more efficient than a home built to 2006 standards. In 2022, there were eight states where average HERS scores for new homes were 50 or less (lowest average of 18 for California). The required energy rating index (ERI) based on the 2021 IECC ranges from 52 to 55 based on climate zone.[116]

- **2021 IgCC / ASHRAE Standard 189.1-2020, International Green Construction Code (IgCC)[117]**
  - According to ASHRAE, more than 20 local jurisdictions (cities and counties) across 13 states have adopted Standard 189.1 in part or in whole. While significant, the market impact of this standard is marginal.
  - In the 2018 edition, Standard 189.1 was wholly incorporated into the International Green Construction Code (IgCC) which is marketed by ICC as part of its "family of codes".
  - The IgCC and ASHRAE 189.1 cover various sustainable building topics including site, water, energy, indoor environment, materials, and resources.
  - The primary decarbonization provisions, other than enhanced energy efficiency that reduces operational energy use (and carbon emissions) by about 10% relative to the ASHRAE 90.1 standard, are limited to basic provisions on recycled material content, bio-based material content, material re-use, construction waste management, and local sourcing. It also includes a **provision requiring EPD transparency**, meaning that 10 products used on the project must have EPD documentation of environmental impacts without any limitations on those impacts. This is an example of the type of provision that sets the stage to then use EPDs to later control or limit material embodied emissions as discussed earlier with regard to BPS and Buy Clean policies.
  - According to ICC's Decarbonization of the Built Environment position document reviewed earlier:
    - "Chapter 9 of the IgCC already contains some provisions to support verification of environmental performance. These are primarily based on EPDs. EPDs have been identified as a **primary tool for transparency** communication of the environmental impacts of products/materials. However, EPDs have not been generated for all materials and products used in construction. The ICC Evaluation Service (ICCES) is an accredited EPD Program Operator, providing the tools necessary for development of product category rules (PCRs) and verification of EPDs and stands ready to assist manufacturers in expanding the availability of EPDs. This allows AHJs to have a trusted partner in the marketplace when needing these EPDs to show compliance. Congress recently passed the Inflation Reduction Act which includes $350 million to support the development and standardization of EPDs and over $4 billion to support their use by the GSA and Department of Transportation."
  - Current proposed or approved addenda to the IgCC/ASHRAE 189.1-2020 standard are now beginning to move beyond just transparency to place **material specification limits on GWP**, expand transparency requirements, and invoke other decarbonization measures such as electrification readiness. For example:
    - Addendum 'ak' adds **product procurement provisions** that require the cradle-to-gate (Stage A1-A3) GWP of less than 125% of the industry average for a given "building product" based on EPD data and rules for determining an industry average. This approach is similar to Buy Clean and "material specification codes" used to limit material embodied carbon emissions as addressed earlier in this report.
    - Addendum 'z' will **require EPDs** for building products representing not less than 25% of the total estimated costs, or a minimum of 30 EPDs;
    - Addendum 'ac' proposes to add **electrification readiness** requirements for buildings intending to use fuel-fired equipment or appliances.

[115] https://www.resnet.us/wp-content/uploads/2022-HERS-Activity-by-State.pdf , last accessed 2/11/2023
[116] https://www.resnet.us/wp-content/uploads/2022-HERS-Activity-by-State.pdf , last accessed 2/11/2023
[117] https://codes.iccsafe.org/content/IGCC2021P1 , last accessed 2/17/2023

- **ANSI/ASHRAE/IES Standard 100-2018, Energy Efficiency in Existing Buildings**
  - Standard 100 provides energy use intensity (EUI) targets and other rules for the reduction of energy use for existing buildings. The EUI targets are set based on a specified fractile of the estimated energy performance distribution of the U.S. building stock within different building occupancy categories or types and by climate zone. Therefore, it provides one means of implementing **building performance standards** as a policy instrument used for existing buildings discussed earlier in this report. Its performance targets are intended to be made progressively more stringent over time.
  - It is currently **adopted by the State of Washington's Department of Commerce** for application to "covered" non-residential commercial buildings of greater than 50,000 square feet.
  - While it is currently focused on reduction of energy use intensity of existing buildings, a new proposed Addendum 'i' seeks to expand the scope and purpose of the standard to address **operational GHG emissions**.
  - Additionally, Addendum 'e' proposes to include a new informative appendix to provide guidance for **locally derived building performance targets** as an alternative to the nationally-derived targets serving as a default in the body of the standard.
- **ANSI/ASHRAE 105-2021, Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions**
  - The 105 standard does not set any criteria for energy performance or GHG emissions.
  - The scope of the standard is for new and existing buildings and its purpose is to facilitate (a) comparison of design and operation strategies, (b) development of building energy performance standards (presumably like ASHRAE 100), and (c) the reporting of operational GHG emissions.
  - For comparison of alternative building designs, it makes use of the terms "avoided energy use" and "avoided GHG emissions" and a means for such comparisons.
  - When considering energy or operational GHG emissions, the 105 standard is based on the DOE "full-fuel-cycle" boundary for its definition of "primary energy" which includes not just the energy content and emissions of combusting the primary energy source itself but also the additional energy for extraction, processing, and transportation of primary fuels to point of use.
  - The standard also includes GWP (CO2e) values for various GHG emissions based on a 20-year and 100-year climate impact time horizon from the point in time of a given GHG emission into the earth's atmosphere.
- **ASHRAE/ICC 240P, Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction, and Operation**
  - According to this newly-formed standard's project committee, this standard is being developed to provide a methodology to quantify and document GHG emissions associated with new and existing buildings over their life cycle, including embodied GHG emissions of building materials and systems.
  - According to ICC and ASHRAE, the intent is to provide a standard of practice for consistent and accurate communication of whole building life cycle analyses (WB-LCA). It is not intended to set benchmarks or establish levels of performance for the life-cycle carbon emissions intensity of buildings. However, it could be used for that purpose once established and also referenced as a means to demonstrate compliance.
  - At the time of this writing, Draft 1 of the standard was open for public review.
- **ASHRAE Standard 228P, Standard Method of Evaluating Zero Net Energy and Zero Net Carbon Building Performance**
  - The 228P standard is intended to be used to determine whether a building or project site has achieved "Zero Net Energy" or "Zero Net Carbon" on an operational basis, meaning that the source energy or carbon flows coming into a site are less than or equal to those flowing outward during building/site operation including any allowed offsets (e.g., purchased renewable energy or carbon offsets).
  - The standard was completed and published in 2023 during the time of this writing.
- **ASTM E2921 – 16a**, **Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems**
  - The purpose of this standard is to support whole building life cycle assessment (WB-LCA) in building codes, standards, and building rating systems by ensuring that comparative assessments of final whole building designs relative to reference building designs are consistent and comprehensive.

- For detailed procedures governing LCA and EPDs, the standard relies on and references various international standards (e.g., ISO). It also presumes the use of appropriate LCA analysis software.
- It does not specify target criteria or limits for the environmental impacts and aspects of sustainability addressed in the standard.
- It deals specifically with material selection for initial construction, including associated maintenance and replacement cycles over an assumed service life, taking operational energy use into account if required or explicitly allowed under applicable code, standard, or rating system.

For a comprehensive listing of existing codes and standards related to decarbonization of buildings, including state and local and international codes, refer to the "ASHRAE Task Force for Building Decarbonization Interim Product: Standards and Codes Table". [118]

4.7 Building Materials – Embodied Carbon Emissions

4.7.1 General

Accounting for embodied carbon emissions of materials is a relatively new concept. However, it is closely related to the older and well-known process of accounting for embodied energy of materials. In fact, one of the most thorough studies of embodied energy of building materials and assemblies was conducted in the 1970s (Hannon et al., 1976; ACHP, 1979); see excerpts included in Appendices A and B.

Similarly and closely related to embodied energy (where such energy is derived from fossil carbon fuels), the embodied GHG emissions of a material include all the emissions that occur in association with that material's origins, processing, use, and final disposition at end of life. However, as mentioned, only certain scopes or stages of emissions are reported for various reasons. For the remainder of this report the embodied emissions data reported are based on Stage A1-A3 (cradle-to-gate) as consistent with Type III EPD reporting, unless otherwise indicated.

According to Esram and Hu (2021) of the American Council for an Energy Efficient Economy (ACEEE):

> As aggressive building energy codes push new construction toward net-zero-energy and net-zero-carbon operations, corresponding efforts to reduce embodied energy and carbon from building construction materials must be pursued to achieve building sector decarbonization goals. As buildings become more and more efficient, embodied carbon will be a greater and greater share of their overall carbon footprint. For example, Chastas et al.'s review (2016) of 90 case studies found that embodied carbon accounted for 26–57% and 74–100% of the total life-cycle carbon emissions of low-energy and near-zero-energy buildings, respectively (Chastas, Theodosiou, and Bikas 2016). Embodied carbon is not "negatable" anymore, hence the need for knowledge and standards for embodied carbon becomes more and more urgent.

The above quote raises the importance of considering embodied GHG emissions together with operational GHG emission savings. This concern is addressed later in this report under the topics of EPD applications for insulation materials used as a part of whole buildings and assemblies. Also addressed later are data regarding the significance of building material embodied GHG emissions relative to global GHG emissions which provides a fundamental basis for understanding the role of material embodied GHG emissions in addressing climate change. For example, earlier in this report it was shown that all annual GHG emissions for the production of all US building materials accounts for about 0.4% of total annual global GHG emissions. Also earlier in this report, it was demonstrated that relative (percentage) amounts of embodied carbon compared to the amount of operational carbon emissions is not what determines whether or not embodied carbon should be considered "negatable".

[118] https://www.ashrae.org/file%20library/about/existing-standards-and-codes__.pdf, last accessed 2/18/2023

Consequently, relative rankings of percentages of embodied carbon attributed to the various materials in a given building are not necessarily helpful in identifying appropriate actions or levels of actions to take with regard to their significance to global climate change which is the fundamental purpose of decarbonization. For example, according to NBI (2022), concrete and steel materials in commercial buildings represent about 50% of embodied carbon emissions in buildings as shown in Figure 60. Whereas Magwood, et al. (2021) and City of Nelson (2022) indicate in Figure 61 for wood frame homes that the major contributors are concrete, insulation materials, cladding, and interior finishes. But, neither of these address the actual magnitude of the embodied carbon emissions in relationship to their significance to the global climate to help inform appropriately focused or moderated policy actions and design decisions. For example, as determined earlier in this report, the GHG emission contribution of the entire US concrete industry is about 0.17% of total global GHG emissions; for concrete used in US buildings the contribution is about 0.09% of total global GHG emissions. And, as will be shown later, the annual production of all US insulation materials is equivalent to about 0.01% of total annual global GHG emissions.

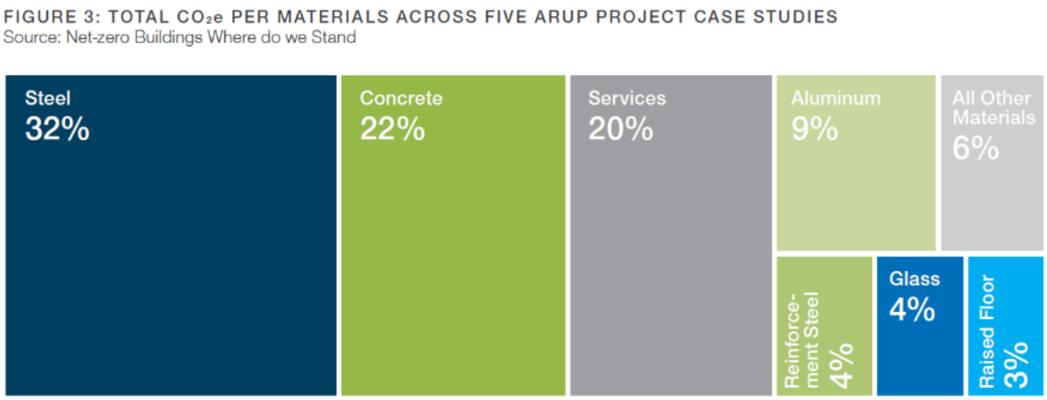


Figure 60. Total CO2e by material type for five building project case studies by ARUP

Source: NBI (2022) based on "Net-Zero Buildings Where do we Stand"

NOTE: Presumably, insulation is in the 6% "all other materials" category.

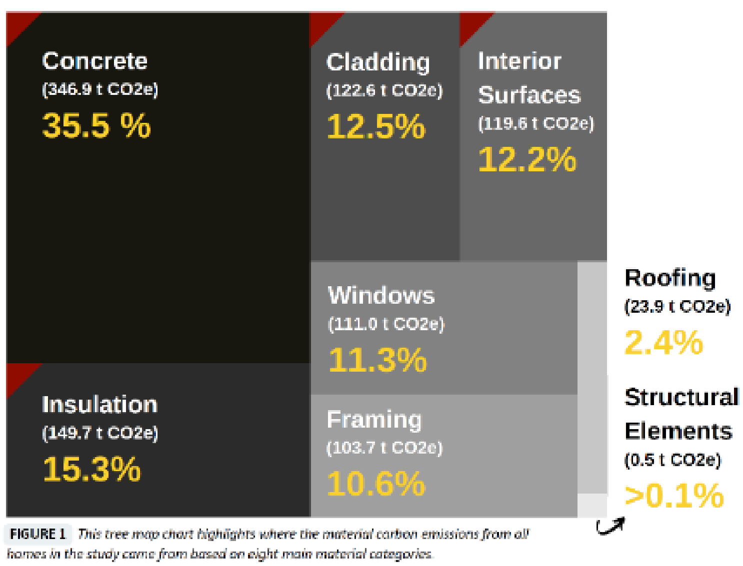


Figure 61. Importance of building material carbon emissions based on percentage

Source: City of Nelson, 2022

NOTE: Wood and other bio-based materials were considered as carbon sinks and, consequently, are effectively not included in the relative percentage tally for this graphic based on Magwood et al. (2021).

Such relative comparisons on the basis of embodied carbon percentages also do not account for the role of certain materials, like building envelope insulations, which have significant potential benefits in enabling economy-wide decarbonization by reducing operational emissions and minimizing demand on an electric grid transitioning to variable renewable sources of power. These important considerations were addressed earlier in this report. Regardless, there are practical considerations that can be informed by such relative comparisons such as where to focus on resource efficient use of materials in building design or, perhaps, carefully considering material specifications or substitutions where any resulting functional trade-offs are properly identified, understood, and addressed (although not at the expense of optimization in the use of multi-functional materials like many insulation products). For example, ensuring that steel is sourced from US steel mills using low-carbon process technologies is a simple way to minimize embodied carbon impacts to the climate in a meaningful and practical way without creating functional trade-offs. Using a more efficient building form and structural system is similarly very practical and impactful. Similarly, use of multi-functional insulation materials can optimize an assembly reducing embodied carbon of the overall assembly while also improving operational emission savings as also addressed earlier in this report (see Section 4.4.1).

As with any scientific problem, the metric for evaluating or solving the problem should be closely connected to the nature of the problem itself, which is global warming and global total GHG emissions, not relative contributions of CO2e emissions of materials compared to each other. The above discussion and consideration of the significance of material embodied emissions in relationship to total global GHG emissions is similar to the approach taken by the EPA in evaluating “key categories” of US emissions as presented in Section 3.2.

Another important concern related to the use of material embodied carbon emissions and EPD data has to do with how the data is handled in making material comparisons and specification decisions. In practice the guidance and limits for making truly equivalent comparisons of EPD data for GWP between different materials (or even materials within the same category such as insulations) may not be consistently followed, particularly because it requires careful scrutiny of EPD data or other data sources which may not all follow the same scope or building life-cycle stages and may include additional factors such as carbon-sequestration and storage for which methods of accounting are not settled in regard to proper comparison in regard to global climate change impacts. Also, guidance is substantially lacking on a critical aspect of making material comparisons even within a given material type. For example, many insulation materials are not functionally equivalent with regard to various design considerations for buildings even though their GWP is reported in terms of functional units established by the insulation material PCR. Many have multi-functional capabilities that render direct comparisons of EPD-reported GWP with other insulation materials to be functionally non-equivalent. Such materials must consider how the material in its end use affects other building assembly design features and impacts, including both operational carbon emissions and embodied carbon emissions based on interaction with other building component impacts influenced by insulation material type and application strategy.

The AIA/CLF guide (AIA-CLF, 2021) does make mention of the need to make material carbon emission comparisons on the basis of functional equivalency or otherwise conduct a WB-LCA to guide decisions as shown in Figure 62. This is extremely important, but not usually straightforward for insulation products for reasons mentioned above.

Checklist: Can I use an EPD to compare these products?

(You must check all of the following boxes for the EPDs of both products in order to fairly compare them.)

- ☐ Functionally equivalent (e.g., strength, stiffness, insulative properties, etc.)
- ☐ Created using the same PCR
- ☐ Include the same life cycle stages
- ☐ Use of one product versus another does not change other aspects of the design or assembly

If you can't check all of these boxes but would like to compare two products, then it is important to use WBLCA or other tools rather than use EPDs.

Figure 62. Checklist for use of an EPD to compare building products
Source: AIA-CLF, 2021

The AIA/CLF guide summarizes its guidance on when a WB-LCA or an EPD-based approach to material specification should be used as shown in Figure 63 below.

Goal	Use a WBLCA	Use an EPD
Measure the embodied carbon savings from building reuse	●	
Identify hot spots at the beginning of a project	●	
Estimate the carbon footprint (GWP impact) of a whole building	●	
Compare the carbon footprints of two building designs	●	
Compare the carbon footprint impact of two systems/assemblies (e.g., steel vs. mass timber; facade options, etc.)	●	
Compare the carbon footprint per unit of two functionally equivalent products from the same (or different) manufacturers (see the checklist above)		●
Compare the carbon footprint of a specific product to third-party targets (see section "Benchmarking Materials") during product selection and procurement		●

Figure 63. When to use WB-LCA vs. an EPD for building product comparisons
Source: AIA-CLF, 2021

In general, there is little discussion to address how materials of even the same type, category, or purpose (e.g., insulation) may not actually be functionally equivalent and may provide different functional attributes than just insulation thermal capability (e.g., R-value). This is particularly problematic because many building designers also may have limited knowledge of different functional performance characteristics and design capabilities of insulation materials other than R-value per inch and material cost. There appears to be a gross oversimplification of the functional performance capabilities and variation between insulation products that teaches away from product selection merely on the basis of functional units of GWP. Education is needed on this matter at the level of policy development as well as building practice.

Finally, EPD databases and embodied carbon analysis tools do not necessarily treat bio-based or wood material GWP in a consistent manner (see earlier discussions on this matter). Some consider bio-based or wood materials to be carbon sinks and assign them negative GWP values while others do not. This too creates disparities in the marketplace and in design decision-making, particularly if materials used in a building are being compared based on their relative percentage contribution of embodied carbon to a building (see Figures 60 and 61). It also can create oddly conflicted design incentives. For example, where a material like wood framing, sheathing, or other bio-based material is categorized as a net carbon sink (i.e., negative GWP value) then its use in a resource inefficient manner would be incentivized because its excessive use may theoretically offset the embodied carbon content of other materials in the same building.

4.7.2 Building Product Embodied Carbon EPD Databases

According to Esram and Hu (2021):

> In this study, we focus on databases that are relevant to the United States and Canada. Table [13] lists nine commonly used and known databases that include regional data samples from the United States and Canada, and consequently their regional characteristics. Using the five criteria that we defined in the Background section of this paper, we evaluated the *accessibility, completeness, quality assurance, standardization,* and *transparency* of each database
>
> Overall, comprehensive embodied carbon data to evaluate all life-cycle stages of buildings in the United States exist and are available to users. Four out of the nine reviewed databases use primary data sources; seven are free for users or tool developers. Some databases, such as ecoinvent, are very comprehensive, containing data on hundreds if not thousands of unique processes. Each process comprises hundreds of input or output flows (see figure 8 for an example of input/output flow(s)). Others, such as the NIST database, have only aggregate-level data, rather than processes and flows for materials and products, partially due to proprietary data concerns. Therefore, the user can only get information for generic products from the NIST database, such as generic brick, generic stucco, and so on.

TABLE 13. Tabulation of Material EPD databases.
Source: Esram and Hu, 2021

Database	Cost of use	Stand-alone versus embedded	No. of datasets	Region	Data source	Life-cycle stage
ecoinvent [a]	EUR 3,800 (USD 4,482)	Standalone, Embedded	18,000+	Global, Europe focus	Secondary [b]	A1–A3, A1–A5, A1–C4
U.S. National Renewable Energy Laboratory (NREL) LCI Database [c]	Free (companies or agencies pay to publish data)	Standalone	600+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
USDA LCA Digital Commons	Free (manufactures and agencies pay to publish data)	Standalone	300+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
NIST BEES database [d]	Free	Standalone, Embedded	Unknown	U.S. focus	Secondary	A1–A3, A1–C4
Quartz [e]	Free	Standalone	102 products	U.S. focus	Secondary (no lingered maintained)	
GaBi database	USD 3,000	Standalone, Embedded	15,000+	Global, Europe focus	Primary and Secondary	A1–A3, A1–A5, A1–C4
Athena database	Free	Standalone	200,000+ (building and construction materials specific)	U.S. and Canada focus	Secondary	A1–A5, A1–C4
Carnegie Mellon database [f]	Free	Standalone	3,500+	U.S., Canada, Germany, Spain, China	Secondary	A1–A3, A1–A5
Environmental Product Declaration (EPD) library	Free	Standalone	149 products [g]	Global	Primary	Vary
Embodied Carbon in Construction Calculator (EC3)	Free	Standalone	47,000+	Global, with a U.S. focus	Primary	A1–A3 (as of 2021)

Sources: [a] Wernet et al. 2016. [b] ecoinvent 2021. [c] NREL 2021. [d] Curran et al. 2002. [e] Quartz 2015. [f] Greenhouse Gas Protocol 2021b. [g] Greenhouse Gas Protocol 2021c.

4.7.3 Building Product Embodied Emissions Benchmarking

Table 14 provides embodied GHG emissions benchmarking data for various building products based on GWP values as reported in surveyed EPDs compiled in the Carbon Leadership Forum's Material Baseline Report (Carlisle, et al., 2021). For an up-to-date listing of GWP of building materials based on North American industry-wide EPDS, refer to the appendix in NBI (2023).

It is noteworthy that materials are not necessarily separated into functionally equivalent categories in Table 14. For example, the first row in Table 14 – Board Insulation – appears to group together all types including wood fiber board, various types of plastic board insulation (EPS, XPS, Polyiso, Phenolic, etc.), mineral fiber board, fiberglass board. Practically none of these materials are functionally equivalent and therefore the benchmarking violates a fundamental EPD comparison rule in this regard. As mentioned earlier, many insulation products have multi-functional capabilities that can affect design decisions and carbon savings in other components of building assemblies. Also, the typical median value appears high even for board insulations like XPS, particularly considering the newer low-GHG emission products (which will be addressed in a later section). However, setting these critical issues aside, Table 14 does provide a useful general and broad characterization of the GWP of various types of building products.

Included in Table 14 is a median, 20th percentile, and 80th percentile estimate of GWP for each category of building product. The 20th percentile represents a value at which 20 percent of the available or surveyed products would fall below the value (or 80% at or above that value). The 80th percentile is a value at which only 20% would have a higher value and this is commonly used as an “exclusion limit” for the material specification and Buy Clean policies discussed earlier in this report. Although such policies are often characterized as “incentives” they are actually using market regulation to indirectly address a root problem that could be far more efficiently resolved if more directly addressed – such as making available alternative renewable or low-carbon combustion fuel sources for energy-intensive processes in the industrial sector as also addressed earlier in this report.

As shown in Table 14, the declared (or functional) units vary by product type according to the product category rules (PCRs) established for each. From an accounting standpoint, it would be far easier and less prone to error if all products’ declared units were based on mass (kg). Thus, for any product its functional characteristic (such as R-value), physical characteristic (such as density), or other characteristics can be easily derived and associated with a given volume and density of material used to achieve a given level of performance in end use. If other units are considered useful, they should be provided as a supplement (not as a substitute for mass based units) in recognition that even functional units do not necessarily capture the actual end use functional characteristics (e.g., effective R-value of insulation based on its use and location in a given type of construction). Thus, uniformed use of functional units can actually promote inconsistent functional comparisons of materials.

TABLE 14. Benchmarked GWP of Building Products
Based on Carbon Leadership Forum's 2021 Material Baseline Report (Carlisle, et al., 2021)

Product	GWP (kg CO2e per Declared Unit)			Declared Unit
	Achievable (Low) 20th percentile	Typical (Median)	Baseline (High) 80th percentile	
INSULATION				
Board (all types incl. foam and fiber products)	2	10	20	‘m^2/R_{si}
Blanket (all types incl. cellulose, light-MF, & FG)	0.5	3	4	‘m^2/R_{si}
Foamed-in-Place (SPF)	2.33	9	20	‘m^2/R_{si}
Blown (all types – cellulose, mineral fiber, & fiberglass)	1	2	3	‘m^2/R_{si}
CLADDING				
Insulated Metal Panel (IMP)	62	107	145	‘m^2
Metal Panel	12	15.3	26	‘m^2
FINISHES				
5/8” Gyp Board	2.5	2.98	4.5	‘m^2
Acoustical Clg Tile	6	11	14	‘m^2
Resilient Flrg	6	11.5	20	‘m^2
Carpet	6	11	20	‘m^2
GLASS				
Flat Glass	1.2	1.4	2.3	kg
STRUCTURE				
Concrete	Typical range = 300-400 kgCO2e/m^3 = 230-310 kgCO2/yd^3 = 0.13-0.17 kgCO2e/kg			
Concrete/shotcrete • 0-2500 psi • 2501-3000 psi • 3001-4000 psi • 4001-5000 psi • 5000-6000 psi	 190 210 260 320 330	 266 291 343 406 429	 340 380 470 580 610	 ‘m^3 ‘m^3 ‘m^3 ‘m^3 ‘m^3
Masonry (solid or hollow and density not indicated)	-	370	545	‘m^3
Steel Rebar and WWF	0.8	0.98	1.7	‘kg
Steel, plate	1.0	1.47	3.0	‘kg
Steel, hollow structural	1.5	2.39	3.0	‘kg
Steel, hot-rolled structural	0.8	1.16	1.7	‘kg
Steel decking	1.5	2.37	3.1	‘kg
Cold-formed steel framing	1.5	1.28	3.0	‘kg
Open-web steel joists	0.7	1.38	2.5	‘kg

Product	GWP (kg CO2e per Declared Unit)			Declared Unit
	Achievable (Low) 20th percentile	Typical (Median)	Baseline (High) 80th percentile	
Aluminum Extrusions	-	8.91	12.4	‘kg
Thermally-improved aluminum extrusions		9.78	13.6	‘kg
Dimension Lumber	50	63	100	‘m^3
Plywood & OSB	200	230	400	‘m^3
Glass Mat Gyp Shtg (1/2”)	-	4.71	6.3	‘m^3
Glass Mat Gyp Shtg (5/8”)	-	5.42	7.2	‘m^3
Engr Wood I-joists	1.0	1.97	6.0	‘m^3
Engr Wood (LSL/LVL/PSL)	230	361	400	‘m^3
Mass Timber (GLT/CLT/NLT)	104	137	200	‘m^3
TABLE NOTE: GWP values for bio-based materials, like wood, do not account for long-term carbon storage (e.g., delayed bio-genic carbon emissions).				

As a comparative to Table 14 and using material data from outside the boarders of North America, the following ranges of carbon emission intensities for common construction products are reported by ISE (2020) for the United Kingdom:

- Concrete elements – 0.07 to 0.18 kg CO2e / kg material
- Structural Steel & Rebar – 0.8 to 2.7 kg CO2e / kg material (depends on product type, typical ~2.0)
- CMU - ~0.1 kg CO2e/kg
- Clay Brick - ~0.2 kg CO2e/kg
- Stone – 0.06 – 0.7 kg CO2e/kg (granite highest 0.7 & limestone sandstone < 0.1)
- Wood – 0.3 (softwood), 0.6 (plywood), glulam and CLT ~0.5 kg CO2e/kg
- Aluminum – 7 to 13 kg CO2e/kg
- Glass – 1.4 to 1.7 kg CO2e/kg
- Plasterboard - ~0.4 kg CO2e/kg (60% recycled content)
- Intumescent Paint (for steelwork) – 2.3 kg CO2e/kg

In most benchmarking exercises, it appears that fastener and connector product GWP data is not included, perhaps because of limited EPD data. However, fasteners and connectors are a key part of most construction, including structural framing systems and building enclosure systems. Investigating the available EPD data for fastening and connectors is beyond the scope of this report.

4.7.4 Product-Specific and Industry-Wide EPD Data for GWP

Concrete

As determined in a prior section and revisited later below, the U.S. concrete industry’s contribution to total global GHG emissions is about 0.17% (including all the material constituents of concrete). Cement is responsible for most of concrete’s carbon footprint; a ton of cement represents about a ton of GHG emissions

(BuildingGreen Inc., 2018). Typical constituents of concrete by volume and mass, excluding steel reinforcement which can vary substantially by application, are shown in Table 15.

TABLE 15. Composition of a typical concrete mix design.

Component	% by Volume	Mass (kg/m^3)	% by mass
Air	1.5%	0	0%
Cement	7.5%	268	11.5%
Fly ash	2.5%	67	2.9%
Water	18.5%	151	6.5%
Fine aggregate	25%	742	31.9%
Course Aggregate	45%	1,098	47.2%
TOTAL	100%	2,326	100%

The manufacturing of cement yields approximately 0.9 pounds of carbon emission equivalents CO2e for each pound of cement produced (Maryland report to Governor on Climate Futures Act). About 60% of the emissions associated with cement are attributed to the release of CO2 from limestone during the heating process to produce "clinker" from which cement is derived. This is a process emission not associated with the combustion of fossil fuels. The remaining 40% is attributed to process heating by way of fossil fuel combustion (primarily natural gas in the US). Addressing the non-energy process emissions can be mitigated through carbon capture, utilization, and storage (CCUS) strategies mentioned earlier in this report.

According to NBI (2022), the US Cement industry's GHG emissions are 68.3 MMT CO2e/yr (0.0683 Gt CO2e/yr). And, according to one assessment:[119]

> The use of cement in concrete is responsible for about 8% of global greenhouse gas emissions caused by humans. That's equivalent to 40% of the United States' emissions, and twice Japan's emissions," said Odukomaiya, a research in NREL's Building Energy Science group. "Concrete is the second-most consumed material globally after water. And most of its emissions – between 80% and 85% -- come from the cement that is used in concrete."

By other estimates, the worldwide production of Portland cement (as the major GHG constituent of concrete) is responsible for 5% to 7% of total global CO2e emissions (which is about one-half to two-thirds of the 11% of total global CO2e emissions attributed to global building and construction materials). See also Figures 16, 26 and 32 in Part 3 of this report for US cement industry emissions associated with US building and construction applications.

According to the Portland Cement Association (PCA) and separately confirmed based on data from sources reviewed earlier in Section 3.3 of this report (e.g., DOE, 2022 and EPA, 2022), the annual contribution of the entire US concrete industry to total annual global and US emissions are as follows:[120]

- US concrete contribution to total global GHG emissions = **0.17% CO2e**
- US concrete contribution to total US GHG emissions = **1.7% CO2e**
- US cement industry contribution to total global GHG emissions = **0.13% CO2e**

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[119] NREL Set To Receive $5.4 Million in Funding to Research Turning Buildings Into Carbon Storage Structures, July 15, 2022, Susannah Shoemaker, https://www.nrel.gov/news/program/2022/nrel-set-to-receive-54-million-in-funding-to-research-turning-buildings-into-carbon-storage-structures.html, last accessed 8/2/2022

[120] https://www.cement.org/sustainability/roadmap-to-carbon-neutrality , last accessed 2/18/2023

Also according to NBI (2022), 51% of US demand for cement is for building construction. Thus, considering only US building applications (excluding infrastructure and other applications), the annual US concrete material contributions to total annual global and US emissions are estimated as follows:

- US concrete for buildings contribution to total global GHG emissions = **0.09% CO2e**
- US concrete for buildings contribution to total US GHG emissions = **0.64% CO2e**
- US cement for buildings industry contribution to total global GHG emissions = **0.065% CO2e**

The PCA also states that concrete can absorb 10% of its CO2 emissions attributed to manufacturing cement during its service life assumed to be 80 years. This "sink" effect is not included in the above assessment.

