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Sustainable Materials Selection in Manufactured Products

A Framework for Design-Integrated Life Cycle Thinking with Case Studies

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Disclaimer

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The authors thank Caroline Dollinger of Energetics for her technical review of this report.

List of Acronyms

AHSS	Advanced High Strength Steel
AMMTO	Advanced Materials and Manufacturing Technologies Office (of the U.S. DOE)
AMO	Advanced Manufacturing Office (of the U.S. DOE)[1]
BF	Blast Furnace (an ironmaking process)
BOF	Basic Oxygen Furnace (a steelmaking process)
CAFE	Corporate Average Fuel Economy
CED	Cumulative Energy Demand
CFRP	Carbon-Fiber Reinforced Polymer
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
CT	Current Typical
DOE	U.S. Department of Energy
DRI	Direct Reduction Ironmaking
EAF	Electric Arc Furnace (a steelmaking process)
EERE	Office of Energy Efficiency and Renewable Energy (of the U.S. DOE)
EIA	Energy Information Administration (of the U.S. DOE)
EPA	Environmental Protection Agency
EPS	Expanded Polystyrene
EV	Electric Vehicle
FMVSS	U.S. Federal Motor Vehicle Safety Standards
FRV	Fuel Reduction Value
FU	Functional Unit
GFRP	Glass-Fiber Reinforced Polymer
GMA	Grocery Manufacturers Association
GWP	Global Warming Potential
ICE	Internal Combustion Engine
IEDO	Industrial Efficiency and Decarbonization Office
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
MECS	Manufacturing Energy Consumption Survey (of the EIA)
NAICS	North American Industry Classification System
NHTSA	U.S. National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PCR	Product Category Rule
PM	Practical Minimum
PUR	Polyurethane
SI	International System of Units (the metric system)

[1] DOE's former Advanced Manufacturing Office was restructured in 2022 to form two new offices: the Industrial Efficiency and Decarbonization Office (IEDO) and the Advanced Materials and Manufacturing Technologies Office (AMMTO). The work described in this report was initiated under AMO prior to the transition.

SOA	State of the Art
TM	Thermodynamic Minimum
XPS	Extruded Polystyrene

Executive Summary

Materials selection can provide a major opportunity to improve the environmental performance of manufactured products. Substitution of conventional materials with eco-friendly options can lower a product's environmental impact while still meeting key application requirements. A prerequisite for sustainability-informed decision-making is that relevant data and information are available for all materials being considered. Here we outline examples of the types and sources of data needed; and we explore key considerations for sustainable materials selection through a series of practical, cross-sectoral case studies.

This report builds on the groundwork of the DOE *Manufacturing Energy Bandwidth Studies*[2], which have served as foundational data references for energy consumption and energy savings opportunities in key manufacturing sectors for over two decades. A key benefit of the *Bandwidth Studies* is that they facilitate at-a-glance comparisons of research and development (R&D) opportunity sizes across industries or materials (Figure ES-1).

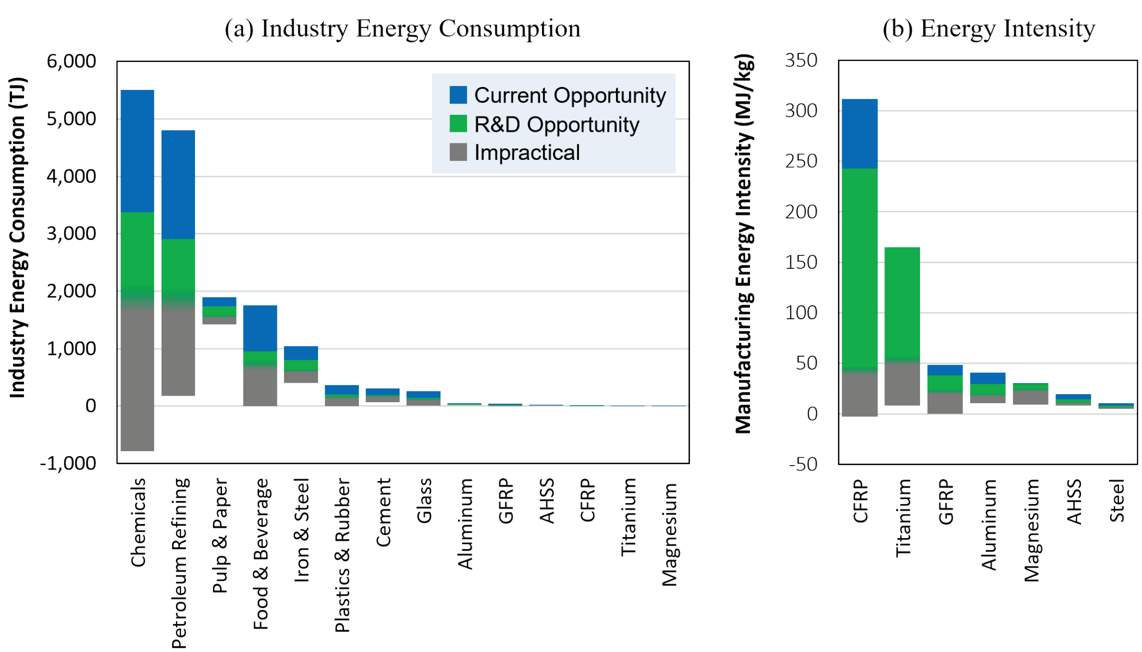

Figure ES-1. Comparison of *Manufacturing Energy Bandwidth Study* results for (a) fourteen industries, showing the total energy consumption (TJ) for each industry in the year 2010; and (b) seven structural materials, showing the manufacturing energy intensity (MJ/kg) of each material.

Figure recreated from Bandwidth Study data (DOE 2015a, DOE 2015b, DOE 2015c, DOE 2015d, DOE 2017a, DOE 2017b, DOE 2017c, DOE 2017d, DOE 2017e, DOE 2017f, DOE 2017g, DOE 2017h, DOE 2017i, and DOE 2017j). Acronyms: AHSS = Advanced High Strength Steel; CFRP = Carbon Fiber Reinforced Polymer; GFRP = Glass Fiber Reinforced Polymer.

[2] The full series of *Manufacturing Energy Bandwidth Studies* is available from: https://www.energy.gov/eere/iedo/manufacturing-energy-bandwidth-studies

While such energy comparisons are informative and provide information at a sectoral level, they cannot be used to compare the environmental performance of one material to another in the context of a specific application. For one, *Bandwidth Studies* measure energy requirements only for processes occurring in a single manufacturing industry—not for all processes involved in making a given commodity material. Second, the substitution rate of one material for another is highly application specific. Additional data and methods are needed to support holistic environmental opportunity analysis, such as:

- Inclusion of greenhouse gas emissions (and emissions reduction opportunities) in in addition to the energy consumption metrics reported in past *Bandwidth Studies*.[3]
- Extending study boundaries for selected industrial products to quantify the cumulative cradle-to-gate energy consumption and greenhouse gas emissions (i.e., the "embodied energy" and "embodied emissions") associated with manufacturing those products.
- Developing new frameworks and methods for objective comparison of materials an applied, design-integrated context—including consideration of material characteristics and application requirements, as conceptually illustrated in Figure ES-2.

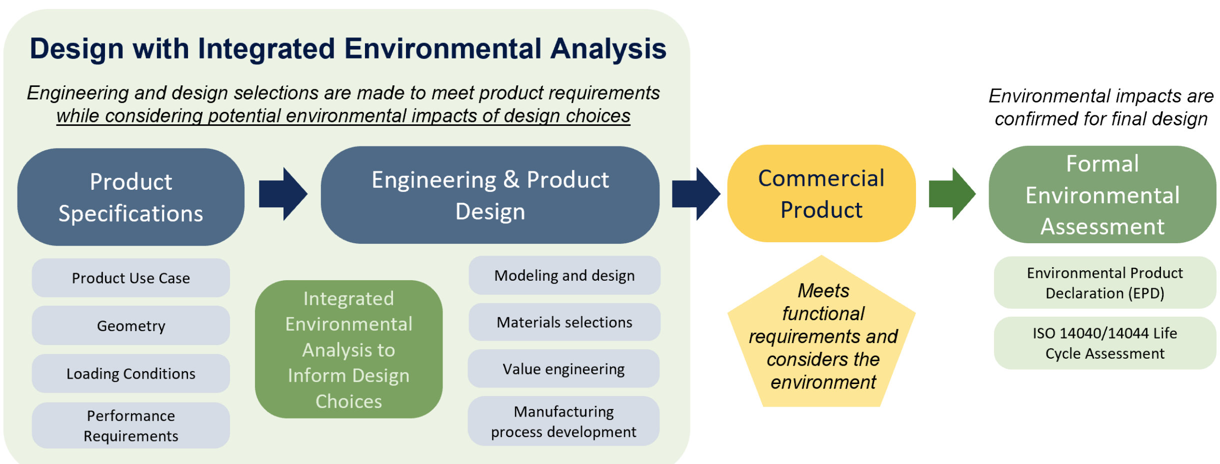

Figure ES-2. A framework for integrating environmental assessment into the design of a manufactured product.

The primary focus of this report is on the integration of life cycle assessment (LCA) principles with materials and product design information and requirements to develop a generalized methodology to **objectively compare materials on the basis of environmental performance in an applied context,** whether using Bandwidth data or other information. Table ES-1 summarizes the analysis steps. At the core of the methodology, simplified mechanical models empower analysts with physics-based functional units that can be expressed symbolically as a function of material properties relevant to the application (such as density, elastic modulus,

[3] Work is underway now at DOE IEDO to generate an updated series of *Bandwidth Studies* that will include emissions metrics in addition to manufacturing energy use.

thermal conductivity, yield strength, etc.). In a design context, this allows any candidate material to assessed in advance for its potential environmental performance before committing to a full LCA or finalizing a specific material choice in product design.

Table ES-1. A Life Cycle Assessment Inspired Framework for Sustainable Materials Selection: Analysis Steps

Analysis Step		Description
1	Define the Application and Analysis Scope	Describe the product system in the context of its end-use application and determine study objectives. Establish the boundaries of the analysis (e.g., cradle-to-gate, cradle-to-use, or cradle-to-grave). Select the environmental metrics that will be considered in the analysis, such as embodied emissions and embodied energy.
2	Define the Functional Unit	Define the functional unit, noting application constraints in specific, quantitative terms that will align with a physical model of the system.
3	Identify Candidate Materials	Generate a list of candidate materials that will be considered for the application. If appropriate, identify a reference material (representing the current standard) to which other materials will be compared.
4	Derive Expression for Minimum Required Functional Unit Mass	Develop a physical model for the product system, simplifying the geometry and physical or operational constraints if needed. Based on the physical model and application constraints, derive a symbolic expression for the minimum required functional unit mass.
5	Gather Material & Environmental Data	Collect material property data for each material as required to estimate the required mass for the functional unit (i.e., gather data for all parameters specified in the mass expression developed in the previous step). Collect environmental performance data for each material (as an impact intensity per unit of mass) based on the metrics selected for the analysis. Data sources may include Bandwidth Studies, life cycle assessment or material property databases, literature sources, and life cycle inventory datasets.
6	Calculate Required Mass	Calculate the minimum required functional unit mass for each candidate material by substituting material properties into the symbolic expression previously developed.
7	Assess Environmental Performance	Calculate the environmental performance of each candidate material by multiplying the required mass of the functional unit (kg) by each of the selected environmental intensity metrics for the analysis, such as embodied energy (MJ/kg) or embodied emissions (kg CO_2-eq/kg). Optionally, results can be calculated separately for each life cycle phase included in analysis.
8	Synthesize Results & Plan Next Steps	Synthesize results by comparing materials based on their cradle-to-gate, cradle-to-use, or cradle-to-grave environmental performance in the application and assess significance and data quality. Document potential environmental impacts and plan the next steps for analysis (such as a follow-on gate-to-grave assessment, sensitivity analysis, additional data requirement, or a full LCA).

Three worked case studies (an insulation panel, a shipping pallet, and an automotive B-pillar component) are included in this report as illustrative examples of the methodology:

- In the **residential insulation** case study, paper wool (where feasible) is found to offer significant life cycle emissions reductions compared to fiberglass batting insulation. Polymer foam insulation materials may also offer cradle-to-gate benefits, but a deeper analysis of the end-of-life phase is necessary to better understand the potential harms from end-of-life disposal of polymer foam insulation products.
- In the **shipping pallet** case study, wood stringer pallets may minimize life cycle emissions for applications that involve light-duty loads and short-haul travel. Wood block pallets minimize life cycle emissions for heavy-duty, long-haul applications. No alternative pallet materials considered here offered an apparent life cycle benefit. However, tradeoffs between materials depend strongly on the specific use case for the pallet, including lifetime, pallet management approach, and expectations for typical dynamic loads. A longer-haul and/or heavier-duty application than the ones considered in this report might result in life cycle benefits for a lightweight aluminum pallet.
- In the **automotive B-pillar** case study, benefits of lightweight materials in the vehicle use phase are often counteracted by penalties in the materials and manufacturing phases. Analysis shows that a carbon-fiber composite or secondary aluminum B-pillar may reduce life cycle emissions in a conventional gasoline vehicle (compared to a conventional steel reference design). An aluminum B-pillar minimizes life cycle emissions in an electric vehicle. Tradeoffs are strongly influenced by vehicle assumptions including lifetime kilometers traveled and (particularly for electric vehicles) the makeup of the electric grid mix.

All three case studies highlight a common theme, which is that application assumptions are critically important for accurate comparisons that can support informed decision making. For example, a carbon fiber B-pillar may offer the best life cycle environmental performance if the B-pillar lasts the lifetime of the vehicle (over 160,000 kilometers) without repair—but a steel or aluminum B-pillar may be superior if the component is likely to require repair or replacement. Likewise, the best material for a shipping pallet designed for single use may not be the same as the best material for a shipping pallet expected to deliver hundreds of product loads over its service life. To maximize environmental performance of products, engineers must integrate environmental principles into conceptualization and design starting at the earliest possible stage, and continually iterate to improve assumptions. The framework presented here may provide a starting point for life cycle thinking in the context of engineering decisions.

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1. Introduction

1.1 Background and Motivation: History of the Bandwidth Studies

Over the past two decades, DOE’s *Manufacturing Energy Bandwidth Studies*[4] have served as a foundational data reference to help understand the range (or “bandwidth’) of potential energy savings opportunities in manufacturing industries. In the energy bandwidth methodology, four different energy consumption values are estimated for an industry or major operation of interest: the **current typical (CT)** value; the **state-of-the-art (SOA)** value; an estimated **practical minimum (PM)** value assuming successful deployment of known (but pre-commercial) R&D technologies; and finally a **thermodynamic minimum (TM)** value for the required material transformation (a theoretical calculation based on Gibbs free energy). Comparison of these four values provides a measure of the scale of potential energy savings opportunities. For a given product or process, the difference between the current typical energy consumption and the state-of-the-art energy consumption can be considered the *current opportunity*, while the difference between the state-of-the-art consumption and practical minimum can be considered the *R&D opportunity*. The difference between the practical minimum and the thermodynamic minimum is considered *impractical* (i.e., not an opportunity for the near- or mid-term). As an example, an energy bandwidth data summary for the U.S. aluminum industry (DOE 2017a) is shown in Figure 1.

Bandwidth studies were prepared for fourteen different industrial sectors between 2015 and 2017 following a consistent methodology. Appendix A provides an overview of the sector coverage and main results of these studies. Bandwidth studies provide a unique, top-down perspective of energy use and energy reduction opportunities in an entire industry—including a breakdown of the specific process operations that contribute most to the opportunity space. This information can be used for energy analysis, R&D funding justifications, and general context of the status of U.S. industry energy performance. Because energy consumption data are expressed as a range, bandwidth data can also be leveraged for sensitivity analysis.

Recently, DOE IEDO has been exploring new uses of manufacturing energy bandwidth study data and methods to support holistic environmental opportunity analysis. For example, work is currently underway to develop a new series of Bandwidth Studies that will include greenhouse gas emissions and emissions reduction opportunities in addition to energy consumption metrics. Another interest is in the development of new methods or frameworks for objective comparison of materials based on bandwidth energy (or emissions) results in an applied context—including consideration of material characteristics and application requirements. The latter interest (the

[4] The full series of *Manufacturing Energy Bandwidth Studies* is available from: https://www.energy.gov/eere/iedo/manufacturing-energy-bandwidth-studies

development of a general decision-support framework for sustainable materials selection in manufactured products) is the primary focus of this report.

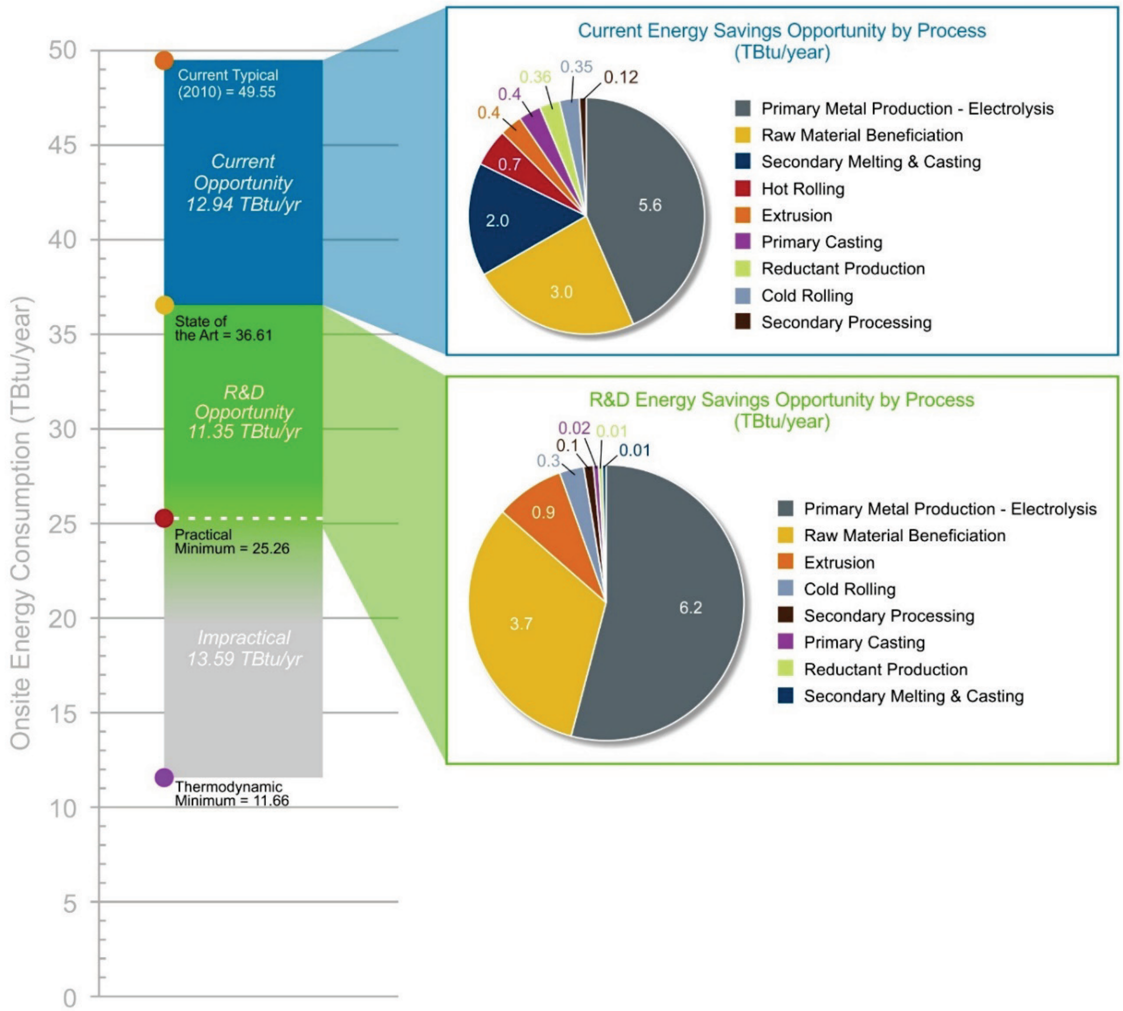


Figure 1. Bandwidth data summary for the U.S. aluminum industry (for the year 2010).

Figure reprinted from DOE 2017a; used with permission.

1.2 Integrating and Comparing Bandwidth Study Results

Bandwidth studies facilitate at-a-glance comparisons of RD&D opportunity sizes across industries. As an illustration, Figure 2 compares summary results of *Manufacturing Energy Bandwidth Studies* published between 2015 and 2017. The *y*-axis shows the estimated energy consumption of each industry in the United States at four different levels of energy performance. The top of each energy band indicates the industry's estimated energy consumption in the United States for the year 2010, based on results of the Energy Information Administration's (EIA's) Manufacturing Energy Consumption Survey (MECS) and other sources. Beneath this uppermost value, color breakpoints represent the estimated state-of-the-art, practical minimum, and thermodynamic minimum energy consumption values—with the thermodynamic minimum representing a theoretical lower bound on energy consumption considering the required chemical transformations to produce the industry's products.[5] The practical minimum value is indicated with color fading bridging the "R&D opportunity" and "impractical" bands. This accounts for uncertainties around energy savings ultimately achievable from emerging and future transformative technologies.

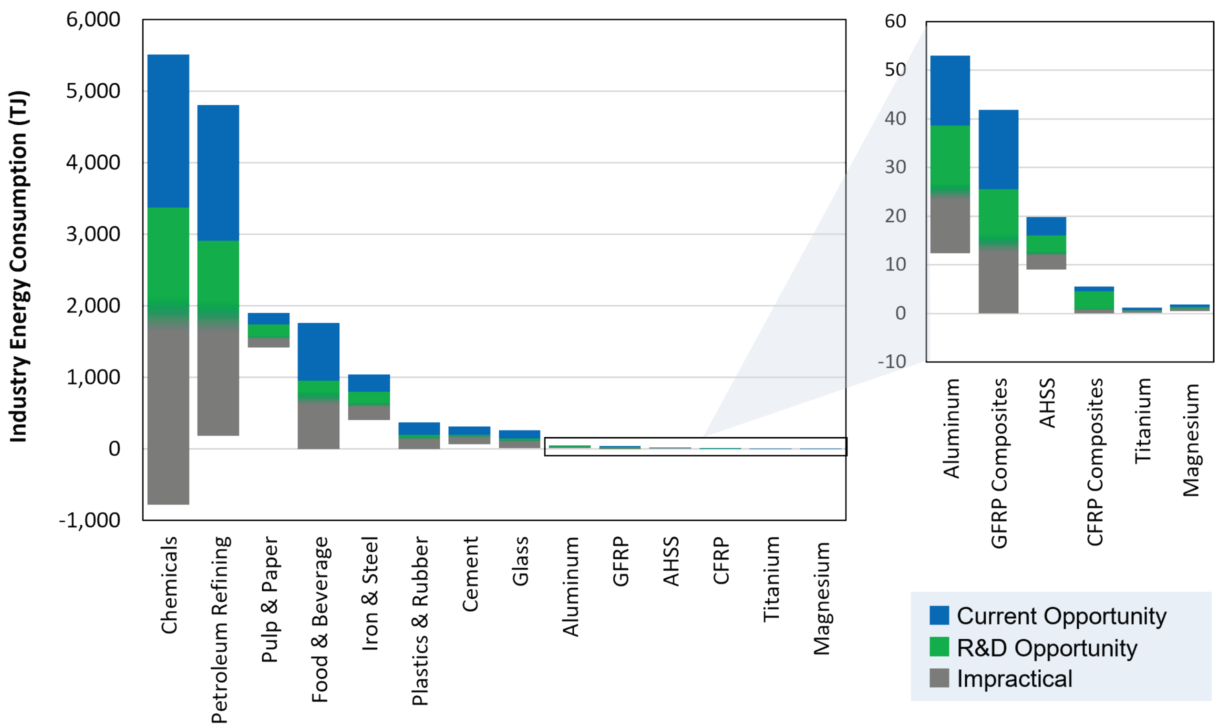


Figure 2. Comparison of industry-level *Manufacturing Energy Bandwidth Study* results for fourteen industries. Smaller industries with energy consumption less than 100 TJ (all of which are growing industries that produce lightweight materials) are shown in a cutaway view.

Figure recreated from Bandwidth Study data (DOE 2015a, DOE 2015b, DOE 2015c, DOE 2015d, DOE 2017a, DOE 2017b, DOE 2017c, DOE 2017d, DOE 2017e, DOE 2017f, DOE 2017g, DOE 2017h, DOE 2017i, and DOE 2017j). Acronyms: AHSS = Advanced High Strength Steel; CFRP = Carbon Fiber Reinforced Polymer; GFRP = Glass Fiber Reinforced Polymer.

For commodity materials, bandwidth results can alternatively be summarized on a *manufacturing energy intensity* basis, expressing energy consumption on a per-unit-production basis (e.g., MJ/kg of the commodity). Figure 3(a) compares the manufacturing energy intensity of seven different structural materials assessed in bandwidth studies. This comparison shows that some of the smallest industries produce materials with very high energy requirements on a specific (per-unit-mass) basis. This is further highlighted in Figure 3(b), which plots the manufacturing energy intensity of each material against its annual production volume. Bubble size in Figure 3(b) is proportional to the total annual energy savings opportunity size for the commodity based on

[5] The theoretical energy requirement (calculated using a Gibbs free energy approach) is negative in some cases because certain chemical transformations release stored energy.

current production.[6] These graphics highlight the small but growing opportunities for energy savings in emerging material manufacturing industries. For example, the absolute opportunity size for carbon-fiber reinforced polymer (CFRP) is small compared to steel—but the relative difference between the current typical and practical minimum energy intensity (in MJ/kg) is large. This is because the annual production volume for steel is over two thousand times higher than that of CFRP. As a result, the total opportunity size for steel is much larger than that of CFRP industry-wide, even though the opportunity on a per-kilogram basis is much higher for CFRP.

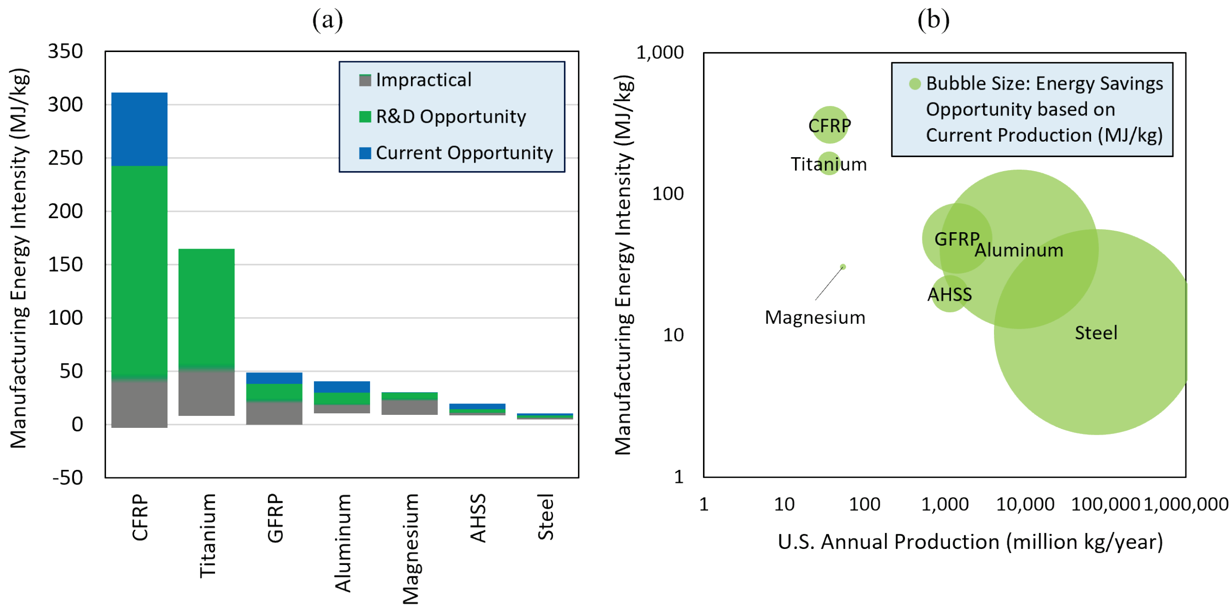


Figure 3. (a) Product-level energy intensity comparison for seven structural materials assessed in the *Manufacturing Energy Bandwidth Studies;* (b) production-adjusted energy savings opportunity size comparison for the same materials. In the opportunity size comparison, the manufacturing energy intensity for each material in MJ/kg (*y*-axis) is plotted versus the annual U.S. production volume in kg (*x*-axis). The bubble size represents the total opportunity size for annual energy reduction (current opportunity + R&D opportunity, in MJ/kg) based on current production volumes. Note that both axes in (b) are logarithmic. A supporting data table appears in Appendix B.

Figure recreated from Bandwidth Study data (DOE 2015d, DOE 2017a, DOE 2017b, DOE 2017c, DOE 2017d, DOE 2017f, and DOE 2017g). Acronyms: AHSS = Advanced High Strength Steel; CFRP = Carbon Fiber Reinforced Polymer; GFRP = Glass Fiber Reinforced Polymer.

Despite their small size, many of the low-production, high-energy-intensity materials shown in Figure 3 will have increasing importance in a clean energy future. For example, composite materials are important for renewable wind energy and hydrogen storage, while lightweight metals are important for transportation lightweighting and other applications. These industries can be thought of as "clean-energy-enabling" industries, in contrast with the traditional "energy-

[6] The total annual energy savings opportunity is calculated as the sum of the current typical and R&D opportunities, both in MJ/year. This is based on the current U.S. annual production of each commodity material.

intensive" industries (such as chemicals, pulp and paper, and iron and steel) that consume the most energy in the U.S. overall. Advancements to reduce energy demand and emissions in both energy-intensive and clean-energy-enabling industries will play important roles in the clean energy transition.

1.3 Leveraging Bandwidth Results for Materials Selection and Comparisons

While head-to-head industry energy consumption comparisons (such as the one in Figure 2) and energy intensity comparisons (such as the one in Figure 3) are informative, it is important to recognize that these data measure energy requirements only for processes occurring in a single manufacturing industry. Energy consumed in other industries involved in the supply chains for that industry are excluded. As a result, the bandwidth studies provide sector-specific estimates of the energy requirements for processes carried out in that sector. Energy intensity values reported in bandwidth studies (e.g., for specific materials or chemicals) should not be interpreted as "embodied energy" or "cumulative energy demand" values because they do not measure the total energy requirements of a product or material.

As an example, consider the iron and steel bandwidth study (DOE 2015d). This study examined energy consumption in the U.S. iron and steel manufacturing sector, as defined by classification code 331110 of the North American Industry Classification System (NAICS).[7] Processes occurring in manufacturing facilities falling under that industry code were included, while processes occurring in other codes were excluded. Significant excluded processes for iron and steel include iron ore, limestone, and coal mining (part of the mining industry, NAICS 212), cokemaking occurring at merchant coke plants (NAICS 324199), final part fabrication via forging or stamping (part of the fabricated metal product manufacturing industry, NAICS 332), and scrap collection, sorting, and shredding for secondary steel (part of the recyclable material merchant wholesaling industry, NAICS 42393). These NAICS-based sector boundaries for iron and steel (and resulting bandwidth study process inclusion) are illustrated in Figure 4. Given study boundaries, the bandwidth value for manufacturing energy intensity for steel, shown in Figure 3, would include contributions from processes contained in NAICS 331110 but not those contained in NAICS 212, 324199, 332, or 42393.

[7] The original bandwidth study stated sector bounds of NAICS 331111, reflecting the 2007 NAICS classification structure. This code is equivalent to NAICS 331110 in the current (2022) NAICS classification structure and has therefore been updated in this report to its present code for clarity. Current and historic NAICS industry definitions are available from the U.S. Census website at https://www.census.gov/naics/.

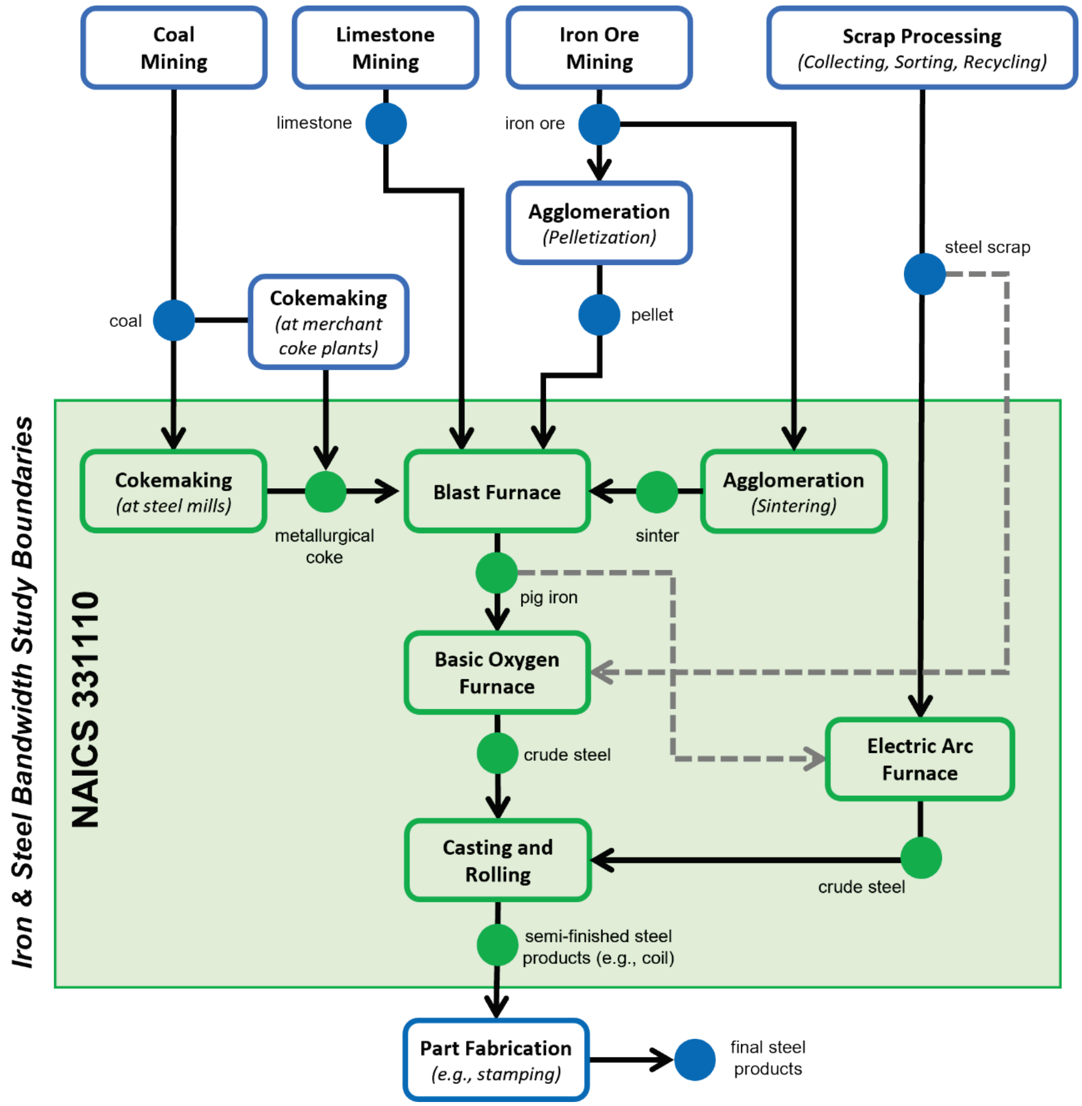


Figure 4. Flow diagram of iron and steel manufacturing showing the boundaries of processes included in the Iron and Steel Bandwidth Study (DOE 2015d)—i.e., those contained in NAICS code 331110, Iron and Steel Manufacturing—and those excluded from the Bandwidth Study because they were not part of NAICS 331110. Direct reduced iron is excluded for simplicity.

Manufacturing energy intensity is a useful metric for understanding process-specific energy requirements and opportunities in a specific sector. However, careful attention must be paid to process inclusion to understand what this metric is measuring. As we saw in the example above, the manufacturing energy intensity for commodity steel would include energy consumed in processes carried out at iron and steel mills—but not energy involved in mining and processing of raw materials such as iron ore. The situation is similar for other commodities. Polymer materials, for example, begin their life cycles as petroleum products before transiting through the Petroleum Refining sector for refining, the Chemicals sector for polymerization, and finally the Plastic & Rubber Products sector for fabrication into plastic shapes. The energy intensity of polymer-related processes in any one of the industries would reflect only a subset of the overall energy requirements for a finished plastic product.

When the main intent of analysis is to compare commodities objectively, the techniques of environmental life cycle assessment (LCA) can be useful. In environmental LCA, the details of resource consumption and environmental impacts are traced throughout each stage of a product's life cycle, facilitating holistic analysis. LCA metrics, further discussed in Section 2.1, span the breadth of environmental impacts that can be induced by a product, and are generally measured cumulatively (e.g., from "cradle-to-gate" or "cradle-to-grave" depending on study boundaries; see Figure 5). *Cumulative energy demand* (CED), also referred to as *embodied energy*, is an LCA metric that measures the cumulative total energy requirements from the extraction of raw materials up to a pre-determined point in the product's life cycle, such as the departure of the finished product from the manufacturing facility's gates (cradle-to-gate) or to the product's end of life (cradle-to-grave). CED can be contrasted with manufacturing energy intensity, which would be considered a "gate-to-gate" metric (i.e., measuring energy consumed within the manufacturing facility's gates). CED can be paired with other measures of environmental performance, such as *global warming potential* (GWP), also referred to as *embodied emissions,* which measures the impact of greenhouse gas emissions. Assessment of a range of environmental metrics allows us to generate a holistic picture of a product or material's overall impact on its environment.