According to NBI (2022) and based on a survey of several thousands of concrete producer EPDs and industry-wide EPDs, the 75th percentile for carbon emission intensity is shown in Figure 64 as a proposed material specification or performance limit for building codes. Also included are data from other sources: NRMCA's industry average EPD[121]; the Marin County California "concrete code"; and the CLF's 2021 baseline report earlier addressed.

	CO_2e Limits in Mixture (75% percentile)*			Marin County	NRMCA[12]	2021 CLF Baselines[15]		
Specified 28-day compressive strength f'c, psi	Maximum kg/m³ (SI)	High-early strength** Maximum kg/m³ (SI)	Lightweight concrete Maximum kg/m³ (SI)	Maximum kg/m³ (SI)	NRMCA Average 50%	Achieable (low) kg/m3 (SI)	Typical (Median) kg/m3 (SI)	Baseline (high)
≤ 2499	302	393	578	260	266	190	266	340
2500-3499	382	497	578	289	291	210	291	380
3500-4499	432	562	626	313	342	260	343	470
4500-5499	481	625	675	339	405	320	406	580
5500-6499	505	657	N/A	338	429	330	429	610
≥ 6500	518	655	N/A	394	498	380	498	710

* Values in this table represent limits for concrete produced in the United States and are based on the 75th percentile of EPDs collected by Building Transparency as of April, 2021. They may or may not pertain to concrete production in other countries, and therefore CO_2e, is always based on the unique availability in any location at any particular time of aggregate, cement, supplements, admixtures and other factors.

** Early high early strength concrete was provided a 130% GWP increase. This allowance derives directly from extensive stakeholder talks with ready mix producers, general contractors, engineers, the cement industry, and public procurement agencies that led to the Marin Code.

Figure 64. Concrete Mixture CO2e Limits and Baseline Data

Source: NBI (2022)

NOTE: The reported NRMCA average values appear to be consistently greater than those reported in NRMCA's industry average EPD report.

According to RMI (2021), the range of embodied carbon emissions of ready-mix concrete products in three states are characterized as shown in Figure 65. A specific Ready-Mix Concrete LLC[122] manufacturer in Euless, TX, reports a GWP(A1-A3) of **375 kg CO2e/m^3** of 24 MPa (3,500 psi) concrete mix which is equivalent to **286 kg CO2e/yd^3** for comparison with Figure 65 or **0.16 kg CO2e/kg** for comparison with Figure 66.

[121] National Ready Mixed Concrete Association (NRMCA), NRMCA Industry Average LCA Project Report—Version 3, Athena Sustainable Materials Institute, February 2020. https://www.nrmca.org/wp-content/uploads/2020/02/NRMCA_LCA_ReportV3_20200416.pdf

[122] https://info.nsf.org/Certified/Sustain/ProdCert/EPD10073.pdf, last accessed 11/15/2023

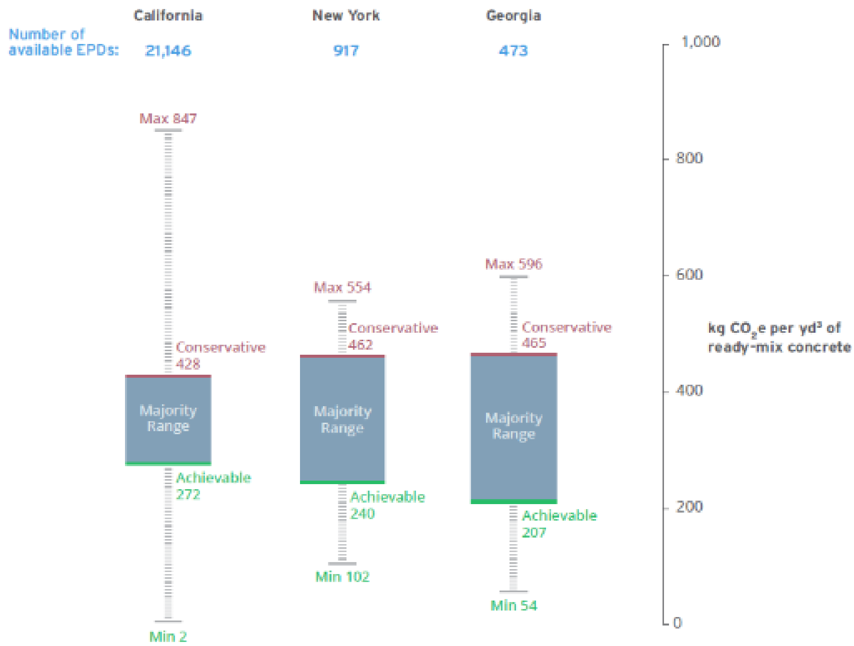

Figure 65. Range of embodied carbon emissions for ready-mix concrete in three states.

Source: RMI (2021) based on the "EC3 Tool"

Note: "Conservative" represents the 80th-percentile and "achievable" represents the 20th percentile.

On a broader scale not necessarily representing the US concrete market, ISE (2020) reports the variation in embodied emissions for different concrete mixes and suppliers as shown in Figure 66.

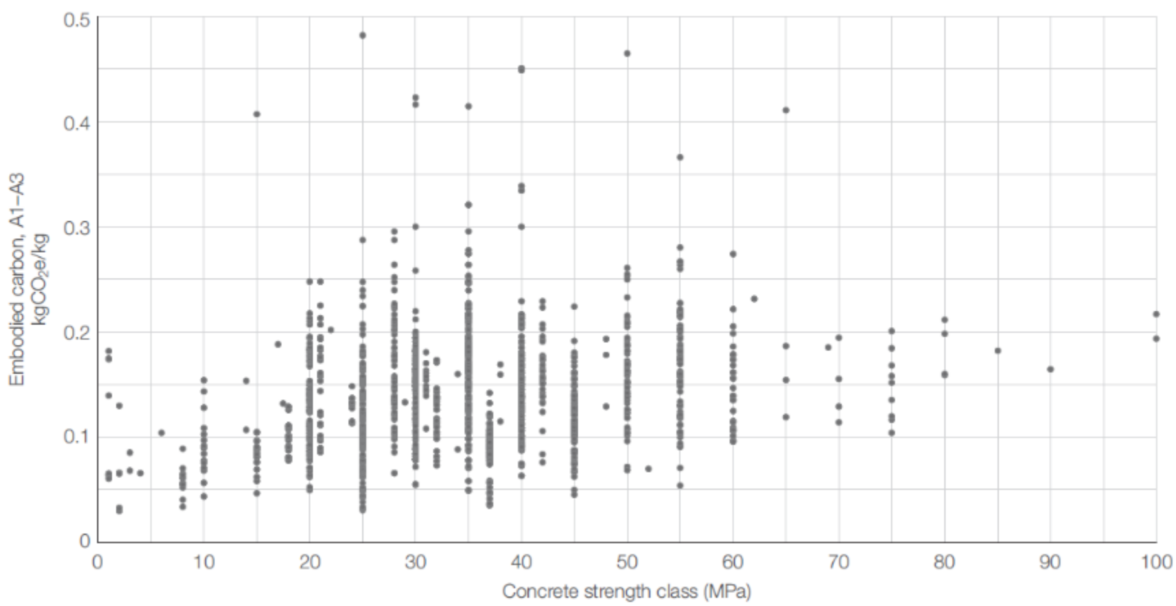

Figure 66. Range of concrete embodied carbon for different levels of compressive strength (1 MPa = 145 psi; e.g., 20 MPa = 2,900 psi, 30 MPa = 4,350 psi, etc.)

Source: ISE (2020)

Structural Steel

According to NBI (2022):

> Steel is the second highest embodied carbon product in commercial construction, following only concrete which is highest. Steel products' embodied carbon is primarily a product of the energy related to steel product manufacturing. Therefore, products manufactured with electricity, over natural gas, and in regions with lower carbon energy grids, will have lower embodied carbon. U.S. steel generally has lower embodied carbon compared to international steel. Steel exporters to the U.S. emit 50-100+% more CO_2 emissions per tonne than U.S. producers, on average. International steel production's energy is often sourced from locales with more extensive coal and natural gas percentages than what is found in the U.S., making American-made steel lower in carbon than most steel derived from countries with higher emission energy sources.

According to the Building Green, Inc. (2020):

> By weight, steel has a much higher embodied carbon footprint than concrete does—with one ton of steel representing approximately a ton of greenhouse gas emissions. According to the World Steel Association, steel production is responsible for 6.6% of greenhouse gas emissions globally—more than Portland cement (see Better Steel, Lower Impacts). Those global numbers reflect use of dirtier technology in much of the world, which is still using basic oxygen furnaces (BOF) rather than electric arc furnaces (EAF). In North America, the industry has mostly switched over to EAF technology—the process used to recycled steel. This, along with a cleaner electrical grid, has resulted in a 36% reduction in the industry's carbon footprint since 1990, according to Mark Thimons, P.E., vice president, sustainability, at the Steel Market Development Institute.
>
> So that's the first rule of thumb for reducing the embodied carbon of steel on a project: specify steel produced in North America—or, if that's not possible, at least specify recycled steel, which uses the better EAF technology. The only other real option for reducing steel's footprint is to use less—a practice that's even promoted by the Steel Market Development Institute, a trade group.

According to RMI (2021):

> The US steel industry is responsible for 104.6 MMT of CO_2 emissions annually, a contribution that makes up 2% of total US emissions. Steel industry emissions have dropped by approximately 60% since 1990, largely due to technological improvements as well as increased recycling of scrap steel.
>
> In recent decades, the US steel industry has shifted away from the use of integrated steel mills and the primary use of blast oxygen furnaces, toward the use of more efficient electric arc furnaces (EAF), which use scrap steel as a primary input. Of all the US steel made in 2016, 70% was manufactured using efficient electric arc furnaces reflecting a switch that has indeed reduced the carbon footprint of steel.
>
> However, steel production remains an incredibly energy intensive process, and steel destined for the built environment is still responsible for 46 MMT of CO_2 emissions annually because EAFs are effectively as "clean" as their energy source.

Based on the above data for CO_2 emissions (excluding other GHGs), US steel products used in the US "built environment" (an unclear category that presumably includes buildings and infrastructure construction, including steel rebar used in concrete, but not automobiles, machinery, and many other steel applications):

- Accounts for (46/104.6) x 100% = 44% of total US steel emissions from all US uses of steel
- Accounts for (0.44 x 0.02) x 100% = 0.88% of total US CO_2 emissions
- Accounts for about (0.10 x 0.0088) x 100% = 0.088% of total global CO_2 emissions

In terms of GHG emissions (CO_2e and not just CO_2), the entire US iron and steel industry accounts for about 0.20% (0.002) of total global CO_2e emissions (see Part 3 – industry subsector emissions). **Therefore, it may**

be concluded that "built environment" uses of steel in the US account for about 0.2% x 44% = 0.09% of global CO2e emissions.

While there certainly remains opportunities to reduce emissions attributed to materials like concrete and steel, the impact on the global climate appear relatively small even though these materials are considered to be the largest contributors among US building and construction materials. Consequently, the greatest climate benefits may be found in focused investment in alternative renewable low-carbon fuels for combustion and, for the steel industry, continued efforts at a national scale to increase the renewable or low-carbon energy content of the electric grid. Investments at this foundational level (e.g., reducing or eliminating the direct and indirect combustion of fossil fuels which accounts for 73% of US total GHG emissions) would have compounding benefits in lowering the emissions attributed to a multitude of products produced in the US and in other sectors of the economy, not just for buildings and construction. Other beneficial actions include resource-efficient use of these materials in building and construction applications.

NBI (2022) surveyed over 100 EPDs and found insufficient data for all steel products, except rebar (used in concrete) which was reported to represent over 90% of the industry. For remaining steel products (structural steel, hollow steel sections, and plates), NBI (2022) relied on industry-wide EPDs and applied adjustments to estimate the percentile values shown in Figure 67.

	Milled Products			Fabricated Product	
	Hot Rolled	Steel Plate	Rebar	Hot Rolled	Rebar
EPD Count:	15	2	51	4	19
90% Percentile	2076	1116	1892	1360	1138
80% Percentile	1270	1082	1074	1360	1094
75% Percentile	1235	1066	1032	1360	1080
50% Percentile	1040	981	852	1360	860
25% Percentile	851	896	728	1360	635
20% Percentile	718	880	728	1360	630
Number of EPDs that comply with 75% percentile	11	1	40	4	14

Figure 67. US steel product GWP (kg CO2e per metric ton of product) based on a study of product EPDs and the US steel industry-wide EPD.

Source: NBI (2022)

Note: The 50% percentile values appear to be 5 to 10% greater than industry average values indicated in the NBI (2022) study. For example, the US steel industry's industry-wide EPD for fabricated Hot-Rolled steel indicates a mean of 1,200 kg CO2e per metric ton of product and is based on a an average of fabrication site or plants, not weighted by the level of production at fabrication sites.[123] Also, in the NBI (2022) report the table units were apparently incorrectly reported as metric tons of CO2e instead of kg CO2e per metric ton of steel.

According to the Steel Framing Industry Association's (SFIA) industry-wide EPD for cold-formed steel framing products[124], the GWP(A1-A3) is **2,440 kg CO2e/metric ton or 2.44 kg CO2e/kg** of product.

[123] https://www.aisc.org/why-steel/resources/leed-v4/#112583 , last accessed 2/20/2023

[124] https://sfia.memberclicks.net/declaration--epd--for-cold-formed-steel-framing , last accessed 11/15/2023

Wood

Much has been said in earlier sections of Part 4 regarding the GWP of wood and other bio-based products and inconsistencies regarding the inclusion and treatment of carbon storage in assessing a net GWP impact (e.g., BuildingGreen, Inc., 2020; ISE, 2020; RMI, 2023).
According to Prestemon, Nepal, and Sahoo (2022):

> "Wood used in the 141 million existing housing units [3] and other end uses and wood discarded in solid wood disposal sites (SWDS) in the United States stored an estimated 9.8 and 9.9 billion tons of carbon dioxide equivalent (CO2e) in 2019 and 2020, respectively. The annual changes in the harvested wood products (HWP) carbon stock between these two years was 110 million tons of CO2e, representing about 16% of net CO2 uptake (flux) from the entire U.S. forest sector in 2019 [4]. Because wood products store carbon for many decades, and because wood can replace carbon-intensive materials such as steel and concrete in construction, the forest products sector can play an important role in mitigating net carbon emissions [5–7]. New housing units are demanded in part to replace the annual loss of approximately 0.4 million housing units [8] due to natural disasters, decay, movement of mobile homes, and market factors (e.g., torn down to make way for new development) [9] and to accommodate a growing and increasingly wealthy population."

According to a 2022 study by the Potsdam Institute for Climate Impact Research:[125]

> "Wood is known as a renewable resource that carries the lowest carbon footprint of any comparable building material as the trees take up CO_2 from the atmosphere to grow. Mishra explains: "Production of engineered wood releases much less CO_2 than production of steel and cement. Engineered wood also stores carbon, making timber cities a unique long-term carbon sink—by 2100, this could save more than 100Gt of additional CO_2 emissions, equivalent to 10% of the remaining carbon budget for the 2°C target."

In general, a strong factual argument can be made for the benefits of responsible forestry management and use of wood products as a means to sequester and store atmospheric carbon, especially in the US where a healthy market demand for wood products tends to drive afforestation and not deforestation.[126] The difficulty appears to be how to properly account for this climate benefit of wood and other bio-based materials in a manner suitable to its various applications, including building materials. This concern was reviewed in Section 4.4.2.

According to the North American industry-wide EPD of the American Wood Council (AWC) and Canadian Wood Council (CWC)[127], the GWP (A1-A3) of **softwood solid-sawn wood framing** without consideration of carbon storage (sequestration) is about **63 kg CO2e per m^3** of softwood material (dry density = 460 kg/m^3). This value is consistent with that reported earlier in Table 14 based on Carbon Leadership Forum's Material Baseline Report (Carlisle, et al., 2021). According to Section 5 for "Additional Environmental Information", the "permanent carbon sequestration, net of biogenic emissions" is equal to **-708 kg CO2e/m^3** such that the net GWP with sequestration is 63 – 708 = **-645 kg CO2e/m^3**. Thus, the significance of whether or not carbon sequestration is considered can present wood materials as having a modest GWP impact or a significant GWP benefit (negative GWP value due to what is considered "permanent" atmospheric carbon storage).

The above carbon sequestration also applies to other wood-based structural materials like **laminated veneer lumber (LVL)** which include non-wood materials such as adhesives. According to the EPD of one LVL product manufacturer[128], the GWP (A1-A3) is reported to be **239 kg CO2e/m^3** (density of 451 kg/m^3) without consideration of carbon sequestration. However, with carbon sequestration considered, the product's GWP is reported as **-230 kg CO2e/m^3**.

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[125] https://phys.org/news/2022-08-timber-cities-emissions-farmland-wood.html, last accessed 2/20/2023

[126] https://www.threetreesforestry.com/post/how-you-can-have-your-carbon-cake-in-the-forest-and-build-with-it-too, last accessed 11/10/2023

[127] https://awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanSoftwoodLumber_20200605.pdf, last accessed 2/20/2023

[128] https://www.astm.org/products-services/certification/environmental-product-declarations/epd-pcr.html, last accessed 2/23/2023

According to the AWC's IW-EPD for North American **Oriented Strand Board (OSB)**: [129]

- Density = 620 lbs/m^3
- GWP (A1-A3) = **243 kg $CO2e/m^3$**
- Permanent Carbon Sequestration, net of biogenic emissions = - 917 kg $CO2e/m^3$
- GWP w/sequestration = 243 – 917 = **-674 kg $CO2e/m^3$**

According to ISE (2020), in the absence of specific data, the carbon sequestered in timber materials can be taken as **-1.64 kgCO2e/kg** where this value is based on standard timber properties and then is subtracted from a GWP value for timber that is reported without including sequestration. This value is equivalent to -712 kg $CO2e/m^3$ (assuming wood material density of 451 kg/m^3) which compares conservatively to the carbon sequestration value of -917 kg $CO2e/m^3$ reported above for OSB and is similar to the -708 kg $CO2e/m^3$ reported above for US softwood solid sawn wood framing.

Glass

As reported earlier in Part 3, the US glass industry represents about 1.3% of total US industry sector emissions which is about 0.02% of total global CO2e emissions. The majority of glass produced is for containers, followed by flat glass and glass wool (e.g., insulation). While data was not found for the relative share of glass production in these categories, it may be assumed that not more than one-half is for flat glass which is used for vehicle glass, building glazing, solar panels, mirrors, picture frames, and a large variety of other applications. Assuming that one-half of the flat glass production is used for buildings, **the flat glass used in U.S. building construction is estimated to contribute about 0.005% to total global GHG emissions and most certainly less than 0.01%.**

According to the industry-wide EPD for flat glass sponsored by the National Glass Association[130], the GWP of flat glass is **1,430 kg CO2e per metric ton of glass material (or about 1.4 kg CO2e/kg consistent with Table 14)**. Flat glass is a generic name for a variety of glass manufacturing methods resulting in an unprocessed annealed state. The GWP value does not include glass that has been further processed for heat treatment, coatings, or any other secondary processing. It is for the "bare" flat glass material excluding any hardware, seals, or framing (metal or wood) commonly used to form a complete window, door, or glass wall system for buildings.

Gypsum Wall Board

According to the Gypsum Association's (GA) industry-wide EPDs for the US:[131]

- ⅝" (15.9 mm) Type X Conventional Gypsum Board, GWP (A1-A3) = **277 kg CO2e / 1000 ft^2**
  - Average unit weight = 10.4 kg/m^2 (2.18 lbs/ft^2)
- ⅝" (15.9 mm) Glass Mat Gypsum Panels, GWP (A1-A3) = **417 kg CO2e / 1000 ft^2**
  - Average unit weight = 12.6 kg/m^2 (2.58 lbs/ft^2)
- ½" (12.7 mm) Lightweight Gypsum Board, GWP (A1-A3) = **207 kg CO2e / 1000 ft^2**
  - Average unit weight = 6.6 kg/m^2 (1.35 lbs/ft^2)
- ½" (12.7 mm) Glass Mat Gypsum Panels, GWP (A1-A3) = **358 kg CO2e / 1000 ft^2**

[129] https://awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanOrientedStrandBoard_20200605.pdf, last accessed 2/24/2023
[130] https://www.glass.org/sites/default/files/2019-12/NGA_EPD_2019_12_16_signed.pdf, last accessed 2/20/2023
[131] https://gypsum.org/life-cycle-resources/, last accessed 11/11/2023

- Average unit weight = 9.9 kg/m^2 (2.03 lbs/ft^2)

According to the United States Geologic Survey (USGS), about 25,000 million square feet (2.3 billion m^2) of gypsum wall board products are produced in the US annually in recent years.[132] Because market share data for the gypsum product types listed above could not be found, a representative GWP for the 25,000 million square feet total market volume is assumed to be roughly 300 kg CO2e/1000 ft^2 (3.2 kg CO2e/m^2). Consequently, the total annual GHG emission contribution for the US gypsum wall board industry for US building and construction is roughly approximated as 80,000,000 tCO2e or about 0.08 GtCO2e. Total global GHG emissions were 59 GtCO2 for 2019 (IPCC, 2022). **Therefore, gypsum wall board products for the US building and construction market represent about 1.3% of total US and 0.14% of total global GHG emissions.** According to the GA's industry-wide EPDs, most of these emissions are associated with direct (e.g., natural gas) and indirect (electricity generation) combustion of fossil fuels.

According to one manufacturer's product-specific EPD, the following GWP values are reported for two gypsum wall board products (among many others):[133]

- USG ½" Sheetrock Brand Ultra-light panels, GWP (A1-C4) = **224 kg CO2e / 1000 ft^2**
- USG ⅝" Sheetrock Brand Firecode X Panels, GWP (A1-C4) = **364 kg CO2e / 1000 ft^2**

Exterior Wall Covering Materials

This review of GWP potential for exterior wall covering materials is far short of being exhaustive and only considers one example each for a cladding material and for a water-resistive barrier (WRB) or air barrier (AB) material. There are many other products used for the purpose of exterior wall coverings. While continuous insulation products, like foam plastic sheathing and mineral or wood fiber boards, are used on the exterior side of walls as part of an exterior wall covering assembly, they were addressed in the previous section.

Clay Brick – Based on the US-Canada industry-wide EPD for clay brick by the Brick Industry Association (BIA)[134], the industry average GWP (A1-A3) value for various types of clay brick is **503 kg CO2e/m^3** with an average clay brick density of 2,120 kg/m^3. The 1 m^3 volume appears to include any voids in each brick unit based on the type of brick. Therefore, bulk densities may vary. The EPD was not clear on this matter although this may have a relatively small effect on variation in the GWP.

Weather-resistive Barrier (WRB/AB) – Based on one manufacture's EPD[135] for two product types (one for home construction and the other for commercial construction), the reported GWP (A1-A3) was **0.497 kg CO2e/m^2** and **0.942 kg CO2e/m^2**, respectively, including all installation accessories such as flashing, tape, and cap staples. The additional GWP for other life cycle stages generally added an additional 5% to the A1-A3 GWP value. The EPD also included other environmental information on energy saving benefits due to assumed levels of building air leakage reduction (e.g., from 1 cfm/sf baseline to 0.40 cfm/sf with the product installed) resulting in global warming payback periods of less than 3 months.

[132] https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-gypsum.pdf, last accessed 11/11/2023

[133] https://www.astm.org/products-services/certification/environmental-product-declarations/epd-pcr.html, last accessed 2/22/2023

[134] https://info.nsf.org/Certified/Sustain/ProdCert/EPD10447.pdf, last accessed 11/15/2023

[135] https://www.dupont.com/content/dam/dupont/amer/us/en/performance-building-solutions/public/documents/en/102-1_DuPont_EPD_Tyvek_Mechanically-Fastened.pdf, last accessed 11/15/2023

Insulation Products

GENERAL

According to an analysis of total annual US insulation material sales[136], and converting those sales to insulation product functional units based on insulation material cost data from RS Means Open Shop Building Construction Costs, and then multiplying those functional units by current insulation material industry average GHG emissions per functional unit, the total annual GHG emissions of all US insulation materials can be roughly estimated to be 0.0058 GtCO2e. **This represents approximately 0.01% of the total global GHG emissions (i.e., 0.0058 GtCO2e / 59 GtCO2e = 0.0001 or 0.01%) and about 0.1% of total US GHG emissions (i.e., 0.0058 GtCO2e / 6 GtCO2e = 0.001 = 0.1%)**.

Furthermore, according to data reviewed earlier in this report, the total US building stock's annual operational GHG emissions is about 1.9 GtCO2e (about 30% of total US GHG emissions). Roughly 40% is attributed to heating and cooling energy use which relates to the function of insulation materials. Proportioning these emissions to just annual new commercial and residential building stock additions and correcting for higher efficiency of newer buildings, new residential and commercial buildings account for about 0.0041 GtCO2e of emissions each year. Comparing this with the 0.0058 GtCO2e emissions for insulation materials sold and used in those same new buildings, a national average payback period (time to the point where operational carbon savings begin to exceed the upfront insulation material embodied carbon emissions) of about 1.4 years can be roughly estimated (i.e., 0.0058/0.0041 = 1.4). **Thus, the current mix of insulation materials used annually in the current US building market and under the current energy supply conditions provide nearly immediate GHG emission savings and substantial GHG emission avoidance benefits over the future life of new or renovated existing buildings**. This topic will be addressed more thoroughly in a later section of this report where both embodied and operational carbon are considered to properly assess the carbon "footprint" and "handprint" of insulation materials using whole-building lifecycle analysis for a "total carbon" approach.

BENCHMARKED EPD DATA

Figure 68 shows results of a study of insulation material embodied carbon emissions by Efficiency Vermont (2022) and further expanded for use in Vermont's Residential Building Energy Standard (RBES). As with the Magwood et al. (2021) study, bio-based insulation materials, like wood fiber, straw, hemp, and cellulose were considered to be carbon-storing materials which remove CO2 from the atmosphere during growth and do not return it back to the atmosphere until after the product's end-of-life disposal and subsequent decomposition. This treatment of carbon sequestration is a somewhat controversial matter as discussed earlier in this report and is not included in the generalized benchmarking data shown earlier in Table 14. Also, it should be noted that some of the XPS insulation GWP values included in Figure 68 are representative of older HFC blowing-agent materials which are being phased out and replaced with those using HFO-blend blowing agents with much lower GWP. This concern also applies to the narrower selection of insulation materials shown in Figure 69, which includes an estimate of the off-gassing of blowing agents during the use stage (Stage B1) of insulation materials that contain blowing agents.

The Efficiency Vermont (2022) study also included case studies of reducing embodied carbon emissions in homes, focusing on insulation materials. But, the case studies all used the older HFC blowing-agent XPS materials as a baseline to assess the benefits of and make recommendations for material substitutions for lower embodied carbon products. Consequently, with the newer low-embodied carbon XPS materials, the carbon-emission-reducing benefits of making insulation material substitutions have been greatly diminished from the study's original findings, rendering some of its key recommendations somewhat moot (particularly in view of the relatively small overall contribution of US insulation materials to global GHG emissions as estimated above and the presently fast GHG emissions payback and substantial avoidance over the life of buildings as will be shown in Section 4.8).

[136] North American Building Thermal Insulation Market Size, Share & Trends Analysis Report, www.grandviewresearch.com, last accessed 3/15/2023

The proposed method for use of the GWP values in the RBES is considered optional in draft form, providing one point (or credit) for simply doing an embodied emissions calculation for insulation materials used to comply with the RBES. Additional points are achieved by making insulation material substitutions that result in an embodied emission intensity of insulation materials of less than 0.5 kg CO2e per square foot of building floor area. Example substitutions generally relied on the bio-based insulation materials shown in Figure 68 having a negative (carbon sink) value for GWP. But, such an approach without the full context of a whole building can result in inefficient design decisions, particularly for multifunctional insulation products that can impact other material choices related to building envelope moisture control and even structural system optimization. Examples of these integrated design considerations include: (1) use of foam insulation on foundations to reduce concrete use and foundation excavation in cold climates by way of the building code's frost-protected shallow foundation technology and (2) use of foam plastic insulation on above-grade building assemblies to improve moisture durability while eliminating other materials such as a separate water-resistive barrier and vapor retarder. Actual design and construction examples were provided earlier in this report.

Material	GWP per 1m^2 RSI-1, kgCO2e
Straw - panel	-10.88
Wood fiber - board	-7.13
HempCrete - block	-5.67
Cellulose - densepack, 3.55 pcf	-2.16
Wood fiber - batt	-1.96
Cellulose - blown/loosefill, 1.29 pcf	-0.83
Fiberglass - batt	0.68
Fiberglass - blown/loosefill	1.30
Phenolic foam - board	1.54
SPF - open cell	1.59
Fiberglass - blown/spray	1.64
Polyiso - board, foil faced	2.32
EPS board, Type I - 10psi	2.63
Polyiso - board, GRF facers (roof)	2.63
Mineral wool - batt	3.25
EPS board, Type IX - 25psi	3.49
Cellular glass - aggregate	3.93
SPF - closed cell HFO	4.00
Mineral wool - board high density	4.06
SPF - roofing HFO	4.74
Mineral wool - blown	5.18
Fiberglass - board	7.37
XPS - board, 15psi HFO/HFC	7.41
XPS - board, 25psi HFO/HFC	8.83
XPS - board, 40psi HFO/HFC	10.26
XPS - board, 60psi HFO/HFC	12.55
SPF - closed cell HFC	14.86
XPS - board, 100psi HFO/HFC	17.10
SPF - roofing HFC	19.33
SPF - 2K-LP HFC	25.46
XPS - board, 15psi HFC	39.04
XPS - board, 25psi HFC	46.51
XPS - board, 40psi HFC	54.04
XPS - board, 60psi HFC	66.06
XPS - board, 100psi HFC	90.05

Figure 68. GWP for various insulation materials

Source: Vermont RBES staff presentation at April 6, 2022 stakeholder meeting, https://publicservice.vermont.gov/efficiency/building-energy-standards/building-energy-standards-update as based on Efficiency Vermont (2022) https://www.efficiencyvermont.com/news-blog/whitepapers/the-high-greenhouse-as-price-tag-on-residential-building-materials

NOTE 1: More detailed data can be found in Table 5 of Efficiency Vermont (2022).

NOTE 2: Many of the values in this table may be based on as few as 1 or 2 EPDs and thus do not constitute a formal benchmarking of the various insulation material types and variations within the types.

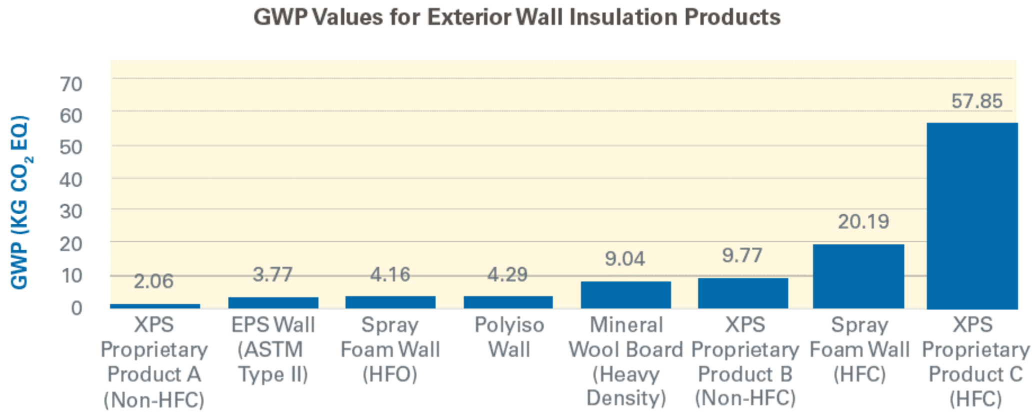

Figure 69. Comparison of GWP values of Exterior Wall Insulation Products (kg CO2e per m^2 per 1-Rsi)
Source: https://www.polyiso.org/page/ComparingGWPWallInsulation

Table 16 is based on Magwood et al. (2021) which listed values of the GWP of insulation materials similar to that of Figure 68, but it uses different units to communicate the information (i.e., kgCO2e for 10 m^2 at R10). The values using conventional GWP functional units of “kg CO2e/m^2-RSI” have been added for consistency with other reported data in this section. Table 16 does not include data for the newer XPS formulations that use substantially lower GWP blowing agents which have now replaced the older formulations. The values in Table 16 are essentially identical to many of the values reported in the material embodied carbon material selection guide prepared for the City and County of Nelson (2022).