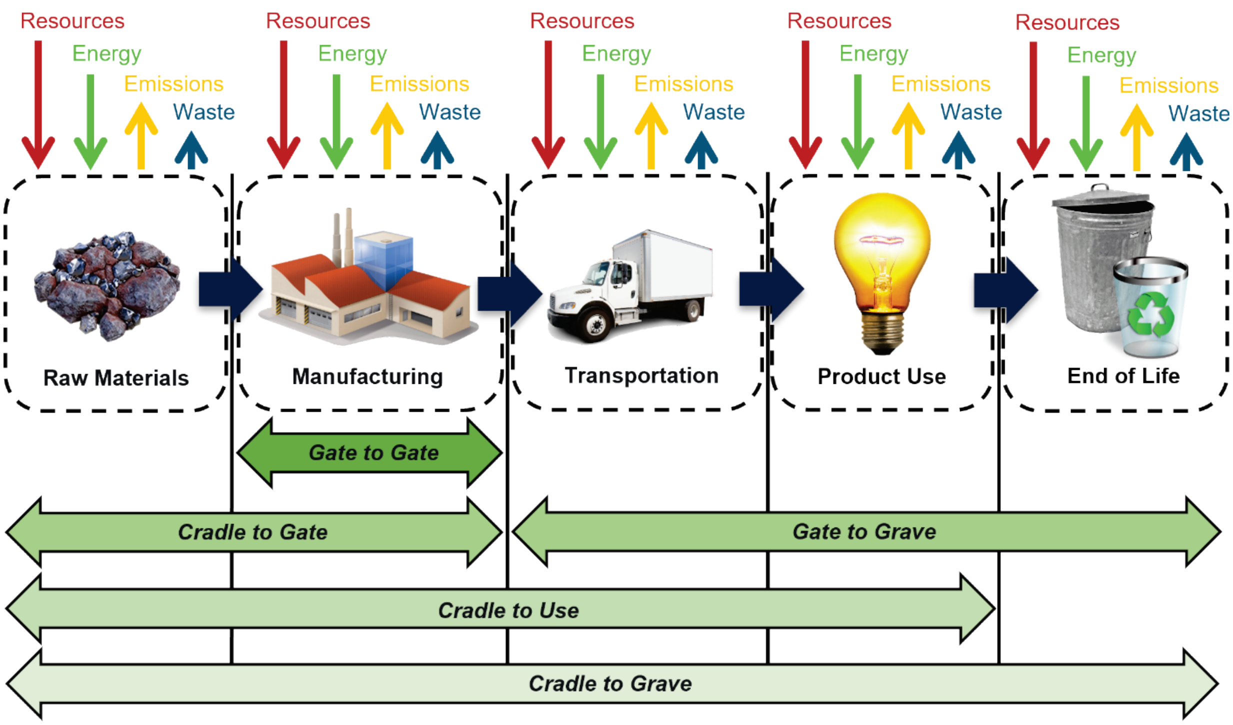


Figure 5. Illustration of different boundary definitions for studies that measure energy and environmental impacts of products: cradle-to-gate, gate-to-gate, cradle-to-use, and cradle-to-grave. Consistent analytical boundaries (i.e., measuring impacts in the same way and for the same product life cycle phases) are critical for objective comparisons between materials or products.

Conventionally, LCA begins after a product is fully designed, as illustrated in Figure 6. This approach is well suited to the preparation of formal environmental documentation, such as

Environmental Product Declarations (EPDs) and ISO-compliant LCA studies.[8] LCA of a mature product requires less iteration on assumptions, and can reduce data uncertainty. However, this approach may miss key opportunities to improve product design based on environmental factors. In a traditional LCA implementation, the environmental analyst may be completely separated from the product design and engineering teams responsible for key product decisions (for example, perhaps the LCA specialist is an external consultant, or is embedded in a regulatory team). This can lead to an "over-the-wall" analysis performed after most or all product decisions are already locked in.

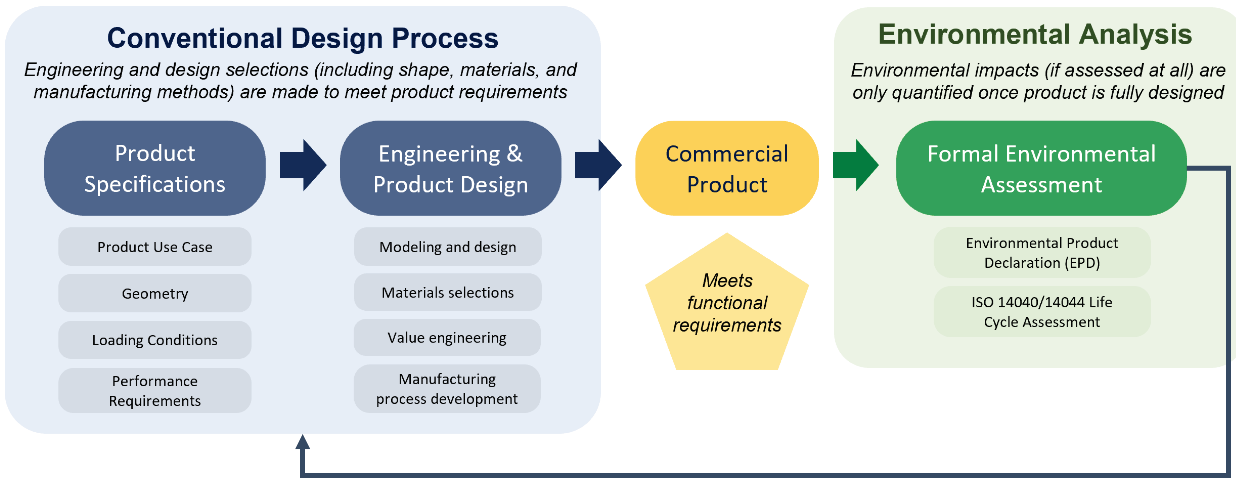


Figure 6. Conventional product design process followed sequentially by a formal environmental assessment of the fully designed product (if one is performed at all); this formal environmental assessment is more likely to impact the next generation of product designs rather than the current generation.

In this report, we present a design-integrated framework for environmental assessment, focusing on methods that can inform materials selection decisions in manufactured products. This framework focuses on techniques for preliminary environmental analysis that can be integrated into early-stage product development, as shown in Figure 7. The approach, which is inspired by environmental LCA and simplified life cycle thinking (LCT) strategies, is illustrated through a series of materials substitution case studies for manufactured products spanning a range of cross-sectoral applications. We discuss how such a framework can be utilized to leverage results of present and future bandwidth studies—including extended bandwidth studies with additional features—as well as other data sources to better understand life cycle opportunities for energy and emissions reductions at the product level. These frameworks can also be used with energy and environmental data from other sources to facilitate objective "apples to apples" comparisons of materials in product designs and concepts.

[8] The phrase "ISO-compliant" is often used informally to assert compliance of an LCA study with International Standards 14040: Life Cycle Assessment – Principles and Framework and 14044 Life Cycle Assessment – Requirements and Guidelines (ISO 2006a, ISO 2006b).

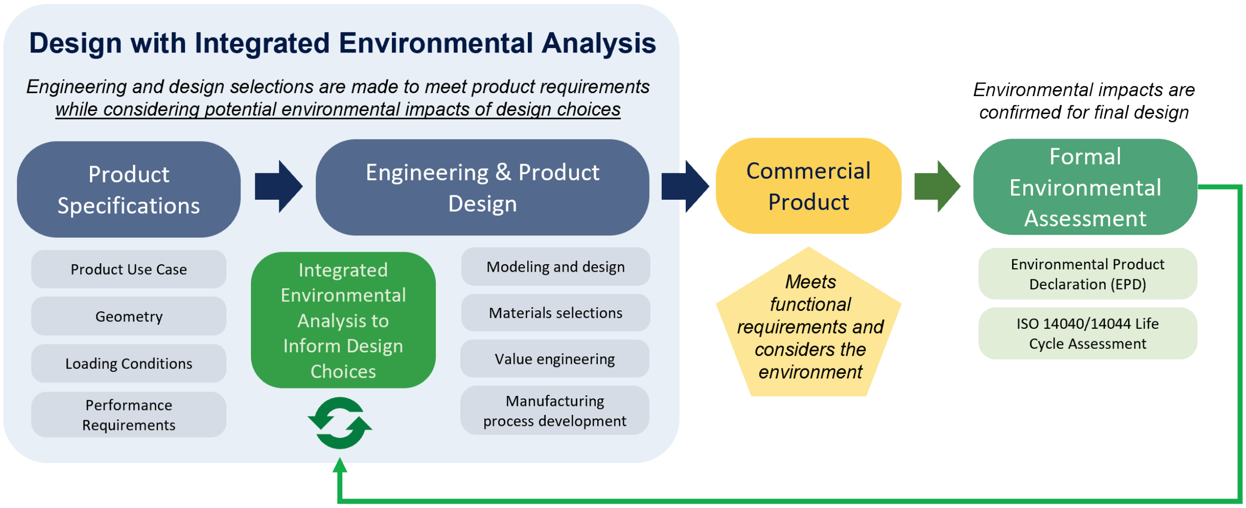


Figure 7. A design-integrated framework for environmental analysis in the context of a specific manufactured product

2. A Life Cycle Thinking Framework for Sustainable Materials Selection

2.1 Life Cycle Assessment (LCA) and Life Cycle Thinking (LCT)

The cumulative environmental impacts of manufactured products result from the various ways products interact with the natural world over their lifetimes. Decisions related to a product's design, manufacturing, use, and end-of-life disposal all contribute to its overall impact. LCA is an analytical method used to assess the environmental impact of a product throughout its life cycle. As formalized by International Standards Organization (ISO) Standards ISO 14040 and ISO 14044 (ISO 2006a, ISO 2006b), a complete LCA includes four main stages: goal and scope definition; inventory analysis; impact assessment; and interpretation (Figure 8). These stages of a formal LCA are further elaborated in Table 1.

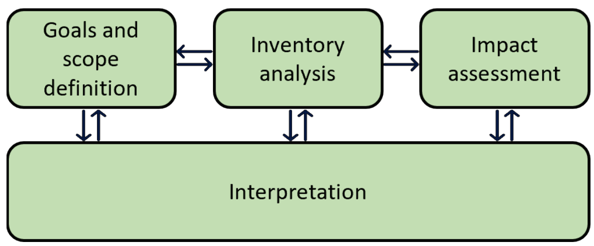


Figure 8. Stages of a formal life cycle assessment, as formalized in ISO 14040 and ISO 14044.

After (ISO 2006a)

LCA studies assess impacts in a wide range of environmental and health impact categories. Depending on the LCA assessment method selected (e.g., TRACI (Bare 2011) or ReCiPe (Huijbregts et al. 2017)), examples of impact categories addressed in an LCA study may include:

- Climate change (global warming potential): impact resulting from emissions of greenhouse gases that trap heat in the atmosphere and cause global warming;
- Terrestrial acidification: impact resulting from the release of acidifying substances (such as nitrates or sulfates) to soils;
- Freshwater and marine eutrophication: impact resulting from over-enrichment of water with phosphorous and nitrogen;
- Human toxicity: impact resulting from the accumulation of toxic chemicals (including carcinogens) in the human food chain or environment;
- Fossil resource scarcity: impact resulting from depletion of fossil resources due to consumption of natural gas, petroleum, or coal; and
- Land use change: impact resulting from agricultural land occupation and transformation.

LCA studies may also assess auxiliary indicators that serve as useful proxies for a product's environmental performance or resource intensity. For example, cumulative energy demand (CED) measures the total direct and indirect energy requirements of a product, including energy demand for raw input materials. Despite not measuring environmental impact directly, CED is straight-forward to calculate, correlates well with other LCA impact categories (Huijbregts et al. 2017) and is easily interpreted given its physically meaningful units (e.g., megajoules (MJ)).

Table 1. Stages of a Formal Life Cycle Assessment (ISO 2006a, ISO 2006b)

LCA stages	Description
Goals and scope definition	Based on study objectives, the analytical boundaries for the study are determined, including the impacts that will be considered and the LCA methods that will be used.
Inventory analysis	Process inputs (material and energy resources) and process outputs (materials, emissions and waste) for each life cycle phase are measured or estimated, generating the mass/energy balance information (the "inventory") required for LCA impact assessment.
Impact assessment	Inventory data are analyzed to determine the resulting environmental impacts. Input and output data in the inventory dataset are mapped to specific environmental impact categories based on their characteristics (for example, CO_2 emissions contribute to global warming potential, while petroleum use contributes to fossil depletion). The impacts in each category are then estimated from the inventory flows using standardized LCA approaches such as ReCiPe (Huijbregts et al. 2017) or TRACI (Bare 2011).
Interpretation	The analyst interprets the results and reports on the key findings of the study, including documenting the methodologies used and significance of the results. If necessary, the LCA scope, inventory, and impact assessment work may be reviewed and revised in an iterative process. For compliance with ISO 14040/14044 standards, LCA studies must be critically reviewed by experts prior to finalization.

Data limitations and cost barriers can make it challenging to deploy a full LCA for pre-commercial products and technologies (Bergerson et al. 2020, Moni et al. 2020). This is unfortunate, considering that environmental assessment may be especially beneficial at this stage to inform materials selections and other design decisions. Luckily, the underlying concepts behind LCA are broadly applicable and have given rise to many simplified approaches and frameworks that can be deployed at any stage of product development. LCA-inspired techniques, broadly grouped under the umbrella of "life cycle thinking" (LCT), can be deployed in forms ranging from informal thought experiments to in-depth scenario assessments. Without necessitating the time and expense of a full ISO-compliant LCA, LCT equips decisionmakers with conceptual frameworks for understanding and weighing environmental impacts holistically.

LCT can be particularly beneficial in early stages of product design and development when a full LCA may be impractical (Liddell et al. 2022).

Examples of simplified LCT frameworks include the streamlined "impact analysis matrix" and related "target plot" visualization popularized in the late 1990s by Thomas Graedel (Graedel 1998). Graedel's method involves assessment of integer scores across permutations of life cycle phases and environmental stressors. Individual scores can be summed to assess an overall "responsible product rating" or visualized at-a-glance in a target (spider) plot, as shown in Figure 9, where the best environmental scores are plotted at the center of the "target", like a bullseye.

(a)

Environmental Stressor (j)

Life Cycle Phase (i)		1 Material Inputs	2 Energy Inputs	3 Emissions	4 Solid Wastes
1	Raw Materials	2	2	3	3
2	Manufacturing	3	1	2	2
3	Transportation	4	2	2	4
4	Product Use	4	2	2	4
5	End-of-Life	4	3	3	2
	Total	17	10	12	15

(b)

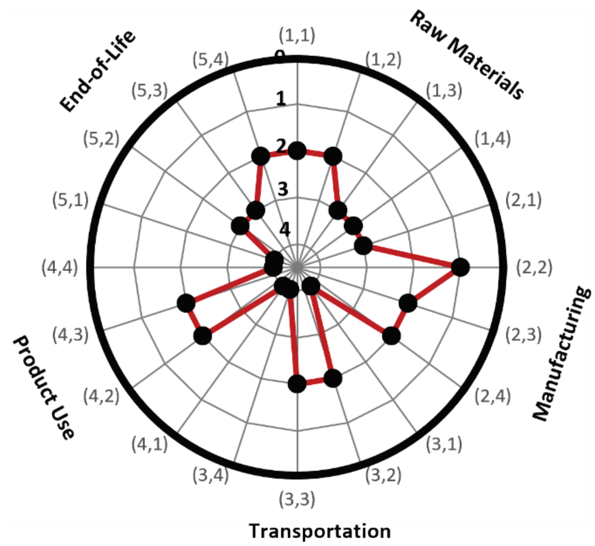


Figure 9. Examples of results visualizations from a matrix-based LCT framework popularized by Graedel for a hypothetical product. In the impact analysis matrix (a), integer scores are assessed for permutations of life cycle phase *i* and environmental stressor *j*. Results can be presented in the form of a "target plot" (b), which plots the score of each matrix entry (i,j) in a spider plot.

After Graedel (Graedel 1998)

Quantitative information about cumulative energy use and emissions over a product's life cycle can also be summarized in simplified energy and carbon "fingerprints" as introduced by Michael Ashby (Ashby 2021); examples are shown in Figure 10. Compared to Graedel's matrix-based method that places equal emphasis on each life cycle phase, Ashby's fingerprint diagrams highlight the life cycle phases that contribute most significantly to the product's cumulative impact. For a simplified "eco-audit," Ashby selects energy and CO_2 (or CO_2-equivalent) emissions as two primary metrics to be assessed, motivated by national and international technical and policy priorities.

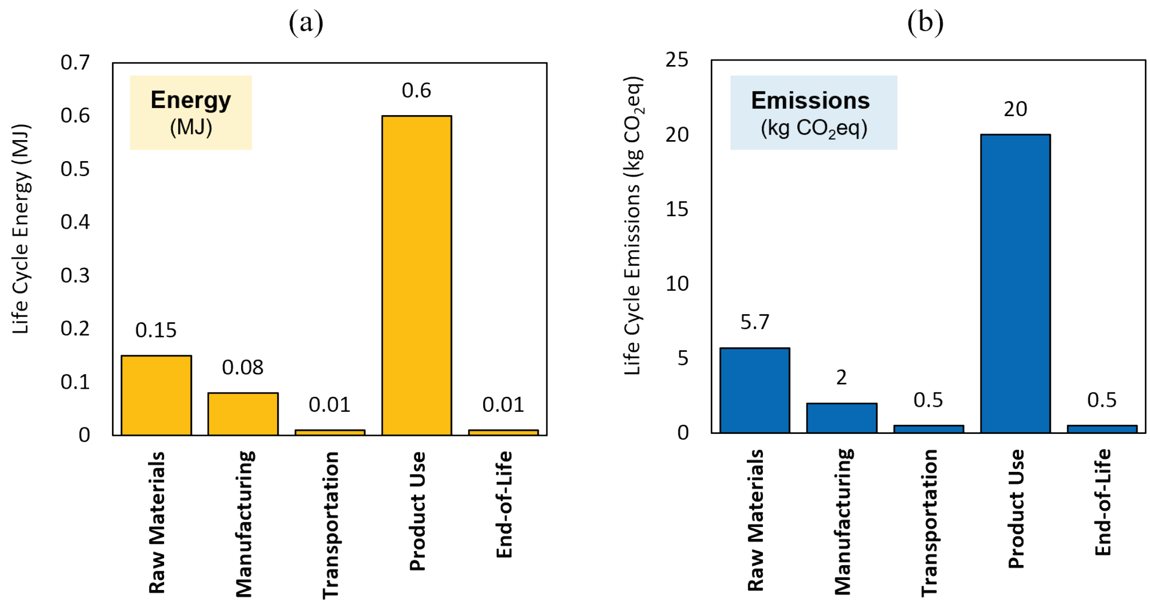


Figure 10. Examples of energy and carbon "fingerprint" plots for a hypothetical product.

After Ashby (Ashby 2021)

Ashby's approaches also include strategies for assessing material tradeoffs (mass, cost, strength, stiffness, embodied carbon, etc.) systematically through penalty functions and material indices derived from application requirements. The use of a material index in materials selection is illustrated through an example in the sidebar below, "Using Material Indices to Support Materials Selection: An Example."

Using Material Indices to Support Materials Selection: An Example

In *Materials and the Environment: Eco-Informed Material Choice* (Ashby 2021), Michael Ashby describes a technique for ranking materials based on multiple criteria through minimization of a "material index" derived based on application constraints.

As an example of this approach, consider a product that can be modeled as a rectangular beam subjected to a bending load. We wish to minimize mass while also satisfying a minimum stiffness constraint. The mass of the beam is given by $m = \rho Lbh$ where ρ is the density of the beam material and L, b, and h are the length, width, and height of the beam respectively. The minimum bending stiffness (flexural rigidity) constraint is given by $S^* = EI$, where S^* is the minimum allowable bending stiffness, E is the elastic modulus, and I is the area moment of inertia (i.e., $I = bh^3/12$ for a beam with a rectangular section).

Combining these expressions by eliminating h gives us a minimum mass of $m = \rho Lb(\frac{12S^*}{Eb})^{1/3}$. Since S*, L, and b are all fixed by the application requirements, this expression can be simplified to $m \propto \rho/E^{1/3}$. Following Ashby's methodology, the right-hand side of this expression represents the "material index" for the application ($M = \rho / E^{1/3}$). The material index should be minimized to address both constraints.

If we also wish to minimize embodied emissions, our index becomes $M = C_m \rho / E^{1/3}$, where C_m is the material's embodied emissions per unit of mass (i.e., the GWP). Minimization of M will select for materials with low GWP and high stiffness-to-weight in the application.

Ashby's physics-based methods are powerful for ranking materials based on their suitability for an application—including sustainability constraints. However, one potential downside of this approach is that a generalized materials selection index, stripped of fixed application constraints, has little physical meaning in the context of the original application. We can't use a material index to directly calculate the mass of a component, or to estimate and compare the overall emissions burdens for different candidate product designs. Material indices are therefore most powerful for early screening of materials for generalized applications.

In this report, we describe a design-integrated framework for sustainable materials selection that combines ideas from Graedel's and Ashby's streamlined LCT approaches with methods from conventional LCA. The methodology described here maintains an application focus throughout the analysis by defining a design-integrated (physics-based) functional unit for the application of interest and making all calculations and material comparisons on this basis.

2.2 Design-Integrated (Physics-Based) Functional Units

In a traditional LCA, inventory flows and impacts are all quantified in terms of an application-specific functional unit. The functional unit describes a quantity of a product based on the performance it delivers in its end-use application, rather than based on the product's weight or volume. For example, if we wish to compare materials for an automotive component, we should compare them on the basis of the mass required to produce that specific component and perform the required function. It would not be appropriate to compare the materials on the basis of mass alone because materials are unlikely to be substituted for one another kilogram for kilogram. Functional units enable fair comparisons across products or systems that serve the same function.

Implicit in a typical functional unit definition is a fully designed product that meets a specific need. For example, we could use LCA approaches to compare "Design A" to "Design B" of a product – but both would require a complete product design. We can take this a step further by creating a design-integrated functional unit that incorporates a symbolic expression into which any suitable material can be "tried out" for the application. Here, a physics-based expression is used to estimate the quantity of material required to meet a specific performance requirement. If necessary, we can simplify complex components by representing them with simplified mechanical models that approximate the application geometry and loading conditions.

While simplified models may not perfectly represent a complex component, they can be very useful in rapidly generating a mass estimate—particularly during the pre-design phase of materials selection, when the final part geometry or loads may not be known. A symbolic expression for required mass can serve as a convenient basis for environmental impact analysis because any material can be substituted into the expression to assess its suitability for the application and compare its potential environmental performance to other candidate materials. Order-of-magnitude results calculated using simplified model representations can be refined at a later stage (for example, using finite element models) once the product's design is finalized. Examples of descriptive, design-integrated functional units and corresponding expressions for the minimum required mass are given in Table 2. Further details of calculations are given in the case studies in the following sections.

Table 2. Descriptive "Design-Integrated" Functional Units with Corresponding Minimum Mass Expressions for Case Studies (for full calculation details for each case study, see Section 3)

Case Study	Descriptive Functional Unit	Symbolic Expression for Minimum Mass of Functional Unit, m_{FU}
Residential Insulation	**Functional Unit:** The mass of insulation required to insulate a 0.093 m^2 wall area with a minimum RSI-3.52 (U.S. "R-20") insulation value over a minimum service life of 60 years.	$m_{FU} = \rho R \lambda A$
Shipping Pallet	**Functional Unit A – Light Duty:** the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes of product load, where each delivery will require the transport of one 181-kg load over a travel distance of 161 km by diesel truck. **Functional Unit B – Heavy Duty:** the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes of product load, where each delivery will require the transport of one 1,134-kg load over a travel distance of 805 km by diesel truck.	$m_{FU} = \frac{m_{pallet} M_{deliv}}{n_{trip} M_{trip}}$
Automotive Component (Structural B-Pillar)	**Functional Unit:** The mass of a 1000-mm-long, 120-mm-wide structural B-pillar for a light-duty vehicle that can safely support the vehicle and provide occupant protection under rollover conditions (U.S. FMVSS 216) and side-impact conditions (U.S. FMVSS 214)	$m_{FU} = \rho L w t_{min}$ where $t_{min} = \max\{t_{vroof}, t_{hroof}, t_{side}\}$ $t_{vroll} = [(48 F_v L^2)/(\pi^2 E w)]^{1/3}$ $t_{hroll} = [(6 F_h L)/(\sigma_y w)]^{1/2}$ $t_{side} = [(5 F_{side} L^3)/(32 E w y_{max})]^{1/3}$

Symbol Definitions: Residential Insulation: ρ = density; R = resistance to conductive heat flow ("R-value"); λ = thermal conductivity; A = insulated area. Shipping Pallet: m_{pallet} = mass of one pallet; M_{deliv} = total mass of product load delivered (by all pallets); n_{trip} = service life (number of expected trips per pallet); M_{trip} = mass of product transported per trip (per pallet). Automotive B-Pillar: ρ = density; L, w = length and width of B-pillar; t_{min} = minimum thickness of B-pillar to satisfy all constraints; F_v, F_h = vertical and horizontal components of rollover (roof crush) load; F_{side} = side impact load; E = Young's modulus; σ_y = yield strength; y_{max} = *maximum allowable deflection of the B-pillar during a side impact crash.* For full details, see Section 3.

2.3 A Framework for Materials Selection & Comparison

Here we present a LCT framework for rapid, design-integrated analysis and comparisons of the potential environmental impacts resulting from materials selection decisions in manufactured products. The analysis steps are detailed in Table 3. Analysis begins with defining the application, determining the appropriate functional unit in descriptive terms, and identifying candidate materials. Next, a physical model for the product system is developed and used to derive a symbolic expression for the minimum required functional unit mass. Material data are substituted into this expression to estimate the required mass for each material. Finally, the functional unit mass is combined with environmental intensity metrics to assess and compare the cradle-to-gate environmental performance for all material options.

Table 3. A Framework for Sustainable Materials Selection: Analysis Steps

Analysis Step		Description
1	Define the Application and Analysis Scope	Describe the product system in the context of its end-use application and determine study objectives. Establish the boundaries of the analysis (e.g., cradle-to-gate, gate-to-gate, or cradle-to-grave). Select the environmental metrics that will be considered in the analysis, such as embodied emissions and embodied energy.
2	Define the Functional Unit	Define the functional unit, noting application constraints in specific, quantitative terms that will align with a physical model of the system.
3	Identify Candidate Materials	Generate a list of candidate materials that will be considered for the application. If appropriate, identify a reference material (representing the current standard) that other materials will be compared to.
4	Derive Expression for Minimum Required Functional Unit Mass	Develop a physical model for the product system, simplifying the geometry and loading conditions if needed. Based on the physical model and application constraints, derive a symbolic expression for the minimum required functional unit mass. *(See examples in the case studies of Section 3.)*
5	Gather Material & Environmental Data	Collect material property data for each material as required to estimate the required mass for the functional unit (i.e., gather data for all parameters specified in the mass expression developed in the previous step). Collect environmental performance data for each material (as an impact intensity per unit of mass) based on the metrics selected for the analysis. Data sources may include LCA or material property databases, literature sources, and life cycle inventory datasets.
6	Calculate Required Mass	Calculate the minimum required functional unit mass for each candidate material by substituting material properties into the symbolic expression previously developed.

7	Assess Environmental Performance	Calculate the environmental performance of each candidate material by multiplying the required mass of the functional unit (kg) by each of the selected environmental intensity metrics for the analysis, such as embodied energy (MJ/kg) or embodied emissions (kg CO_2-eq/kg). Optionally, results can be calculated separately for each life cycle phase included in analysis.
8	Synthesize Results & Plan Next Steps	Synthesize results by comparing materials based on their life cycle environmental performance in the application, and assess significance and data quality. Document potential environmental impacts and plan the next steps for analysis (such as a follow-on gate-to-grave assessment, sensitivity analysis, additional data requirement, or a need for a full LCA).

This is a flexible methodology that can be combined with other DOE resources for LCA and simplified LCA, including (for example) the Techno-economic, Energy and Carbon Heuristic Tool for Early Stage Technologies (TECHTEST) spreadsheet tool for simplified LCA and TEA (DOE 2023); and the Materials Flows through Industry webtool developed by NREL (NREL 2022). A focus that differentiates the contribution of this report is on the development of physics-based functional units that facilitate integration of LCA/LCT techniques with product design.

This framework is demonstrated for a diverse set of product systems in the case studies of Section 3. In the case studies, each product is represented by a mechanical model consisting of a monolithic (single-material) component with a simplified geometry (such as a beam or panel) under loading conditions such as a beam or panel.

2.4 Accounting for the Full Life Cycle

In some of the case studies presented in this report, analysis considers only the cradle-to-gate portion of the product life cycle, capturing product-related impacts incurred up to the point of the product's departure from the manufacturing facility's gates. In general, an LCA would only exclude phases of the life cycle if there is a reason to believe that the excluded phases have no significant impacts (or that excluded impacts will be equal across all product options). For many applications, this will not be the case, and we might wish to follow up with a gate-to-grave analysis, or at minimum a use phase analysis.

For example, significant use phase impacts would be expected in a lightweighting application for the transportation sector, so it will not be sufficient to compare lightweight materials to conventional materials on a cradle-to-gate basis alone. Sections 4 and 5, which explore two transportation-related case studies (materials selection for a shipping pallet and for a lightweight automotive component) include calculations through the use phase ("cradle-to-use") to illustrate steps to account for expanded life cycle boundaries in a simplified framework.

In other cases, the gate-to-grave may be less important but still potentially significant. For example, in the residential insulation case study discussed in Section 3, the functional unit is defined such that all insulation materials will be expected to deliver equal performance during the product use phase. Nonetheless, each material has unique constraints and features that may impact where and how it can be used. For example, fiberglass wool insulation has much greater water and fire resistance than does a cellulose-based paper wool product, whereas paper wool has greater potential for recyclability at end-of-life. Short of completing a full cradle-to-cradle analysis, qualitative life cycle information can be quickly and conveniently captured in a "stoplight" matrix (generalized in Figure 11) that includes color-coding and brief notes to highlight potential concerns at each life cycle phase. This simple conceptual tool is useful for flagging potential supply chain problems, performance issues, or end-of-life considerations that may be explored in more detailed analysis at a later stage.

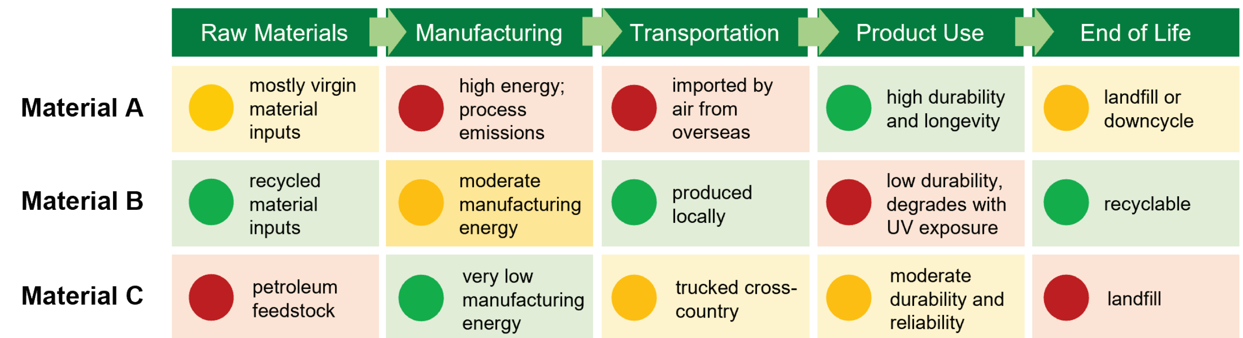


Figure 11. Example of a "stoplight matrix" for a hypothetical product, highlighting key environmental considerations and potential tradeoffs across the life cycle phase for several different material options.

In the following sections, we present worked examples of the sustainable materials selection framework described above as applied to four case studies for manufactured products with end uses in residential, energy, and transportation sectors. The analysis will follow the methodology described in this section, including the analysis steps laid out in Table 3.

3. Case Study: Materials Selection for Residential Insulation

Figure 12. Fiberglass insulation being installed in a residential building.

3.1 Application Overview and Analysis Scope

Consider the selection of a wall insulation material for a residential building application (Figure 12). Building thermal envelope requirements are often expressed as a minimum insulation "R-value" for a wall, ceiling, or floor. R-value is a measure of thermal resistance per unit area, and its value depends on both the insulation layer thickness t (a thicker layer will provide a higher R-value) and the thermal conductivity λ (a lower thermal conductivity will provide a higher R-value). R-value is defined by the following expression:

$$\mathrm{R} = t/\lambda \tag{1}$$

Typical minimum R-values for buildings constructed in the United States range from R-15 to R-35, depending on climate and local rules. The 2018 International Energy Conservation Code specifies a minimum wall insulation value of R-20 for a broad swath of mild-moderate to cool U.S. climate zones (e.g., Tennessee, Idaho, Massachusetts) (IECC 2018).

For this case study, we will define an application R-value of R-20 (i.e., R = 20 $ft^2 \cdot °F \cdot h/Btu$) and compare six candidate insulation materials that can provide this level of insulation performance. Since the product use phase is assumed to be equivalent for all materials (all will provide the same R-value), a cradle-to-gate analysis is deployed. However, end-of-life considerations will also be noted for each material. Cradle-to-gate embodied energy (i.e., CED) and cradle-to-gate embodied emissions (i.e., GWP) will be the two environmental metrics included in high-level assessment. The same methodology could be applied to other metrics.

3.2 Functional Unit Definition

The functional unit for this case study should describe a quantity of insulation material based on the performance it delivers in its end-use application; examples of functional units for different critical functions and applications were given in Table 2. To satisfy application requirements, each candidate insulation material will need to provide thermal resistance at the level of R-20, indicating a thermal resistance of 20 $ft^2 \cdot °F \cdot h/Btu$ (expressed in Imperial units). In the International System of Units (SI), the equivalent value is RSI-3.52, indicating a thermal resistance of 3.52 $m^2 \cdot K/W$. Based on this R-value, we can define our functional unit as follows:

Functional Unit for Residential Insulation: the mass of insulation required to insulate a 0.093 m^2 (1 ft^2) wall area with a minimum "R-20" (RSI-3.52) insulation value over a minimum service life of 60 years.

This functional unit is illustrated schematically in Figure 13.

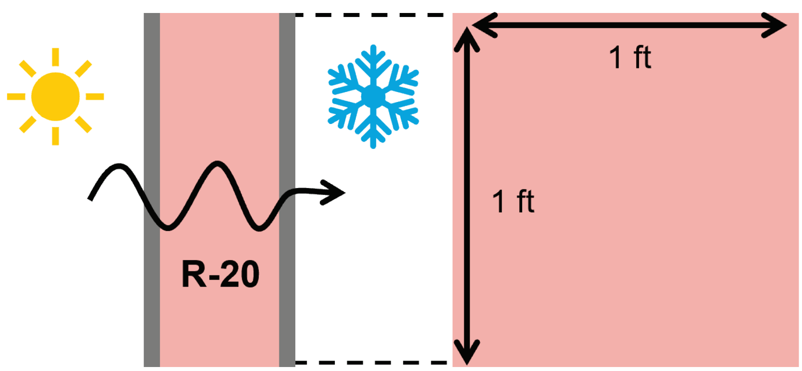


Figure 13. Schematic depiction of the functional unit for residential insulation.

3.3 Candidate Materials

Many available insulation products can meet the key performance requirements of an R-20 insulation application. In this case study, we will consider the following materials:

- Fiberglass wool batting

- Mineral wool (also known as "stone wool") batting
- Expanded polystyrene (EPS) board
- Extruded polystyrene (XPS) board
- Polyurethane (PUR) board
- Cellulose-based paper wool

Fiberglass wool batting, as an industry standard product, will be considered the reference material for this case study.

3.4 Functional Unit Mass Expression

Our next step will be to derive an expression for the functional unit mass. The mass of an insulation layer is given by

$$m = \rho t A, \tag{2}$$

where ρ is the density, t is the layer thickness, and A is the insulated area. Earlier, we noted that an insulation product's R-value is equal to the layer thickness t divided by the thermal conductivity λ. Eliminating t across equations (1) and (2) gives $m = \rho R \lambda A$. Defining the application required R-value as R*, we can express the required mass to fulfil the functional unit as:

$$m_{FU} = \rho(R^{*})\lambda A \tag{3}$$

where:

ρ = density;

$R*$ = required resistance to conductive heat flow ("R-value");

λ = thermal conductivity; and

A = insulated area.

Note that service life was included in the descriptive functional unit but does not appear in equation (3). We assume that all candidate insulation materials can meet the 60-year service life criterion in the functional unit without replacement. For many products, if service life is expected to vary from material to material, a lifetime factor could be applied in equation (3) to ensure equivalence by accounting for replacement timelines (e.g., by modifying the expression as $m_{FU} = \rho R^{*} \lambda A L$, where L is a lifetime multiplier). However, for residential insulation, we assume that routine replacement is generally impractical except in the context of a major renovation. In this case, minimum product lifetime becomes a screening parameter: all suitable materials must provide adequate insulation performance over the 60-year lifetime of the building or major renovation cycle, and any materials that cannot satisfy this criterion are eliminated from consideration.

3.5 Material & Environmental Data

Each candidate insulation material offers a unique combination of characteristics including both material properties (density and thermal conductivity) and environmental metrics (embodied energy and embodied emissions). Key properties of the candidate insulation materials are summarized in Table 4, with reference information given in Table 5.

Table 4. Key Properties of Residential Insulation Materials

Material	Density ρ (kg/m³)	Thermal Conductivity λ (W/m·K)	Embodied Energy (MJ/kg)	Embodied Emissions (kg CO_2-eq/kg)
Fiberglass wool	38.0	0.380	87	6.0
Mineral (stone) wool	82.5	0.365	45	3.0
EPS foam board	22.5	0.034	116	5.8
XPS foam board	31.0	0.034	115	8.1
PUR foam board	33.3	0.031	108	7.4
Paper wool	55.0	0.040	10	1.4

Table 5. References Used to Estimate Key Properties of Residential Insulation Materials Listed in Table 4. (For each property, the average value from the sources listed was adopted.)