TABLE 16. GWP values for wall cavity and board insulation materials based on Magwood et al. (2021)

Insulation Type	R-value per inch	Global Warming Potential (GWP)	
		kg CO2e for 10m^2 at R10	kg CO2e / m^2-RSI
Wall Cavity Insulations			
Straw bale	3.3	-128	-7.3
Hempcrete	2.1	-76	-4.3
Hemp fiber batt	3.7	-31	-1.8
Wood fiber batt	3.8	-19	-1.1
Cellulose batt	3.6	-14	-0.8
Cellulose dense packed	3.7	-13	-0.74
Fiberglass batt	3.6	12	0.68
Mineral wool batt	3.8	23	1.3
Wool batt	3.6	23	1.3
ccSPF with HFO blowing agent	6.6	73	4.1
ccSPF with HFC blowing agent	6.6	232	13.2
Board Insulations			
Wood fiber (EU imports)	3.6	-36	-2.0
EPS foam with graphite	4.7	49	2.8
Polyiso foam	6.5	50	2.8
Mineral wool	4.3	51	2.9
EPS foam	4	66	3.8
XPS foam	5	987	56.1

For foam plastic insulation materials, a recent study benchmarked current product embodied carbon as shown in Table 17 (Schmidt and Chertak, 2023).

TABLE 17. Embodied Carbon of Foam Plastic Insulation Materials (kg CO2e/m^2 per 1 RSI) for Typical Building Envelope Applications

Insulation Material	Embodied Carbon (kg CO_{2e}/m^2)
XPS	5.63
EPS	3.78
Polyisocyanurate (Wall)	3.49
Polyisocyanurate (Roof)	3.46
cc-SPF	4.21
oc-SPF	1.68

Source: Schmidt and Chertak (2023)

EPS BOARD INSULATION

According to the EPS Industry Association's (EPSIA) industry-wide EPD for expanded polystyrene (EPS) insulation board:[137]

> The functional unit used for this study is 1 m² (10.765 ft²) of insulation material with a thickness that gives an average thermal resistance RSI = 1 m²•K/W (R-value 5.68 ft²•hr•°F/BTU) and with a building service life of 60 years. The thickness of the ASTM C578 Type I EPS insulation required for the functional unit is 4.01 cm (1.58 in).

Table 18 summarizes various material property data based on an industry-wide EPD and the ASTM C578 and CAN/ULC S701 standards for various types of EPS insulation. A GWP of 2.78 kg CO2e /m²-RSI as reported in the EPD applies to Type I EPS which has a compressive strength of 10 psi, an R-value per inch of R3.6/in (RSI 0.25/cm), and a minimum density of 0.9 lbs/ft³ (15 kg/m³). For US building code applications of EPS as foam plastic insulating sheathing (FPIS) continuous insulation (ci) on building walls, the minimum required FPIS material compressive strength is 15 psi (generally) which requires a higher density of EPS material corresponding to ASTM C578 Type II EPS with a reported GWP of 3.77 kg CO2e/m²-RSI. For comparison, one proprietary Type II EPS product reports a GWP of 2.8 kg CO2e/m²-RSI . Certain below-grade applications may require greater compressive strength, so the GWP of EPS depends on the nature of the application and the appropriate specification of a type of EPS.

TABLE 18. Summary of EPS data for GWP (A1-C4) and other relevant material properties

Property	**Units**	**ASTM C578 EPS Types**							**CAN/ULC S701**		
		Type XI	**Type I**	**Type VIII**	**Type II**	**Type IX**	**Type XIV**	**Type XV**	**1**	**2**	**3**
GWP (functional units)	kg CO2e/ **m²-RSI**	2.51	2.78	3.38	3.77	4.77	6.39	7.78	2.68	3.74	4.72
GWP (mass units)	kg CO2e/ **kg**	4.50	4.64	4.95	4.77	4.79	4.90	4.83	-	-	-
Thermal Resistance	R/in (RSI/cm)	3.1 (0.22)	3.6 (0.25)	3.8 (0.26)	4.0 (0.28)	4.2 (0.29)	4.2 (0.29)	4.3 (0.30)	3.75 (0.26)	4.04 (0.28)	4.27 (0.29)
Compressive Resistance	Psi (kPa)	5 (35)	10 (69)	13 (90)	15 (104)	25 (173)	40 (276)	60 (414)	10 (70)	16 (110)	20 (140)
Density	lb/ft³ (kg/m³)	0.7 (12)	0.9 (15)	1.15 (18)	1.35 (22)	1.80 (29)	2.40 (38)	3.00 (48)	-	-	-

1 RSI (K-m²/W) = 5.678 R-value (5.678 ft²-hr-°F/Btu)
TABLE NOTE: Table values do not include any facer materials, if applicable to a given EPS product. Also, a GWP (A1-A3) value would be approximately 97% of the values tabulated above for A1-C4 lifecycle stages.
Source: Based on https://www.epsindustry.org/sustainable-eps-insulation , last accessed 2/21/2023

XPS BOARD INSULATION

An industry-wide EPD could not be found for the US extruded polystyrene (XPS) industry as represented by the Extruded Polystyrene Association (XPSA). However, a range of GWP values for various XPS types are shown in Table 19 based on the product-specific EPD data sources indicated. This may be compared to a limited selection of XPS data previously reported in Figures 68 and 69, and Tables 16 and 17.

[137] https://www.epsindustry.org/sustainable-eps-insulation, last accessed 2/21/2023

TABLE 19. Summary of XPS data for GWP (A1-C4) and other relevant material properties

Property	Units	ASTM C 578 XPS Types				
		Type X	Type IV	Type VI	Type VII	Type V
GWP (HFC)	kg CO2e / **m²-RSI**	44.8	53 - 60	62 - 70	76 - 96	103
GWP (HFO blend)		4.5 – 7.6	4.3 – 9.0	4.5 – 10.5	5.3 – 12.8	11.1 - 17.4
GWP (HFC)	kg CO2e / **kg**	74.7	74.1 – 83.9	74.7 – 84.3	74.9 – 94.6	74.3
GWP (HFO blend)		7.7 – 12.7	6.1 – 12.6	5.4 – 12.6	5.2 – 12.6	8.0 – 12.6
Thermal Resistance	R/in (RSI/cm)	5.0 (0.35)	5.0 (0.35)	5.0 (0.35)	5.0 (0.35)	5.0 (0.35)
Compressive Resistance	Psi (kPa)	15 (104)	25 (173)	40 (276)	60 (414)	100 (690)
Density	lb/ft³ (kg/m³)	1.3 (20.8)	1.55 (24.8)	1.8 (28.8)	2.2 (35.2)	3 (48.1)

TABLE NOTES:

1. Table values do not include any facer material. Where included facers add about 0.1 to 0.2 kg CO2e/m²-RSI to the tabulated values for a typical facer on one or both sides of the XPS board or panel.
2. Table data is based on the following sources and GWP is presented as a range where more than one product's data is included:
   - https://www.owenscorning.com/en-us/corporate/sustainability/product-sustainability/product-transparency-standards , last accessed 2/22/2023
   - https://www.beyondblue.dupont.com/styrofoam-brand-st-100-series-xps.html ,last accessed 2/22/2023
   - https://cdn.scscertified.com/products/cert_pdfs/SCS-EPD-07177_Kingspan-Insulation_XPS60_070121.pdf , last accessed 2/22/2023
   - file:///C:/Users/Owner/Downloads/kingspan-greenguard-xps-25psi-environmental-product-declaration-en-us.pdf , last accessed 2/22/2023
   - file:///C:/Users/Owner/Downloads/kingspan-greenguard-xps-40psi-environmental-product-declaration-en-us.pdf , last accessed 2/22/2023

The latest XPS products with modern low-GWP blowing agents have a embodied GHG emissions footprint that is a mere 1% of what it was in the 1970s (two orders of magnitude reduction in embodied emissions) as shown in Figure 70. Even within the last decade, the GWP of XPS has been reduced by about 90% to about 10% of its GWP value in 2013. It is noteworthy that this achievement far exceeds the goal set in the NASEM (2021) document for US federal climate policy which called for a 30% reduction in GWP of building materials by 2030 (see Part 2 of this report).

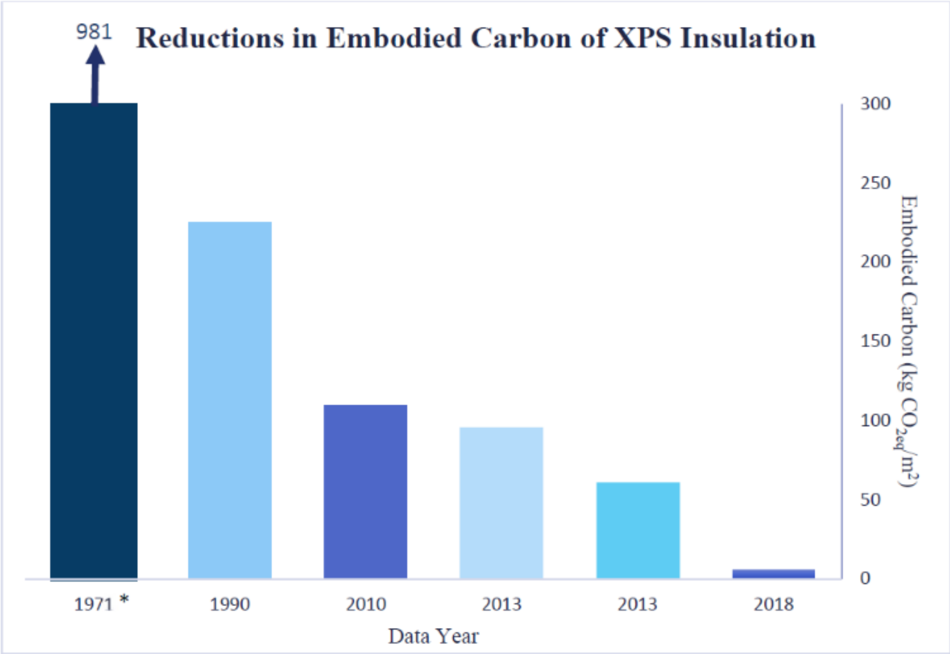

Figure 70. Reductions of embodied carbon for XPS insulations from 1971 to 2018.
Source: Schmidt and Chertak (2023)
NOTE: The left-most bar is truncated with the value of 981 shown for clarity; the units are kg CO2e/m^2 for 1 RSI.

But, in a recent Green Building Advisor article, the following statement is made regarding selection of insulation products based on a "holistic understanding of their environmental and social impacts":[138]

> "… good is often confused with less bad. Good is a fundamental shift in material composition, whereas less bad is incremental. For example, this [new generation of XPS rigid foam] is less bad than previous versions, but it is still made of foam, and it still has a high lifecycle carbon impact. I argue that a good product is made of carbon-storing natural resources like wood or cork."

Based on the above quote and many other embodied carbon policy and design guides reviewed earlier in this paper, even significant reductions in the GWP of any type of foam product (EPS, XPS, Polyiso, and spray foam) may be considered insufficient by some, particularly with respect to the climate goal of achieving a totally zero GHG emissions economy by 2050, including all building materials. Thus, bio-based alternatives to foam insulation products are being promoted (e.g., cellulose, wood fiber, cork, straw, and sheep's wool, etc.). Government-funded R&D efforts also are aimed at bio-based alternatives to foam plastic insulation, such as the National Renewable Energy Laboratory's (NREL) $5.4 million to research methods to "turn buildings into carbon storage structures" including alternative bio-based insulation "carbon sink" materials by a grown composite of cellulose and fungi (mycelium) that has thermal performance claimed to be "comparable to plastic foam – bringing the team closer to a direct (and cleaner) replacement for plastic insulation."[139]

[138] https://www.greenbuildingadvisor.com/article/five-factors-of-good-building?oly_enc_id=4124G5637590A0Y, last accessed 1/29/2023

[139] NREL Set To Receive $5.4 Million in Funding to Research Turning Buildings Into Carbon Storage Structures, July 15, 2022, Susannah Shoemaker, https://www.nrel.gov/news/program/2022/nrel-set-to-receive-54-million-in-funding-to-research-turning-buildings-into-carbon-storage-structures.html, last accessed 8/2/2022

POLYISOCYANURATE BOARD INSULATION

Polyisocyanurate (polyiso or PIR) uses a low-GWP blowing agent (pentane). According to the Polyiso Industry Manufacturers Association (PIMA) and its industry-wide EPD[140] for "polyiso wall insulation boards", ASTM C1289 Type I, Class 1 & 2 polyiso boards have a GWP (A1-C4) of **4.29 kg CO2e/m²-RSI** corresponding to 0.866 in (2.2 cm) thickness and 1.08 kg of material. The GWP in terms of mass is **3.97 kg CO2e/kg**. Some specific products can have a GWP as low as 2.8 kg CO2e/m²-RSI. The density of polyiso is about 45 kg/m³ and its ASTM C1289 minimum R-value per inch varies with thickness such that 1 inch is R-6, 1.5 inches is R-9.9 and 2 inches is R-12. For pre-calculated GWP values for typical thicknesses and areas, see Figure 71.

IMPACT CATEGORY / ENVIRONMENTAL INDICATOR	UNIT	1.0-inch Thick R_{IP}: 6.5		2.0-inch Thick R_{IP}: 13.1		3.0-inch Thick R_{IP}: 19.7	
		Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²
GWP: Global Warming Potential	kg CO_2 eq	6.79E-01	7.30E+00	9.20E-01	9.90E+00	1.17E+00	1.26E+01

Figure 71. GWP for all life-cycle stages (A1-C4) for common polyiso wall insulation.
Source: https://www.polyiso.org/page/EPDs, last accessed 2/22/2023
NOTE: The tabulated GWP values account for the presence of typical foil facers.

In PIMA's Industry-wide EPD for "polyiso roof insulation boards" the GWP is addressed for two types of product based on the facers used:

- Glass fiber reinforced cellulosic facer (GRF) polyiso roof insulation boards: **4.36 kg CO2e / m²-RSI**
- Coated glass facer (CGF) polyiso roof insulation boards: **5.96 kg CO2e / m²-RSI**

For pre-calculated GWP values for typical thicknesses and unit surface areas, see Figure 72.

Product: Glass Fiber Reinforced Cellulosic Facer (GRF) Polyiso Roof Insulation

IMPACT CATEGORY / ENVIRONMENTAL INDICATOR	UNIT	1.8-inch Thick R_{IP}: 10.3		2.6 -inch Thick R_{IP}: 15		3.5-inch Thick R_{IP}: 20.5	
		Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²
GWP: Global Warming Potential	kg CO_2 eq	7.64E-01	8.23E+00	1.07E+00	1.15E+01	1.43E+00	1.54E+01

Product: Coated Glass Facer (CGF) Polyiso Roof Insulation

IMPACT CATEGORY / ENVIRONMENTAL INDICATOR	UNIT	1.8-inch Thick R_{IP}: 10.3		2.6-inch Thick R_{IP}: 15		3.5-inch Thick R_{IP}: 20.5	
		Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²	Per 1 ft²	Per 1 m²
GWP: Global Warming Potential	kg CO_2 eq	1.16E+00	1.25E+01	1.46E+00	1.58E+01	1.82E+00	1.96E+01

Figure 72. GWP for all life-cycle stages (A1-C4) for polyiso roof insulation with GRF facer.
Source: https://www.polyiso.org/page/EPDs, last accessed 2/22/2023

Since 2001, PIR products have seen a reduction in GWP to about 3% of what it was in 2001 (a 97% reduction in GWP) as shown in Figure 73. As noted earlier in Figure 58 for XPS, this achievement for PIR far exceeds the goal set in the NASEM (2021) document for US federal climate policy execution which called for a 30% reduction in GWP of building materials by 2030 (see Part 2 of this report).

[140] https://www.polyiso.org/page/EPDs, last accessed 2/22/2023

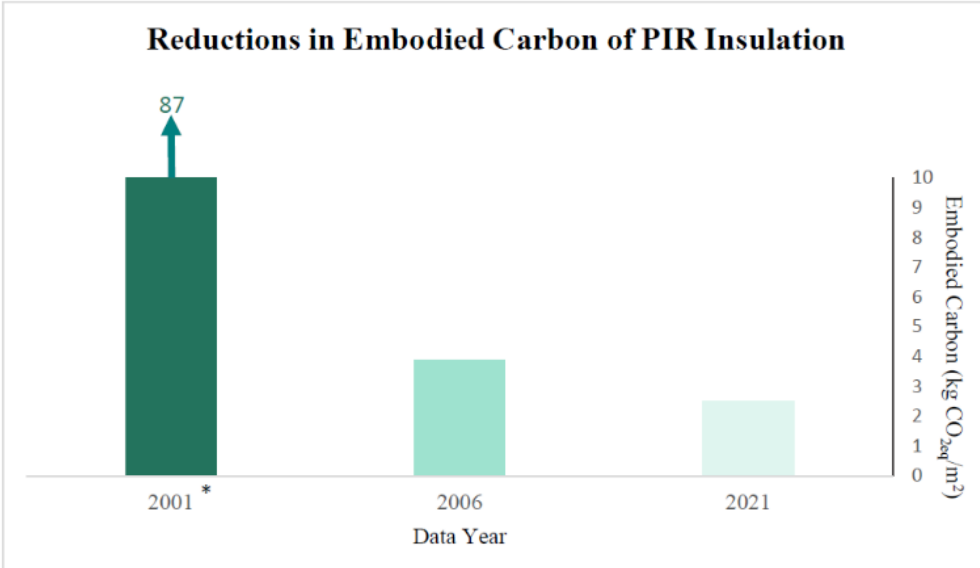

Figure 73. Reductions in embodied carbon of PIR insulation from 2001 to 2021.

Source: Schmidt and Chertak (2023)

NOTE: The left-most bar is truncated with the value of 87 shown for clarity; units are kg CO2e/m^2 for 1 RSI.

CELLULOSIC FIBER BOARD INSULATION

According to the American Wood Council's (AWC) industry-wide EPD for North American Cellulosic Fiberboard (CFB), the following data describes the GWP of the product with and without consideration of "permanent" carbon storage (sequestration): [141]

- GWP (A1-A3) = **295 kg CO2e/m^3** (density of 254 kg/m^3 @ 4%MC; 235 kg/m^3 dry) or **1.2 kg CO2e/kg**
- Initial carbon sequestration at gate = 430 kg CO2e/m^3 (based on 50% of dry weight being carbon from cellulose and multiplying by ratio of molecular weights of CO2 and C)
- Permanent carbon sequestration (initial less landfill emissions at year 100) = 238 kg CO2e/m^3
- GWP with permanent sequestration at 100 years = 295 – 238 = **57 kg CO2e/m^3** or **0.22 kg CO2e/kg**
- Another source suggests that the GWP with sequestration is **-47 kg CO2e/m^3** [142]

According to the EPD, 72% of the embodied energy in producing the CFB product is from fossil fuel sources (e.g., combustion of coal, natural gas, and petroleum).

The North American Fiberboard Association's (NAFA) industry-wide EPD for North American Cellulosic Fiberboard differs from the AWC's version as follows: [143]

- GWP (A1-A3) = **196 kg C02e/m^3** (density of 239 kg/m^3) or 0.82 kg CO2e/kg
- Permanent carbon sequestration = 340 kg CO2e/m^3
- GWP with sequestration = 196 – 340 = **-144 kg CO2e/m^3** or **-0.57 kg CO2e/kg**

Neither of the above EPDs include typical surface coatings (like asphalt) used on CFB products for building sheathing, commonly known as "black jack" in the residential construction industry.

[141] https://corrim.org/wp-content/uploads/2017/12/AWC_EPD_Cellulosic_FiberBoard.pdf, last accessed 2/24/2023

[142] https://www.fpl.fs.usda.gov/documnts/pdf2021/fpl_2021_sahoo003.pdf, last accessed 2/24/2023

[143] https://www.fiberboard.org/uploads/pdf/Nafa_EPD_NorthAmericanCellulosicFiberboard.pdf, last accessed 2/24/2023

For insulating wood fiberboard, the R-value is R-1.3 for a typical ½" thick panel, or 2.6 R per inch. To achieve 1 RSI would require (5.678 R/RSI) / (2.6 R/in) = 2.18 inch/RSI. For a 1 m^2 area of a panel at 2.18 inch thickness, the volume is equal to 0.055 m^3 of material. Therefore, the GWP (A1-A3) in terms of insulation material functional units (kg CO2e/m^2-RSI) is 0.055 x 295 = **16.2 kg CO2e/m^2-RSI** (per AWC IW-EPD) or **10.8 kg CO2e/m^2-RSI** (per NAFA IW-EPD), both without consideration of carbon sequestration. With sequestration considered, the GWP values are **3.14 kg CO2e/m^2-RSI** and **-7.92 kg CO2e/m^2-RSI**, respectively. Given the range of values and differences of what is or is not included in the material composition in the EPDs referenced, there may confusion as to an appropriate GWP value for wood fiberboard products.

Based on the AWC's industry-wide EPD, the GWP of CFB products with sequestration included when presented in terms of insulation functional units (e.g., 3.14 kg CO2e/m^2-RSI) is of comparable magnitude to the GWP values of the EPS, XPS (HFO), and Polyiso GWP values presented earlier above for foam plastic rigid insulation boards.

MINERAL WOOL INSULATION

According to the industry-wide EPD and transparency summaries on mineral wood insulations by the North American Insulation Manufacturers Association (NAIMA), three mineral wool products have the following GWP average values:[144,145]

- Heavy Density Mineral Wool Board, GWP (A1-A3) = **8.16 kg CO2e / m^2-RSI** (mass = 4.20 kg and thickness = 34 mm or density of 123 kg/m^3); therefore, on mass-basis GWP = **1.94 kg CO2e / kg**
- Light Density Mineral Wool Board, GWP (A1-A3) = **3.33 kg CO2e / m^2-RSI** (mass = 1.72 kg and thickness = 39 mm or density of 44 kg/m^3); therefore, on mass-basis GWP = **1.94 kg CO2e / kg**
- Loose Fill Mineral Wool, GWP (A1-A3) = **1.56 kg CO2e / m^2-RSI**

Considering the full life-cycle (A1-C4) the GWP potential of mineral wool is slightly greater. For example:

- Heavy Density Mineral Wool Board, GWP (A1-C4) = **9.04 kg CO2e / m^2-RSI**
- Light Density Mineral Wool Board, GWP (A1-C4) = **4.04 kg CO2e / m^2-RSI**

According to one product-specific loose fill mineral wool EPD, the GWP value could be as much as 15% less than the industry-wide average depending on the product brand selected, its density, and its primary purpose (such as sound deadening and fire-safing vs. insulation).

Also, according to one product-specific EPD for mineral wool board with a 40 kg/m^3 density, the following GWP value are reported which are about **one-third the industry-wide average values** for "light-density" mineral wool board:[146]

- GWP (A1-A3, excluding facer) = 0.88 to 1.33 kg CO2e/m^2-RSI (two plants)
- GWP (A1-C4, excluding facer) = 1.17 to 1.6 kg CO2e/m^2-RSI (two plants)
- GWP with renewable energy offset (A1-A3, excl. facer) = 0.51 to 0.91 kg CO2e/m^2-RSI (use of renewable energy offsets is not permitted by PCR at least in part because they do not actually change the emissions directly attributed to the product)
- Depending on facer used, add 0.2 to 0.9 kg CO2e/m^2 to GWP values reported above.

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[144] https://insulationinstitute.org/im-a-building-or-facility-professional/commercial/environmental-considerations/, last accessed 2/22/2023

[145] https://www.jm.com/content/dam/jm/global/en/building-insulation/Files/BI%20Toolbox/Mineral-Wool-Environmental-Product-Declaration.pdf, last accessed 2/22/2023

[146] https://www.owenscorning.com/en-us/corporate/sustainability/product-sustainability/product-transparency-standards, last accessed 2/22/2023

FIBERGLASS BATT INSULATION

According to one manufacturer's product-specific EPD, fiberglass batt insulation has the following GWP values:[147]

- GWP (A1-A3, excluding facer) = **0.464 kg CO2e/m^2-RSI**
- GWP (A1-C4, excluding facer) = **0.504 kg CO2e/m^2-RSI**

For facer material add, 0.125 kg CO2e/m^2 for kraft facing and 0.539 kg CO2e/m^2 for foil facing in determining the total GWP for the R-value and thickness of material used in a given application.

The generalized value for fiberglass batt insulation previously reported in Figure 68 showed a GWP of **0.68 kg CO2e/m^2-RSI.** However, this should not necessarily be taken as representing an industry average value. Also, one manufacture of fiberglass batt insulation (Owens Corning Ecotouch® PINK® Fiberglass Batt & Roll Insulation) reports in the product's EPD a 17% reduction in GWP from its 2011 to 2016 dataset.

SPRAY FOAM INSULATION

Like XPS board insulation, spray foam insulations have two varieties based on the GWP of the blowing agents used (HFC vs. HFO). The lower-GWP blowing agent is HFO and is replacing HFC, just as is the case with XPS insulation. This has a significant benefit in reducing the product's GWP.

Spray foam also comes in two varieties in terms of its cell structure: open cell and closed cell. There also are differences in other properties and functional capabilities beyond just R-value. Primarily it is density that sets apart the different spray foams and their applications as shown in Figure 74 from the Spray Polyurethane Foam Association's (SPFA) industry-wide EPDs for HFC and HFO varieties:[148,149]

Name	Roofing	2K-LP	Closed cell	Open cell
Density [lb / ft^3]	2.5 to 4.0	1.8 to 2.0	1.5 to 2.4	0.5 to 0.7
Thermal resistivity [R / in]	6.2 to 6.8	6.1 to 6.2	6.2 to 7.0	3.6 to 4.5
Air impermeable material	✓	✓	✓	✓
Integral vapor retarder	✓		✓	
Water resistant	✓		✓	
Cavity insulation		✓	✓	✓
Continuous insulation	✓		✓	✓
Low-slope roofing	✓			
Structural improvement	✓		✓	

Figure 74. Typical SPF properties.
Source: https://www.astm.org/products-services/certification/environmental-product-declarations/epd-pcr.html

[147] https://www.owenscorning.com/en-us/corporate/sustainability/product-sustainability/product-transparency-standards, last accessed 2/22/2023
[148] https://www.astm.org/products-services/certification/environmental-product-declarations/epd-pcr.html, last accessed 2/22/2023
[149] https://www.astm.org/products-services/certification/environmental-product-declarations/epd-pcr.html, last accessed 2/22/2023

The industry average GWP (100 year) for life-cycle stages A1-C4 for spray foam of the various types shown in Figure 74 are summarized as follows:

- Roofing (HFC) = 16.2 kg CO2e/m^2-RSI
- Roofing (HFO) = 4.96 kg CO2e/m^2-RSI
- 2K-LP (HFC) = 35.8 kg CO2e/m^2-RSI
- 2K-LP (HFO) = 3.8 kg CO2e/m^2-RSI
- Closed cell (HFC) = 20.2 kg CO2e/m^2-RSI
- Closed cell (HFO) = 4.16 kg CO2e/m^2-RSI
- Open cell = 1.66 kg CO2e/m^2-RSI

It should be noted that the newer HFO blowing agent formulations represent a 75-90% reduction in GWP over the HFC varieties.

CELLULOSE LOOSE-FILL INSULATION

Conventional cellulose loose-fill insulation uses recycled paper and electricity to power the manufacturing process. While recycled paper (which comes from trees) sequesters carbon like other bio-based products, it actually extends the carbon storage of paper products that are recycled. However, this is not factored into the **GWP of 0.704 kg CO2e/m^2-RSI** reported in the Cellulose Insulation Manufacturers Association's (CIMA) industry-wide EPD.[150] It does separately report biogenic carbon removal of 0.0235 kg CO2/m^2-RSI with a greater biogenic carbon emission of 0.0445 kg CO2/m^2-RSI.

Bio-based vs. Other Materials

The previous section reviewed available data on the GWP of various insulation products. However, when the GWP potential is offset by carbon sequestration and storage of carbon in bio-based materials (with limited consideration of end-of-life final emissions back into the atmosphere), the GWP presents a very favorable selection bias for bio-based products. This effect is shown in images like Figure 75 (RMI, 2021) used in various guides to clearly show the GWP potential benefits (green or negative GWP values) of bio-based materials in comparison to those that have non-negative GPW values (colored yellow to red in accordance with increasing GWP).

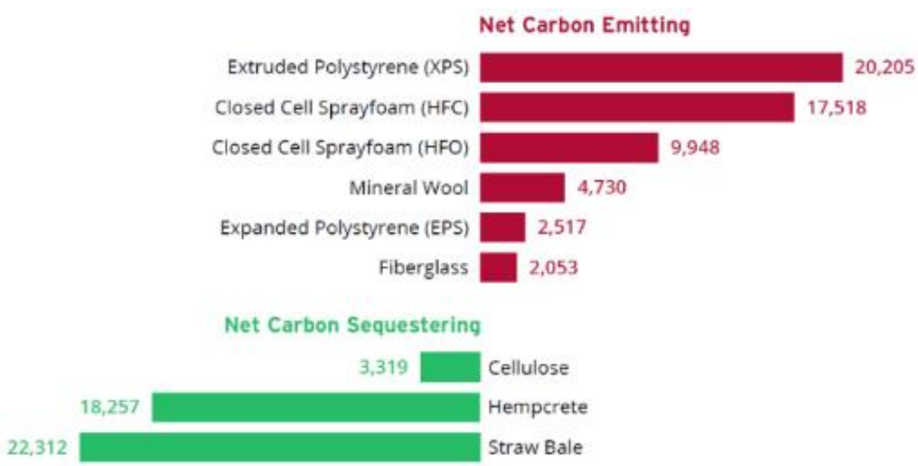

Figure 75. Embodied carbon of insulation materials (kg CO2e based on R-20 at 234 m2)

[150] https://cellulose.org/wp-content/uploads/2022/09/CIMA-Environmental-Product-Declaration-Conventional-Loose-Fill-Cellulose-Insulation.pdf, last accessed 2/22/2023

Source: RMI (2021) based on Chris Magwood, 2019, Opportunities for CO2 Capture and Storage in Building Materials

RMI (2021) also makes direct comparison of functionally different materials on a material mass basis as shown in Figure 76. This approach tends to misrepresent not only the functional differences in materials but also the differences in density and coverage for a whole building application which can result in a skewed sense of relative impacts of materials. This is particularly evident in the implied comparison of EPS to steel or concrete materials or the comparison of straw to steel. This information is essentially meaningless without the context of a whole building which places demands and constraints on functional attributes and amount of materials used to construct the building to meet its design objectives and code compliance. Such comparisons should only be made in the context of a complete building assembly or a whole building system.

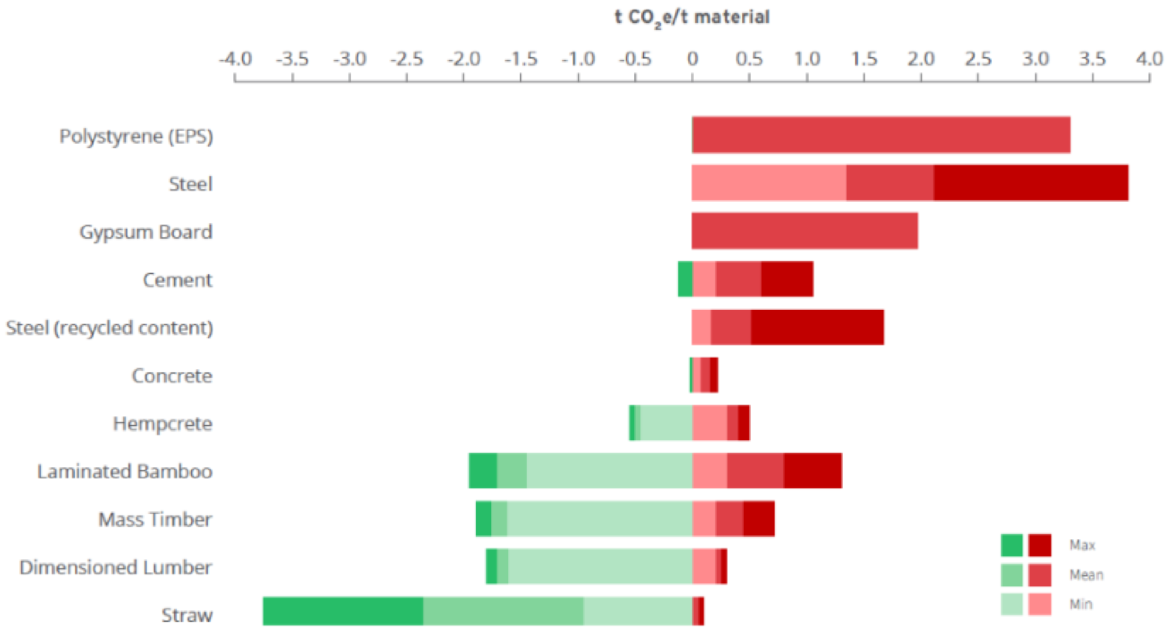

Figure 76. CO2e emissions and storage capacity of building materials.
Source: RMI (2021) based on Table S6 of Galina Churkina et al., “Buildings as a Global Carbon Sink,” Nature Sustainability, 2020.

The City of Nelson (2022) uses similar data to provide guidance on insulation material substitutions which tend to preference bio-based carbon storage materials as shown in Figures 77 and 78. A note is included with Figure 78 that gives some caution regarding insulation material substitutions and consideration of differences in performance. However, without appropriate guidance, few users may understand the significance of that note in making material selections based on these figures and perhaps only on equivalent material functional units and R-value, and not its actual system performance attributes.

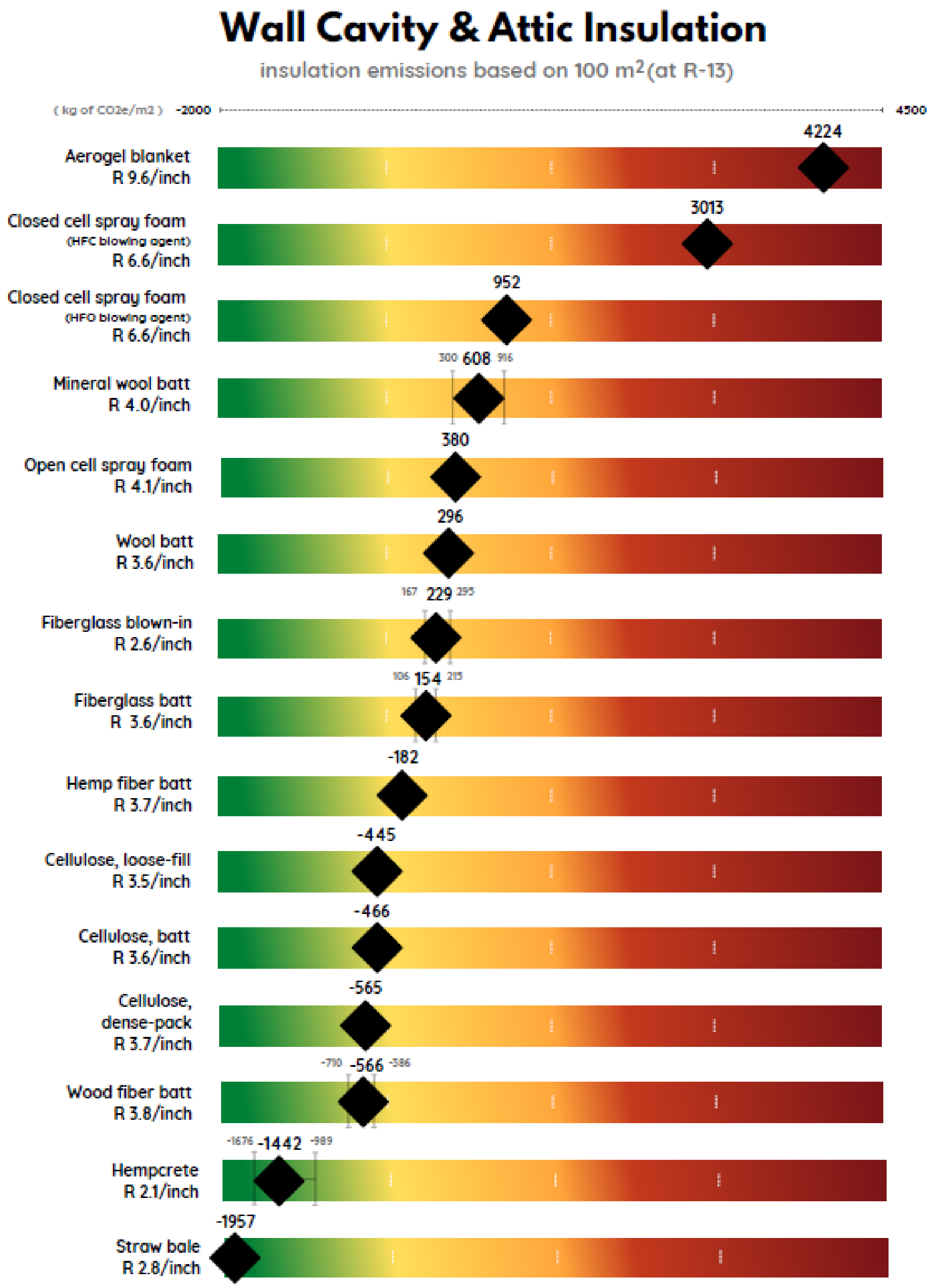

Figure 77. Cavity insulation material embodied carbon emissions
Source: City of Nelson (2022) based on Magwood et al. (2021)

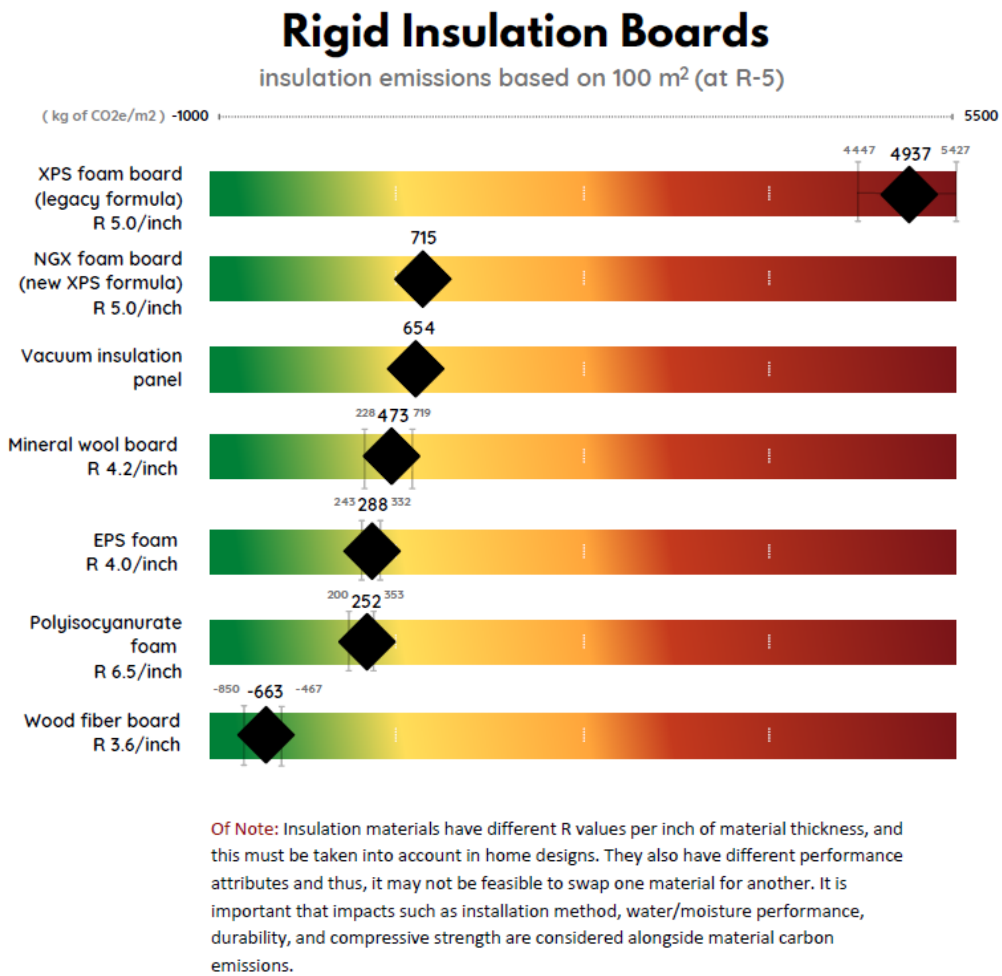

Figure 78. Continuous insulation (rigid board) insulation material embodied carbon emissions
Source: City of Nelson (2022) based on Magwood et al. (2021)

Efficiency Vermont (2022) provides a similar color scheme to provide selection guidance based on the "co-benefits" of substituting insulation materials as shown in the chart of Figure 79.

Material	GHG impact[a]	Recycled content[b]	Toxic emissions[c]	Notes[d]
Wood fiber	Lowest / best			
Cellulose	Lowest / best			
Fiberglass	Low			Avoid formaldehyde binders
Polyisocyanurate	Low			Chlorinated flame retardant (otherwise fairly inert) Toxic manufacturing process
EPS (expanded polystyrene)	Low			Brominated flame retardant
Open-cell spray foam	Low			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Phenolic foam	Low		See note	Phenol formaldehyde content, but low emissions
Mineral wool	Medium		See note	Choose low-emitting products
Closed-cell spray foam, HFO	Medium			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Closed-cell spray foam, HFC	Highest / worst			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
XPS (extruded polystyrene)	Highest / worst			Brominated flame retardant (otherwise fairly inert) Toxic manufacturing process

[a] Lowest: < 0 kgCO_2e including carbon content, per 1 m^2 RSI-1. Low: < 5. Medium: 5-10. High > 10. Calculations are based on analysis within this report.

[b] From "BuildingGreen Guide to Insulation." Green indicates significant recycled content or renewable material. Red indicates little or no recycled content and fossil fuel-based materials in typical products.

[c] From BuildingGreen Guide to Insulation." Green indicates relatively low toxic emissions during use from typical products. Red indicates potential high toxic emissions from typical products or during manufacturing or application.

[d] From BuildingGreen, "Environmental Notes" in "Key Environmental and Performance Factors for Insulation Materials" table.

Figure 79. Co-benefits of insulation material substitution based on assessment of GHG impact, recycled content, and toxic emissions.
Source: Efficiency Vermont (2022)

Similar depictions are used to guide selection of cladding and flooring materials as shown in Figures 80 and 81 (City and County of Nelson, 2022). These material choices can have a significant impact on the embodied emissions of a whole building, yet they too have significant architectural, functional, and performance differences that must be considered in making design decisions regarding substitutions.

In accordance with a Green Building Advisor article including an interview with Chris Magwood, the intent of graphical depictions and comparisons of GWP of bio-based vs. non-bio-based materials is as follows:[151]

> RMI's 2021 report on carbon details a number of low-cost and no-cost substitutions that can lower embodied carbon substantially. Choosing concrete mixes carefully, for example, can lower carbon emissions by as much as 33% with little or no increase in cost. Switching insulation may yield a carbon savings of 16% with no cost premium.

151 https://www.greenbuildingadvisor.com/article/a-new-carbon-tool-nears-its-public-debut, last accessed 3/4/2023

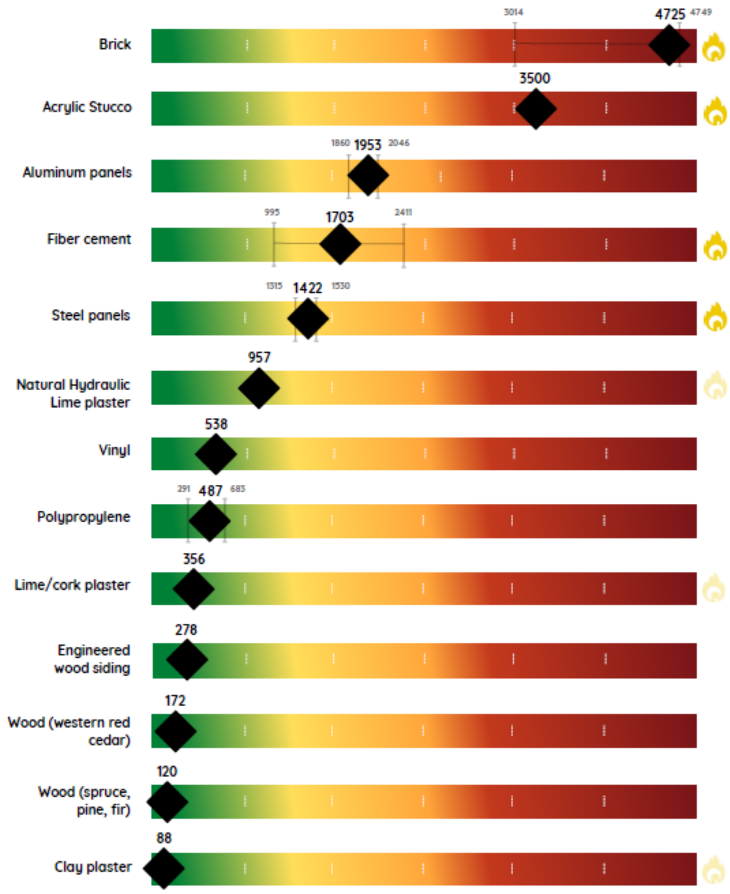

Figure 80. Cladding embodied GHG emissions (kg CO2e per 100m2)
Source: City of Nelson (2022) based on Magwood et al. (2021)

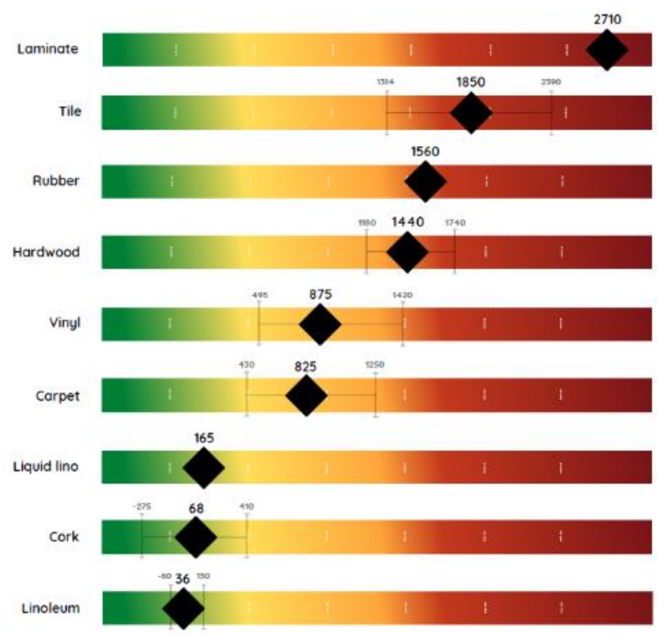

Figure 81. Flooring embodied GHG emissions (kg CO2e per 100m2)
Source: City of Nelson (2022) based on Magwood et al. (2021)

4.8 Critical EPD Application Considerations for Insulation Products

4.8.1 Evaluating Embodied + Operational Emissions is Crucial

Unlike most other building materials, insulation has a unique ability to improve the energy efficiency of a building by reducing operational energy use and associated GHG emissions over the service life of a building. This is the primary purpose and function of insulation. Therefore, an approach to decarbonization of insulation materials that focuses solely on material embodied carbon emissions (based on EPD reported GWP) is incomplete and will omit important decarbonization benefits of insulation materials realized during the use phase of a building. Such a material-based approach also risks causing unintended consequences potentially affecting building performance if used as a primary basis for substitution of building materials for structure, enclosure, and other functions. For these reasons, insulation materials must be evaluated in a manner that properly considers or indexes the relationship of insulation material embodied carbon emissions to the avoided carbon emissions they beneficially invoke during their use phase in a building. Several relevant studies will be reviewed in this section in chronological order. They all rely on principles and methods of whole-building lifecycle analysis (WB-LCA) which will be addressed more generally in the final section of this report.

The objective of a study by Kosny, Yarbrough, and Desjarlais (1998) at the Oak Ridge National Laboratory (ORNL) was to "develop a procedure for evaluating the energy and global warming impacts of alternative insulation technologies for U.S. commercial building applications". In their study they proposed a concept known as Total Equivalent Warming Impact (TEWI) which is the sum of direct and indirect impacts of GHG emissions (e.g., the savings of operational GHG emissions during use less the impact of insulation material embodied emissions during the full life-cycle of a building). The TEWI was employed as an index as follows:

$$\Delta TEWI = [TEWI_{(uninsulated\ building)} - TEWI_{(insulated\ building)}] / [TEWI_{(uninsulated\ building)}\}$$

A ΔTEWI value of less than one represents net carbon emission reduction or avoidance for the insulated building. The baseline for the above index is an uninsulated building which would be appropriate for assessing the impact of an insulation design for a new building. However, the baseline for an existing building may be based on an existing insulation amount to determine the ΔTEWI for an incremental increase in the existing insulation amount. The same approach also can be used to evaluate an incremental increase in insulation for a new building that exceeds minimum energy code insulation requirements. Further, as the baseline insulation level is increased well above that of an uninsulated building, diminishing returns in making incremental insulation improvements will eventually occur for both energy savings and related GHG savings (as indexed by ΔTEWI in the above equation or other methods addressed later in this section).

Using the above equation, the authors found ΔTEWI values ranging from 0.12 to 0.32 for two case study buildings in Atlanta and two effective building envelope R-values of 4 and 7. For Chicago, the ΔTEWI values ranged from 0.24 to 0.44. These effective R-values represents a small-to-moderate incremental improvement to an uninsulated building envelope, generally well below current US model energy code requirements for new construction. The case study building was a strip mall using either masonry or steel frame construction.

Of course, the magnitude of operational carbon emission savings or avoidance associated with the use of insulation materials in building thermal envelopes will depend on the expected life of a building (and the insulation materials), the current and future mix of HVAC equipment used to condition future new buildings (e.g., gas furnace vs. heat pump), and the future mix of energy sources used to generate electricity in the local or regional electric power grid (e.g., coal, natural gas, wind, solar, nuclear, hydro, etc.). It also will depend on the efficiency of the heating and cooling equipment used to condition the building. These variables are common to all methods of evaluating the magnitude of operational carbon emissions for comparison to embodied emissions.

Franklin Associates (2001) conducted a thorough study of the carbon emissions payback period (i.e., the time after building operations begin where operational emissions savings equal the upfront carbon investment). The study considered a representative house in both US and Canadian climates and weighted the results by housing population data in each climate region. The study evaluated the energy and GHG emissions savings that would occur with the addition of 5/8-inch thick continuous insulation to the exterior walls of the existing housing stock. The baseline exterior walls were assumed to be 2x4 wood frame construction with R-13 batt insulation in the stud cavities. The continuous insulation was represented by a combination of XPS and PIR insulation materials commonly used in the market at that time. The findings indicated substantial GHG emission savings over a 50-year time period after retrofit of the existing housing stock. The results for the US indicated an average payback of 2.09 years on the basis of energy savings compared to the embodied energy of the continuous insulation. The embodied energy payback varied from 1.4 to 3.0 years from cold to warmer climates in the US. Similarly, the GHG emissions payback was on average 12.5 years and ranged from 6 to 25 years in colder and warmer climates of the US, respectively. However, these payback periods were based on older formulations of XPS and PIR insulations that had embodied emissions about 30 times greater than the modern products used today (see Section 4.7.4). Studies reviewed later in this section update this work and demonstrate that the material emissions reductions over the past 30 years have dramatically improved (reduced) the GHG emissions payback time.

Subsequently, a more comprehensive study of the GHG emissions savings of XPS and PIR products was conducted Mazor, Mutton, Russell, and Keoleian (2011). The purpose of the study was to guide the evolution of insulation material development and to evaluate environmental performance across different insulation materials for diverse applications. It also was intended to help guide policy recommendations for effective insulation investments for applications including building roofs, walls, and floors of commercial. The scope of study addressed residential buildings in North America, Europe, and Asia for installations from 1971 to 2011, with projections for installations through 2025. An application lifetime of 50 years was assumed in the study of 28 different combinations of climate zone, building construction, and insulation conditions. It also considered changes in the XPS and PIR blowing agents over the same timeframe (but excludes the lower embodied carbon XPS and PIR products currently available). As illustrated in Figure 82, a comprehensive life-cycle model was constructed to evaluate the GHG emissions from insulation products at all lifecycle stages and the operational emissions avoided by reducing heating loads during the use stage. Avoided emissions by reduced cooling loads were ignored as a simplification.

The findings of the report addressed total GHG savings (the sum of embodied and operational emissions) for an assumed 50-year lifecycle and also considered the concept of payback which is the time required for the annual CO2e savings from insulation use to offset the CO2e embodied emissions of the insulation. **Based on the study, the average CO2e emissions savings to embodied emission ratio was reported to be 48:1 (also known as "avoidance ratio") with a range from 3 to 1,800.** In other words, the embodied GHG emissions investment in the use of XPS and PIR insulation resulted in a typical GHG emissions savings 48x greater over a the 50-year life cycle. Use of current XPS and PIR material GWP values for lower-GHG blowing agents available today would further improve (increase) the avoidance ratio.

The payback time for the variation of the blowing agents considered in the study were evaluated and graphically illustrated in the "bubble" graphic shown in Figure 83 (Mazor, Mutton, Russell, and Keoleian, 2011). The bubble type indicates blowing agent type and the bubble size indicates the magnitude of 50-yr life cycle GHG emissions savings. The sensitivity of payback time to other important variables, such as amount of existing insulation and mechanical equipment efficiency, were also evaluated and presented in similar graphic form. **In general, the payback time was often 1 year or less for low GHG blowing agents more reflective of current foam plastic insulation products in today's market.** This finding is also reflected in a more recent paper by Schmidt and Chertak (2023) addressed later below.

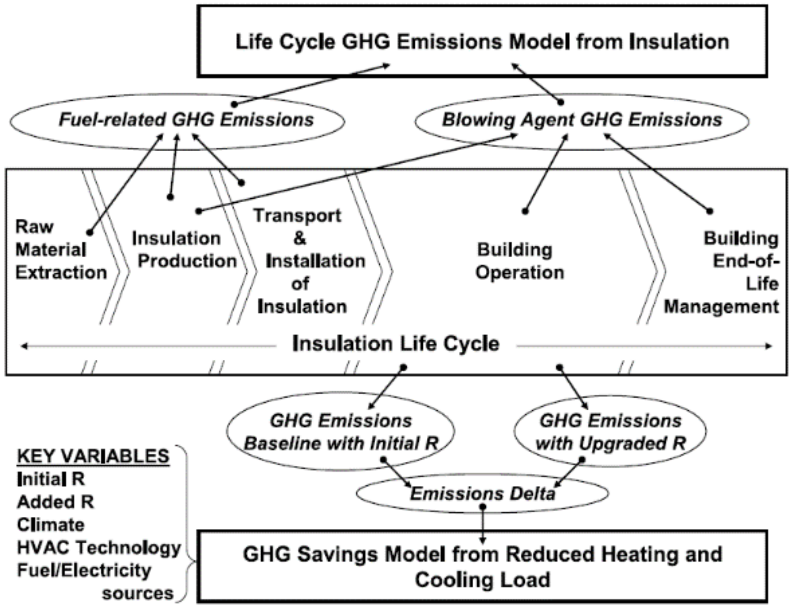

Figure 82. Life cycle stages for building insulation and key elements of GHG emission and savings models.
Source: Mazor, Mutton, Russell, and Keolian (2011)

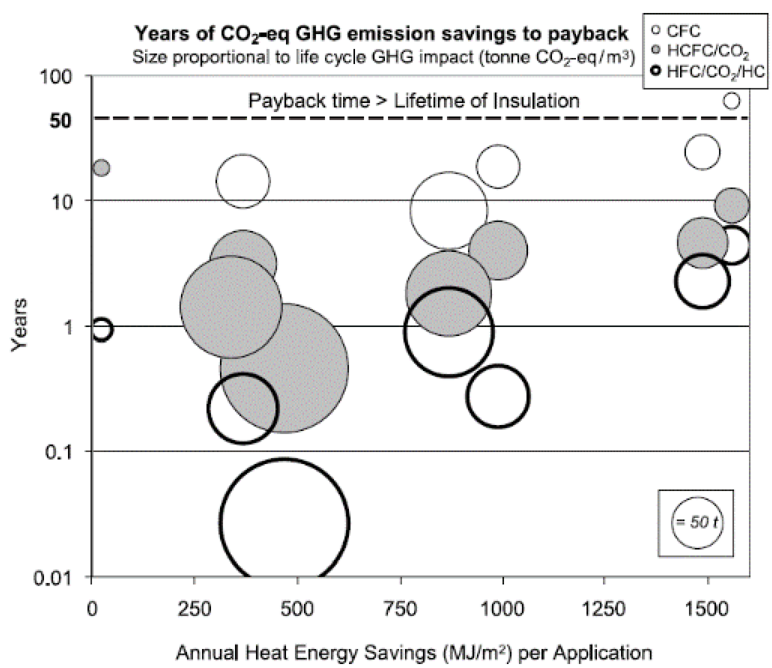

Figure 83. Influence of XPS and PIR blowing agent on GHG emissions based on payback time and lifecycle savings.
Source: Mazor, Mutton, Russell, and Keolian (2011)

In 2014, another study by ORNL expanded on and improved the concept of TEWI presented earlier (Shrestha, Bhandari, Biswas, and Desjarlais, 2014). The authors recognized the following:

> While insulation materials have a positive impact on the environment by reducing energy consumption in buildings, they also have some negative environmental impacts associated with their 'embodied energy'. The total lifetime environmental impacts of insulation materials are a summation of: (1) direct impacts due to their

embodied energy, and (2) indirect or environmental impacts avoided due to the reduced building energy consumption.

The authors developed a simplified algorithm based on regressions of whole building energy modeling to develop a means to quickly assess the lifetime energy and environmental impacts and benefits (e.g., carbon emission avoidance) of insulation materials. Two spreadsheet tools calculated embodied energy and GWP of insulation materials, the estimated energy savings, and the avoided environmental impacts due to the use of insulation materials in buildings. As with other studies reviewed in this section, such an approach could also be adapted to assess specific building assemblies, such as walls and roofs, in a manner consistent with a whole-building lifecycle analysis (and also consistent with the approach to evaluate embodied energy used in the 1970s – see Appendices A and B).

The authors found that operational carbon emissions savings based on energy savings caused by including code-minimum insulation in representative commercial buildings (16 types) for all US climates ranged from about 100 to 750 times the GWP represented by the embodied carbon emissions of the insulation materials used in the building envelope. These GHG emissions avoidance ratios were based on a 60-yr life cycle and were significant for all insulation materials considered (polyiso, XPS, EPS, and Aerogel) despite their large differences in material GWP and the use of now outdated GWP values. In fact, the XPS and polyiso materials used in the study were of the older variety using high GWP blowing agents which have been replaced by low-GWP blowing agents having as much as an order of magnitude lower GWP (see EPD data on insulation materials in Section 4.7.4). The greater savings values were associated with colder climates and lower-GWP insulation materials. **Also, lower values were determined separately for existing buildings with an incremental insulation improvement at year 30 that resulted in positive (beneficial) GHG emissions avoidance ratios ranging from 4 to 16 for the remaining 30 years of service life.** It was noted that these avoidance ratios also tend to decrease (diminishing benefits) as building heating and cooling equipment efficiencies improve and the electric power grid (to the extent used for heating and cooling of buildings) becomes increasingly transitioned to renewable or low-carbon energy sources (e.g., solar, wind, hydro, nuclear, etc.) in displacement of fossil fuels (e.g., natural gas and coal).

The PCR used to develop EPDs for North American insulation products includes guidance on consideration of additional environmental information in “Section 7.2 Energy Savings During Use” (UL, 2018). However, the PCR does not factor operational carbon savings into the reported GWP of insulation materials because it is dependent on a multitude of different scenarios in end use as noted above. This concern with end use scenarios is not all that different from the consideration of carbon sequestration of bio-based materials which is subject to many factors and assumptions related to forestry practices, use conditions, and end-of-life scenarios. The insulation material PCR does not mention or characterize the concept of an “avoidance ratio”. It also requires use of sophisticated energy modeling tools to evaluate specific use scenarios, thus effectively prohibiting the simplified tools and approaches noted in the studies discussed above. However, it does not prohibit the market from using such simplified methodologies to estimate building energy use and GHG emissions savings together with consideration of EPD-reported GWP data for materials.

In compliance with Part B, Section 7.2, of the insulation industry PCR (UL, 2018), the industry-wide EPD for polyiso roof insulation reports GHG emissions savings for roof insulation applications.[152] The approach and assumptions are described in the EPD as follows:

- analyzed life-cycle embodied energy and CO2e emissions of polyiso insulation relative to operational savings of primary energy demand and CO2e emissions;
- used a retail strip mall as case study with roof insulation levels below current ASHRAE Standard 90.1 requirements; and,

[152] https://www.polyiso.org/page/EPDs, last accessed 2/22/2023

- evaluated the impact of replacing and adding insulation to bring the roof up to code during roof replacement at 35 years. A roof recover was assumed to occur at 17.5 years as a standard practice prior to the roof replacement at 35 years. The roof recover (simply placing an additional roof membrane over the initial roof membrane) was not factored into the analysis because it is a separate matter and results in no change to the originally installed roof insulation.

The main conclusions based on national averages are as follows:[153]

- With regard to energy savings, a national average primary energy demand (PED) savings ratio ("PED Savings Ratio") of 28:1 was found. The PED savings ratio is the life-cycle operational building energy savings divided by embodied primary energy demand associated with the polyiso insulation material. The ratio is greater for the generally colder climate of Canada. A break-even point (energy savings neutrality) occurred at about 15 months where operational energy savings begin to exceed the embodied energy of the polyiso insulation with a shorter re-coup period for Canada. This is known as the "PED Recoup Period".
- **With regard to GWP (CO2e Emissions), a 34:1 CO2e avoidance ratio (45:1 in Canada) was found with a CO2e recoup period (payback time) of 13 months (9 months in Canada).** Thus, net carbon emissions savings (i.e., payback) was observed to occur generally within about one year of building operation just due to the incremental addition of roof insulation to an existing building roof at the time of a routine roof replacement.

Similarly, an EPD for FOAMULAR® NGX ™ XPS Insulation (Owens Corning) reports net energy and GHG emission avoidance in terms of net MJ or net kg CO2e saved (first year) and a **payback time to net zero energy or GHG emissions impact ranging from 0.5 to 1.1 years** depending on climate and wall assembly type (cinder block or steel stud). This payback range is consistent with the range reported above in the PIMA industry-wide EPD for polyiso roof insulation materials. In an EPD for the FOAMULAR® XPS, which uses the higher GWP HFO blowing agent (discontinued), the payback times for energy are the same (i.e., no difference in thermal performance because the R-value is the same) but the payback times for GHG avoidance are longer, ranging from 3.0 to 6.5 years as expected, instead of 1 year or less. The EPD for Ecotouch® PINK® Fiberglass Batt & Roll Insulation (Owens Corning) reports a payback time of 38.5 days in Chicago and 59.1 days in Phoenix based on operational energy savings (compared to no insulation) relative to embodied energy of the insulation. The GHG emissions avoidance ratio was not reported.

In 2021, KPMB Architects conducted a study of the embodied carbon of various insulation materials which considered the operational GHG emissions payback over time (KPMB, 2021). The 11 insulation material types considered were XPS, Polyiso, spray foam, EPS, mineral fiber, fiberglass batts, blown cellulose, and others. Unfortunately, the study used now outdated GWP data for the XPS products which are shown as blue and yellow lines at the bottom of the chart in Figure 84. With this correction, essentially all insulation materials are relatively tightly grouped and provide a fast payback on GHG emissions (e.g., generally less than 1.5 years with nearly identical and equally substantial GHG savings within several years). Figure 84 is for a case where natural gas is used for heating a building and the insulation serves to reduce the direct combustion of fossil fuel by reducing the building's heating demand.