Material	Density ρ (kg/m³)	Thermal Conductivity λ (W/m·K)	Embodied Energy (MJ/kg)	Embodied Emissions (kg CO_2-eq/kg)
Fiberglass wool	Grazieschi 2021	Grazieschi 2021	Casini 2022, Su et al. 2016, Schiavoni et al. 2016	Casini 2022, Su et al. 2016, Schiavoni et al. 2016
Mineral (stone) wool	Grazieschi 2021	Grazieschi 2021	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011
EPS foam board	Grazieschi 2021	Grazieschi 2021	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011
XPS foam board	Grazieschi 2021	Grazieschi 2021	Casini 2022, Su et al. 2016, Schiavoni et al. 2016	Casini 2022, Su et al. 2016, Schiavoni et al. 2016
PUR foam board	Grazieschi 2021	Grazieschi 2021	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011	Casini 2022, Su et al. 2016, Schiavoni et al. 2016, Bribian et al. 2011
Paper wool	Grazieschi 2021	Grazieschi 2021	Bribian et al. 2011, Schmidt et al. 2004, Ijjada and Nayaka 2022	Bribian et al. 2011, Schmidt et al. 2004, Ijjada and Nayaka 2022

From Table 4, paper wool insulation has the lowest embodied emissions on a weight basis, followed by mineral wool. However, this does not imply that these two materials will necessarily have the lowest cradle-to-gate emissions on a performance-equivalent basis. For example, mineral wool has relatively high thermal conductivity and high density compared to other options. This means that we will need a lot more mineral wool (in terms of product mass) to achieve the same insulation performance as other materials. Functional-unit-based calculations are necessary to accurately rank insulation materials in terms of environmental impact.

3.6 Calculation of Functional Unit Mass

Substitution of material properties (Table 4), the functional unit insulated area (0.093 m^2), and the required R-value (3.52 $m^2 \cdot K/W$) into equation (3) gives us the required functional unit mass of each insulation material. These calculations are tabulated in Table 6, which highlights the order-of-magnitude differences in required mass across the candidate insulation products. Compared to the fiberglass wool reference material, nearly twice the mass of mineral wool would be required to achieve the same insulation performance. Conversely, the required mass of the plastic foam insulation products (EPS, XPS, and PUR) is less than 10% than that of the fiberglass product to deliver the same insulation value.

Table 6. Comparison of Functional Unit Mass for Residential Insulation Materials (where the functional unit represents the quantity of material required to insulate a 1 ft^2 (0.093 m^2) area at a R-20 (RSI-3.52) level)

Material	Functional Unit Mass (kg)
Fiberglass wool	4.73
Mineral (stone) wool	9.87
EPS foam board	0.25
XPS foam board	0.34
PUR foam board	0.34
Paper wool	0.71

3.7 Environmental Performance Assessment

We can combine the environmental data shown in Table 4 with the functional unit mass calculations (Table 6) to assess and compare environmental performance objectively across the insulation products considered in this case study. The product of the functional unit mass and the weight-based embodied energy (MJ/kg) gives the embodied energy of the functional unit (MJ). Likewise, the product of the functional unit mass and the weight-based embodied emissions (kg CO_2-eq/kg) gives the embodied emissions of the functional unit (kg CO_2-eq). Results are of these calculations are displayed in Table 7.

Table 7. Comparison of Embodied Energy and Embodied Emissions for Insulation Materials

Material	Embodied Energy per unit mass (MJ/kg)	Embodied Emissions per unit mass (kg CO_2-eq/kg)	Functional Unit Mass (kg)	Embodied Energy for Functional Unit (MJ)	Embodied Emissions for Functional Unit (kg CO_2-eq)
Fiberglass wool	87	6.0	4.73	412	28.3
Mineral (stone) wool	45	3.0	9.87	442	29.3
EPS foam board	116	5.8	0.25	29	1.5
XPS foam board	115	8.1	0.34	39	2.7
PUR foam board	108	7.4	0.34	36	2.5
Paper wool	10	1.4	0.71	7	1.0

Figure 14 compares the embodied emissions of each insulation product on the basis of both mass and functional unit. On a mass basis, as noted earlier, mineral wool and paper wool have the lowest cradle-to-gate emissions—and the polymer foams have high embodied emission values. However, on a functional unit basis, this ranking shifts. Paper wool still performs the best—but on a functional basis, the polymer materials outperform the fiberglass and mineral wool products on account of their much lower density and thermal conductivity. This comparison highlights the importance of considering functional equivalence in materials selection decisions.

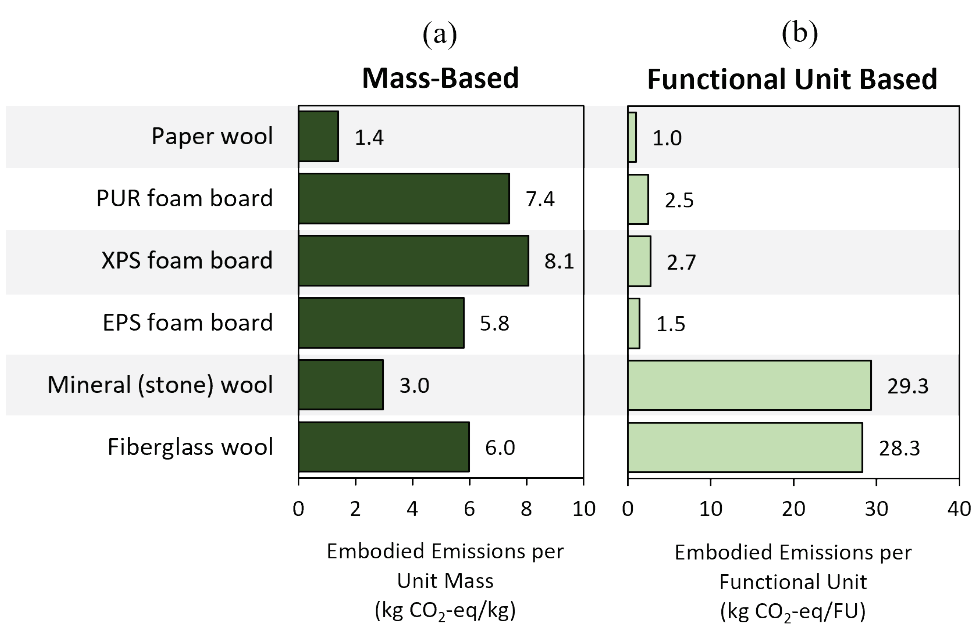


Figure 14. Comparison of embodied emissions for insulation materials on the basis of (a) mass and (b) the application functional unit.

3.8 Results Synthesis and Next Steps

The comparisons in Figure 14 provide useful information for decision-making. Nonetheless, it would not be correct to conclude that the top-ranking materials in Figure 14 are definitively the most sustainable insulation materials. Sustainability has many dimensions, and this simplified analysis focused on discerning order-of-magnitude differences in cradle-to-gate embodied energy and embodied emissions. A full LCA study would include additional impact categories and would likely expand the scope beyond cradle-to-gate to examine factors associated with transportation, use, and end of life processing—requiring a more involved effort for data collection and analysis.

Short of conducting a comprehensive LCA, a stoplight matrix can assist us in quickly pinpointing potential "pain points" for each material through a systematic, qualitative review of each life cycle phase—including impact categories and life cycle phases not yet considered. Figure 15 gives a simple example for the insulation products considered in this case study.

	Raw Materials	Manufacturing	Transportation	Product Use	End of Life
Fiberglass wool	mostly virgin material inputs	high manufacturing energy & emissions	moderately dense material	industry standard; water resistant; good fire rating	landfill or downcycle
Mineral wool	mostly virgin material inputs	high manufacturing energy & emissions	dense; high fuel use to transport	industry standard; water resistant; good fire rating	landfill or downcycle
EPS foam	petroleum feedstock	moderate manufacturing energy & emissions	very lightweight material	good water resistance, lower fire rating	landfill
XPS foam	petroleum feedstock	produced with high-GWP blowing agents	lightweight material	good water resistance, lower fire rating	landfill
PUR foam	petroleum feedstock	moderate manufacturing energy & emissions	lightweight material	good water resistance, lower fire rating	landfill
Paper wool	recycled feedstock	very low manufacturing energy & emissions	lightweight material	low fire and water resistance; loose-fill may not be practical to install	recycle, incinerate, or compost

Figure 15. A "stoplight matrix" summarizing potentially significant considerations for each phase of the product life cycle for six residential insulation products.

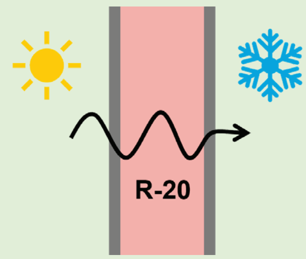
This simple chart provides a framework for documenting considerations (including key environmental and non-environmental factors) for every phase of the product life cycle. For example, we saw earlier that paper wool insulation had the lowest impact in terms of energy consumption and emissions—but it may be important to note that this material may not be well suited to every insulation application. Similarly, the polymer foams also performed well in terms of cradle-to-gate emissions, but this benefit may be counteracted by their poor environmental prospects at end-of-life: these materials are produced from petroleum-based feedstocks and are typically landfilled.

Based on the results of this case study (including the additional considerations noted in the stoplight matrix), we can identify the following next steps to expand on this analysis:

- Conduct an in-depth analysis of the end-of-life phase of the product life cycle for the range of insulation materials to better understand capabilities and current practices for recycling, downcycling, incineration, and composting of end-of-life products.
- Perform a full LCA to confirm and better understand the screening results of this analysis, which suggest that paper wool and polymer foam board insulation materials (especially EPS) may offer an emissions reduction benefit compared to industry-standard fiberglass batting.

A summary of the analysis for this case study is given in Table 8.

Table 8. Framework-Based Analysis Summary for the Residential Insulation Case Study

Residential Insulation Case Study: Analysis Summary		
Analysis Step		**Case Study Outcomes**
1	Define the Application and Analysis Scope	**Analysis objectives:** In this screening analysis, our goal is to compare the environmental performance of several different insulation products that deliver equivalent insulation value. **Study boundaries:** cradle-to-gate **Selected environmental metrics:** embodied energy; embodied emissions 
2	Define the Functional Unit	**Functional unit:** The mass of insulation required to insulate a 1 ft^2 (0.093 m^2) wall area with a minimum "R-20" (RSI-3.52) insulation value over a minimum service life of 60 years.
3	Identify Candidate Materials	**Candidate materials:** fiberglass wool; mineral wool; EPS foam board; XPS foam board; PUR foam board; cellulose-based paper wool.
4	Derive Expression for Minimum Required Functional Unit Mass	**Functional unit mass:** $$m_{FU} = \rho R \lambda A$$ where ρ = density; R = thermal resistance ("R-value"); λ = thermal conductivity; and A = insulated area
5	Gather Material & Environmental Data	*See Table 4*
6	Calculate Required Mass	*See Table 6*
7	Assess Environmental Performance	*See Table 7*
8	Synthesize Results & Plan Next Steps	**Key findings:** Cradle-to-gate analysis suggests that paper wool (where feasible) and foam board insulation materials may offer life cycle emissions reduction benefits compared to the benchmark insulation material (fiberglass batting) in a residential setting. **Next steps:** analyze the end-of-life phase to better understand the potential benefits of recyclable or compostable insulation products and the potential harms from landfilled end-of-life materials; perform a full LCA to confirm and better understand screening results.

4. Case Study: Materials Selection for Light-Duty and Heavy-Duty Shipping Pallets

Figure 16. Product parcels packed on a block-style wooden shipping pallet.

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4.1 Application Overview and Analysis Scope

Consider the selection of a shipping pallet for product transportation, storage, and delivery. Shipping pallets (Figure 16) are designed to carry loads of products as they move through the supply chain. The dimensions of shipping pallets are standardized for interchangeability and maneuverability using forklifts. The most common pallet size in North America has a footprint of 1.22 m × 1.02 m (48 in × 40 in), aligning with a Grocery Manufacturers Association (GMA) recommended standard. Standard pallets are available in a range of materials (including wood, plastic, aluminum, steel, and cardboard) and designs (the most common being stringer and block). Stringer pallets use boards ("stringers") to support the upper deckboards and product load, whereas block pallets use solid blocks to support the upper deck and product load. Block pallets are often, but not always, deployed in heavier duty applications than stringer pallets. The suitability of a given pallet type for an application depends on the specifics of how the pallet will be used.

For this case study, we will define two sets of application constraints representing different pallet loading and usage conditions:

Light-Duty Pallet Application Requirements:

- Standard GMA pallet footprint of 1.22 m x 1.02 m (48 in × 40 in)
- Maximum dynamic load of 181 kg (400 lbs)
- Average trip distance of 161 km (100 miles) by diesel truck

Heavy-Duty Pallet Application Requirements:

- Standard GMA pallet footprint of 1.22 m x 1.02 m (48 in × 40 in)
- Maximum dynamic load of 1,134 kg (2,500 lbs)
- Average trip distance 805 km (500 miles) by diesel truck

The functional units defined in this case study will incorporate these constraints. Because pallet mass impacts use phase fuel consumption (i.e., truck diesel) and related emissions for the pallet during its use for product transportation, we will adopt a cradle-to-use scope for this analysis. Environmental metrics assessed in this analysis will be embodied energy (i.e., CED) and embodied greenhouse gas emissions (i.e., GWP).

4.2 Functional Unit Definition

The functional units for this case study are based on the Underwriters Laboratories (UL) *Product Category Rule (PCR) Guidance for Wooden Pallets* (UL 2019), which specifies that functional units (FUs) for wooden shipping pallets should be defined as follows:

> *"Life cycle impact assessment will be performed using the FU selected as 100,000 lbs pallet loads of product delivered using wooden pallets ... The number of pallets required to transport 100,000 lbs of material will be calculated using the estimated number of trips made by the selected wooden pallet and its load-carrying capacity."*

While the UL standard functional unit basis of 45.4 metric tonnes (100,000 lbs) of product delivered applies specifically to wood pallets, it is general enough to be suitable for all pallet materials and designs. In our descriptive functional units, we will expand on this basis by also specifying a maximum dynamic load rating and average trip distance for each application. Separation of light-duty and heavy-duty applications into two distinct functional units allows us to assess and rank materials separately for different use cases—including those where the typical load may be well below the load-carrying capacity of the pallet.

For the light-duty pallet, we will specify a relatively lightweight product load of 181 kg (400 lbs) and a short average trip distance of 161 km (100 miles):

Functional Unit A—Light-Duty Pallet: the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes (100,000 lbs) of product load, where each delivery will require the transport of one 181-kg (400-lb) load over a travel distance of 161 km (100 mi) by diesel truck.

Meanwhile, for the heavy-duty pallet, we will assume a higher load of 1,134 kg (2,500 lbs), the standard load rating for a GMA shipping pallet. For the heavy-duty application, we will also specify a longer travel distance of 805 km (500 miles) per trip, resulting in the following functional unit:

Functional Unit B—Heavy-Duty Pallet: the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes (100,000 lbs) of product load, where each delivery will require the transport of one 1,134-kg (2,500-lb) load over a travel distance of 805 km (500 mi) by diesel truck.

Constraints for light- and heavy-duty shipping pallets are illustrated schematically in Figure 17(a) and Figure 17(b) respectively.

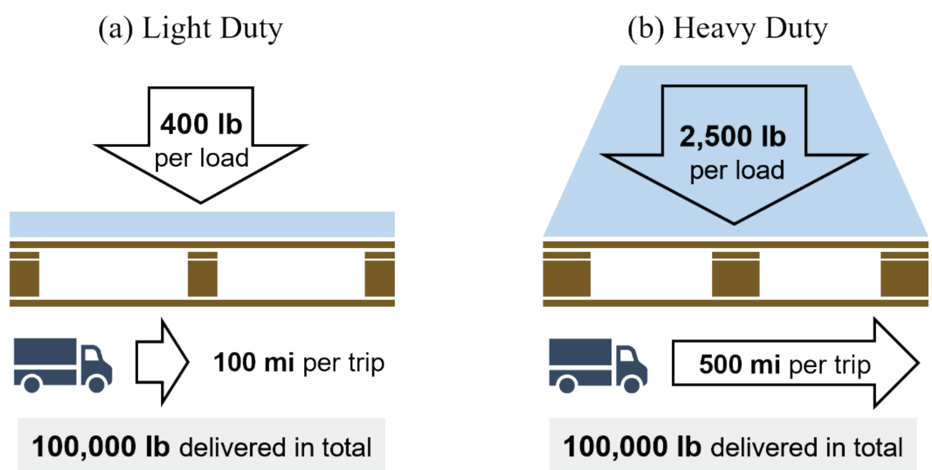

Figure 17. Schematic depiction of the respective functional units for (a) light-duty and (b) heavy-duty shipping pallets.

4.3 Candidate Materials

GMA-size shipping pallets are available in many different materials and designs. In this case study, we will assess and compare the following pallet options:

- Wood Stringer Pallet (light duty)
- Wood Block Pallet (heavy duty)
- High Density Polyethylene (HDPE) Stringer Pallet
- Aluminum Block Pallet

- Galvanized Steel Block Pallet
- Corrugated Cardboard Block Pallet (light duty)
- Corrugated Cardboard Block Pallet (heavy duty)

Wood is the most common pallet material today, with both stringer and block designs widely used. For this case study, the wood stringer pallet (light duty) will be considered the reference material for light-duty applications, and the wood block pallet (heavy duty) will be considered the reference material for heavy-duty applications.

4.4 Functional Unit Mass Expression

Our next step will be to derive an expression for the functional unit mass. The number of pallets required to deliver a total product load of M_{deliv} is given by

$$n_{pallet} = \frac{M_{deliv}}{n_{trip} M_{trip}}, \quad (4)$$

where n_{trip} is the service life of the pallet (expressed as the number of trips per pallet) and M_{trip} is the mass of product delivered in a single trip (which must not exceed the dynamic load-bearing capacity of the pallet). The mass of the functional unit is the product of the mass of an individual pallet m_{pallet} and the total number of pallets required:

$$m_{FU} = m_{pallet} \times n_{pallet} = \frac{m_{pallet} M_{deliv}}{n_{trip} M_{trip}}, \quad (5)$$

where:

m_{pallet} = the mass of an individual pallet;

M_{deliv} = the total mass of product load delivered (i.e., 45.4 metric tonnes);

n_{trip} = the number of lifetime trips made per pallet; and

M_{trip} = the mass of product load delivered per trip.

Note that travel distance does not appear as a parameter in the functional unit mass expression (5); however, it will be included in calculations of product use phase impact in section 4.7.

4.5 Material & Environmental Data

Data for pallet mass, expected service life (number of trips), and dynamic load-bearing capacity are summarized in Table 9 for each pallet material/design combination under consideration. Data were drawn from literature sources and pallet product data, as shown in Table 10.

Table 9. Functional Characteristics of Shipping Pallets of Different Material-Design Configurations.

Pallet Material	Pallet Design	Service Life (Trips per Pallet)	Pallet Mass (kg)	Dynamic Load Bearing Capacity (kg)
Wood	Stringer – Light Duty	10	14.1	450
Wood	Block – Heavy Duty	66	33.1	1,130
HDPE	Stringer	66	22.2	2,270
Aluminum	Block	450	23.1	2,270
Steel	Block	450	40.8	4,540
Cardboard	Block – Light Duty	1	4.5	200
Cardboard	Block – Heavy Duty	1	5.8	650

Table 10. References Used to Estimate Key Properties of Shipping Pallets Listed in Table 4.

Pallet Material	Pallet Design	Service Life (Trips per Pallet)	Pallet Mass (kg)	Dynamic Load Bearing Capacity (kg)
Wood	Stringer – Light Duty	Alanya-Rosenbaum et al. 2021	Alanya-Rosenbaum et al. 2021	Alanya-Rosenbaum et al. 2021
Wood	Block – Heavy Duty	Alanya-Rosenbaum et al. 2021	Alanya-Rosenbaum et al. 2021	Alanya-Rosenbaum et al. 2021
HDPE	Stringer	Khan et al. 2021	Grainger 2022a	Grainger 2022a
Aluminum	Block	estimated	Grainger 2022b	Grainger 2022b
Steel	Block	estimated	Grainger 2022c	Grainger 2022c
Cardboard	Block – Light Duty	assumed single-use	Kraftpal 2022a*	Kraftpal 2022a
Cardboard	Block – Heavy Duty	assumed single-use	Kraftpal 2022b*	Kraftpal 2022b

* product data for cardboard pallets were available for a standard European size pallet of 1200 mm x 800 mm, not the functional unit (GMA) size of 1220 mm x 1020 mm. Mass data were scaled by area to estimate the mass of a GMA-sized pallet. The load bearing capacity was assumed to be the same.

Data from NREL's *Materials Flow through Industry* (MFI) web tool (NREL 2022) were used to estimate the embodied energy and greenhouse gas emissions for each pallet raw material (wood, HDPE, aluminum, steel, and cardboard). Table 11 shows the material descriptions of the product recipes in MFI used as proxy for each pallet material, as well as the environmental data pulled from the tool.[9]

[9] Embodied energy is calculated from MFI output data as the sum of the net process, feedstock, electricity, and transportation energy (in MJ) listed in the "Total Fuels" tab for 1 kg of the commodity. Embodied emissions is

Table 11. Estimated Embodied Energy and Emissions Data for Shipping Pallet Materials (data drawn from NREL's *Materials Flow through Industry* web tool)

Pallet Material	Material Definition in MFI used as proxy	Embodied Energy (MJ/kg)	Embodied Emissions (kg CO_2-eq/kg)
Wood	Wood, Hard	0.52	0.03
HDPE	Polyethylene, High Density	74.4	2.95
Aluminum	Aluminum, Ingot	69.3	4.51
Steel	Steel, Alloyed	51.6	7.59
Cardboard	Corrugated Paper Product	19.2	1.35

4.6 Calculation of Functional Unit Mass

We can calculate the required functional unit mass for each pallet configuration and duty specification (light-duty or heavy-duty) by substituting pallet and application information into equation (5). Pallet mass m_{pallet} and pallet service life n_{trip} are listed in Table 9; the total product load delivered M_{deliv} is 45.4 metric tonnes for both functional units; and the product load delivered per trip M_{trip} is specified in the functional unit: 181 kg for the light-duty pallet and 1,134 kg for the heavy-duty pallet. Note that the dynamic load bearing capacity listed in Table 9 does not factor directly into the functional unit mass calculation. Instead, dynamic load rating is used as a screening criterion. Since a pallet should not be loaded above its dynamic load rating, pallet configurations with a dynamic load-bearing capacity below the required per-trip product load do not meet application requirements and will be excluded from consideration. In this case, all pallet materials meet the constraints of the light-duty application. However, three pallet configurations will be excluded in the heavy-duty application because their dynamic load-bearing capacity rating is less than the specified trip load of 1,134 kg.

Functional unit mass calculations for light-duty and heavy-duty applications (and the number of pallets required) for each pallet option are tabulated in Table 12. The table shows that for the light-duty application, many more pallets are required to transport the total load of 45.4 metric tonnes because the trip load is smaller but the service life (number of trips per pallet) is assumed to be the same. This comparison highlights the importance of considering the expected trip load for an application, since it may be impractical to load pallets to their maximum capacity when transporting lightweight products. Note that in all of these calculations, the number of pallets in the functional unit is allowed to be a non-integer value. This is based on an assumption that a

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calculated as the sum of the net process, electricity, and transportation greenhouse gas emissions (in kg CO_2eq) listed in the "Total Emissions" tab for 1 kg of the commodity.

practical pallet implementation would involve large numbers of product loads, greatly exceeding the functional unit total load of 45.4 metric tonnes, such that each pallet could be used for the entirety of its useful life (even if this exceeds 45.4 metric tonnes in total product loads delivered). As such, a functional unit pallet count of less than one is considered permissible. (If this were not the case, analysis would require adjustment to reflect a shortened pallet service life.)

Table 12. Comparison of Functional Unit Mass for Shipping Pallets under Light-Duty and Heavy-Duty Application Constraints

Pallet Material	Pallet Design	Light-Duty		Heavy-Duty	
		Number of Pallets	Functional Unit Mass (kg)	Number of Pallets	Functional Unit Mass (kg)
Wood	Stringer – Light Duty	25	353	n/a*	n/a*
Wood	Block – Heavy Duty	3.8	124	0.61	44.2
HDPE	Stringer	3.8	84.2	0.61	29.7
Aluminum	Block	0.56	12.9	0.09	4.5
Steel	Block	0.56	22.7	0.09	8.0
Cardboard	Block – Light Duty	250	1,130	n/a*	n/a*
Cardboard	Block – Heavy Duty	250	1,460	n/a*	n/a*

*n/a: configuration does not meet application requirements because the pallet's dynamic load rating is less than the designated single load mass.

4.7 Environmental Performance Assessment

We can combine the environmental data shown in Table 11 with the functional unit mass calculations in Table 12 to assess and compare cradle-to-gate environmental performance across pallet materials. The product of the functional unit mass and the weight-based embodied energy gives the embodied energy of the functional unit. Likewise, the product of the functional unit mass and the weight-based embodied emissions gives the embodied emissions of the functional unit. Results are of these calculations are displayed in Table 13 for the light-duty functional unit and in Table 14 for the heavy-duty functional unit. On a cradle-to-gate basis, wood pallets offer the best environmental performance (lowest embodied energy and emissions) for both functional units. While the metal and plastic options have lower functional unit mass, these materials also have much higher specific embodied energy and emissions than wood. Overall, cradle-to-gate energy and emissions is minimized for the wood pallets.

Table 13. Comparison of Cradle-to-Gate Embodied Energy and Embodied Emissions Results for Pallet Material/Design Configurations under Light-Duty Application Constraints.

Light-Duty Pallet					
Pallet Material & Design	Embodied Energy per unit mass (MJ/kg)	Embodied Emissions per unit mass (kg CO_2-eq/kg)	Light-Duty Functional Unit Mass (kg)	Cradle-to-Gate Energy for Functional Unit (MJ)	Cradle-to-Gate Emissions for Functional Unit (kg CO_2-eq/kg)
Wood Stringer – Light Duty	0.52	0.03	353	182	9
Wood Block – Heavy Duty	0.52	0.03	124	65	3
HDPE Stringer	74.4	2.95	84.2	6,260	248
Aluminum Block	69.3	4.51	12.9	890	58
Steel Block	51.6	7.59	22.7	1,170	172
Cardboard – Light Duty	19.2	1.35	1,130	21,820	1,536
Cardboard – Heavy Duty	19.2	1.35	1,460	28,050	1,975

Table 14. Comparison of Cradle-to-Gate Embodied Energy and Embodied Emissions Results for Pallet Material/Design Configurations under Heavy-Duty Application Constraints.

Heavy-Duty Pallet					
Pallet Material & Design	Embodied Energy per unit mass (MJ/kg)	Embodied Emissions per unit mass (kg CO_2-eq/kg)	Heavy-Duty Functional Unit Mass (kg)	Cradle-to-Gate Energy for Functional Unit (MJ)	Cradle-to-Gate Emissions for Functional Unit (kg CO_2-eq/kg)
Wood Stringer – Light Duty	n/a*	n/a*	n/a*	n/a*	n/a*
Wood Block – Heavy Duty	0.52	0.03	44.2	23	1
HDPE Stringer	74.4	2.95	29.7	2,210	88
Aluminum Block	69.3	4.51	4.5	314	20
Steel Block	51.6	7.59	8.0	413	61
Cardboard – Light Duty	n/a*	n/a*	n/a*	n/a*	n/a*
Cardboard – Heavy Duty	n/a*	n/a*	n/a*	n/a*	n/a*
*n/a: configuration does not meet application requirements because the pallet's dynamic load rating is less than the designated single load mass.					

Our analysis has focused thus far on cradle-to-gate performance. However, use phase considerations are also significant for shipping pallets. Heavier pallets and greater distances traveled will be associated with higher fuel use during truck transportation. The total distance traveled by pallets to fulfil the functional unit (Table 15) depends on the load size, the number of pallet trips required to transport the full load of 45.4 metric tonnes, and the distance per trip.

Table 15. Total Pallet Distance Traveled (pallet-km) for Light-Duty and Heavy-Duty Functional Units

Functional Unit	Trip load (kg)	Total load (kg)	Number of pallet trips required	Trip distance (km)	Total distance traveled (pallet-km)
Light-Duty / Short-Haul	181	45,360	250	161	40,230
Heavy-Duty / Long-Haul	1,134	45,360	40	805	32,190

The CO_2-equivalent emissions for diesel truck transport is estimated as 0.0062 kg CO_2-eq per metric tonne-kilometer, the default value in the 2021 version of Argonne National Laboratory's GREET tool (Argonne 2021). We can calculate the overall CO_2-equivalent emissions associated with the pallet's use by multiplying this value by the product of pallet mass and the total pallet distance traveled. These calculations are shown in Table 16 for both the light-duty, short-haul functional unit and the heavy-duty, long-haul functional unit. In the use phase, the lightest-weight pallets perform best in the light-duty, short-haul application: cardboard pallets have the lowest emissions, followed by the light-duty wood stringer pallet. However, in the case of the heavy-duty, long-haul application, the HDPE and aluminum pallets have the lowest use-phase emissions. This is because of their lower mass compared to other pallet options that meet the minimum dynamic load-carrying capacity application requirement.

Table 16. Comparison of Use Phase Emissions (in Diesel Truck Transport) for Shipping Pallets in Light-Duty, Short-Haul and Heavy-Duty, Long-Haul Applications

Pallet Material & Design	Mass of one pallet (kg)	Light-Duty / Short-Haul		Heavy-Duty / Long-Haul	
		Pallet mass × distance (kg-km)	Use Phase Emissions for Functional Unit** (kg CO_2-eq)	Pallet mass × distance (kg-km)	Use Phase Emissions for Functional Unit** (kg CO_2-eq)
Wood Stringer – Light Duty	14.1	567,300	3.5	n/a*	n/a*
Wood Block – Heavy Duty	33.1	1,331,700	8.3	1,065,400	6.6
HDPE Stringer	22.2	894,200	5.5	715,400	4.4
Aluminum Block	23.1	930,700	5.8	744,600	4.6
Steel Block	40.8	1,642,500	10.2	1,314,000	8.1
Cardboard – Light Duty	4.5	182,500	1.1	n/a*	n/a*
Cardboard – Heavy Duty	5.8	234,700	1.5	n/a*	n/a*

* n/a: configuration does not meet application requirements because the pallet's dynamic load rating is less than the designated single load mass.

** calculated based on a CO_2-equivalent emissions for diesel truck transportation of 0.0062 kg CO_2-eq/tonne-km (Argonne 2021).

Cradle-to-use results[10] for all pallets are summarized in Table 17 and compared graphically in Figure 18 for both functional units. On the whole, the wood pallets have the lowest life cycle emissions in the light duty, short-haul application (with similar performance by the light-duty wood stringer pallet and heavy-duty wood block pallet). In the heavy-duty, long-haul application, the wood block pallet has the lowest life cycle emissions. These results suggest that life cycle greenhouse gas emissions cannot be reduced significantly by transitioning from the reference configurations (wood stringer pallet for the light duty application and wood block pallet for the heavy-duty application) to other pallet materials. However, tradeoffs between materials are strongly affected by application-specific load mass and trip distance, highlighting the importance of including these parameters in impact assessments. In a longer-haul or higher-load application, the aluminum pallet could become a strong contender on a life cycle environmental basis.

Table 17. Cradle to Use Emissions for Shipping Pallets in: Light-Duty, Short-Haul and Heavy-Duty, Long-Haul Applications

Pallet Material & Design	Light-Duty / Short-Haul			Heavy-Duty / Long-Haul		
	Functional Unit: the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes of product load, where each delivery will require the transport of one 181-kg load over a travel distance of 161 km by diesel truck.			Functional Unit: the combined mass of GMA-sized pallets required to deliver 45.4 metric tonnes of product load, where each delivery will require the transport of one 1.134-kg load over a travel distance of 805 km by diesel truck.		
	Materials & Manufacturing Emissions (kg CO_2-eq)	Use Phase Emissions (kg CO_2-eq)	Cradle-to-Use Emissions (kg CO_2-eq)	Materials & Manufacturing Emissions (kg CO_2-eq)	Use Phase Emissions (kg CO_2-eq)	Cradle-to-Use Emissions (kg CO_2-eq)
Wood Stringer – Light Duty	9	3.5	12.8	n/a*	n/a*	n/a*
Wood Block – Heavy Duty	3	8.3	11.6	1	6.6	7.8
HDPE Stringer	248	5.5	253.6	88	4.4	91.9
Aluminum Block	58	5.8	63.7	20	4.6	25.1
Steel Block	172	10.2	182.2	61	8.1	68.8
Cardboard – Light Duty	1,536	1.1	1,538	n/a*	n/a*	n/a*
Cardboard – Heavy Duty	1,975	1.5	1,977	n/a*	n/a*	n/a*

* n/a: configuration does not meet application requirements because the pallet's dynamic load rating is less than the designated single load mass.

[10] End-of-life has not been included in this assessment but is likely to be significant for shipping pallets; this topic is briefly discussed in the following section and recommended as a next step for analysis.

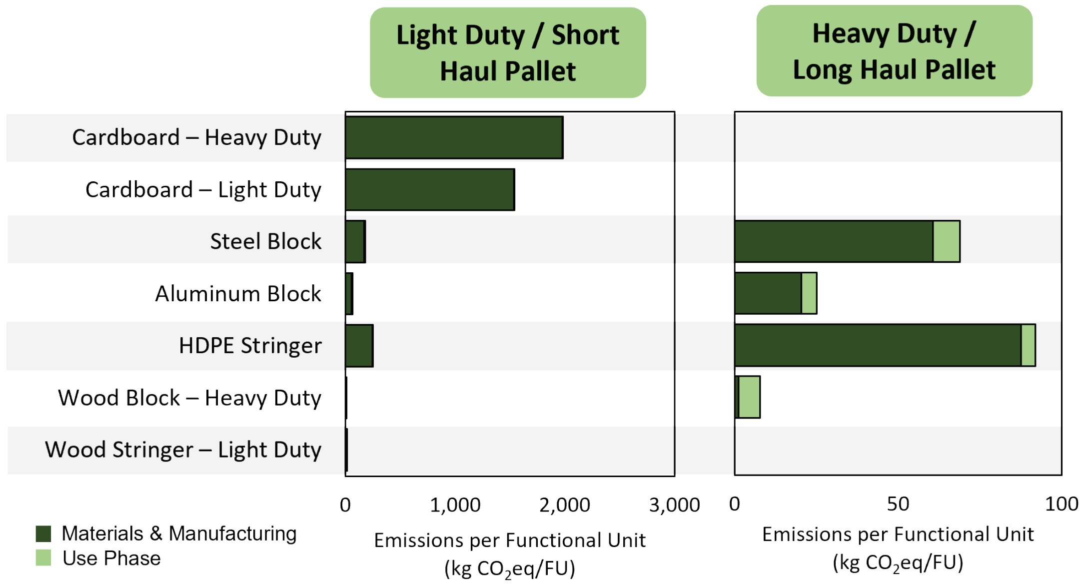


Figure 18. Comparison of cradle-to-gate emissions for shipping pallets in light-duty / short haul and heavy-duty / long haul applications. Three pallet configurations are excluded from the heavy-duty comparison because they did not meet minimum application needs.

4.8 Results Synthesis and Next Steps

The comparisons in Figure 18 provide useful information for decision-making, however, it is important to keep in mind that the analysis just presented was focused on a limited set of environmental metrics and performance criteria. The stoplight matrix of Figure 19 notes some additional considerations that may be important to a decision maker, including repairability, pest resistance, and final disposition of the pallet at the end of its useful life.

	Raw Materials	Manufacturing	Transportation	Product Use	End of Life
Wood	renewable (if sustainably harvested)	low manufacturing energy & emissions	moderately high mass	industry standard; repairable; pest susceptible	re-use boards; downcycle; biodegradable
HDPE	petroleum feedstock	moderate manufacturing energy & emissions	moderately high mass	durable but not repairable; pest-free; non-reactive	landfill most likely; recycling possible
Aluminum	virgin or recycled metal raw material	moderate manufacturing energy & emissions	moderately high mass	durable but not repairable; expensive; pest-free; non-reactive	recycle
Steel	virgin or recycled metal raw material	moderate manufacturing energy & emissions	heavy; high fuel use to transport	durable but heavy; high load rating; may corrode	downcycle
Cardboard	renewable (if sustainably harvested)	high functional unit energy & emissions given single use	very lightweight; low fuel use to transport	one-time use; susceptible to pests and water	recycle; biodegradable

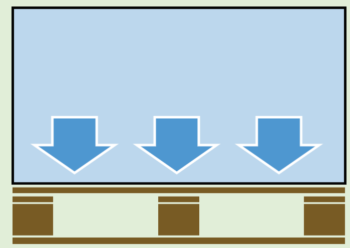
Figure 19. A "stoplight matrix" summarizing potentially significant considerations in each phase of the product life cycle for five different shipping pallet materials.

Based on the results of this case study (including the additional considerations noted in the stoplight matrix), we can identify the following next steps to expand on this analysis:

- Extend the analysis from cradle-to-use to cradle-to-grave by conducting an in-depth analysis of the end-of-life phase of the product life cycle for each shipping pallet configuration. This would inform opportunities for repairing, remanufacturing, recycling, and downcycling of end-of-life pallets of different materials.
- Confirm specific application constraints for pallet use and management (particularly the number of uses and anticipated product loads per use) to refine analysis and improve the usefulness and applicability of results.
- Perform a full LCA to confirm and better understand the screening results of this initial analysis and explore impacts in additional environmental categories.

A summary of the analysis for this case study is given in Table 18.