[153] Findings as summarized by Jerry Phelan, Covestro (retired), pers. comm. 2/21/2022

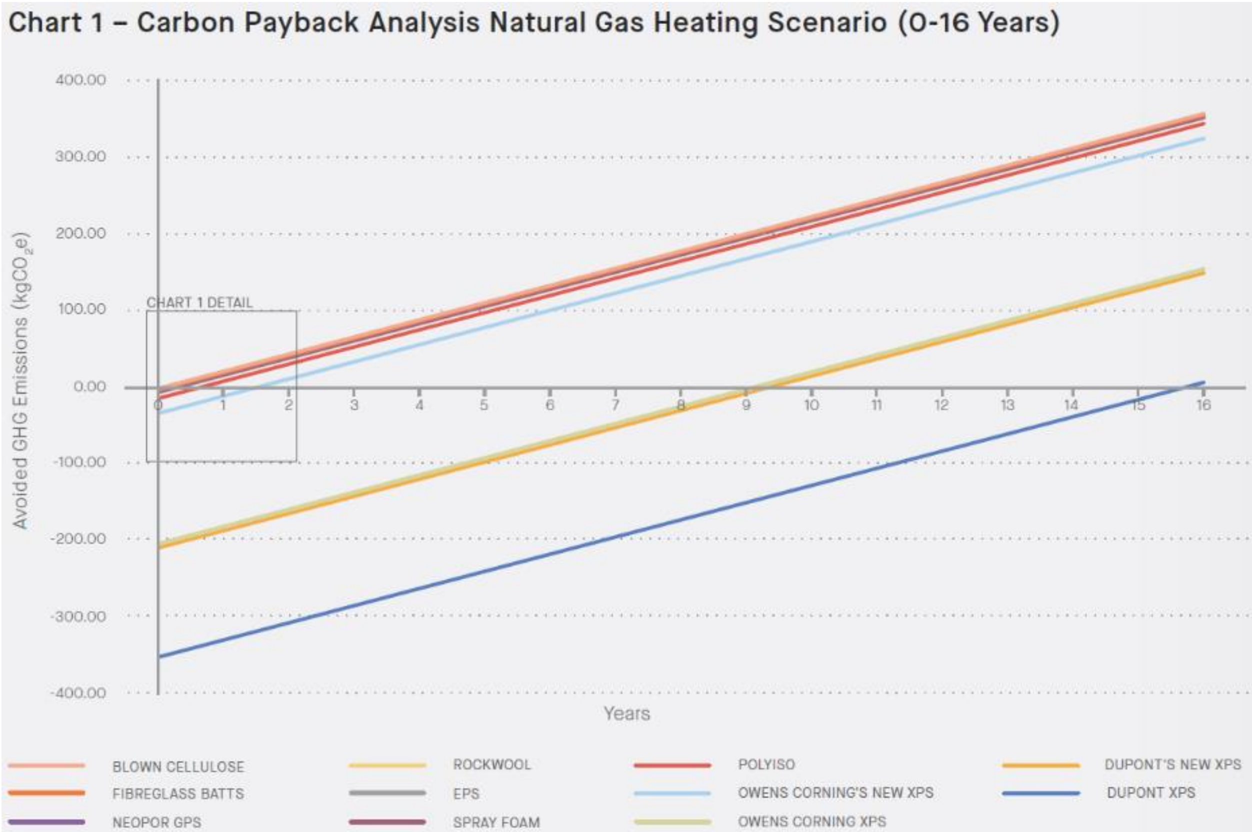

Figure 84. Carbon Payback for Case Study of a Building Heated by Natural Gas Combustion

Source: KPMB Architects (2021)

NOTE: The yellow and dark blue lines at the bottom of the chart are based on outdated GWP values for XPS insulation (refer to the light blue line as representative of current XPS materials which are grouped in close proximity with all other insulation types)

Figure 85 is for the case where a heat pump is used in a region with a low-carbon electric grid. Making the same correction as noted above for the XPS materials, essentially all insulation materials perform the same in terms of carbon emissions payback and avoidance or savings over time (although small due to the assumed clean electric grid). In the scenario of Figure 85, the key role of any insulation material is to reduce electricity demand and energy cost, particularly since any difference in embodied carbon is essentially insignificant in terms of climate impact (i.e., the total contribution of all insulation materials used in the US for building construction result in less than 0.01% of total global CO2e emissions annually as estimated in Section 4.7.4). Insulations of all types also continue to play an important role for affordability by reducing energy bills regardless of the source of the energy used in the future.

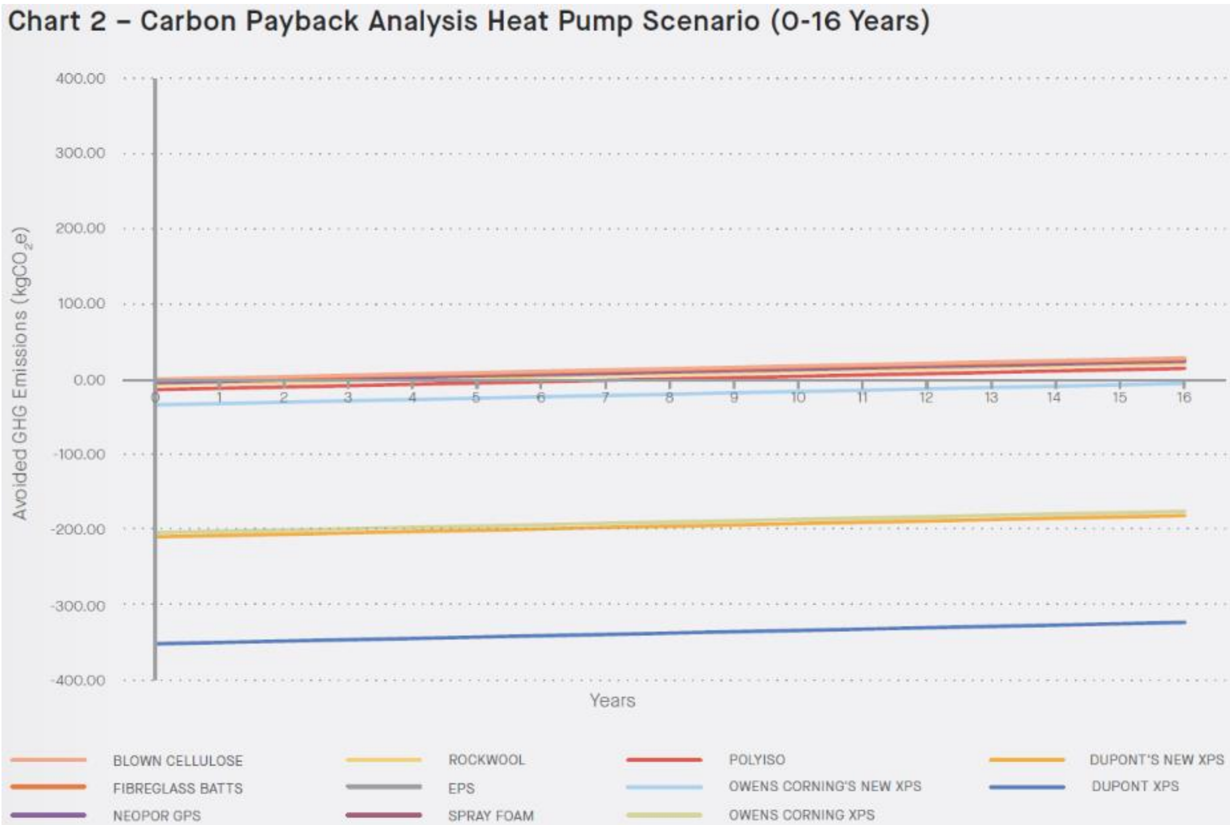

Figure 85. Carbon Payback for Case Study of a Building Conditioned by a Heat Pump in a Region with a Low-Carbon Electric Grid.

Source: KPMB Architects (2021)

NOTE: The yellow and dark blue lines at the bottom of the chart are based on outdated GWP values for XPS insulation (refer to the light blue line as representative of current XPS materials which are grouped in close proximity with all other insulation types)

The KPMB Architects study also evaluated the relationship of embodied to operational carbon (i.e., “total carbon”) in the consideration of incremental increases in the R-value of the various insulation materials as shown in Figure 86 (for same building case study as Figure 84). Again, with corrections mentioned above for the XPS products, all of the insulation materials including the newer XPS products in today’s market perform similarly with GHG emissions savings increasing (but at a diminishing rate) as the R-value increases as would be expected. However, the charts do show that high GWP insulation materials (which is no longer applicable to current low-GWP XPS products and blowing agents) can exhibit a trough-shaped (concave) total carbon curve meaning that a theoretically optimum R-value occurs at the lowest point of the curve where the only performance metric considered is total carbon emissions. A similar chart was also done for the heat pump case and shows a similar trend for all insulation materials, but with much lower total GHG emission savings due to the clean electric grid assumed.

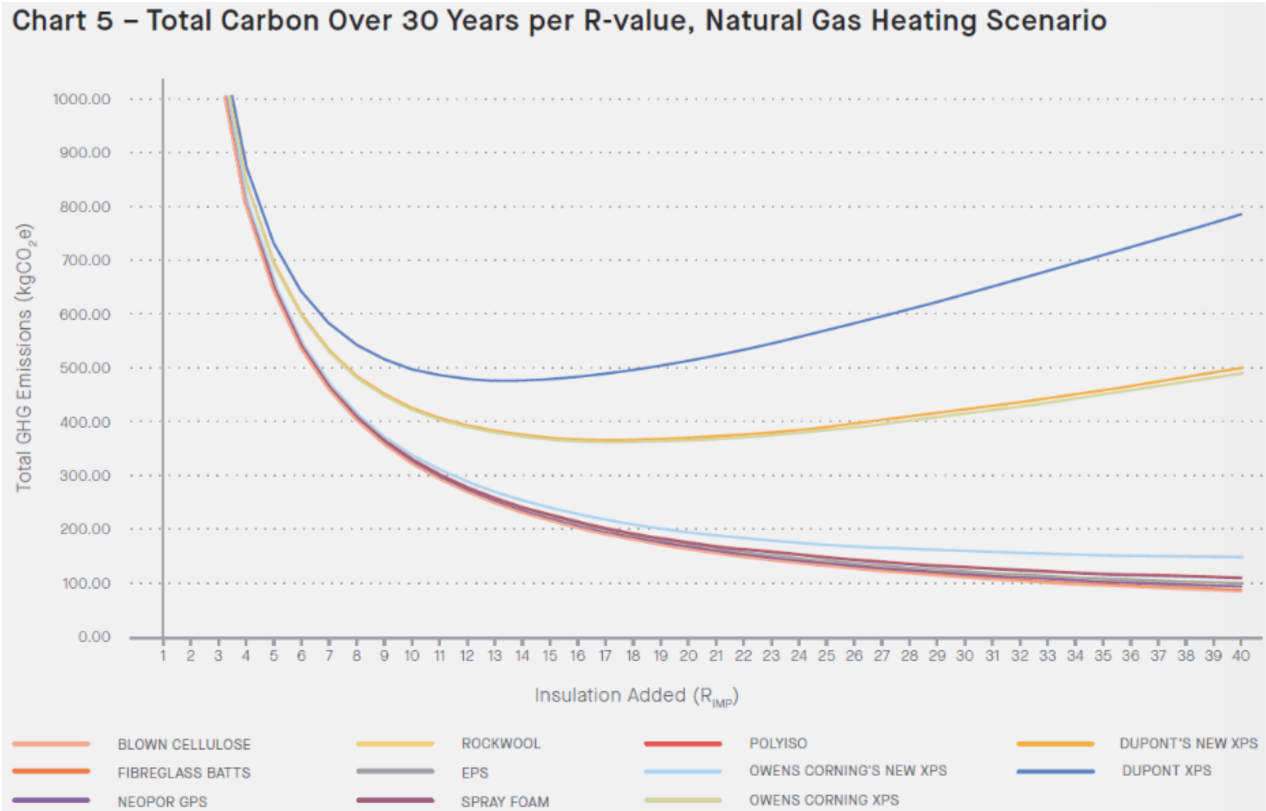

Figure 86. Total carbon for a 30-year Lifecycle per Incremental Change in Insulation R-value using a Natural Gas Heating Scenario

Source: KPMB Architects (2021)

NOTE: The yellow and dark blue curves at the top of the chart are based on outdated GWP values for XPS insulation (refer to the light blue line as representative of current XPS materials which are grouped in close proximity with all other insulation types)

Echenagucia, Moroseos, and Meek (2022) conducted a parametric study of building envelopes to understand the relative importance of operational and embodied carbon emissions and how they vary with climate, energy grid carbon intensities, and material embodied carbon. They completed a total carbon analysis for over 25,000 different residential and office buildings in six different US cities with varying heating and cooling degree days (i.e., 751 – 4017 HDD18ºC and 1118 – 4023 CDD10ºC) and varying current energy grid carbon intensities (i.e., 0.135 – 0.559 kg CO2e/kWh) with varying rates of reduction in grid carbon intensity per future year (i.e., 0%, 2%, 3% and 5% reduction per year). Heating and cooling by an air-source heat pump was used in all cases. The envelope variations included window-to-wall ratios (WWRs), wall assemblies, shading devices, glazing types and air infiltration rates. The intent of the “total carbon” envelope analysis was to provide insight for designers and policy-makers to guide decisions aimed at reducing climate impacts by considering optimization of envelope assemblies to minimize lifecycle carbon emissions.

The authors used the EC3 embodied carbon calculator tool and the DOE’s EnergyPlus whole building energy modeling software. The flowchart for their analysis methodology is shown in Figure 87. The parametric strategy was an “exhaustive search process” where results from the analysis methodology were collected in a database and analyzed for trends, optimal solutions, and gaps in knowledge. Key parameters were considered to be the WWR and wall assemblies as they played a significant role in both embodied and operational carbon emissions. For both residential and commercial office buildings the selection of insulation materials was polyiso exterior continuous insulation (of varying thicknesses from 0 to 6 inches) and cellulose cavity insulation (varying from 0 to 9.25 inches thick which wood or steel stud depths varying accordingly).

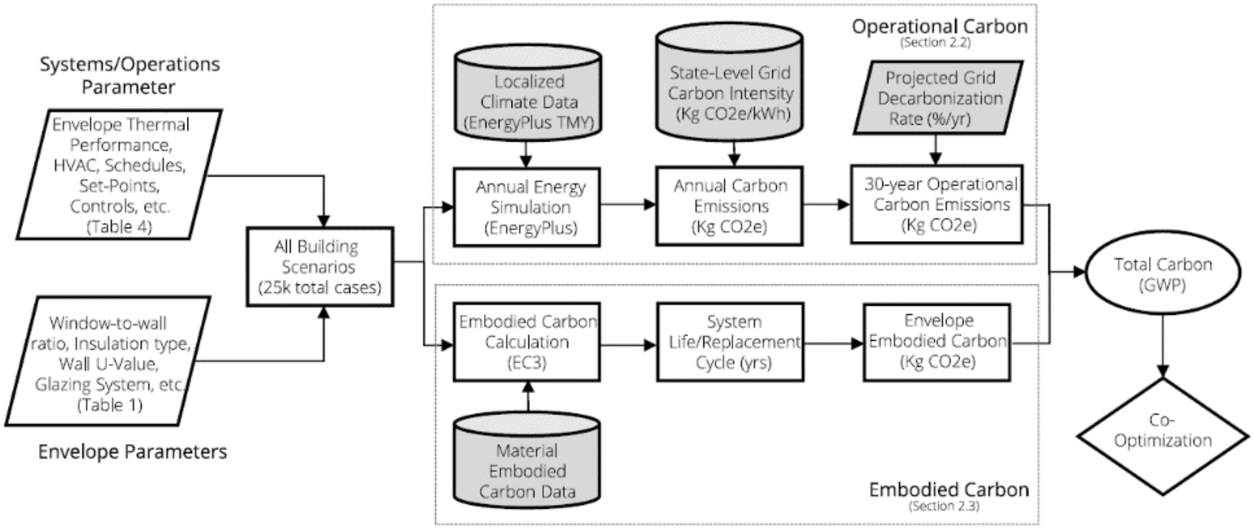

Figure 87. Total carbon methodology flow chart
Source: Echenagucia Moroseos, and Meek (2022)

The study produced results like those shown in Figure 88 based on the best-case electric grid with the highest assumed rate of future emissions intensity reduction for the office building case only. The variation in WWR shows a modest impact on the magnitude of total carbon. Also, the different assemblies with different insulation levels shown in the vertical bars within each WWR generally show a relatively small change in comparison to the magnitude of total carbon. In all cases, operational emissions (gray colored portion of the bars) exceed the embodied emissions (green portion of the bars) in the total carbon assessment. Even so, there are opportunities to optimize these small differences by selecting assemblies that minimize the total carbon emissions. But, this is not necessarily a complete means of optimization. For example, the study did not consider other beneficial impacts of insulation materials for envelopes, such as multi-functional assembly optimization and the reduction of energy demand that impacts the amount of grid power required to meet the population's energy demand and creates difficulties with the electric grid transition to lower-carbon energy sources. These are matters of energy efficiency (as discussed earlier in this report) that also have implications and inter-relationships with optimizing embodied and operational emissions for a given building in a given climate and electric grid situation.

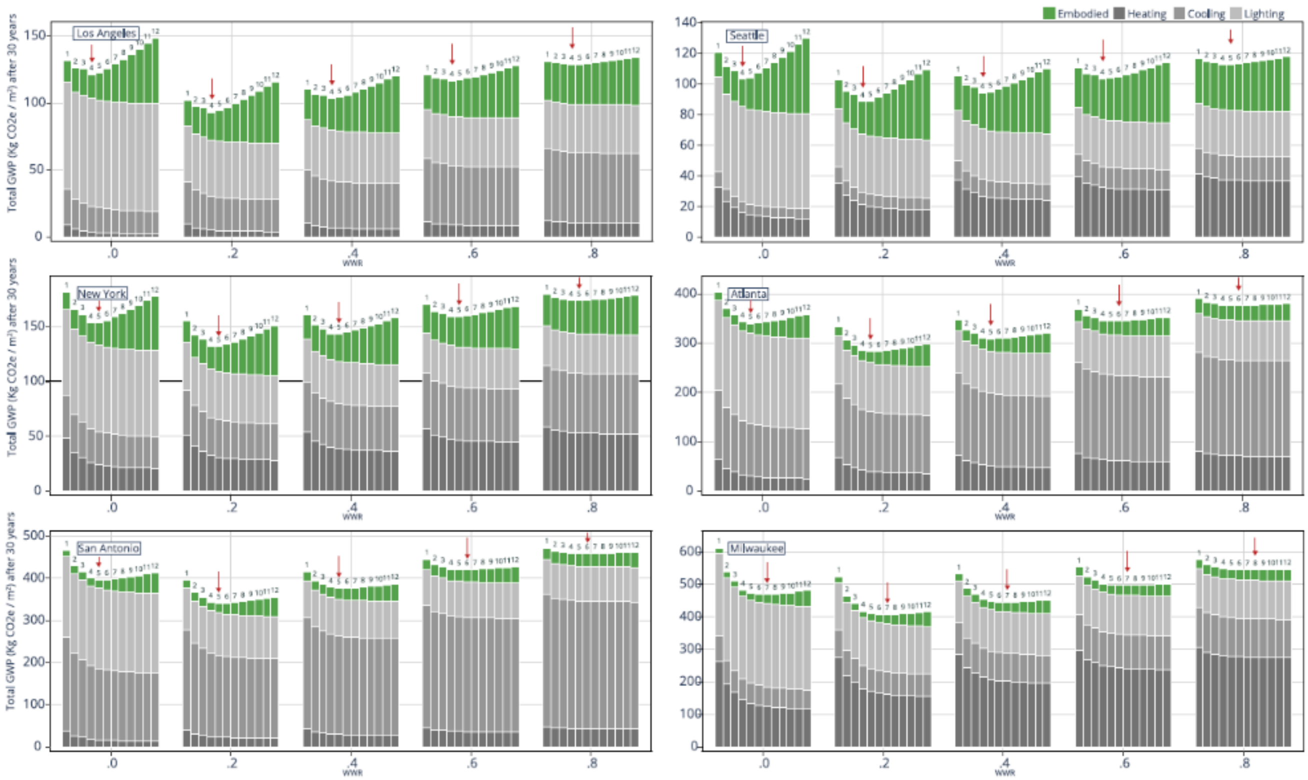

Figure 88. Example total carbon analysis of embodied (green) and operational (gray) carbon emissions for six US cities and 12 different steel frame wall assembly conditions and a range of window-to-wall ratios (WWR) for a typical mid-rise office building conditioned with a high-efficiency heat pump [y-axis is total GWP in kg CO2e/m^2 for 30-year time period].

Source: Echenagucia, Moroseos, and Meek (2022)

To appropriately address climate impacts as well as other important related impacts such as the cost of energy (which is a significant factor in assessing energy code efficiency measures), an assembly or whole building optimization procedure should be based on a cost-benefit optimization including the cost of insulations and future energy cost savings together with a social cost of carbon (see Section 1.4) applied to the embodied and operational emissions. All the future costs and savings would then be discounted to a present value which includes the impacts of energy use as well as the cost of future climate damages as represented by the social cost of carbon value. Such an optimization process would be more complete and useful for design and policy decisions in support of the report's intended objective. Refer to Section 4.8.6 for additional information.

The author's did provide some potentially significant policy guidance by comparing the study's optimization results to the 2021 International Energy Conservation Code (IECC) insulation requirements. As shown in Figure 89, it was found that, except in the milder climates, there was opportunity to gain total carbon reductions by increasing the minimum code insulation requirements. This opportunity was most significant for the colder climate studied and those with a higher emission intensity electric grid. This limited opportunity to improve envelope thermal performance (from the perspective of optimizing total carbon emissions) may be because both energy cost and social cost of carbon were not factored into the final optimization which was based only on total carbon. It may also be influenced by the exclusive use of heat pumps for heating in the study without consideration that it will take time to transition away from natural gas heating as a part of an unfolding building electrification movement.

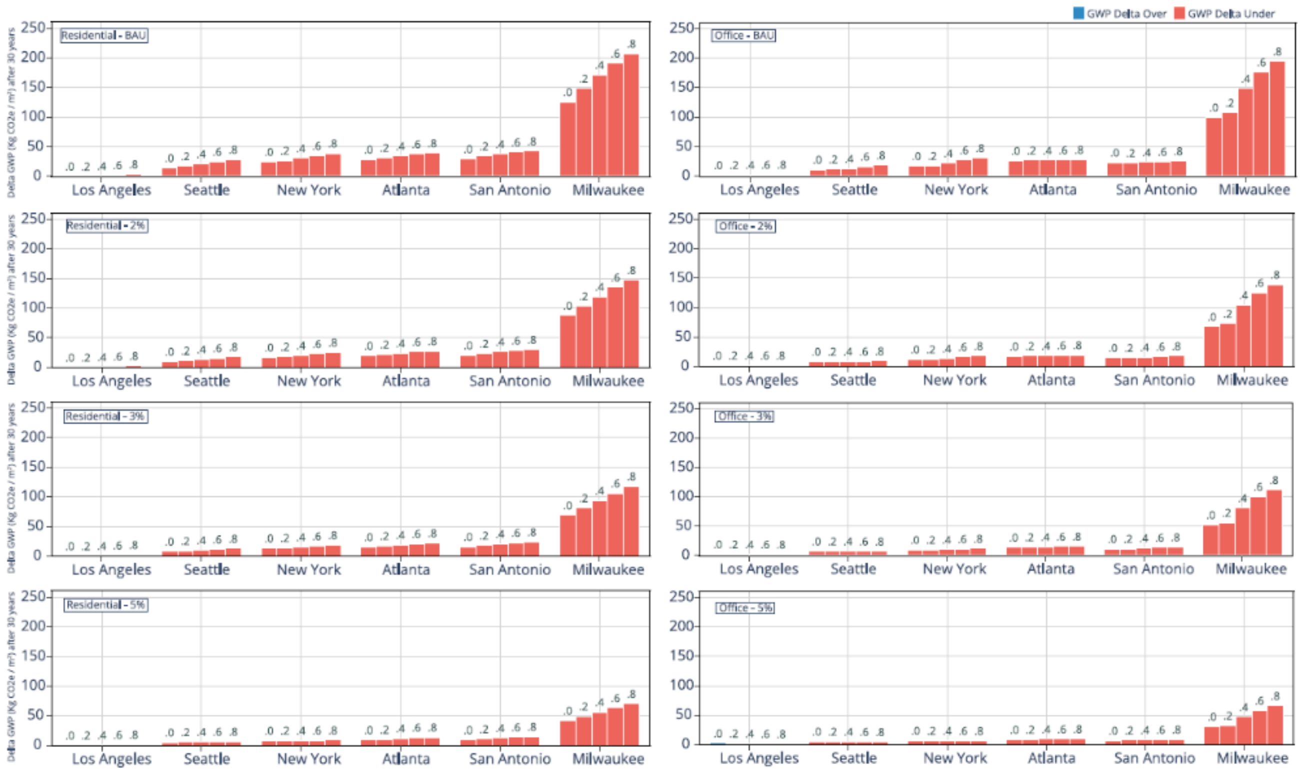

Figure 89. Building wall assembly excess carbon emission intensity (kg CO2e/m2/yr) due to sub-optimal insulation wall levels in the 2021 IECC.
Source: Echenagucia, Moroseos, and Meek (2023)

Finally, a study evaluating the energy and total GHG emissions payback and lifecycle savings was conducted for the use of modern foam plastic insulation materials (XPS, polyiso, and spray foam) with their current low-embodied carbon blowing agents (Schmidt and Chertak, 2023; ICF, 2023). A typical residential and commercial office building were studied in two US climate zones (Climate Zones 3 and 5 per the IECC) representative of the bulk of US building activity and climate conditions. The insulation levels evaluated were consistent with minimum 2021 IECC insulation R-values. Both the whole building and the individual building envelope assemblies (walls, floors, and foundation) were evaluated for payback time and overall life cycle (75 years) GHG emissions impact (savings) due to the considered insulation designs exclusively using foam plastics for cavity and exterior continuous insulation.

The study selected a representative energy grid and applied three renewable energy cost scenarios – high, medium, and low – which govern the rate of the future electric grid transition or decarbonization in accordance with the National Renewable Energy Labs (NREL) Cambium scenarios.[154] The heating systems considered included both direct fossil fuel combustion (e.g, natural gas furnace) and heat pump technology in accordance with current mix in new construction. Cases with all natural gas furnace and all electric heat pump technology applications were also considered.

The findings for GHG emissions payback time were reported in the time frame of months rather than years because of the fast payback determined for all of the considered foam plastic insulation types, assemblies, and whole building scenarios. **In general, the GHG emissions payback time for the whole building and individual envelope assembly scenarios was found to be less than 12 months (1 year) and less than 2 months in some scenarios (e.g., wall insulation for the residential building in Climate Zone 5 using a heat pump across all of the electric grid transition scenarios). The ratio of total life cycle operational**

[154] https://www.nrel.gov/analysis/cambium.html, last accessed 12/26/2023

carbon savings to insulation embodied carbon investment (i.e., avoidance ratio) was found to range from 30:1 to 348:1 for the residential building prototype depending on heating system and electric grid factors. For the commercial office building prototype, the avoidance ratio ranged from 18:1 to 305:1, again depending on heating system and electric grid factors. The only exception to the above findings was related to slab insulation which was found to be inappropriately addressed in the whole building energy model employed resulting in a potentially significant underestimation of operational energy savings.

The key findings of the paper by Schmidt and Chertak (2023) and study by ICF (2023) for building envelop applications of EPS, XPS, SPF and PIR foam plastic insulations are summarized by the graphic in Figure 90.[155,156]

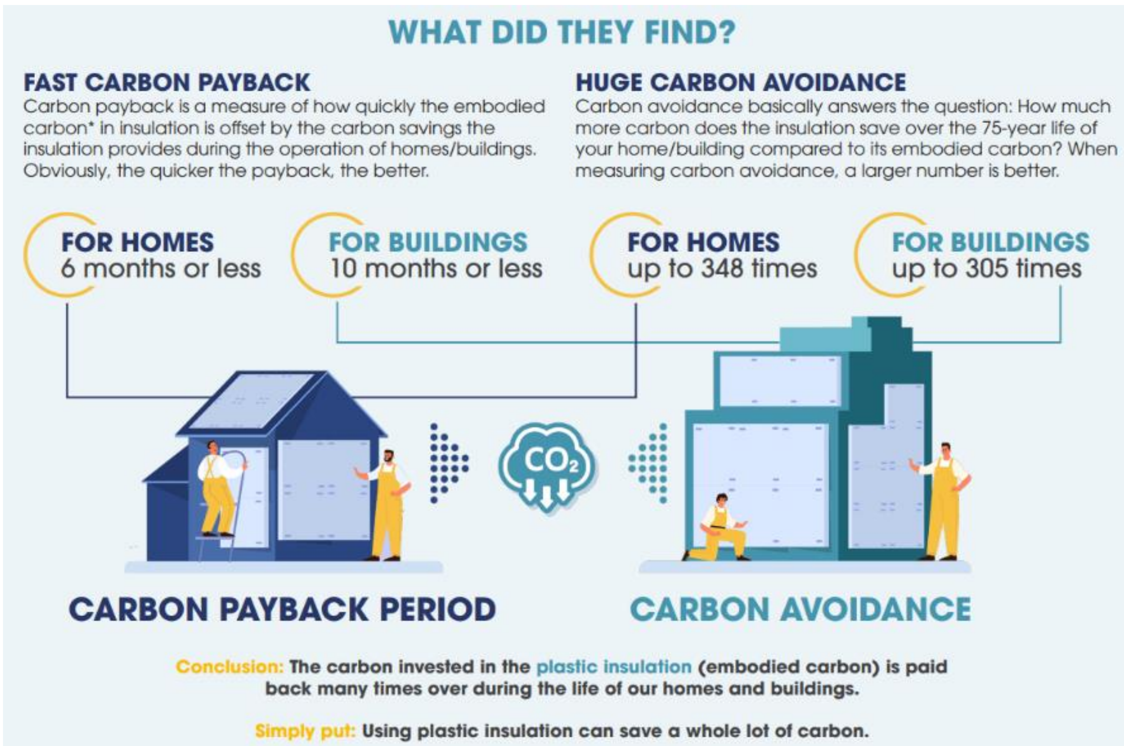

Figure 90. Fact Sheet: “Using plastic insulation can save a whole lot of carbon”[157]

Taken as a whole, the various total GHG emission studies reviewed in this section demonstrate that it is crucial to consider both embodied and operational emissions when assessing the climate benefits (or impacts) of any insulation material whether for design or policy-making purposes. The neglect of the total carbon footprint and handprint of insulation materials can have unintended consequences that distract from the overall goals of any climate mitigation strategy. It also can potentially result in counter-productive signals against energy efficiency which is a foundational aspect of supporting the broader transition to an effectively decarbonized future. For this reason, holistic approaches to help make decarbonization technically and economically feasible (especially for existing buildings) should be pursued with energy efficiency as an important part of a rational pathway for total carbon emissions reductions. An example of such a holistic approach is illustrated in Resource Efficient

[155] https://www.americanchemistry.com/better-policy-regulation/plastics/resources/unlocking-carbon-savings-with-plastic-insulation-materials, last accessed 12/26/2023

[156] https://www.americanchemistry.com/better-policy-regulation/plastics/resources/determination-of-total-carbon-impact-of-plastic-insulation-materials, last accessed 12/26/2023

[157] https://plasticmakers.org/wp-content/uploads/2023/11/ACC-Factsheet-Using-Plastic-Insulation-Can-Save-a-Whole-Lot-of-Carbon-v8-1.pdf, last accessed 12/26/2023

Decarbonization (RED) strategy shown in Figure 91.[158,159] Furthermore, such an approach is needed to address the significant challenge of electrifying buildings through a grid that is in transition to more renewable and variable power sources (e.g., wind and solar) while still needing to accommodate the demand for heating, particularly in colder climates (Rosenow and Hamels, 2023).