Table 18. Framework-Based Analysis Summary for the Shipping Pallet Case Study

Shipping Pallet Case Study: Analysis Summary		
Analysis Step		**Case Study Outcomes**
1	Define the Application and Analysis Scope	**Analysis objectives:** In this screening analysis, our goal is to compare the environmental performance of shipping pallet materials for light- and heavy-duty applications. **Study boundaries:** cradle-to-use **Selected environmental metrics:** embodied energy; embodied emissions 
2	Define the Functional Unit	**Functional Unit A – Light Duty:** the combined mass of GMA-sized pallets required to deliver 100,000 lbs (45.4 metric tonnes) of product load, where each delivery will require the transport of one 400-lb (181-kg) load over a travel distance of 100 mi (161 km) by diesel truck. **Functional Unit B – Heavy Duty:** the combined mass of GMA-sized pallets required to deliver 100,000 lbs (45.4 metric tonnes) of product load, where each delivery will require the transport of one 2,500-lb (1,134-kg) load over a travel distance of 500 mi (805 km) by diesel truck.
3	Identify Candidate Materials	**Candidate materials:** wood; HDPE; aluminum; steel; cardboard
4	Derive Expression for Minimum Required Functional Unit Mass	**Functional unit mass:** $$m_{FU} = \frac{m_{pallet} M_{deliv}}{n_{trip} M_{trip}}$$ where m_{pallet} = mass of one pallet; M_{deliv} = total mass of product load delivered (by all pallets); n_{trip} = service life (number of expected trips per pallet); and M_{trip} = mass of product transported per trip (per pallet)
5	Gather Material & Environmental Data	*See Table 9 and Table 11*
6	Calculate Required Mass	*See Table 12*
7	Assess Environmental Performance	*See Table 13 and Table 14*
8	Synthesize Results & Plan Next Steps	**Key findings:** Wood stringer pallets minimized life cycle emissions for the light-duty, short-haul application considered here, while wood block pallets minimized life cycle emissions for the heavy-duty, long-haul application. **Next steps:** analyze the end-of-life phase to better understand end-of-life impacts; refine application assumptions for pallet use and management to improve accuracy of results and comparisons; perform a full LCA to explore impacts in other environmental impact categories not yet considered.

5. Case Study: Materials Selection for a Lightweight Automotive Component

Figure 20. The body-in-white of a light-duty vehicle with the B-pillar (central support beam) highlighted.

Image copyright Adobe Stock #307336372; used under license. Emphasis of the B-pillar added by the authors.

5.1 Application Overview and Analysis Scope

In this case study, we will consider the selection of materials for an automotive structural component: the B-pillar. The B-pillar is an important vertical support member in most light-duty vehicles, positioned between the front and rear passenger doors (Figure 20). Its primary functions are to support the roof and provide occupant protection in the event of a crash. In the United States, vehicle safety is assured by compliance with Federal Motor Vehicle Safety Standards (FMVSS) as regulated by the U.S. National Highway Traffic Safety Administration (NHTSA). Two automotive FMVSS safety standards that apply most directly to the B-pillar are FMVSS 216a, *Roof Crush Resistance* (49 C.F.R. Part 571, §216a) and FMVSS 214, *Side Impact Protection* (49 C.F.R. Part 571, §214). Briefly, these safety standards are summarized as follows:

- **U.S. FMVSS 216a (Roof Crush Resistance)** establishes the minimum structural requirements for the passenger compartment roof. Safety performance is tested by applying a specified load through a rigid block to the edge of the vehicle's roof (in the vicinity of the A and B pillars) and measuring the linear intrusion of the block into the passenger compartment.

- **U.S. FMVSS 214 (Side Impact Protection) establishes** minimum performance requirements for protection of occupants in a side impact crash. In one required test, the side of the test vehicle is struck with a moving deformable barrier that approximates the size and shape of a second vehicle; safety performance is assessed by measuring accelerations and body forces sustained by anthropomorphic test dummies.

Mild steel, the conventional material for a B-pillar in a light-duty vehicle, offers strong safety performance at a relatively low material cost—but since steel is heavy compared to lightweight composites and metals, associated fuel consumption (in the vehicle use phase) can be high. Lightweighting opportunities for the B-pillar include substitution of steel with alternate materials such as advanced high-strength steel (Tisza and Czinege 2018), fiber-reinforced polymer composites (Park et al. 2012), and aluminum (Lee and Moon 2021). U.S. automakers are incentivized to lightweight vehicles through Corporate Average Fuel Economy (CAFE) standards that limit each manufacturer's vehicle-fleet-average greenhouse gas emissions (49 C.F.R. Part 531). Nonetheless, it is important to recognize that emissions benefits of lightweighting may be counteracted by an emissions penalty in the manufacturing phase if the lightweight materials deployed are energy- and emissions-intensive compared to the materials they replace (Sunter et al. 2015, Morrow et al. 2016). A life cycle approach facilitates holistic consideration of these potentially competing impacts.

For this case study, a functional unit is defined for an automotive B-pillar in alignment with FMVSS 216a and 214 safety standards. Leveraging a simplified mechanical model for the B-pillar, we explore the impact of different lightweighting strategies on life cycle greenhouse gas emissions associated with this component. The analysis scope for this case study is cradle-to-use (through the use phase; excluding end-of-life). The environmental metrics assessed include embodied energy (i.e., CED) and embodied emissions (i.e., GWP).

5.2 Functional Unit Definition

The functional unit for this case study is based on the B-pillar's safety performance under the constraints of two applicable U.S. safety standards, FMVSS 216a (roof crush resistance) and FMVSS 214 (side impact protection):

Functional Unit: the mass of a 1000-mm-long, 120-mm-wide structural B-pillar for a light-duty vehicle that can safely support the vehicle and provide occupant protection under rollover conditions (U.S. FMVSS 216a) and side-impact conditions (U.S. FMVSS 214).

Real-world automotive B-pillars have complex designs that may include variable width and thickness along the length of the component, curvature that conforms with the vehicle's body contours, and design elements that improve aesthetics and facilitate joining and stability. Here this component is very roughly simplified as a beam (or column) with a high-aspect-ratio rectangular cross-section (Figure 21). The fixed length and width dimensions of the B-pillar are drawn from literature values (Ikpe et al. 2017a, Ikpe et al. 2017b), while the B-pillar thickness is taken as a free parameter that can be adjusted to meet structural requirements. The functional unit mass for a B-pillar meeting the minimum performance requirements of each safety standard is estimated based on simplified beam models, based on the assumptions detailed below.

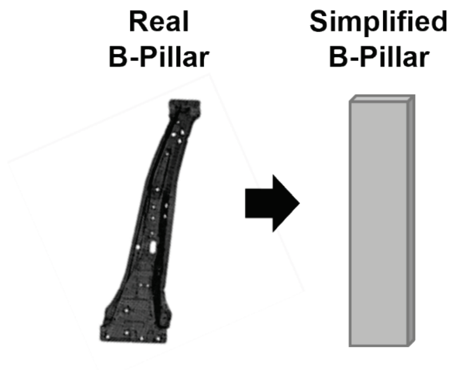


Figure 21. Simplification of the B-pillar as a beam with a rectangular cross-section.

5.2.1 FMVSS 216a: Roof Crush Resistance

FMVSS 216a (49 C.F.R. Part 571 §216a), *Roof Crush Resistance*, tests a vehicle's ability to withstand the forces of a rollover crash without excessive roof crush into the occupant compartment. In the standard compliance test, a load is applied to the edge of the roof through a rigid block oriented at an angle of 25° from vertical, as shown in Figure 22(a). Since the test is intended to assess safety under rollover conditions, the magnitude of the test load is determined based on the vehicle's mass. For a light-duty vehicle with a gross volumetric weight rating of 2,722 kg or less, the applied load is 3.0 times the unloaded weight of the vehicle in kilograms, multiplied by the acceleration due to gravity (9.8 m/s^2) to calculate a test force in Newtons. A vehicle passes the test if the rigid test block travels no more than 127 mm after its initial contact with the roof (with any greater displacement of the test block considered noncompliant due to excessive intrusion into the passenger compartment). An additional requirement specifies a maximum force on the head of an anthropomorphic test dummy seated in the front outboard seating position on the side of the vehicle being tested.

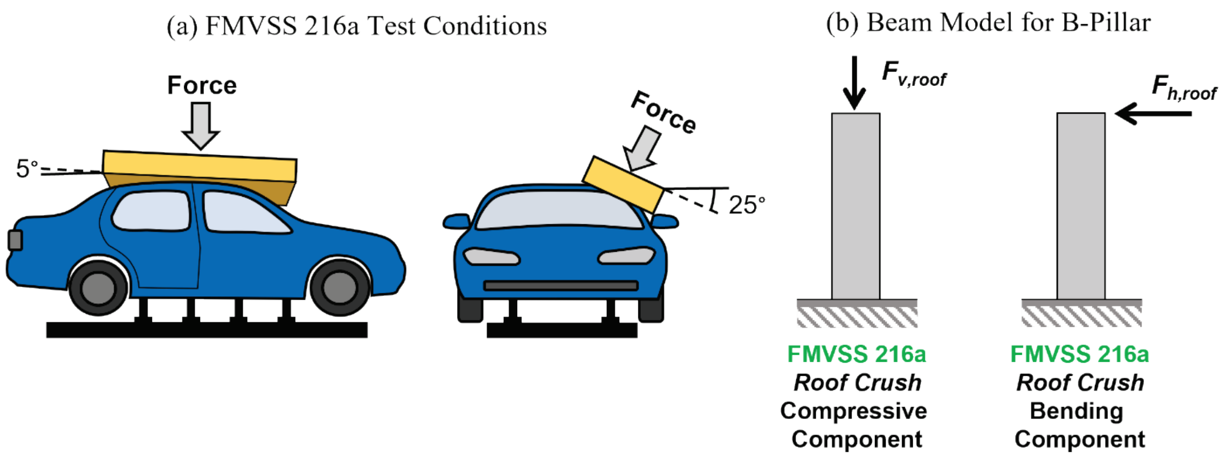


Figure 22. (a) Schematics of FMVSS 216a (Roof Crush Resistance) test, shown from side and front views; and (b) simplified beam model of loading conditions on the central B-pillar.

In this analysis, we simplify the geometry and loading conditions of the FMVSS 216a test as shown in Figure 22(b). We assume a vehicle curb weight of 1,300 kg (a typical mass for a small sedan such as a Honda Civic). This mass corresponds to a roof crush test force of 38,220 N (three times the curb weight multiplied by 9.8), applied to the roof edge at an angle of 25° from vertical. This load would be supported by a combination of structural members in the vehicle, including A-, B-, and C- pillars as well as other components. We assume that the central B-pillar supports 30% of the total roof loading on each side of the vehicle, leading to a B-pillar load of F_{roof} = 11,470 N). In our simplified model, we represent the B-pillar as a column or beam built-in (i.e., to the floor pan) at its lower end. At the upper, free end, we represent the roof crush load as two components: a vertical compression load and a horizontal bending load. Given the 25° loading angle, the magnitude of the vertical and horizontal roof loads on the B-pillar are given by

$$F_{v,roof} = F_{roof} \cos(25°)\text{; and} \quad (6)$$

$$F_{h,roof} = F_{roof} \sin(25°). \quad (7)$$

Based on the total roof load of 11,470 N, the magnitude of the vertical compression load is 10,390 N and the magnitude of the horizontal bending load is 4,390 N. For the purposes of this functional unit, we will assume that the B-pillar meets the requirements of FMVSS 216a if it can withstand these roof crush forces without buckling or plastic yielding. While some buckling/bending of the B-pillar could be permissible in the FMVSS standard (the standard simply limits overall displacement; some plastic deformation is expected and permitted), this will enable a conservative estimate of component mass.

5.2.2 FMVSS 214: Side Impact Protection

FMVSS 214 (49 C.F.R. Part 571 §214), *Side Impact Protection*, includes three major compliance tests: the door crush resistance test, the moving deformable barrier test, and the vehicle-to-pole test. The moving deformable barrier test, intended to simulate the conditions of a vehicle-to-vehicle side impact, involves an impact in the vicinity of the B-pillar. In this test, a moving deformable barrier (consisting of a trolley-mounted rigid block with a deformable aluminum honeycomb face and bumper) impacts the side of the stationary test vehicle at an impact velocity of 53 km/hour. The total ballasted mass of the moving deformable barrier system is 1,368 kg (70 F.R. 153), and the wheels of the deformable barrier are rotated to an angle of 27° from center such that the barrier's line of forward motion is diagonal with respect to its centerline, as shown in Figure 23 (a). A vehicle passes the test if all accelerations and body forces sustained by anthropomorphic test dummies are below specified limits in the standard.

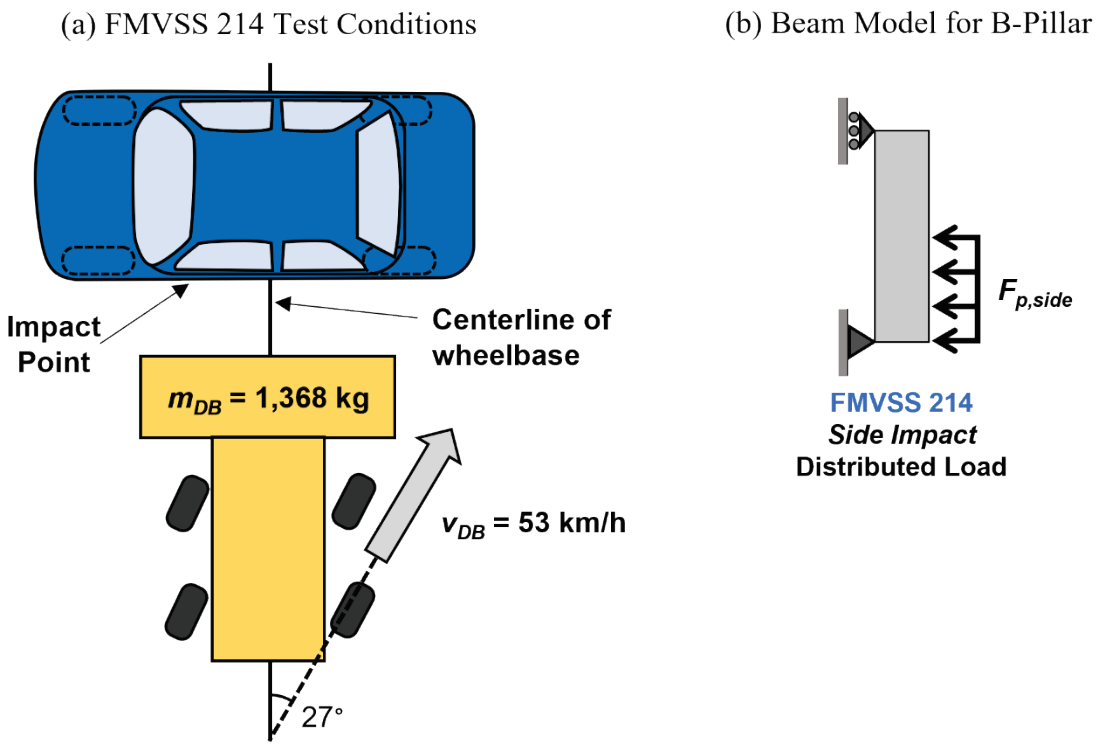


Figure 23. (a) Schematic of FMVSS 214 (Side Impact Protection) moving deformable barrier test and (b) simplified beam model of loading conditions on the B-pillar.

To assess the requirements of this standard, we will again simplify the geometry and loading conditions of the FMVSS 214 test in a beam model. Noting that the deformable barrier's face is 1,676 mm wide by 559 mm high, we will model the side impact force as a distributed load on the lower half of the 1-meter-high B-pillar, as shown in Figure 23(b). We can estimate the impact force F_{side} as

$$F_{side} = (m_{DB} v_{DB}{}^2)/(2s) \,, \tag{8}$$

where m_{DB} and v_{DB} are the mass and velocity of the deformable barrier and s is the slowdown distance or "crumple zone" for the impact (i.e., the combined linear deformation experienced by the deformable barrier and test vehicle during the impact event). Assuming a crumple zone of 0.4 meters, the overall side impact force is estimated as F_{side} = 370,630 N, impinging at an angle of 27° from perpendicular. We assume that 30% of that force is absorbed by the B-pillar. The perpendicular component of the force is given by

$$F_{p,side} = (0.50)F_{side}\cos(27°), \quad (9)$$

and its value is 99,070 N. For the purposes of this functional unit, we assume that the B-pillar meets the requirements of FMVSS 214 if it can withstand an impact force of this magnitude (at the pillar midpoint) with a maximum deflection of 0.2 meters.

5.3 Candidate Materials

Suitable materials that might be considered for an automotive B-pillar include mild steel, high-strength steel, aluminum, carbon-fiber reinforced polymer composites, and multi-material combinations. Further variations for the metals include primary (virgin) material and secondary material recycled from scrap. In the case of steel, the two major production routes include primary steel produced via the blast furnace / basic oxygen furnace (BF/BOF) steelmaking process (from virgin iron ore or scrap) and secondary steel produced via the electric arc furnace (EAF) route (from scrap steel). Similarly, primary aluminum is extracted and refined from aluminum-containing bauxite ore (a mined resource) via the Hall-Héroult electrolytic conversion process, whereas secondary aluminum is produced by remelting and processing aluminum scrap. While the properties of primary and secondary metal can differ, for the purposes of this analysis, we assumed that the mechanical properties of mild steel produced via BF/BOF and EAF routes were identical; likewise, we also assumed that primary and secondary aluminum had identical mechanical properties. However, considering purity differences, we assumed that advanced high strength alloy steel for the automotive sector would be produced through the BF/BOF route to ensure product quality.

In this case study, we will assess and compare the following material options:

- Primary mild steel from virgin iron ore, via BF/BOF process
- Secondary mild steel from scrap, via EAF process
- High-strength alloy steel
- Primary aluminum
- Secondary aluminum from scrap
- Carbon-fiber reinforced polymer (CFRP)

While the BF/BOF steelmaking process is the most common globally, the majority of steel produced in the United States (63%) is produced through the EAF process (Hasanbeigi and

Springer 2019). However, only about 27% of automotive steel comes from recycled content (Argonne 2021). Primary mild steel will therefore be considered the reference material for the B-pillar in this case study.

5.4 Functional Unit Mass Expression

Next, we will derive an expression for the functional unit mass based on the functional unit criteria and mechanical model assumptions laid out in section 5.2. The mass of the simplified B-pillar is given by

$$m_{FU} = \rho L w t_{min} \tag{10}$$

where:

ρ = density of B-pillar material;
L = length of the B-pillar (1000 mm in functional unit);
w = width of the B-pillar (120 mm in functional unit); and
t_{min} = the minimum thickness of a B-pillar satisfying all performance requirements.

To calculate t_{min}, we will use simplified column/beam representations of FMVSS 216a and FMVSS 214 loadings to determine the minimum thickness of the B-pillar required to satisfy all conditions. In all, three performance criteria must be met:

- No buckling of the B-pillar under the vertical (compression) component of the roof-crush load (FMVSS 216a);
- No plastic yielding of the B-pillar under the horizontal (bending) component of the roof-crush load (FMVSS 216a); and
- No more than 0.2 meters of deflection of the B-pillar under the distributed side-impact load (FMVSS 214).

The representations of these three criteria are illustrated in Figure 24 and the loads determined in section 5.2 are listed in Table 19 for reference. The overall minimum B-pillar thickness will be the highest value of t_{min} calculated across the three performance constraints:

$$t_{min} = \max\left[t_{min,vroof}, t_{min,hroof}, t_{min,side}\right]. \tag{11}$$

Calculations for t_{min} under each constraint follow in sections 5.4.1, 5.4.2, and 5.4.3.