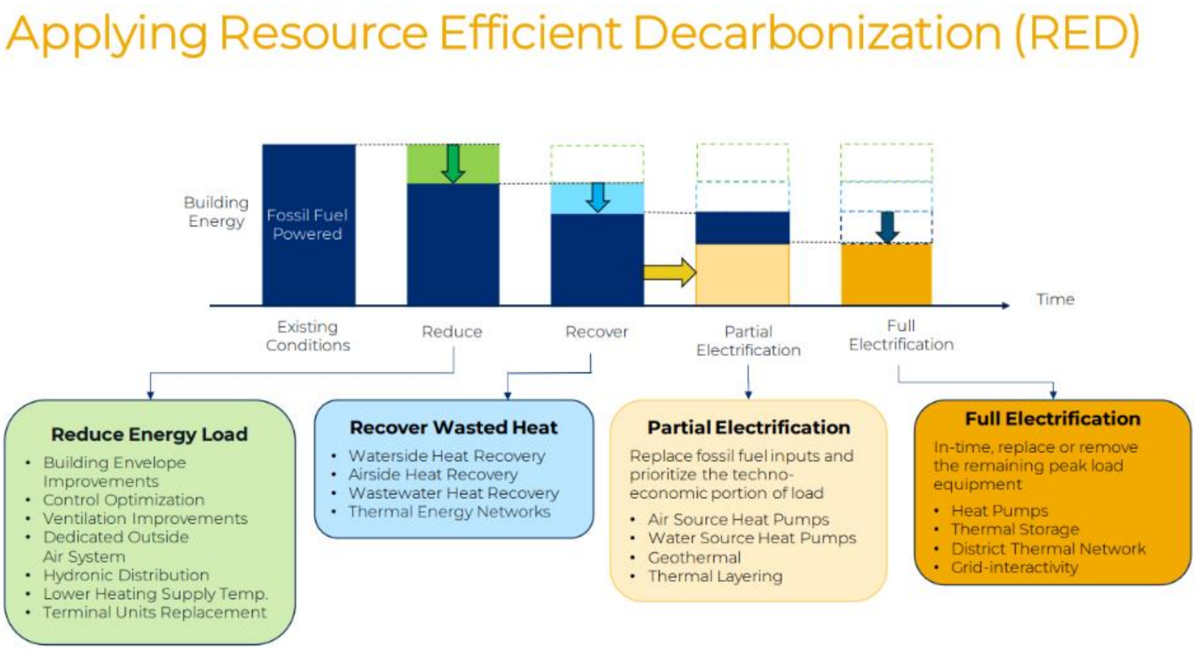

Figure 91. Time-sequenced approach to existing building decarbonization as successfully used in the RED strategy.[160]

Future work should be undertaken to simplify the types of total carbon analyses reviewed in this section which are necessary to understand both energy savings and total carbon emissions benefits of insulation materials (e.g., payback and avoidance ratio). A simplified and reasonably accurate tool would reach a broader audience (not just researchers or specialized building modelers) and better enable informed decisions by manufacturers, building practitioners, design professionals, and policy-makers. Such a tool also should couple embodied and operational carbon emissions with the social cost of carbon so that the economics of energy efficiency (e.g., fuel cost savings and insulation material cost) can be rationally coupled with the economics of mitigating future climate impacts. Finally, the tool should provide guidance on optimization opportunities, such as leveraging the multi-functional applications of foam plastic insulations to reduce total emissions and construction cost in a resource-efficient manner.

4.8.2 Significance of GWP Improvements (EPD History)

One of the primary and original purposes for EPDs was to enable the ability to track and manage GHG emissions of and improvements for various products including building materials such as insulation. As addressed in Section 4.7.4 on the embodied GHG emissions of various building materials, it was shown that many building products have shown significant improvements in their carbon footprint. This is particularly true for some of the foam plastic insulation materials where improvements have reduced product GWP values by as much as two orders of magnitude and over 90% within the past 10 years or so as shown earlier in Figures 70 and 73 based on Schmidt and Chertak (2023). It also was noted that these reductions far exceed the 30% reduction in embodied emissions of building materials by 2030 as a recommended federal policy consideration

[158] file:///C:/Users/Owner/Downloads/111_resource_efficient_decarbonization.pdf, last accessed 11/15/2023
[159] https://www.nyserda.ny.gov/All-Programs/Empire-Building-Challenge/Empire-Building-Challenge-Projects, last accessed 11/15/2023
[160] file:///C:/Users/Owner/Downloads/Resource%20Efficient%20Decarbonization%20(1).pdf, last accessed 11/15/2023

by NASEM (2021) as reviewed in Part 2 of this report. Other insulation materials also have made notable reductions in embodied GHG emissions.

While various Buy Clean policies and material standards or codes have been implemented or proposed to “incentivize” use of lower-carbon building materials by establishing GWP limits, there has been no attention given to incentivizing a culture of improvement by rewarding improvement rather than creating somewhat arbitrary limits or cut-offs. An approach that incentivizes continual improvement on an individual manufacturer or product basis should be given serious consideration as a policy alternative to current conceptions of Buy Clean policies and material GWP specification standards, particularly where manufacturers have already made substantial and on-going investments to reduce material GHG emissions. This alternative approach is particularly important for insulation materials given the diversity of insulation products and functions within the broadly defined class of insulation materials. It was also shown earlier in Section 4.7.4 that most insulation materials have GPW values that are within +/- 5 kg CO2e/m^2-RSI of each other and are generally less than 10 kg CO2e/m^2-RSI. The only exceptions may be for special applications such as foundations of cryogenic facilities where high compressive strength (higher density) foam plastics are needed to support structural and lift-truck loads on slabs of cryogenic facilities.

Incentivizing continual embodied emissions improvements of insulation materials (rather than exclusions) is particularly valuable as a means to responsibly support energy efficiency as a necessary foundation for efficient and effective decarbonization of the electric grid by suppressing energy demand. Consequently, it also promotes significant life cycle GHG emissions savings and payback for all modern insulation materials now of similarly low GWP. The role of building envelope insulation in operational carbon emissions avoidance and payback was addressed in the immediately prior section to bring awareness to the crucial need to consider both embodied and operational GHG emissions when evaluating the climate impacts and benefits of insulation materials. An improvement-based incentive (rather than exclusion limits) is also practical given the climate benefits of essentially all modern insulation materials, the now small differences in embodied GHG emissions, the unique multi-functional differences and capabilities, and the very small overall contribution of all US building insulation materials produced annually to the total annual global GHG emissions (i.e., less than 0.01%) which is the subject of the next section.

4.8.3 Relevance and Significance to Global Climate Change

As evaluated in Sections 4.2 and 4.7.4, the total annual GHG emissions associated with embodied emissions of all US insulation materials annually produced for building and construction applications is about 0.01% of total annual global GHG emissions. The significance of this observation is not meant to detract from the need to incentivize continual improvements as mentioned in the previous section. But, it should give pause to making significant and indiscriminate material trade-off decisions purely on the basis of reducing insulation material carbon emissions to zero or by a small margin based on the relatively small GWP differences now existing between nearly all common insulation materials, including foam plastics.

This concern with the small significance of insulation embodied GHG emissions to global climate change is particularly evident when compared to the significant life cycle operational GHG emissions savings and generally fast payback benefits that were demonstrated in Section 4.8.1 for essentially all modern insulation materials in common end use conditions. It is also important given that insulation materials have different multi-functional capabilities that can promote durability and resilience of buildings (e.g., resistance to moisture and occupant protection during hot or cold extremes and power outages).

4.8.4 Leveraging Benefits of Multi-functional Insulation Materials

Multi-functional capabilities of insulation products can provide GHG emissions savings and other benefits in the design of overall building assemblies by satisfying the functional requirements that additional materials would otherwise need to provide. For example some foam plastic insulations can be used as an air barrier (providing additional energy and GHG emissions savings) as well as a water-resistive barrier and means of vapor control to protect the building from loss of service life due to water intrusion damage. It can also be used to avoid embodied emissions by enabling more efficient (and reduced) use of concrete in building foundations. Earlier in Section 4.4.1 of this report, an actual case study building project was summarized as follows to illustrate some of these multi-functional capabilities and benefits:

> For example, a recent case study of an efficiently designed single-family home demonstrates this concern in a simple manner (Pages-Ruiz, 2022). The foam plastic insulating sheathing (FPIS) continuous insulation (ci) material specified was able to support several inter-related design functions resulting in cost, energy, material resource, and overall GHG emission savings as follows:
>
> - FPIS ci was used resulting in improved energy and operational carbon savings due to reduced thermal bridging for essentially the same insulation material R-value in the original design.
> - The FPIS ci served as siding backer and additional fastening of the interior gypsum wallboard allowed it to serve a multi-functional purpose as code-compliant wall bracing which eliminated the cost and upfront embodied GHG emissions associated with a separate exterior structural sheathing material.
> - Additional cost and carbon emission savings also where made possible by specifying a FPIS ci product that also could serve as the wall's code required water-resistive barrier and air-barrier, thereby eliminating another material layer and its cost and upfront GHG emissions (although not done on this particular project).
> - The exterior continuous insulation was continued down the exterior wall assembly to include the foundation slab perimeter such that a code-compliant frost-protected shallow foundation could be used to eliminate many cubic yards of concrete and minimize foundation excavation (reducing construction cost and the embodied GHG emissions attributed to the foundation by more than 2 metric tons of CO2e) while delivering better than code-minimum energy efficiency.
> - In summary, operational energy and GHG emissions were reduced through improved energy efficiency of the walls and foundation by the use of FPIS ci; embodied GHG emissions were reduced by use of FPIS ci as a multifunction sheathing material on above-grade walls together with a multi-functional use of interior gypsum wallboard as wall bracing; multi-functional use of FPIS ci on the foundation resulted in significantly reduced concrete usage, excavation, and overall embodied GHG emissions of the foundation; with these multifunctional applications of FPIS ci, the first cost of the overall building was reduced by several thousand dollars.
>
> In the above real-life building design and construction example, if the insulation materials used in the project had been selected or excluded purely on the basis of material GWP functional units (even among a like category of materials such as thermal insulation), then much of the energy, GHG emissions, and cost savings would not have been realized. Instead, the project would have become a major missed opportunity to cost-effectively achieve significant decarbonization benefits while also making the home more affordable with higher than code-minimum energy efficiency.

It is extremely important that embodied carbon policies, like "Buy Clean" or "material specification codes" avoid counter-productive impacts on materials that provide multi-functional building assembly and performance optimization opportunities that are not captured by a singular focus on material GWP.

4.8.5 Functional Units Don't Represent Actual Performance in End Use

As stated in Section 4.4.1:

> Insulation materials have different properties and uses that determine their effectiveness in saving energy in end use. These differences are not represented by the functional units used to represent GWP values published in material EPDs. Insulation materials use a functional unit for GWP of kgCO2e/m^2-RSI. The R-value or RSI (R-value in SI units) is based solely on the material thermal resistance property and not the effective R-value in end use as part of a building thermal envelope assembly. For example, continuous insulation minimizes building thermal bridges caused by the structural materials of a building whereas cavity insulation is thermally bridged by building structural members resulting in a 15% to 60% reduction in the effective thermal property used as the basis for "functional units" in EPD reporting of GWP. Therefore, insulation material selection based solely on

> compared GWP and functional units reported in EPDs will completely miss this important end use distinction that has significant influence on operational carbon emissions and energy use of a building. This problem can be overcome only by comparison of insulation materials at the level of a building envelope assembly (at a minimum) or whole building life cycle analysis using a "total carbon" approach. In particular, the whole building or assembly analysis would need to account for the assembly thermal performance (i.e., U-factor) including the presence of thermal bridges in specific assembly applications to accurately account for differences in operational energy and carbon emission savings attributed to different insulation applications, even for materials of like kind and function.

4.8.6 Addressing Embodied and Operational Carbon Emissions Objectively in Cost-Benefit Analyses Including the Social Cost of Carbon

While use of a whole-building life cycle analysis methodology or "total carbon" approach is necessary to evaluate the optimization of building assemblies and insulation applications (see Section 4.8.1 and 4.9), it omits the means to do this in a climate risk-consistent manner. For insulated building thermal envelope assemblies, the risk-consistent impacts to climate can be addressed by including the social cost of carbon (see Section 1.4) in the cost-benefit analysis methodologies used to evaluate and justify US model energy codes and standards. Currently, only operational energy savings and costs of energy and materials are considered. With addition of the social cost of carbon, it would allow both operational carbon emission savings and embodied carbon costs to be evaluated without necessitating the use of arbitrary goals for energy efficiency or limits for embodied carbon emissions of buildings. Use of an appropriate social cost of carbon would thereby drive both energy efficiency and material embodied carbon improvements in an objective and climate risk-consistent manner.

4.9 Whole Buildings & Assemblies – Life Cycle Analysis Applications

Whole building life cycle analysis principles were used in the previous section to evaluate the carbon emissions payback time and life cycle avoidance ratio for many typical insulations used in typical building envelopes for commercial and residential building constructions. Such analyses are crucial to a proper and complete understanding of the role of all modern insulation materials and energy efficiency as a foundational solution to help mitigate climate change. While the previous section introduced the practical value of whole-building life cycle analysis, including its application to evaluate insulation applications in building assemblies, this section looks at the topic in a more general sense.

According to Autodesk, a major supplier of CAD software to the building design and construction industry, the value of a "total carbon" or whole-building life cycle analysis (WB-LCA) approach to decarbonization is described as follows:[161]

> Measuring the embodied and predicted operational carbon impacts of a building is one way the AEC industry can estimate and quantify the potential environmental impact of a building or other aspect of the built environment in the planning and design phases, long before it is built.
>
> One benefit is the ability to compare and make informed trade-offs between embodied and operational carbon associated with design decisions. For example, imagine you want to compare the total carbon of a window type for a new building design. You could evaluate the trade-offs between double- versus triple-pane insulated glazing units and compare the long-term operational energy and carbon savings of the higher-performing triple-pane window versus the upfront embodied carbon of sourcing more glass and other raw materials necessary to install a triple-pane window. In some cases, the energy savings of the better-performing window over an estimated building lifespan may not offset the embodied carbon of the window itself. The ability to evaluate total carbon impacts of both embodied and operational carbon during the design process can enable optimization and reduction of potential contributions to GHG emissions.

[161] https://redshift.autodesk.com/articles/what-is-embodied-carbon, accessed 12/14/2022

According to a recent ASHRAE Journal article on the importance of whole life carbon assessment in evaluating both operational and embodied carbon, "the goal of embodied carbon emissions reduction is to use less material first, use recycled or bio-based products when possible and then to specify low carbon materials by examining carbon content of materials."[162] Esram and Hu (2021) posed the following research need regarding whole-building decarbonization and the relationship of reductions in operational carbon emissions (and energy use) to reduction in embodied carbon emissions:

> As new buildings become more efficient and the utility grid becomes less carbon intensive, the operational carbons of buildings will decrease. The question is whether reduction of operational carbons is at the cost of increasing embodied carbon. The trade-offs between operational and embodied carbon need to be investigated further to achieve optimal results.

Design trade-off decisions related to the balance of embodied and operational carbon emissions are best guided by a WB-LCA, or at least an analysis at a building assembly level. But, as noted and evidenced earlier in this report on several occasions, selecting materials based just on material GWP values from EPDs can result in unintended consequences, non-optimal trade-offs, or missed opportunities. Thus, the scope of a WB-LCA must be expanded to include other important functional design considerations than just operational and embodied carbon emissions.

In studying material embodied GHG emissions of Canadian wood frame homes, the City of Vancouver (2022) found that the average material carbon emissions intensity (MCI) per conditioned floor area was 193 kg CO_2e/m^2 with a maximum value as high as 357 kg CO_2e/m^2. By further normalizing this data to a functional basis of number of bedrooms, the average was 80.9 kg CO_2e/m^2/bedroom with a range of 20.9 to 218 kg CO_2e/m^2/bedroom. The City of Vancouver (2022) recommended a baseline MCI of 200 kg CO_2e/m^2 for the purpose of limiting whole building carbon emissions based on cradle-to-gate (A1-A3) emissions for all structure, enclosure, and partition materials. But, these benchmarks, being based only on material GWP, lack any association with operational GHG emissions benefits that are substantial for essentially all insulation materials in most building applications (see Section 4.8.1). The carbon savings during the operational phase of buildings tend to dwarf the embodied carbon investment in insulation. Also, as shown in Section 4.7.4, the differences in GWP of essentially all modern insulation materials are now relatively small and the overall contribution of all US insulation materials is less than about 0.01% of total global emissions (with payback in less than year and multiplied over the remaining life of a building). These benefits of insulation materials become obscured when applying metrics like MCI as a means to guide or regulate the specification of all materials used in a building as a whole.

Regardless, the City of Vancouver (2022) recommended the following as a means to limit material GWP from a whole-building perspective, noting that energy efficiency of the building was generally not correlated with GWP of the materials used (partly because multi-functional insulation applications were not considered):

> **Regulate whole buildings, not individual materials.** This study calculates emissions from whole houses (including all structure, enclosure and partition materials, but excluding MEP, appliances, millwork and surface finishes) to achieve net emissions for the house as well as emissions by floor area and occupant. It is recommended that some version of whole-house measurement is used and that the regulation of specific materials be avoided. Material substitutions at the whole house level indicate that even if some high-emission materials are used, a reasonable level of emissions can be achieved. Regulating whole buildings ensures that homebuilders have the greatest flexibility to achieve appropriate emissions levels and avoids the need to directly regulate individual material types for which emissions are constantly improving.
>
> **Concrete.** Concrete is the leading contributor to emissions from the sample houses, representing over 36 percent of all material emissions. The use of Canadian average data for concrete emissions may have overstated the impact of concrete, but no product-specific data was available. Ensuring that product-specific EPDs for concrete

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[162] https://www.nxtbook.com/nxtbooks/ashrae/ashraejournal_JQOPLS/index.php#/p/48, last accessed 3/4/2023, McConahey, E., Why Whole Life Carbon Assessment is Important, ASHRAE Journal, February 2022.

are available and used in calculations will help to ensure that the city's targets are being met accurately. Reducing the amount of concrete used in house designs and specifying low-emission concrete are two of the leading strategies for meeting the city's reduction goals.

Insulation. Insulation was the second largest contributor to emissions from the sample houses. Carbon-storing insulation materials were not commonly used in the sample houses, but the results of the material substitution study indicate that the use of carbon-storing insulation materials is a leading strategy to reduce emissions.

Embodied and operational emissions. The houses in the study achieve a range of energy performance levels, from code minimum to net zero ready and Passive House. There was no direct correlation between embodied emissions and energy efficiency level, with some highly efficient homes also achieving lower than average MCI. The City of Vancouver does not need to adjust its performance requirements in order to achieve its desired embodied carbon reductions.

The Carbon Leadership Forum (CLF) conducted an embodied carbon benchmark study for commercial buildings using WB-LCA (Simonen, Rodriquez, McDade, and Strain, 2017), but excluding its combination with operational emissions for a total carbon perspective. The CLF study is summarized by Esram and Hu (2021) as follows:

> The Carbon Leadership Forum conducted an embodied carbon benchmarking study in 2017 by compiling the embodied carbon results from 1,191 building LCA studies, including office, education, multi- and single-family residential buildings, and so on. (Simonen et al. 2017). Half of the entries are from buildings in Northern America. The study found that the upfront carbon emission is typically less than 1,000 kgCO2e/m^2; 50% of the office buildings in the database have upfront carbon emissions between 200 and 500 kg CO2e/m^2. (As a reference, Living Building Challenge's Zero Carbon Certification requires the total embodied carbon emissions of the certified project to be less than 500 kg-CO_2e/m^2.) The study provides a good reference for benchmarking embodied carbon in buildings; however, the sample size is insufficient to provide statistically significant results.

Esram and Hu (2021) also summarize a whole building case study of three buildings by RMI (2021), also excluding consideration of total carbon emissions but calling attention to it, as follows:

> The whole-building approach encourages innovative strategies that utilize alternative structural systems, building technologies, and construction techniques and processes. To enable a whole-building approach, standards are needed to guide design teams to create baseline cases, compare alternative design approaches, and set carbon reduction targets. RMI's case studies of three typical construction types for low- and mid-rise commercial buildings in the United States show that up-front embodied carbon (A1–A5) can be reduced by 19 – 46% with less than a 1% cost premium (Esau et al. 2021). This is largely accomplished through material-level substitution. A whole-building approach can yield even greater savings. As with reducing operational energy use, these early-state design choices have substantial impacts on reducing a building's embodied carbon, as changes and interventions become more costly and constrained in a later project stage. As new buildings become more efficient and the utility grid becomes less carbon intensive, the operational carbons of buildings will decrease. The question is whether reduction of operational carbons is at the cost of increasing embodied carbon. The trade-offs between operational and embodied carbon need to be investigated further to achieve optimal results.

Finally, Esram and Hu (2021) summarize another whole building case study by Shadram et al. (2019) where WB-LCA was used to evaluate optimization of embodied and operational carbon emissions:

> Shadram et al. conducted a study on a hypothetical eight-story multifamily residential building located in Stockholm, Sweden using a multi-objective optimization approach to examine the trade-off between embodied and operational carbon impacts (Shadram et al. 2019). The variables in the study included the window-to-wall ratio and the floor, roof, and wall insulations (i.e., insulation types and thickness) used in the exterior construction elements of the building. The energy simulations showed that the embodied carbons quickly decrease as the operational carbons increase, and that decrease slows down until it plateaus.
>
> The authors were able to find optimal solutions that resulted in the lowest life-cycle carbon footprint. One of the solutions has a higher operational carbon impact compared to the initial design but significantly reduces the

> embodied carbon impact. It is also worth noting that the study showed that expanded polystyrene is an optimal insulation material for the exterior walls and floors, and cellulose is a better choice for the roof than mineral wool. Petroleum-based products (mostly used for rigid and spray foam insulations such as expanded polystyrene and extruded polystyrene) have higher embodied carbon footprints than blown-in insulations (e.g., fiberglass and cellulose), if compared at the material level. Although the finding from this case study does not universally apply to all buildings, it highlights the importance of whole-building-level analysis, considering the whole life cycle of a building.

The study by Shadram et al. (2019) performs the same type of analysis that was done over 40 years prior by Hannon et al. (1976) for embodied energy of building materials in building assemblies and related impacts on operational energy use (see Appendix A). However, the WB-LCA tool used by Shadram was far more sophisticated allowing multiple results from various assembly permutations and material selections to be evaluated and plotted as shown in Figure 92 to visualize the optimization process (considering both operational and embodied carbon impacts) and to help identify optimal solutions. It also used much advanced and expanded data on the embodied emissions of building materials available in Europe, specifically Sweden. The insulation material selection variables used in the optimization process are shown in Figure 93.

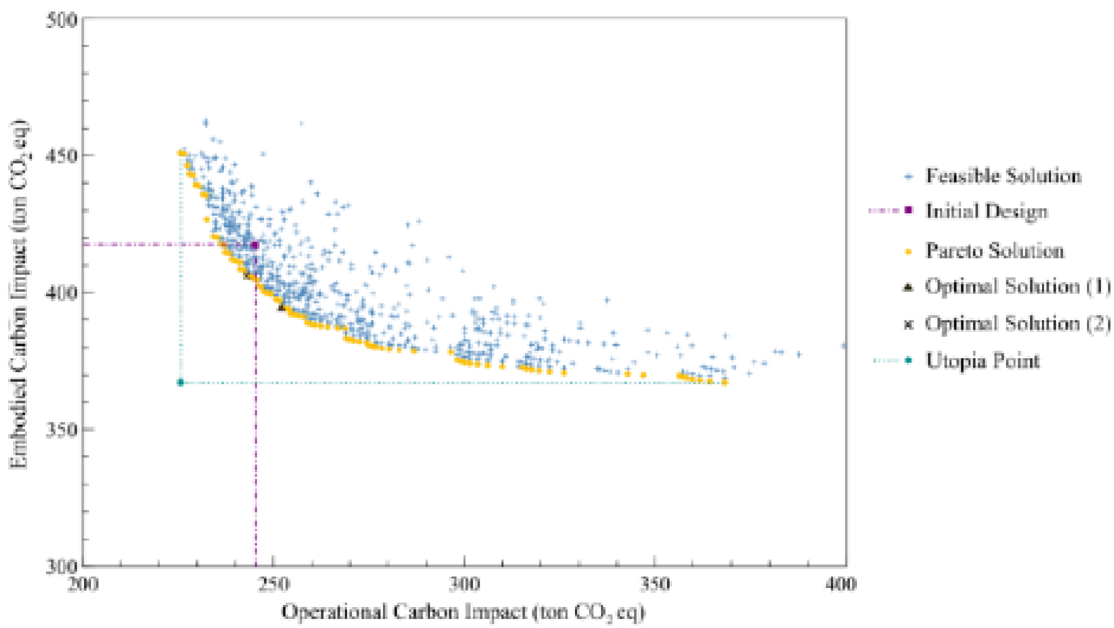

Figure 92. Scatter chart of initial design and various solutions for whole building optimization of operational and embodied carbon emissions for a hypothetical multifamily residential building located in Stockholm, Sweden.

Source: Shadram et al. (2019)

Design variable number	Design variable type	Alternatives
1	Floor insulation type	Polyisocyanurate, EPS
2	Floor insulation quantity (thickness) (m)	0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4
3	Wall insulation type	Polyisocyanurate, EPS, Mineral wool
4	Wall insulation quantity (thickness) (m)	0.05, 0.08, 0.1, 0.15, 0.17, 0.22, 0.25, 0.27, 0.32, 0.34
5	Roof insulation type	Mineral wool, Cellulose
6	Roof insulation quantity (thickness) (m)	0.5, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5
7	WWR	0.2, 0.25, 0.3, 0.35, 0.4

The discrete variables considered in this trade-off optimization approach along with their alternatives.

Figure 93. Insulation materials and thickness variables considered in whole building optimization of embodied and operational carbon emissions
Source: Shadram et al. (2019)

According to Shadram et al. (2019):

> In figure 3, initial design demonstrates the result of embodied versus operational carbon impact launched from the initial WWR and materials (see table 1). Pareto solutions indicate a set of non-dominated solutions where there are no other feasible solutions that enhance one objective without degrading another. Finally, the utopia point displays an imaginary target (lowest embodied and operational carbon impact) which cannot be achieved as a trade-off exists among the objectives. As shown in figure 3, two optimal solutions have been chosen in this study. The first optimal solution (1) is the solution which results in the lowest life cycle carbon footprint. This solution has a higher operational carbon impact compared to the initial design, but reduces significantly the initial design's embodied carbon impact. The second optimal solution (2) is the solution that results in the lowest life cycle carbon footprint among the solutions that outperform the initial design in terms of embodied and operational carbon impact. Table 3 presents the design variables and carbon footprint reduction associated with the optimal solutions of the multifamily residential building located in Stockholm.

The two optimal solutions mentioned in the quote above are shown in Figure 94.

Design variable / carbon impact	Initial design	Optimal solution (1)	Optimal solution (2)
Var. 1 (floor insulation type)	EPS	EPS	EPS
Var. 2 (floor insulation thickness) (m)	0.3	0.1	0.1
Var. 3 (wall insulation type)	EPS	EPS	EPS
Var. 4 (wall insulation thickness) (m)	0.25	0.27	0.32
Var. 5 (roof insulation type)	Mineral wool	Cellulose	Cellulose
Var. 6 (roof insulation thickness) (m)	0.3	0.5	0.5
Var. 7 (WWR)	0.3	0.4	0.35
Embodied carbon impact (tonCO2eq)	417.6	394.7	406.2
Operational carbon impact (tonCO2eq)	245.2	252.1	243
Life cycle carbon footprint (tonCO2eq)	662.8	646.8	649.2
Life cycle carbon footprint reduction (tonCO2eq)		16	13.6

The design variables and carbon footprint reduction for the optimal solutions

Figure 94. Details of two optimal solutions determined from whole building optimization of embodied and operational carbon emissions for various insulation variables
Source: Shadram et al. (2019)

Regarding the optimal solutions shown in Figure 94, Shadram et al. (2019) draw the following observations:

> As shown in table 3, except for two of the design variables (i.e. wall insulation thickness and WWR), the other design variables are identical for both optimal solutions. The results indicate that with respect to the trade-off optimization of embodied versus operational carbon impact trade-off, EPS is an optimal insulation material for the exterior walls and exterior floors while for the roof construction, cellulose can be a better choice compared to mineral wool. In addition, the results suggest that thinner insulation is the optimal choice for the exterior floor while for the roof and exterior wall constructions, thicker insulations are more beneficial. The total life cycle carbon footprint reduction relative to the initial design is estimated to be 16 (tonCO_2eq) and 13.6 (tonCO_2eq) for the first and second optimal solution, respectively. This amount of carbon footprint reduction is equivalent to more than 2 years of the initial design's operational carbon impact of the multifamily residential building. The results of the case study indicate that a major part of the carbon footprint is embodied related which was also reported in the previous study by Chastes et al [5]. It is of note that a significant part of the embodied carbon impact comes from concrete structural components.

The above study, while slightly different in its approach to evaluating WB-LCA data to find optimal solutions, is similar to several of the studies reviewed in Section 4.8.1 that considered optimization as well as a metric to gage insulation climate impact benefits in terms of a carbon emissions payback time and lifecycle carbon emissions avoidance ratio. All of these WB-LCA studies do not consider applications of multi-functional insulation materials as a means for further optimization of building assemblies.

SUMMARY & CONCLUSIONS

A summary of the findings and conclusions of this report is as follows:[163]

- **Climate change is a serious concern.** Current and future impacts of global warming are real and significant, but the magnitude and regional variation of expected future climate impacts remain very uncertain. (See **PART 1**.)
- **Climate goals and policy development would benefit from rational cost-benefit analyses and optimization.** While well-intentioned, the current very ambitious posture of climate goals and related policies is not necessarily founded on robust cost-benefit analyses for optimization. Such analyses would provide an objective science-based accounting of estimated policy costs, harms, and benefits in mitigating estimated future climate impacts. It would serve as a means to better optimize goals, inform policy decisions, and direct priorities. It also would provide meaningful transparency and objectivity to help form a common vision for determining and implementing optimal solution pathways to mitigate climate change. (See **Section 1.4** and **PART 2**.)
- **The social cost of carbon provides a rational cost-benefit basis to assess climate policy.** The social cost of carbon represents the cost of future climate change impacts to humanity and the planet due to carbon dioxide (CO2) and other GHG emissions. It enables cost-benefit analyses whereby the benefits (avoided climate impacts) of a proposed policy to reduce emissions can be compared with the cost of implementing the policy in a climate risk-consistent manner. Consequently, many consider the social cost of carbon to be a key factor in guiding climate policy decisions. It also is potentially the single most effective and efficient means to drive an appropriate economy-wide response to reduce GHG emissions where used as the basis for a responsibly administered carbon tax policy (or tax incentive for decarbonization investments based on realized GHG emission reductions). Unfortunately, application of the social cost of carbon has seen limited use (or has been significantly under-valued) as a means to establish climate goals and related policies, regulations, programs, and mitigation measures. (See **Section 1.4**, **Section 2.3.4**, and **Section 4.8.6**.)
- **Combustion of fossil fuels is the dominant source of global and US GHG emissions.** Combustion of fossil fuels accounts for 92% of US CO2 emissions and 73% of US GHG emissions across all sectors of the US economy. The transportation and electric power sectors of the US account for about two-thirds of the emissions associated with the combustion of fossil fuels in the US (or about half of total US GHG emissions). Therefore, decarbonization of the electric power sector is a hub for decarbonization of transportation, building, and industry sectors as they strive to increasingly electrify. (See **PART 3**.)
- **Energy efficiency to improve energy productivity is crucial to decarbonization.** Energy efficiency has broad and reliable economic and climate benefits through any future decarbonization pathway. Regardless of the path for or rate of future decarbonization, reducing fossil fuel combustion emissions through increased energy efficiency and improved energy productivity should be the primary focus of any effective plan to decarbonize the US economy. Furthermore, the same investment in energy efficiency also will maximize and extend the productive use of available low-carbon or renewable energy sources, particularly as the electric power generation sector continues its transition to renewable energy from solar, wind, and other renewable resources or low-carbon technologies. (See **PART 2**, **PART 3**, **Section 4.3**, and various other sections in **PART 4**.)
- **Data is lacking to effectively rank building materials in relationship to their significance or contribution to global climate change.** Based on the available data reviewed and assessed in this report, an initial attempt to broadly characterize US building materials' GHG emissions in relationship to total global GHG emissions is shown in **TABLE 20** and visualized in **Figure 95**. This approach is similar to the "key category" approach used by EPA to evaluate categories of emissions from within various

[163] For each bulleted finding or conclusion, a reference to parts and sections of this report is provided for substantiation and additional information. However, these referenced portions of the report are not necessarily exhaustive of all the information documented or referenced on a given topic.

economic sectors, such as the industry sector as presented in **Section 3.2**. The percentage of total global GHG emissions provides an objective basis for assessing the climate mitigation significance (or potential benefit) of any policy action taken to reduce those emissions. (Data sources used to develop **TABLE 20** and **Figure 95** are included in footnote 1 of **TABLE 20**.)

- **Eliminating the embodied GHG emissions of US building materials will have a relatively small effect on global climate change.** As shown in **TABLE 20** and **Figure 95**, the annual production of all US building materials represents about 0.4% of total annual global GHG emissions (0.6% if other construction applications are included). While this finding is not meant to suggest that improvements or innovations should not be pursued, it does suggest that embodied carbon policies should be carefully rationalized and focused to avoid unintended consequences with minimal benefit to the climate. This concern is particularly important to building insulation materials. (See **Section 4.8**.)
- **Embodied GHG emissions associated with US building and construction materials have seen significant reductions in the US.** For example, the US iron and steel industrial sector has seen a 64% decrease in CO2e emissions from 1990 to 2020 due to restructuring, technology improvements, and increased scrap steel use (see **Section 3.2**). In addition, products such as foam plastic insulation materials have GHG embodied emissions that are as little as $1/100^{th}$ of the what it was in the 1970s and reduced by 75 to 90% (or more) in recent years by innovative advancements in low global warming potential (GWP) blowing agents (see **Section 4.7.4**). These improvements far surpass the recommended goal of a 30% reduction in GWP for building materials in US federal climate policy by the National Academies of Science, Engineering, and Medicine (see **Section 2.3.4**). Commonly used insulation materials in the US now have generally low GWP values of typically less than about 9 $kgCO2e/m^2$-RSI (see **Section 4.7.4**.)

TABLE 20. Greenhouse Gas Emissions for World, US, US Economic Sectors, and US Building & Construction Materials (2020)[1]

Source	Gross GHG Emissions (GtCO2e)[2]	% of Total Global GHG Emissions (see Figure A)	% of Total US GHG Emissions	% of Total US Bldg & Const Mat'l Emissions
Global Total (~80% FFC)	59	100%		
US Total (~73% FFC)	6.0	10.1%	100%	
GHG Emissions by US Economic Sectors (EPA, 2022)				
Transportation	1.63	2.8%	27%	
Electric Power	1.48	2.5%	25%	
Industry[3]	1.43	2.4%	24%	
Buildings	0.79	1.3%	13%	
Agriculture	0.64	1.1%	11%	
GHG Emission by US Building & Construction Material Types (Embodied Emissions – Subset of Industry Emissions Reported Above)[3]				
Concrete	0.100	0.17%	1.7%	28%
Gypsum Board & Panels	0.080	0.14%	1.3%	22%
Steel (structural)	0.052	0.09%	0.9%	13%
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Building Insulations (all types)	0.006	0.01%	0.10%	1.7%
Flat Glass for Glazing	0.005	0.008%	0.08%	1.4%
---	---	---	---	---
All Others (unquantified)	0.12	0.2%	2.0%	34%
TOTAL - all bldg.& const. mat'ls: TOTAL - bldg. mat'ls only:	0.36 0.24	0.61% 0.41%	6% 4%	100% 68%

% FFC = percentage of GHG emissions from fossil fuel combustion

TABLE NOTES:

1. Sources of data in TABLE A include IPCC (2022), EPA (2022), NASEM (2021), USCA (2021a), and DOE (2022) as reported and analyzed in this report including **Figure 11** of Part 2, **Figure 17**, and **TABLE 6** and **TABLE 7** of Part 3, and material data evaluated in several subsections of Part 4 from sources as indicated therein (in particular see **Section 4.7.4** for building and construction materials).
2. 1 GtCO2e = 1 billion metric tons of CO2e = 1 trillion kg of CO2e emissions (equivalent to CO2 emissions from the combustion of about 110 billion gallons of gasoline); data in table is based on gross emissions, excluding carbon sinks.
3. About 25% of industry emissions (1.43 GtCO2e) are associated with emissions that are attributed downstream to building and construction materials as embodied emissions (0.36 GtCO2e).

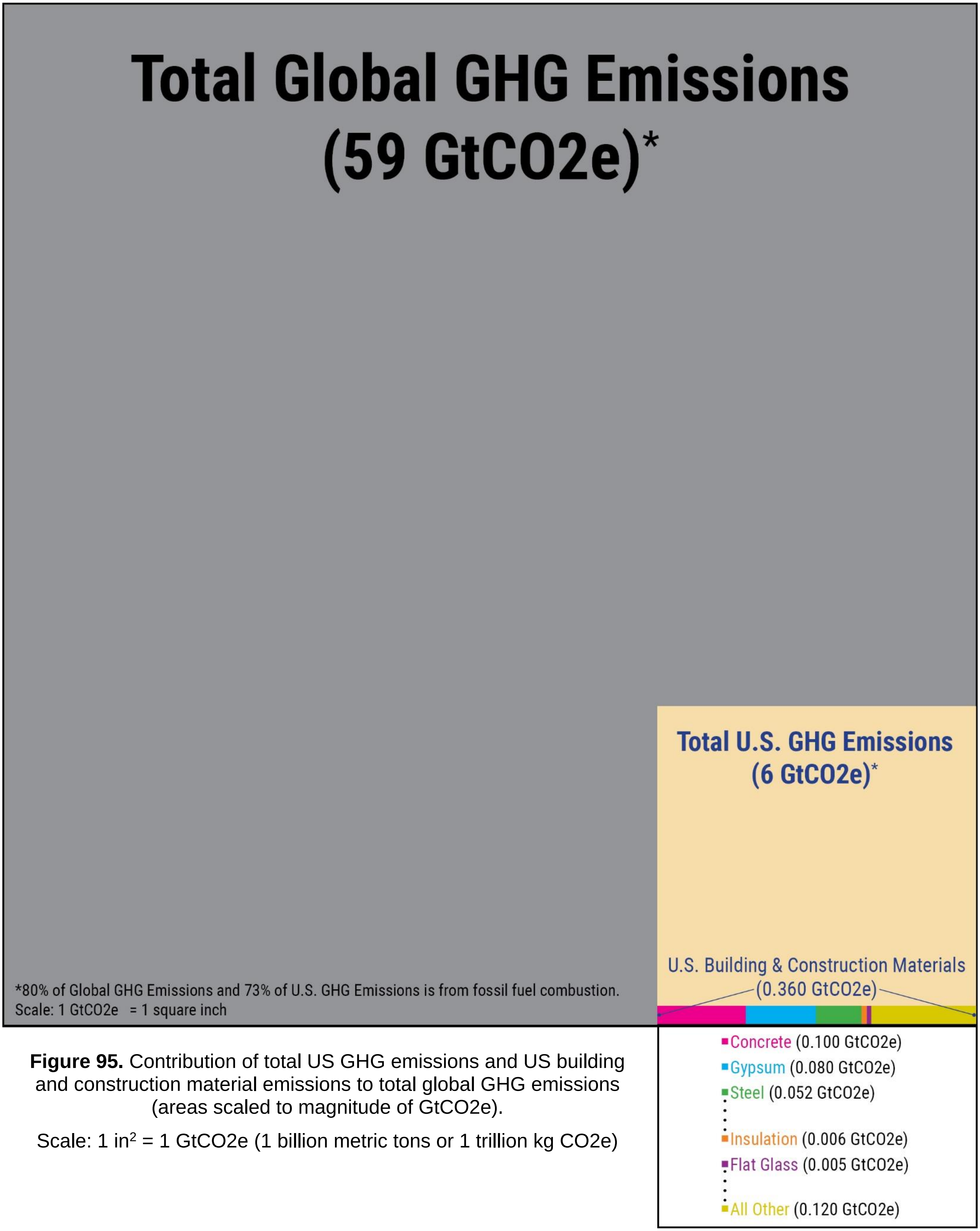

Figure 95. Contribution of total US GHG emissions and US building and construction material emissions to total global GHG emissions (areas scaled to magnitude of GtCO2e).

Scale: 1 in^2 = 1 GtCO2e (1 billion metric tons or 1 trillion kg CO2e)

- **Insulation materials reduce "total carbon" emissions.** Building insulation materials save more operational carbon emissions through their use than is invested in their manufacturing as embodied carbon emissions. Insulation materials of all types commonly used in the US generally provide an embodied carbon payback within one year after initiation of building operation. Thus, the approximate 0.01% (1/100th of a percent) of total annual global GHG emissions attributed to US insulation product manufacturing in a given year (see **TABLE 20**) is typically paid-back in the first year of use in new buildings. Furthermore, typical insulation material applications for US buildings yield life-cycle carbon savings ranging from 20x to 300x greater than the initial embodied carbon investment. (See **Section 4.8.1**.)
- **Insulation materials provide diverse functions and often under-recognized opportunities for building performance optimization, resource efficiency, resiliency, and affordability.** For materials like insulation that provide energy efficiency and are a key solution to the global warming problem, special care must be taken to avoid unintended consequences of controlling their use through narrowly focused material embodied carbon policies. These efforts often promote substitutions on the basis of the functional units and small differences in the magnitude of GWP, while inadvertently downplaying important end use considerations related to building operational emissions savings, energy demand reduction, and optimization of building assemblies through multi-functional insulation materials and methods of use that promote energy efficiency, durability, safety, resilience, resource efficiency, and cost-effectiveness of high-performance buildings. (See **Section 4.3**, **Section 4.4**, **Section 4.8.4**, and **Section 4.8.5**.)
- **The building material embodied carbon movement is strong and their message is urgent.** Many organizations and thought leaders claim building material embodied carbon emissions will be "100% of the problem" once building operational emissions become net zero in the future. Therefore, building material embodied emissions must be completely and urgently eliminated to avoid the most severe future climate consequences (see examples in **Section 4.2**). Consequently, over 40 federal, state, or local policies are now focused on embodied emissions of building and construction materials (see **Section 4.6**). While initially focused on higher carbon intensity materials (like concrete as shown in **TABLE 20**), some embodied carbon policies are beginning to address other materials like insulation that have more than an order of magnitude lower contribution to global GHG emissions (see **TABLE 20**) and provide significant total carbon savings in use (see **Section 4.8.1** Evaluating Embodied + Operational Emissions is Crucial). Many non-government organizations have produced or are working on codes, standards, guides, and voluntary programs similarly aimed at minimizing or eliminating material embodied carbon emissions by 2050 and favoring use of bio-based or carbon-sequestering materials without necessarily considering important functional implications (see **Section 4.6**, **Section 4.8.4**, and **Section 4.8.5**).
- **The US building material industry in general, and the insulation industry in particular, lack a coordinated and proactive engagement in decarbonization policy-making processes and related developments.** The absence of effective engagement presents a risk of missed opportunities to guide rational policy solutions and avoid those that may be considered ineffective. The findings and recommendations of this report are intended to provide a foundation for informed and effective engagement in policy development. The policy development venues of interest may include federal, state, or local governments; voluntary programs administered by various non-government organizations; standards developers; and US model building or energy code developers.

RECOMMENDATIONS

A summary of the recommendations in this report is as follows:

A. **Build strong alliances with industry partners and rational thought-leaders.** Industry needs to effectively engage in policy development already in progress. While the goal of such advocacy should align with the reality of climate change and interest in mitigating its impacts, industry should aim to build a common vision and strategy to influence and support rational policies for the US building industry.

B. **Advocate for cost-benefit analyses and optimization of decarbonization policy.** Cost-benefit analyses incorporating the social cost of carbon should be routinely conducted to evaluate policy options and help optimize actions and priorities related to building operational and material embodied carbon emissions. Such analyses should be conducted with transparency and in a manner that bounds uncertainties (high and low extremes) in characterizing climate impact cost, climate policy cost, and climate policy effectiveness. In addition, the focus of such analyses and optimization should consider categories of operational emissions and material embodied emissions based on their magnitude and relevance to global GHG emissions and mitigating global climate change (see **TABLE 20** and **Figure 95**).

C. **Implement public policy and public/private investment that encourages the development and use of viable low-carbon energy sources across major sectors of the economy.** This action will have multiplying effects throughout the economy, including the reduction of building sector operational GHG emissions and embodied emissions associated with the manufacturing of building materials.

D. **Focus continued effort on energy efficiency regardless of energy source as a means to improve energy productivity and reduce energy demand and GHG emissions.** Energy efficiency of buildings – efficiently insulated building envelopes and efficient heating and cooling equipment – will reduce overall US energy demand. Energy demand reduction is needed to effectively enable decarbonization of buildings together with the electric power generation system that serves as a hub for decarbonization of other sectors such as industry and transportation. Therefore, energy efficiency has a broad and inter-related application across all US economic sectors.

E. **Structure embodied GHG emissions policies to promote and protect investment in building material decarbonization.** Building materials will tend to decarbonize as US energy sources decarbonize in tandem with efficient use of energy as core policy objectives addressed in recommendations C and D.[164] Therefore, policies specifically focused on influencing material embodied carbon emissions downstream from the actual emissions must be carefully considered as supplementary actions. Such policies should incentivize and protect the upstream investments made by industry to innovate and employ technology advancements that actually reduce material embodied emissions.

F. **Promote a "total carbon" optimization approach for the evaluation of building insulation materials and assemblies.** A total carbon approach would properly account for both embodied GHG emissions and operational GHG emissions savings such that optimal building assembly and system solutions can be intelligently considered. Unlike most other building materials, insulation materials are inextricably linked to their purpose of supporting building energy efficiency to reduce operational energy demand and associated emissions. Furthermore, essentially all modern US insulation materials provide substantially more carbon savings during use than emitted during their production. Therefore, single metric evaluations – like GWP used to evaluate only the embodied carbon of an assembly or product – are especially inappropriate as a means for insulation material selection decisions or policies. This concern is particularly true for insulation products that have multifunctional capabilities important to the

[164] For non-energy-related GHG emissions associated with materials or their manufacturing processes, specific policies should be considered on a case-by-case basis and recognize non-energy-related uses of fossil fuels (for feedstock, not combustion) as necessary for many valuable US products and not a significant contributor to global warming. The CO2e emissions from non-energy use of fuels (e.g., feedstock for manufacturing) is less than 3% of the total emissions from fossil fuel combustion for energy based on EPA data (see **Figure 16** in Section 3.2 of this report).

overall optimization of building envelope assembly construction and performance. Also, different insulation applications that impact functional performance characteristics of actual building assemblies in end use are not adequately represented by the functional units used to quantify GWP. These factors can be properly addressed only by use of a total carbon approach in combination with functional performance optimization of overall building assemblies.

Additional specific recommendations include the following:

1. **Request that the US EPA or others investigate a means to provide a break-down of building material emissions that are attributed to building and construction materials.** Currently, there are significant gaps in knowledge of the global GHG contribution of various US building materials. Such information is needed to provide a rational ranking and prioritization to guide the focus of public policy and private-sector efforts to achieve the largest potential climate benefit with the least effort, cost, and uncertain return on mitigation investment. (See **TABLE 20** and **Figure 95**, which attempt to provide this information for a limited portion of US building and construction materials.)
2. **Update the Product Category Rule (PCR) for building thermal envelope insulation to include an accounting of the operational GHG emissions savings (avoidance) that occur as a result of insulation material use in building thermal envelopes.** Such rules should specifically mention and permit quantification of operational carbon savings (or avoidance) and payback period (i.e., the time required during use to offset the upfront embodied carbon of the insulation material). The PCR should provide necessary assumptions for such calculations. It should also recognize a simplified method of analysis of operational carbon emissions savings for indexing purposes. Sophisticated whole-building energy models and characteristic building population datasets should not be necessary to reasonably index the carbon avoidance and payback time for common uses of building insulation materials.
3. **Create a voluntary "carbon smart" material certification program (or standard) customized for insulation materials that rewards or incentivizes market use.** This program would consider: (1) Environmental Product Data (EPD) showing a history of reduced or optimized carbon footprint over time, (2) the ability to achieve tiered ranges of carbon emission payback time or carbon emission avoidance ratio based on representative building or building assembly end-use conditions by climate zone or national average, or (3) both. This opportunity also relates to the recommendations included in item 2 above and item 4 below, but is not dependent on them.
4. **Develop a simplified "total carbon" analysis tool for whole buildings or specific building assemblies for evaluation of insulation strategies.** The tool should be focused on assessing insulation materials as used in complete building assemblies. The tool should include a simplified means to assess energy use and operational carbon emission savings and be able to quickly assess different combinations of assembly materials in a fast and transparent manner to facilitate design optimization (e.g, resource efficient assemblies, optimized use of multifunctional insulation and building materials, etc.). Output metrics should include a combination of checks (those for code compliance and those related to total energy use and carbon emissions), as well as a carbon emissions payback period and avoidance ratio for a specified baseline building condition and climate zone. This tool could be used to support policy positions, market education (see item 5 below), and other efforts (see items 2 and 3 above).
5. **Develop case studies to demonstrate the use of foam plastic insulation materials to optimize "total carbon" and overall performance of code-compliant building assemblies.** For example, foam plastic continuous insulation on foundations can significantly reduce concrete volume and carbon emissions for foundation construction in cold climates with significantly reduced first cost. For above grade walls, multi-functional foam plastic continuous insulation can be used to economize wall assemblies while eliminating the need for other materials such as vapor retarders and water-resistive barriers. Case studies can reveal these opportunities in a way that can be readily understood by the building industry and design practitioners, as well as policy developers. The tool described in item 4 above would provide the means to generate various case studies.

6. **Advocate for a rational and risk-consistent value for the social cost of carbon.** The social cost of carbon should be included as a requirement in various cost-benefit policy instruments and regulations at the federal and state levels, including adopted building energy codes and standards. Where such cost-benefit analyses use a rational and climate-risk-consistent value for social cost of carbon, they should be deemed to be compliant with US federal, state, and local climate policy objectives and goals that, generally, are not similarly cost-benefit justified in a manner consistent with the economic impacts of future climate change and the cost to mitigate.
7. **Implement a "total carbon" approach for US model energy codes and standards.** Operational GHG emissions costs (not just market-priced operational energy cost) should be included in the currently required cost-benefit analysis methods to address their omission of "hidden costs" of GHG emissions from fossil energy sources. This can be achieved by use of a rational science-based value for the social cost of carbon (see item 6 above). The total carbon approach would help guide and advance energy codes in an objective and cost-effective manner to promote energy efficiency and meet climate goals. It will also help to avoid the potential harms or unintended consequences to energy efficiency and building performance that an embodied carbon insulation material selection approach might otherwise cause, particularly as US buildings and operational energy sources become increasingly decarbonized.
8. **Include event-based triggers in existing buildings policies for energy efficiency and decarbonization improvements.** Existing buildings remain the largest and most challenging problem for decarbonization of buildings in the US. Current building performance standard (BPS) approaches tend to use a fixed timeline for meeting their targets. This tends to result in untimely and costly building upgrades that can be a strong deterrent to achieving existing building improvements. BPS policies should be coupled with specific maintenance and renovation events that provide an opportunity for energy efficiency and decarbonization improvements at a time when they are most cost effective to execute. Such an approach for building alterations is currently an approved change for the pending 2024 edition of the International Energy Conservation Code (IECC).
9. **Provide guidance documents that properly caution against making EPD comparisons of insulation materials solely based on a material's functional unit.** Different insulation materials have different compressive strength capabilities, moisture resistance properties, moisture management capabilities, fire performance characteristics, and functional applications that can even affect structural material usage. Such considerations in decarbonization policies and voluntary programs addressing embodied carbon appear to be significantly lacking. There is an apparent lack of understanding of these factors associated with the appropriate, effective, or optimal use of modern insulation products in the integrated design of various building assemblies and applications.
10. **Encourage the demonstration of ongoing improvement through EPD GHG emissions reporting to reward investment in embodied GHG emissions reductions, irrespective of how a given product might compare with others of similar kind or function.** This approach promotes investment by individual US manufacturers to reduce manufacturing emissions attributed to materials as embodied emissions. Current policy approaches that arbitrarily benchmark and periodically shift material GWP limits in the downstream market, deselect materials that exceed those shifting limits, and perhaps eventually exclude materials with any amount of attributed carbon emission (despite the manufacturers having made significant and beneficial carbon emission reduction investments) should be avoided or used very judiciously. The goal should be to incentivize and protect investment in decarbonization, not discourage or penalize it. One concept is presented in item 11 below.
11. **Prevent "carbon infiltration" of imported materials from undermining US manufacturer investment in decarbonization.** Setting a GWP "cap" for US insulation materials in a way that does not exclude US manufacturers will serve to protect past and future investment in decarbonization rather than penalizing US material choices that have different performance and functional attributes.

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APPENDIX A

Embodied & Operational Energy Analysis of Building Assemblies

Hannon, B., R. Stein, B. Segal, D. Serber, and C. Stein. 1976. *Energy Use for Building Construction: Final Report*. Prepared by Center for Advanced Computation, University of Illinois at Urbana-Champaign and Richard G. Stein & Associates, Architects. Washington, DC: Energy Research and Development Administration. https://www.osti.gov/biblio/7301380

The following are excerpts from the above-referenced report.

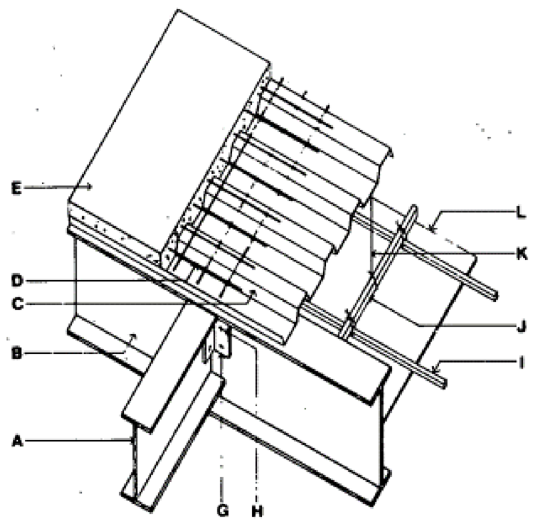
1) Determining Embodied Energy for Building Assemblies:

D.1 ENERGY IN TYPICAL BUILDING ASSEMBLIES

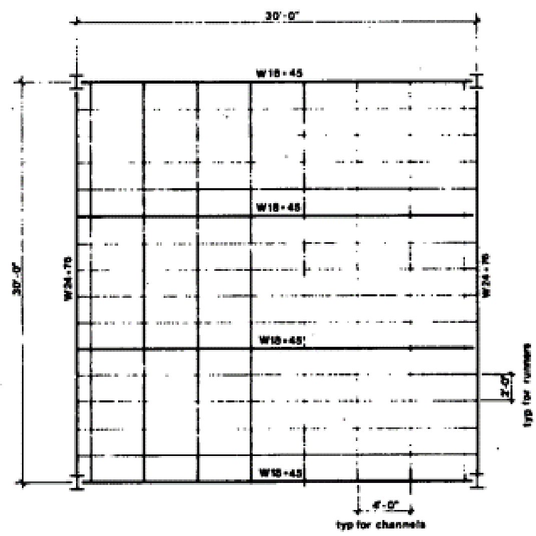
Once the energy embodiment of various units of building materials is estimated, it is then possible to compare the energy needed to construct interchangeable assemblies which satisfy similar performance requirements (structural, fire resistance, acoustical, maintenance, etc.). It is also possible to reexamine energy efficiency of alternatives by comparing the energy cost of providing, say, extra insulation or double glazing with the operational energy saved thereby, and to arrive at an energy payback time. This comparison is exactly parallel with the calculation of capital payback which would be done as a matter of course. Then, by adding the operational energy demand implied by a particular assembly - an exterior wall section, one square foot in area, for example - to the energy embodied in its material components, together with the energy embodied in materials necessary to maintain it, such as paint, caulking, replacement of shingles, and so forth, it is also possible to estimate the life cycle energy cost of comparable assemblies and to extend such an analysis to an entire building. Tables D-1 to D-3 compute the energy embodied in a section of floor slab 30' by 30' square, typical of comtemporary high-rise office buildings. Three interchangeable structural systems have been shown: Steel, concrete, and composite. In spite of their names, all three use both steel and concrete in varying proportions. They all reflect the basic structural properties of these two materials, steel having strength in both compression and tension and concrete having strength in compression only.

STANDARD STEEL SYSTEM TYPICAL FLOOR BAY

TYPICAL CONSTRUCTION



FRAMING PLAN



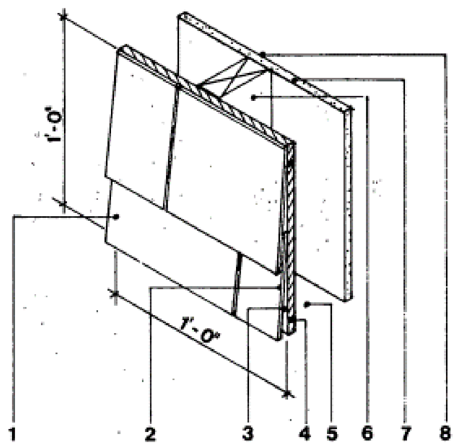
	Material	Size	Quantity	Weight/ Unit	Total Weight (30 x 30 Bay)	Embodied Energy (Btu/Unit)	Total Embodied Energy
A.	Filler Beams	W 18 x 45	90 ft	45 lb/ft	4,050 lb	22,707 Btu/lb	91,963,350 Btu
B.	Girder	W 24 x 76	30 ft	76 lb/ft	2,280 lb	22,707 Btu/lb	51,771,960 Btu
C.	Steel Deck	20 gauge	900 ft^2	2.15 lb/ft^2	1,935 lb	27,836 Btu/lb	53,[illegible],660 Btu
D.	Temp Reinf	6 x 6 #8/#8	900 ft^2	.30 lb/ft^2	270 lb	24,187 Btu/lb	6,530,490 Btu
E.	Conc Deck	4" thick	900 ft^2	.33 ft^3/ft^2	300 cu ft	96,087 Btu/cu ft	28,826,100 Btu
F.	Girder Angles	3½" x 5/16" x 10"	4	6.0 lb ea	24 lb	22,707 Btu/lb	544,968 Btu
G.	Filler Angles	3½" x 5/16" x 7"	12	4.2 lb ea	50.4 lb	22,707 Btu/lb	1,144,432 Btu
H.	Bolts	3/4" H.S. Bolts	36	.55 lb ea	19.8 lb	26,625 Btu/lb	527,175 Btu
I.	Channels	1½" x 3/4" x 1/8"	210 ft	1.20 lb/ft	252 lb	22,707 Btu/lb	5,722,164 Btu
J.	Runners	3/4" x 3/4" x 3/32"	480 ft	.72 lb/ft	346 lb	22,707 Btu/lb	7,856,622 Btu
K.	Wirehangers	¼" diam	98 ft	.17 lb/ft	16.6 lb	34,385 Btu/lb	570,791 Btu
L.	Gyp Board	½" thick	900 ft^2	2.0 lb/ft	1,800 lb	3,485 Btu/lb	6,273,000 Btu
							263,450,334 Btu

÷ 900 = 292,723 Btu/SF

Giving brick veneer on frame construction with no insulation an index of 100, the comparative sections rank as follows:

Section	Btu/SF	Energy Embodiment Index (For this comparison)
Brick Veneer on 2 x 4 Frame with no insulation	119,566	100.0
Wood Shingle on 2 x 4 Frame with no insulation	25,426	21.3
Brick Veneer on 2 x 4 with 3½" insulation	126,426	105.7
Wood Shingles on 2 x 4 Frame with 3½" insulation	32,286	27.0

WOOD FRAME WALLS



	CONSTRUCTION	R VALUE		EMBODIED ENERGY (BTU/SQ FT) IN BLDG SECTION
1.	OUTSIDE SURFACE (15 MPH WIND)	.17		-
2.	WOOD SHINGLES (1/2" x 8" LAPPED)	.87		7,315
3.	BLDG PAPER (ASPHALT)	.15		-
4.	PLYWOOD (1/2")	.62		7,705
5.	4" AIRSPACE	.97		-
6.	2" x 4" @ 16" o.c.	-	4.35	3,486
7.	GYPSUM WALLBOARD (1/2")	.45		6,920
8.	INSIDE SURFACE (STILL AIR)	.68		-
		3.91	4.35	25,426

U = 1/R = .26   U = .23 @ FRAMING

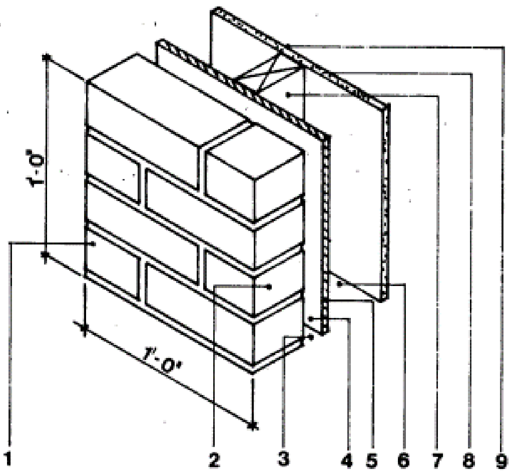
ADJUSTED U (TO ACCOUNT FOR FRAMING) = .25

ADDITION OF INSULATION	R VALUE	EMBODIED ENERGY (BTU/SQ FT) IN BLDG SECTION
ADD 3 1/2" BATT INSULATION	11.00	ADD 6,860
DEDUCT R VALUE OF AIR SPACE	.97	
	10.03	
ADD TO ABOVE R VALUE	3.91	
	13.79	32,286

U = 1/R = .07   U = .23 @ FRAMING

ADJUSTED U (TO ACCOUNT FOR FRAMING) = .085

BRICK ON WOOD FRAME WALLS



	CONSTRUCTION	R VALUE		EMBODIED ENERGY (BTU/SQ FT) IN BLDG SECTION
1.	OUTSIDE SURFACE (15 MPH WIND)	.17		-
2.	BRICK & MASONRY (4")	.44		105,004
3.	1" AIRSPACE	.97		-
4.	BUILDING PAPER (ASPHALT)	.15		-
5.	PLYWOOD (3/8")	.47		5,779
6.	4" AIRSPACE	.97		-
7.	2" x 4" @ 16 o.c.	-	4.35	3,486
8.	GYPSUM WALLBOARD (3/8")	.32		5,297
9.	INSIDE SURFACE	.68		-
		3.98	4.35	119,566

U = 1/R = .25 U = .23 @ FRAMING
ADJUSTED U (TO ACCOUNT FOR FRAMING) = .24

ADDITION OF INSULATION	R VALUE	EMBODIED ENERGY ((BTU/SQ FT) IN BLDG SECTION
ADD 3 1/2" BATT INSULATION	11.00	ADD 6,860
DEDUCT R VALUE OF AIRSPACE	.97	
	10.03	
ADD TO ABOVE R VALUE	3.98	
	14.01	126,426

U = 1/R = .07 U = .23 @ FRAMING
ADJUSTED U (TO ACCOUNT FOR FRAMING) = .085

NOTE: The same assembly approach together with EPDs for the materials can be used to determine the embodied GHG content or GWP (tCO2e) for an assembly while also considering other functional differences related to thermal performance (U-factor), moisture control, and multi-functional material optimizations (e.g., replacement of certain single-function materials with strategic use of multifunctional materials).

2) Determine the Assembly Life Cycle Net Energy Impact (Embodied + Operational GHG emissions)

D.2 <u>ENERGY COST LIFE CYCLE</u>

To understand the energy implications of building with various materials, one must look not only at the energy embodied in the construction and construction materials, but also at the energy demand which that construction imposes in terms of the operation of the completed building and the energy required to maintain or replace materials.

In some cases, such as alternate structural systems satisfying the same performance requirements, operational energy demand will not vary. In others, such as the amount of insulation in an exterior wall or double versus single glazing, the demand for operational energy may vary a great deal.

The demand for operational energy depends not only on the thermal qualities of the wall (or other assembly) but also on the location of the building. The thermal qualities of the wall are expressed by the "<u>U-Factor</u>," which is based on the thermal resistance of the various materials which make up the wall, and which indicates the number of Btu which will flow through one square foot of a material or assembly in one hour's time when there is a temperature difference of one degree Fahrenheit on opposite sides of the wall[7].

The average annual temperature variation, which will differ with the location of the building, is expressed by "degree days." The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) estimates that at 65° F. and below (outside temperature) one must start up a heating system in order to maintain 68° F. inside. The number of degrees below 65° F. of a given day's average temperature is equal to the number of heating degree days for that day. The U.S. Department of Commerce, National Oceanic and Atmospheric Administration has established annual heating and cooling degree day data for locations throughout the United States, based on a 30-year average Since the degree day data refer to one average temperature for an entire day, one must multiply heating degree days by 24 to arrive at "degree hours" compatible with the U-factor (an hourly measure) in order to estimate the total number of Btu which would flow through a given wall or assembly in a year. This Btu flow (which must be counteracted by the building's heating system) is equal to the operational energy demand for heating posed by the given wall or assembly.

Operational energy demand for space heating per square foot of wall or other portion of the exterior envelope can thus be computed by the following formula:

Annual Heating Demand (Btu) = Heating Degree Days x 24 (hours/day) x U-Factor (Btu/hour)

Location	Heating Degree Days[8]	Annual Demand
Atlanta, GA (Atl)	3,095	x 24 = 74,280 x U = Btu/SF
New York City (NYC)	4,848	x 24 =116,352 x U = Btu/SF
Champaign-Urbana, IL (Ch-Urb):	5,641	x 24 =135,144 x U = Btu/SF

The U-values for the uninsulated walls shown in Figures D-4 and D-5 are .25 (wood shingle) and .24 (brick veneer). The U-values for walls with 3½" of insulation are .085 for both. The following table shows the annual Btu demand per square foot of these four wall types for the three locations cited above:

	Wall Type	U-Value	Atl	NYC	Ch-Urb
A.	No insulation, wood shingles	.25	18,600	29,100	33,800
B.	No insulation, brick veneer	.24	17,800	27,900	32,400
C.	3½" insulation, wood or brick	.085	6,300	9,900	11,500

The addition of insulation to a typical 2 x 4 frame wall is now generally acknowledged to be cost effective. It is also highly energy effective. In New York City, addition of insulation will save an average 18,600 Btu/SF of wall annually at an additional embodiment (from Figure D-4) of 6,860 Btu. Energy payback (Btu saved versus extra Btu embodied) will be in approximately 1/3 heating season.

Figure D-6 plots the total energy embodied in and demanded by one square foot of a series of frame walls located in New York City over a period of 20 years. The walls are similar to those shown in Figures D-4 and D-5; however, five more alternative shingle walls with depth of wall and insulation increasing in 2" increments have been added. Table D-7 outlines the characteristics of the walls selected for investigation.

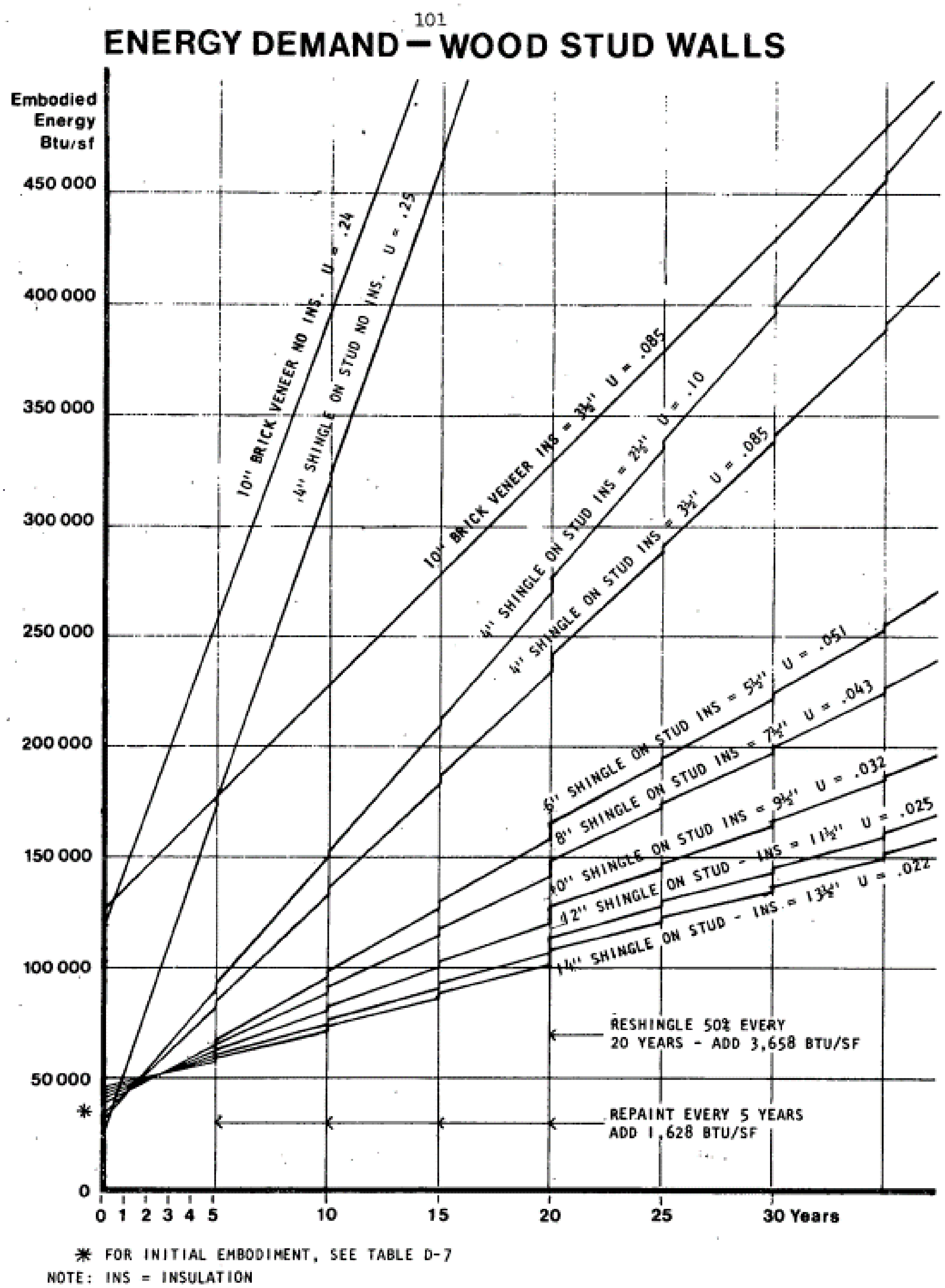
Several conclusions may be drawn from observation of the diagram. First of all, compared with no insulation at all, the energy embodied in insulation of any thickness will be paid back in terms of operational energy saved within one heating season. Second, 5½" of insulation will have an energy payback relative to 3½" of insulation within 1 heating season. And third, all thicknesses of insulation greater than 3½" will have demanded the same total number of Btus in a period of 3½ heating seasons. After this time, walls with more insulation will demand correspondingly less energy. (See Table D-7).

Three and one half inches of insulation is now used routinely in 2" x 4" exterior walls in residential construction and 5½" in a 2" x 6" stud wall is becoming more and more common. Thicknesses greater than that provide ever smaller increments of operational savings.

Only a portion of the wall will be solid (without openings), however. Glass areas will also have different properties regarding thermal transfer depending on whether they are single or double glazed. Table D-8 outlines these.

(This comparison deals only with the inducted thermal transfer characteristics of walls. In addition, heat is transferred, beneficially or detrimentally, as a result of infiltration and opening of windows, doors and louvers. Furthermore, by admitting light, which makes energy-supplied artificial light unnecessary and by admitting air for natural, non-mechanical ventilation, the wall serves to influence the energy requirements of the space other than thermally.)

3) Compare Embodied + Operational Energy Demand over Life Span of Different Assembly Options



NOTE: With planned electrification of U.S. buildings and increasing supply of electricity generated from renewable (low-to-zero carbon emisssions) electricity, the rate and extent to which these transitions occur in the future will cause the above linear trends to become non-linear curves with decreasing slope over time where used to evaluate embodied and operational GHG emissions instead of energy consumption.

4) Example Data for Specific Assemblies (e.g., walls) or Components (e.g., windows):

COMPARISON OF ENERGY EMBODIMENT AND ANNUAL OPERATIONAL ENERGY DEMAND FOR HEATING IMPOSED BY 1 SQUARE FOOT OF WOOD FRAME WALL WITH VARYING THICKNESS OF INSULATION

Nominal Wall Thickness	Type of Framing	Insul.	U-Factor	Embodied Energy (Btu)	Annual Demand (Btu)	Total Energy Consumed Over 20 Years (Btu)	No. 6 Fuel Oil Equivalent (Gal)
Brick Veneer Walls							
10"	2 x 4 @ 16"	0	.24	119,566	27,924	678,046	4.52
10"	2 x 4 @ 16"	3½"	.085	126,426	9,889	324,206	2.16
Shingled Walls							
4"	2 x 4 @ 16"	0	.25	25,426	29,088	617,356	4.12
4"	2 x 4 @ 16"	2½"	.10	31,126	11,635	273,996	1.83
4"	2 x 4 @ 16"	3½"	.085	32,286	9,889	240,236	1.60
6"	2 x 6 @ 24"	5½"	.051	34,670	5,934	163,520	1.09
8"	2 x 8 @ 24"	7½"	.043	38,074	4,889	146,024	0.97
10"	(2) 2 x 4 @ 24"	9½"	.032	40,174	3,770	125,744	0.84
12"	(2) 2 x 4 @ 24"	11½"	.025	42,274	2,932	111,084	0.74
14"	(2) 2 x 4 @ 24"	13½"	.022	44,374	2,560	105,744	0.70

Additional Embodiment for Maintenance (Shingled Walls)

Paint - one coat every 5 years: 1,628 Btu/SF

Reshingle 50% every 20 years: 3,658 Btu/SF

(Brick veneer walls are assumed to be maintenance free.)

COMPARISON OF ENERGY EMBODIMENT AND OPERATIONAL ENERGY DEMAND FOR HEATING IMPOSED BY 1 SQUARE FOOT OF SINGLE OR DOUBLE GLAZING

		1 SF Embodied Btu	U-Factor	Annual Demand/SF NYC (4,848 deg day)
Glass:	a) Single glass	15,430	1.13	131,477 Btu
	b) Double with +¼" sp	30,860	.65	75,628 Btu
	c) Double with +½" sp	30,860	.58	67,484 Btu

Compared with a) single glazing:

b) Double with ¼" sp — uses 15,430 Btu more to produce; demands 55,849 less annually; pays back in ¼+ heating season

c) Double with ½" sp — uses 15,430 Btu more to produce; demands 63,993 less annually; pays back under ¼ heating season.

Compared with b) double glazing with ¼" space:

c) Double with +½" sp — uses the same Btu to produce; demands 8,144 less annually.

Over a 20-year period, 1 Square Foot of glass will require (Embodiment & Demand)

		No. 6 Fuel Oil Equivalent (gal)
a) Single glass:	2.64 million Btu	17.6
b) Double with ¼" sp	1.54 million	10.3
c) Double with ½" sp	1.38 million	9.2

5) Consideration of Embodied Energy "Pay-back" and Air Infiltration Operational Energy Impacts

It will be seen that by increasing the energy embodiment in the walls and roof 6 percent, the annual energy demand through conducted heat loss is reduced 48 percent. The additional energy embodied, 10 million Btu is repaid in about 1/3 of a heating season.

Infiltration, a function of air flowing through the cracks around each opening and through gaps in the construction will also have an effect on heating demand, adding an additional 41,785,544 Btu/year*

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*Consider only doors and windows. The crack around each door will be 19'-4" long. The crack at each window will be 18' long (perimeter plus 4' length where the window sections meet). Therefore, doors will account for 38.66 LF and windows will account for 414 LF of crack.[9] (There is also infiltration resulting from incomplete caulking, porosity of brick and block, joints in siding, etc.)

At a wind velocity of 15 mph, approximately 25 cu ft of air per hour will enter between sash and frame of a weather-stripped wood casement window per linear foot of crack. 25 x 414 = 10,350 cu ft of air per hour.

At the same wind velocity, approximately 35 cu ft of air per hour will enter between door and frame of a weather-stripped wood door per foot of crack. 35 x 38.66 = 1,353 cu ft of air per hour.

Total hourly air flow will be 11,703 cu ft of air per hour.

The heat required to raise 1 pound of air 1° F. is .24 Btu. The density of air averages .075 lbs/cu ft. Thus, 11,703 cu ft x .075 lbs/cu ft x 24 Btu/lb = 210.7 Btu.

210.7 Btu x 4,848 NYC degree days x 24 hours = 24.5 million Btu/year. (Equivalent to 163.4 gallons of No. 6 fuel oil.)

Further, if, in toto, the doors are opened 30 times per day and are left open for 10 seconds average, this represents a total of 300 seconds, or 5 minutes or 1/12 of an hour per day. The volume of air in cubic feet introduced at 15 miles per hour is:

$$\frac{3' \times 6.67' \times 5{,}280' \times 15}{12} = 132{,}066 \text{ cu ft/day}$$

Energy required to heat this per degree per day is:
132,066 cu ft/day x .075 lbs/cu ft x .24 Btu/lb = 2,377 Btu/degree day.

Total Btu required per year for doors is:
2,377 x 4,848 degree days = 11,523,696 Btu/year.

Assume window air passage from open windows would be half the air loss through doors = an additional 5,761,848 Btu/year. Total heat loss from infiltration and air passage through doors and windows =
24,500,000 + 11,523,696 + 5,761,848 = 41,785,544 Btu/year.

Therefore, the total heating requirement to counteract conducted heat loss and infiltration = Building a) 67,333,208 + 41,785,544 = 109,118,752 Btu/year.
Building b) 35,227,700 + 41,785,544 = 77,013,244 Btu/year.*

Stated in other terms, of the 1.053 x 10^9 Btu embodied in the entire building (from Table C-1: 702,047 Btu/SF average for 1-Family Residences x 1,500 SF), approximately 168.86 x 10^6 Btu (or 16%) in Building a) and 178.80 x 10^6 Btu in Building b) are in the shell of the building where thermal exchanges take place.

Of the 109.12 x 10^6 annual Btu heating requirement for Building a): 67.33 x 10^6 Btu, 62% is as a result of the conducted heat loss through the building skin. Adding the insulation and double glazing for Building b) (at an energy cost of 10 x 10^6 Btu), results in an annual fuel saving of 32.11 x 10^6 Btu and changes the pattern of energy use to one in which the infiltration is the predominant factor in heat loss, since now, of 77.013 x 10^6 Btu, only 35.227 x 10^6 Btu (or 46%) is due to conducted heat loss.

6) Overall Summary of Study, Findings, and Conclusions

CONCLUSIONS

This report has been the result of a successful collaboration between Richard G. Stein and Associates, a private architectural firm, and the Energy Research Group at the Center for Advanced Computation, University of Illinois, a multi-disciplinary research center in a major university. To the energy input-output matrix already developed at the Center for Advanced Computation, Richard G. Stein and Associates were able to add the detail and specific professional information required for the production of data useful to the construction field and governmental bodies consistent with the integrity of the rest of the matrix. The methodology combined the extraction of information from government sources (Bureau of Economic Analysis, Bureau of the Census, and others) construction industry statistical information sources (Dodge Reports, McGraw Hill Information Service, Means Co., Inc., etc.) and from private sources (RGS&A files, CAC library, consulting engineers, construction management consultants, materials producers, trade associations, etc.). The data in this report are from 1967, the most recent year with complete economic and energy use reporting. Conclusions are broadly applicable to other years and serve as a base to observe changes.

Until now, the entire emphasis in energy conservation in buildings has been on their operation. This has been because building operation has been a visible large target, susceptible to rapid modification as a result of straightforward changes in operation methods as well as physical modification of the buildings themselves.

On the basis of this report, the energy used in constructing buildings can be more clearly understood - in broad terms and in detail.

By using the large computer model at the Center for Advanced Computation, Richard G. Stein and Associates and the Center for Advanced Computation together were able to extract base information on:

1. The total energy embodied in new construction in 1967, divided into 49 separate sectors according to construction type.

2. The division between energy used in new building construction (18 sectors), building maintenance and repair construction (4 sectors), new non-building construction (14 sectors), and non-building maintenance and repair construction (13 sectors).

3. The energy embodied in direct energy purchased and used at the jobsite for each category and the energy embodied indirectly in the materials and assemblies brought to the jobsite.

4. The division by percentage within each construction category of materials required from all other sectors of the economy supplying products to the construction industry, both building and non-building.

5. The energy embodiment per unit of the major building materials, including all energy for the entire process up to incorporation in the building.

6. Application of the unit energy embodiment values to specific characteristic assemblies, demonstrating not only the energy embodied in initial construction, but also lifetime energy cost comparisons based on operation and maintenance energy in addition to the original cost.

7. The amount of energy embodied in each new building sector prorated per square foot of building constructed for that sector in 1967.

8. The flow of energy through the economy starting with energy sources in their natural state and following their entire conversion to embodied energy through the energy industries into the production of materials and on into incorporation in buildings. Diagrams have been developed but not completed with all detail.

Extracting significant detail from the report, the following factual details and conclusions can be noted:

1. The entire construction industry required 7,235.6 trillion Btu (10.82 percent of total U.S. energy consumption) in 1967. Of this, New Building Construction required 3,421.6 trillion Btu (over 47 percent of the industry total and over 5 percent of the U.S. total) and Building Maintenance and Repair accounted for an additional 733.5 trillion Btu (over 10 percent of the industry and 1 percent of U.S.). The Non-building sectors required 2,499.9 trillion Btu for new construction (34.5 percent of the industry total and nearly 4 percent of U.S.) while Non-building Maintenance and Repair required 580.6 trillion Btu (8 percent of the industry and under 1 percent of U.S.).

2. Within the new building construction sectors the largest single category was 1-family residences, accounting for over 1.17 percent of the U.S. total, followed by industrial buildings (0.7 percent) and educational buildings (0.66 percent) and residential alterations or additions and office buildings (0.39 percent each). The remaining 13 categories vary from 0.35 percent to 0.05 percent.

3. Within the non-building construction categories, highways was by far the greatest energy user, accounting for 1.55 percent of the entire U.S. energy use. Just as some of the building sectors may include substantial increments of energy for non-building activity (e.g. parking lots for shopping centers or bunker silos for farm service construction), so some of the non-building sectors may include a significant increment of building. Non-building sectors such as electric utilities, for example, include the housing for generating and transmission equipment, which fall into the building construction category. However, they also include large increments for specialized materials and machinery. New Construction, Military, is listed in non-building sectors, although a major part of the construction it represents (judging by the relatively large percentage of embodied energy attributable to metal doors) may be in buildings; however, it is not possible to break down the data within a given sector into building and non-building projects.

4. One fifth as much energy is used in construction of new buildings as in operating the entire stock of existing buildings. With reduced energy requirements for building operation, some building types will use as much energy in the building process as in ten years of operation.

These percentages reflect the 1967 economy. It would be possible to approximate any other year, based on the divisions reported either by dollar or square foot, and then, without accounting for changes in construction methods in the years after 1967, to revise the model for the construction industry. It is also possible (inherent in the I/O method) to develop with a high degree of accuracy the resulting shifts across the economy caused by shifts in construction commitments. One such shift could be from 1-family residences to garden apartments and high-rise residential. Another could be from highway construction to mass transit. A third could be a major commitment to solar technology rather than electricity for space and water heating across the country.

There is a wide variation in energy embodiment per square foot of building among the different building categories. The highest energy-using category is Laboratories, requiring 2,074,056 Btu per square foot, and the lowest is Farm Service, requiring 149,071 Btu per square foot, a 14 to 1 ratio. Among the largest energy-using categories, there are also important differences in quantities. Single-family residences require 702,047 Btu. In examining the profile of distribution, it becomes apparent that the importance of wood, a material with low energy embodiment is the major reason. Hospital buildings, which require 1,722,200 Btu - only slightly less than laboratories - have over 30 percent of their energy in specialty items and systems that do not appear as significant contributors to less specialized buildings. These would include the transportation and conveyor systems, the sterilizing equipment, the extensive use of stainless steel and aluminum for equipment, the use of plastic piping systems, etc. The average for all the categories listed is 935,440 Btu per square foot.

It is essential to bear in mind that all the figures given are average figures. They do not reflect regional differences that require different detailing, such as the deeper footings that are required for buildings in Minnesota where there is a deep frost line in comparison with Southern California where there is no frost problem, or the difference required to satisfy special programmatic requirements, as the equipment in a complicated research hospital as opposed to a facility that is primarily a long-term residential center for the chronically ill. Moreover, as other studies in the report demonstrate, there are means available in building to satisfy similar performance requirements in assemblies with markedly different energy embodiments.

An informed choice in materials selection can reduce building energy use appreciably. A sample analysis of three interchangeable floor systems typical of high-rise office construction demonstrated that the production of a reinforced concrete structure will use less than 60 percent of the energy needed to produce a comparable standard steel structure. For the floor alone, not including columns, concrete would require 172 MBtu/SF compared to 293 MBtu/SF for steel. Although, in general, dollar cost has not been a consideration in this report, it should be noted that concrete and steel systems are generally similar in overall cost for large, repetitive systems, and cost is not typically the major consideration in choosing one over the other. Applied to the total area of office buildings in a given year (157.6 million SF in 1967) the difference in embodied energy is significant. (19 trillion Btu, equivalent to 3 million barrels of No. 6 oil.).

Another analysis of walls typical of 1-family residential construction and with equivalent thermal resistance capabilities has been made. Both are wood frame construction; however, one has a brick veneer exterior and the other is shingled. The brick veneered wall is 4 to 5 times as energy intensive per square foot as the shingled one - a function of the high energy intensity of brick compared to the low energy intensity of wood. This analysis has been carried further, adding more insulation in 2-inch increments to deeper stud walls and comparing not only the energy embodied in construction of the assemblies, but also the energy demanded by the thermal characteristics of the walls for heating the spaces which these walls (which range from 4" deep with 0" insulation to 14" deep with 13½" insulation) would enclose. Extension of this analysis to a similar consideration of single versus double glazing, and flat roofs with 3½" of mineral wool insulation versus 5½", has allowed us to make a general comparison between the outer shells of two typical 1,500 square foot, 1-family residences, either of them in accordance with construction practices today. The first, which has 3½" of insulation in the walls, 3½" insulation in the roof, and single glazing, would have an embodied energy value of 168,867,724 Btu. Operational energy demand would be 67,333,208 Btu per year for heat lost through thermal transmission. The second, which has 5½" of insulation in both roof and walls and double glazing would have an embodied energy value of 178,799,380 Btu (5.9 percent more than the first example) and an operational energy demand due to thermal transmission losses of 35,227,200 Btu/year (48 percent lower than the first example). In addition, both buildings would require a further input of operational energy of 41.8 million Btu/year to counteract heat lost through infiltration, opening of doors and windows, etc. Thus, the total energy which these buildings would cause to be consumed, either in their construction or in their operation over a period of 20 years, would be 168.9 + 20 (67.3 + 41.8) million Btu = 168.9 + 2,182 million Btu = 2,350.9 million Btu for the first building and 178.8 + 20 (35.2 + 41.8) million Btu = 178.8 + 1,540 million Btu = 1,718.8 million Btu for the second - a reduction of 27 percent. It is evident that, although in both these cases, the energy embodied is a small percentage of the energy which will be demanded over a period of time, the choice of materials of construction will have a significant effect nonetheless. This is particularly true in the case of materials and assemblies inherent in 1-family construction, which in 1967, out of 49 construction sectors, accounted for a total amount of energy second only to highway construction, amounting by itself to 1.17 percent of all energy consumed in the United States in that year.

APPENDIX B

Life Cycle Analysis Methodology for Buildings

ACHP (Advisory Council on Historic Preservation). 1979. *Assessing the Energy Conservation Benefits of Historic Preservation: Methods and Examples*. Washington, DC: ACHP. achp.preservation50.org/wp-content/uploads/2017/01/1979-Energy-Conserv-and-Hist-Pres.pdf.

The report focuses on renovation and re-use and benefits of extending the life of the embodied energy (or carbon emissions) within existing buildings while improving their operational energy use efficiency to reduce future energy use and operational carbon emissions. Excerpts follow…

Rehabilitation of existing buildings requires much less initial investment of energy than constructing comparable new facilities.

- The Grand Central Arcade, an adaptive reuse of a hotel in Seattle's Pioneer Square Historic District, required less than one-fifth as much energy for rehabilitation materials and construction activities than would have been needed to produce the materials for and build a comparable new facility. The rehabilitation "savings" came to more than 90 billion Btus or over 700,000 gallons of gasoline.

- Rehabilitation of the Lockefield Garden Apartments would potentially require only one third as much energy for materials and construction processes as a new complex providing the same services. In this case, the rehabilitation "savings" would be equivalent to over 2250 billion Btus or almost 2 million gallons of gasoline.

- An extensive rehabilitation of "Austin House", a 3-unit apartment adaptive reuse of a Capitol Hill carriage house in Washington, DC, left only the exterior shell intact. Even so, the rehabilitation materials and construction activities required less than half as much energy as would have been required in the materials and building of an equivalent new structure. Initial rehabilitation "savings" for this small structure (2700 s.f.) are over 1000 million Btus or over 8000 gallons of gasoline.

IT IS IMPORTANT THAT PRESERVATION RECEIVE PROPER CREDIT FOR ITS ENERGY SAVINGS

- Once energy is embodied in a building, it cannot be recovered and used for another purpose--8 bricks embody energy equivalent to a gallon of gasoline but cannot fuel a car.
- Preservation saves energy by taking advantage of the nonrecoverable energy embodied in an existing building and extending the use of it.
- Because the energy embodied in an existing building was invested long ago, and is nonrecoverable, its economic value is not adequately recognized by normal economic comparisons of preservation versus new construction.
- Publicizing the energy conservation benefits of preservation can increase public awareness of this hidden benefit of preservation, even though the energy savings do not translate directly into dollar savings in the marketplace.

THE ENERGY CONSERVATION ANALYSIS METHODS AND TOOLS DEVELOPED BY THE COUNCIL CAN BE APPLIED AT ANY POINT IN THE DECISIONMAKING PROCESS, REGARDLESS OF THE AMOUNT OF DETAIL OF INFORMATION AVAILABLE

- The Council's objectives for this study were twofold:
  - Provide methods for determination of the energy conservation aspects of renovation.
  - Demonstrate application of resultant methods to actual preservation examples.
- The analysis methods are intended to be useful in a variety of applications:
  - The techniques are designed to be usable by individuals or groups with different skill levels and expertise.
  - The particular analytical problems or questions to be addressed will involve different levels of detail depending on the availability of information and resources.
  - Highly detailed procedures, while useful to some, require more time and money than can be practically invested in many cases.
- To accomplish these goals, the Council has developed a series of computation techniques for different levels of detail and precision:
  - Building Concept Model—simple methods
  - Building Survey Model—intermediate methods
  - Building Inventory Model—detailed methods.

Basically, the study provides three different levels of LCA to assist in decisions regarding preservation (re-use) vs. new building construction. The levels vary in purpose and accuracy and also the demand for information and complexity of analysis. For example, the concept model makes use of benchmarked typical Energy Use Intensities (EUI) for different types of buildings to asses operational energy use. For embodied energy (correlated to embodied carbon), generic values of embodied energy intensity (MBtu/sqft of floor area) are used. Similar generic values for demolition are also provided. These data are derived from Hannon et al. (1976) – see Appendix A. Examples of such data are shown below:

EXHIBIT 1
Embodied Energy of Materials and Construction[1]
Per Square Foot of Construction

	MBTU/Sq. Ft.
Residential - 1 Family	700
Residential - 2-4 Family	630
Residential - Garden Apt	650
Residential - High Rise	740
Hotel/Motel	1130
Dormitories	1430
Industrial Buildings	970
Office Buildings	1640
Warehouses	560
Garages/Service Stations	770
Stores/Restaurants	940
Religious Buildings	1260
Educational	1390
Hospital Buildings	1720
Other Nonfarm Buildings	1450
a. Amusement, Social & Rec	1380
b. Misc Nonresidential Bldg	1100
c. Laboratories	2070
d. Libraries, Museums, etc.	1740

EXHIBIT 2
Demolition Energy of Construction Materials for Existing Buildings

Construction Type	Building Size		
	Small 5000-15,000 s.f.	Medium 50,000-150,000 s.f.	Large 500,000-1,500,000 s.f.
Light (e.g., wood frame)	3100 Btu/s.f.	2400 Btu/s.f.	2100 Btu/s.f.
Medium (e.g., steel frame)	9300 Btu/s.f.	7200 Btu/s.f.	6300 Btu/s.f.
Heavy (e.g., masonry, concrete)	15,500 Btu/s.f.	12,000 Btu/s.f.	10,500 Btu/s.f.

CLIMATIC REGIONS

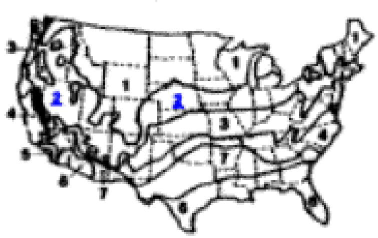

EXHIBIT 3
Annual Operational Energy (MBtu/sf)[1]

Building Type	Nation	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7
Office	64	65	76	65	61	51	50	64
Elementary	65	114	70	68	70	53	48	57
Secondary	52	77	66	55	51	37	41	34
College/Univ.	65	67	70	46	59	—	—	83
Hospital	190	—	200	171	227	207	—	197
Clinic	69	84	72	71	65	61	59	59
Assembly	61	58	76	66	51	44	68	57
Restaurant	159	162	178	186	144	123	137	137
Mercantile	84	99	98	86	81	67	83	80
Warehouse	65	75	82	65	50	36	37	39
Residential Non-Housekeeping	95	99	84	94	125	90	93	106
High Rise Apt.	49	53	53	52	53	34	29	—
Multifamily Low Rise	43	58	55	41	31	27	22	32
Single Family Attached	47	65	54	45	37	35	33	45
Single Family Detached	69	104	73	61	52	43	38	58
Mobile Homes	75	103	84	81	67	42	54	70

[1] PHASE ONE/BASE DATA for the development of ENERGY PERFORMANCE STANDARDS FOR NEW BUILDINGS, HUD, DOE, January, 1978

The building inventory model is the most intensive and relies on a data set of material embodied energy values also derived from Hannon et al. (1976) – see Appendix A. This data set serves the same purpose as modern-day material embodied carbon databases derived from EPDs.

EXHIBIT 11
(Continued)

Material Classification	Description	Unit	Embodied Energy Per Material Unit
STONE & CLAY PRODUCTS (Continued)			
Cement, Hydraulic (Continued)	Brick & Structural Clay Tile	-	-
	Brick, except Ceramic Glazed + Refractory		
	Bldg or Common Brick & Face (2-1/4"x3-5/8"x7-5/8")	1 brk	14,300
	Other Brick (Paving, Floor & Sewer) (2-1/4"x3-5/8"x7-5/8")	1 brk	25,600
	Glazed Brick + Structural Hollow Tile		
	Structural Clay Tile except facing including load bearing & non-load bearing tile	1 tile	27,700
	Facing tile (structural) & Ceramic glazed brick (2-1/4"x3-5/8"x7-5/8")	1 brk	33,400
	Unglazed & salt glazed facing tile (8"x5"x11")	1 tile	68,200
	Ceramic Wall & Floor Tile	-	-
	Quarry tile & Promenade Tile	sq ft	51,000
	Ceramic Mosaic Tile & Accessories - Unglazed	sq ft	63,600

EXHIBIT 11
(Continued)

Material Classification	Description	Unit	Embodied Energy Per Material Unit
STONE & CLAY PRODUCTS (Continued)			
Concrete Blocks	Structural Block - Heavy weight aggregate 8"x8"x16"	1 blk	31,800
	Structural Block - Decorative		
	Brick (2-1/4"x3-5/8"x7-5/8")	1 brk	5,000
	Ready Mix Concrete	cu yd	2,594,000
	Lime	-	-
	Quicklime	1 T	6,867,000
	Hydrated Lime	1 T	9,464,000
	Dead Burned Dolomite	1 T	9,748,000
	Gypsum Products		-
	Calcined gypsum bldg materials, bldg plasters & prefab bldg materials	1 T	6,970,000
	Other calcined gypsum	1 T	4,362,000
	PRODUCT EXAMPLE - GYP BOARD		
	Size / lb/sq ft	Total Btu/sq ft	
	3/8" / 1.52	5,300	
	1/2" / 2.00	7,000	
Mineral Wool	Mineral Wool for Structural Insulation		
	Loose Fiber (Blowing + Pouring + Granulated Fiber)	sh T	12,826,000