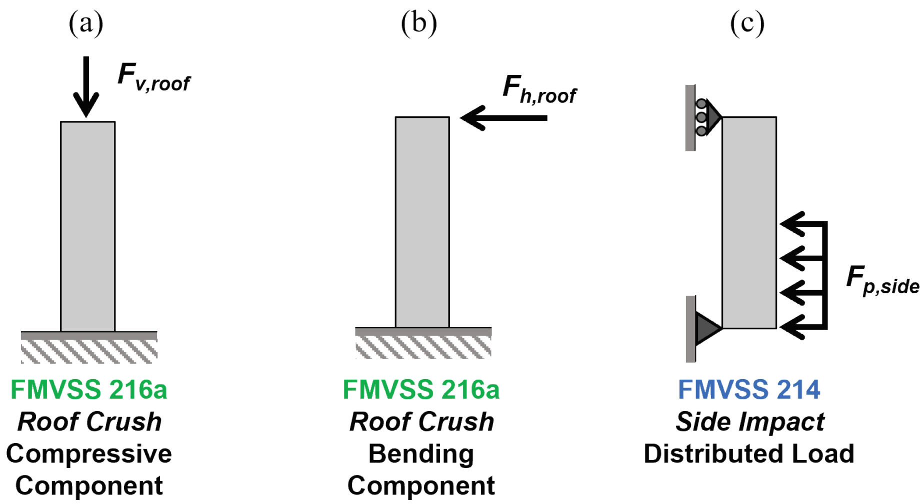


Figure 24. Simplified beam representations of the loading conditions of FMVSS 216a and FMVSS 214: (a) vertical (compressive) and (b) horizontal (bending) components of the FMVSS 216a roof crush load; (c) distributed load representing the FMVSS 214 side impact.

Table 19. Beam Loads for FMVSS 216a and FMVSS 214 (as calculated in section 5.2)

Load Description	Symbol	Magnitude (N)
Vertical (compressive) component of the FMVSS 216a roof crush load	$F_{v,roof}$	11,470
Horizontal (bending) component of the FMVSS 216a roof crush load	$F_{h,roof}$	4,390
Perpendicular component of the FMVSS 214 side impact load	$F_{p,side}$	99,070

5.4.1 Roof crush compression constraint

We will begin by estimating the minimum thickness of the B-pillar that satisfies the stiffness constraint imposed by the vertical component of the roof crush load (Figure 24(a)). The critical force for unstable bending (i.e., buckling) of a column in compression is given by the Euler column formula (see, e.g., Gere and Goodno 2009, Chapter 11):

$$F_{v,crit} = \mathrm{C}\pi^2 EI/L^2, \tag{12}$$

where I is the area moment of inertia about the axis of rotation ($I = wt^3/12$ for a rectangular cross section) and C is a constant determined by the end conditions. For a column that is built-in at one end and free the loaded end, $C = ¼$ (Gere and Goodno 2009). Eliminating I, we find that the minimum column thickness to avoid buckling under the roof crush load is:

$$t_{min,vroof} = \left[\frac{48F_{v,roof}L^2}{\pi^2 Ew}\right]^{1/3}. \tag{13}$$

Substituting the B-pillar dimensions (L = 1.0 m, w = 0.12 m) and the vertical component of the roof crush load ($F_{v,roof}$= 11,470 N) into equation (13) gives us an expression for the minimum B-pillar thickness satisfying this constraint (where E is expressed in MPa):

$$t_{min,vroof} = [0.42/E]^{1/3}. \tag{14}$$

5.4.2 Roof crush bending constraint

Next, we will estimate the minimum thickness of the B-pillar necessary to satisfy the strength constraint imposed by the horizontal component of the roof crush load (Figure 24(a)). The "yield moment" (i.e., the bending moment in the beam when it reaches its yield stress σ_y) is given by the flexure formula (see, e.g., Gere and Goodno 2009, Chapter 6):

$$M_y = \sigma_y I/c, \tag{15}$$

where c is the distance to the point furthest from the neutral axis (in this case, $c = t/2$), and I is the area moment of inertia about the axis of rotation ($I = wt^3/12$ for the rectangular cross section considered here). The maximum moment occurs at the built-in base of the beam, and is equal to $M_y = F_yL$ where F_y is the critical force that will induce yielding. Eliminating I in equation (15) to solve for the minimum thickness that will avoid plastic yielding in the beam, we find:

$$t_{min,hroof} = \left[\frac{6F_{hroof}L}{\sigma_y w}\right]^{1/2}. \tag{16}$$

Substituting the B-pillar dimensions (L = 1.0 m, w = 0.12 m) and the horizontal component of the roof crush load ($F_{h,roof}$ = 4,390 N) into equation (13) gives us an expression for the minimum B-pillar thickness satisfying this constraint (where E is expressed in MPa):

$$t_{min,vroof} = \left[0.22/\sigma_y\right]^{1/2}. \tag{17}$$

5.4.3 Side impact deflection constraint

The last constraint on the B-pillar is that it must not deflect more than 0.2 meters under the distributed side-impact load shown in Figure 24(c). The maximum deflection of a simply-supported beam with a load distributed over one-half of its length, as shown, is given by (see, e.g., Gere and Goodno 2009, Table G-2)

$$y_{max} = 5F_{p,side}L^3/(384EI), \tag{18}$$

where:

E is the elastic modulus; and

I is the area moment of inertia (i.e., $I = wt^3/12$ for a beam with a rectangular section).

Eliminating I and solving for t gives us

$$t_{min,side} = \left[\frac{5F_{p,side}L^3}{32Ewy_{max}}\right]^{1/3}. \quad (19)$$

Substituting the B-pillar dimensions (L = 1.0 m, w = 0.12 m), maximum allowable deflection (y_{max} = 0.2 m), and the side impact load ($F_{p,side}$ = 99,070 N) into equation (19) gives us an expression for the minimum B-pillar thickness satisfying this constraint (where E is expressed in MPa):

$$t_{min,side} = [0.52/E]^{1/3}. \quad (20)$$

5.5 Material & Environmental Data

The minimum mass of a B-pillar satisfying all constraints will depend on material properties of the material selected—namely, the material density ρ (which appears in equation 10), the elastic modulus E (which appears in equations 14 and 20), and the yield strength σ_y (which appears in equation 17). These key material properties for the candidate B-pillar materials are summarized in Table 20. Material property data were drawn from the matweb.com (Matweb 2022) online data repository, where most data are manufacturer-provided. The matweb.com database materials that were selected to represent each candidate B-pillar material are identified in Table 21. As noted above, for mild steel and aluminum, the same properties are assumed for primary and secondary material.

Table 20. Key Material Properties of Candidate B-Pillar Materials

Material	Description	Density ρ (kg/m³)	Elastic Modulus E (MPa)	Yield Strength σ_y (MPa)
Mild Steel	AISI 1080	7,850	205,000	585
High-Strength Steel	22MnB5	7,800	210,000	1,100
Aluminum	6061-T6	2,700	68,900	255
CFRP	60 wt.% CF in an epoxy matrix	1,590	152,000	2,415

Table 21. Names of Materials in the matweb.com Data Repository (Matweb 2022) Used to Estimate the Material Properties of B-Pillar Materials in Table 4.

Material	Density ρ (kg/m³)	Elastic Modulus E (MPa)	Yield Strength σ_y (MPa)
Mild Steel	AISI 1080 Steel, as rolled	AISI 1080 Steel, as rolled	AISI 1080 Steel, as rolled
High-Strength Steel	Ovako 22MnB5 Steel	Ovako 22MnB5 Steel	ArcelorMittal Usibor® 22MnB5 Ultra High Strength Steel, Hot Rolled

Aluminum	Alclad Aluminum 6061-T6, T651	Alclad Aluminum 6061-T6, T651	Alclad Aluminum 6061-T6, T651
CFRP	Weighted average of Hexcel® HexTow® AS4 12K Standard Modulus Carbon Fiber (60 wt%) and Hexcel® Hexply® 8552 Epoxy Matrix (40 wt%)	Hexcel® HexTow® AS4D Carbon Fiber – Epoxy Composite	Hexcel® HexTow® AS4D Carbon Fiber – Epoxy Composite

Data from the *Materials Flow through Industry* (MFI) web tool (NREL 2022) were used to estimate the cradle-to-gate embodied energy and greenhouse gas emissions for each B-pillar material. Table 11 shows the material descriptions of the product recipes in MFI used as proxy for each material, as well as the environmental data pulled from the tool.[11]

Table 22. Estimated Cradle-to-Gate Embodied Energy and Emissions Data for B-Pillar Materials (data drawn from NREL's *Materials Flow through Industry* web tool)

B-Pillar Material	Material Definition in MFI used as proxy (and process route, if multiple)	Embodied Energy (MJ/kg)	Embodied Emissions (kg CO_2-eq/kg)
Primary Mild Steel	Steel, Unalloyed (LD Converter)	41.7	6.7
Secondary Mild Steel	Steel, Unalloyed (Electric Arc Furnace)	7.9	0.5
High-Strength Steel	Steel, Ultra High Strength (LD Converter)	45.5	7.1
Primary Aluminum	Aluminum, Primary, Ingot	136.5	8.9
Secondary Aluminum	Aluminum, Secondary, Ingot	13.6	0.9
CFRP	Carbon Fiber Reinforced Plastic (polyacrylonitrile (PAN) based carbon fiber)	254.8	14.4

5.6 Calculation of Functional Unit Mass

To calculate the required functional unit mass for each candidate B-pillar material, our first step will be to calculate the minimum pillar thickness satisfying all constraints by substituting material data into equations 14, 17, and 20. The highest value of t_{min} across all constraints is the limiting value, and can be used to calculate the functional unit mass with equation 11. Calculations are shown in Table 23 and Table 24. The bending component of the roof crush load (a strength-critical constraint) was the limiting constraint for all materials except for the CFRP composite. For the CFRP composite, the limiting constraint was the side impact constraint, which imposes a stiffness-critical requirement.

[11] Embodied energy is calculated from MFI output data as the sum of the net process, feedstock, electricity, and transportation energy (in MJ) listed in the "Total Fuels" tab for 1 kg of the commodity. Embodied emissions is calculated as the sum of the net process, electricity, and transportation greenhouse gas emissions (in kg CO_2eq) listed in the "Total Emissions" tab for 1 kg of the commodity.

Table 23. Minimum B-Pillar Thickness Satisfying Each Constraint

B-Pillar Material	Minimum thickness (mm)			Limiting constraint
	Roof Crush Compressive $t_{min} = (0.81/E)^{1/3}$	Roof Crush Bending $t_{min} = (0.42/\sigma_y)^{1/2}$	Side Impact $t_{min} = (0.86/E)^{1/3}$	
Primary Mild Steel	12.7	19.4	13.6	Roof Crush Bending
Secondary Mild Steel	12.7	19.4	13.6	Roof Crush Bending
High-Strength Steel	12.6	14.1	13.5	Roof Crush Bending
Primary Aluminum	18.3	29.3	19.6	Roof Crush Bending
Secondary Aluminum	18.3	29.3	19.6	Roof Crush Bending
CFRP	14.0	9.5	15.0	Side Impact

Table 24. Comparison on Functional Unit Mass for B-Pillars of Different Materials

B-Pillar Material	Limiting Constraint	B-Pillar Thickness (mm)	Density (kg/m^3)	B-Pillar Mass (kg)
Primary Mild Steel	Roof Crush Bending	19.4	7,850	18.3
Secondary Mild Steel	Roof Crush Bending	19.4	7,850	18.3
High-Strength Steel	Roof Crush Bending	14.1	7,800	13.2
Primary Aluminum	Roof Crush Bending	29.3	2,700	9.5
Secondary Aluminum	Roof Crush Bending	29.3	2,700	9.5
CFRP	Side Impact	15.0	1,594	2.9

The mass of the B-pillar ranged from 3 kg to 18 kg, depending on the material selected. These values are roughly in-line with literature values considering the simplified model for the B-pillar and conservative assumptions adopted here. For example, one group reported masses of 13 kg and 9 kg for two candidate B-pillar designs for the Ford Fusion for boron steel and dual-phase advanced high-strength steel respectively (Hardwick and Outerridge 2016). Since the same material properties were assumed for primary and secondary mild steel, and for primary and secondary aluminum, the minimum thickness and mass values are likewise the same for primary and secondary variations of these materials. This assumption would likely require refinement in a more comprehensive LCA study. In any case, the environmental performance of the primary and secondary materials will be different.

5.7 Environmental Performance Assessment

We can combine the environmental data shown in Table 22 with the functional unit mass calculations in Table 24 to assess and compare cradle-to-gate environmental performance across B-pillar materials. The product of the functional unit mass and the weight-based embodied energy gives the embodied energy of the functional unit. Likewise, the product of the functional unit mass and the weight-based embodied emissions gives the embodied emissions of the functional unit. Results are of these calculations are displayed in Table 25. All of the alternative lightweight materials considered reduced cradle-to-gate emissions for the B-pillar compared to the baseline material (primary mild steel) while satisfying all performance constraints. On a cradle-to-gate basis, secondary aluminum and secondary mild steel were roughly tied for the best environmental performance (lowest embodied energy and emissions) based on application constraints. While the CFRP B-pillar has a lower mass, it also has much higher embodied energy and emissions. CFRP has a high strength but is unexceptional in stiffness; the elastic modulus E of CFRP is lower than that of conventional mild steel. As a result, side impact (stiffness-critical) was the performance-limiting constraint for CFRP, whereas for all other materials the limiting constraint was roof crush bending (strength-critical). This suggests that a multi-material solution (e.g., metal with CFRP reinforcement) could be advantageous in this application—and is in fact common in practice for automotive B-pillars. However, based on a simplified single-material component model of the B-pillar, cradle-to-gate emissions are minimized for secondary aluminum or secondary steel.

Table 25. Comparison of Cradle-to-Gate Embodied Energy and Embodied Emissions Results for B-Pillar Materials.

B-Pillar Material	Embodied Energy per unit mass (MJ/kg)	Embodied Emissions per unit mass (kg CO_2-eq/kg)	B-Pillar (Functional Unit) Mass (kg)	Cradle-to-Gate Energy for Functional Unit (MJ)	Cradle-to-Gate Emissions for Functional Unit (kg CO_2-eq/kg)
Primary Mild Steel	41.7	6.7	18.3	761	122.6
Secondary Mild Steel	7.9	0.5	18.3	144	8.8
High-Strength Steel	45.5	7.1	13.2	602	93.2
Primary Aluminum	136.5	8.9	9.5	1,298	84.5
Secondary Aluminum	13.6	0.9	9.5	129	8.6
CFRP	254.8	14.4	2.9	733	41.3

Our analysis has focused thus far on cradle-to-gate performance; next, we will consider the use phase for the B-pillar. Energy savings for automotive lightweighting can be estimated through the use of a fuel reduction value (FRV), expressed in units of L/(100 km·100kg)—i.e., liters of motor gasoline saved per 100 kilometers traveled per 100 kg of mass reduced. The FRV is based on the mass-dependent component of vehicle energy consumption. Typical FRVs for internal combustion engine (ICE) vehicles are in the range of 0.10–0.40 L/(100 km·100kg), depending on factors such as vehicle size, drive cycle, and whether or not the powertrain is resized to match performance after lightweighting (Luk at al. 2017, Kim et al. 2016). For electric vehicles (EVs), FRVs are on the order of 0.04–0.09 L_{eq}/(100 km·100kg) (Luk at al. 2017, Kim et al. 2016), equivalent to 0.36–0.80 kWh/(100 km·100kg).[12] Based on representative FRV values and other assumptions shown in Table 26, the energy use and greenhouse gas emissions associated with the use phase of a B-pillar is tabulated in Table 27 for each material. Whether the B-pillar is deployed in an ICE vehicle or an EV, use phase emissions are directly related to the component mass.

Table 26. Assumptions for B-Pillar Use Phase Energy and Emissions Calculations

Parameter	Assumed value
Fuel Reduction Value (FRV) – ICE Vehicle	0.20 L/(100 km·100kg)
Fuel Reduction Value (FRV) – EV	0.50 kWh/(100 km·100kg)
Vehicle Lifetime (total kilometers traveled) (ORNL 2022)	244,840 km
U.S. average well-to-wheels CO_2-eq emissions for motor gasoline (Argonne 2021)	2,880 g CO_2-eq / liter
U.S. average well-to-wheels CO_2-eq emissions for grid electricity (Argonne 2021)[13]	439 g CO_2-eq / kWh

Table 27. Comparison of Use Phase Energy and Emissions (Over Vehicle Lifetime) for B-Pillars of Different Materials in Different Vehicle Scenarios: Internal Combustion Engine Vehicles and Electric Vehicles

B-Pillar Material	B-Pillar Mass (kg)	Use Phase Energy & Emissions for B-Pillar			
		ICE Vehicle (Motor Gasoline)		Electric Vehicle (U.S. Grid)	
		Energy (MJ)	Emissions (kg CO_2-eq)	Energy (MJ)	Emissions (kg CO_2-eq)
Primary Mild Steel	18.3	2,868	258	807	98
Secondary Mild Steel	18.3	2,868	258	807	98
High-Strength Steel	13.2	2,068	186	582	71
Primary Aluminum	9.5	1,489	134	419	51
Secondary Aluminum	9.5	1,489	134	419	51
CFRP	2.9	454	41	128	16

In Table 28, the use-phase energy and emissions from Table 27 are summed with the cradle-to-gate values in Table 25 to calculate total life cycle energy and emissions through the use phase for the B-pillar, assuming a 244,840 km vehicle lifetime—typical for a U.S. light-duty vehicle (ORNL 2022). Results are displayed graphically in Figure 25 for the ICE vehicle and in Figure 26 for the EV, including a comparison of mass-based and functional-unit-based emissions. In the mass-based plots, cradle-to-gate (materials and manufacturing) and use phase emissions are

[12] Conversion: 8.89 kWh per L_{eq} of motor gasoline, based on energy content of electricity (3.6 MJ/kWh) and of motor gasoline (32 MJ/liter)
[13] GREET 2021 (Argonne 2021) uses Annual Energy Outlook 2019 data (national average) for the default U.S. electric grid mix.

assessed per kilogram of B-pillar material, ignoring differences in material quantity required for the application. In contrast, the functional-unit-based plots account for such differences. Materials are ranked very differently in these two methods, since benefits of high-performance and lightweight materials are not captured in the mass-based assessment. The deviation between the mass-based and functional-unit-based plots highlight the importance of comparing materials "apples to apples" – i.e., on the basis of their performance.

Table 28. Cradle-to-Use Energy and Emissions for a B-Pillar of Different Materials

B-Pillar Material	B-Pillar Mass (kg)	Life Cycle Energy & Emissions for B-Pillar			
		ICE Vehicle (Motor Gasoline)		Electric Vehicle (U.S. Grid)	
		Energy (MJ)	Emissions (kg CO_2-eq)	Energy (MJ)	Emissions (kg CO_2-eq)
Primary Mild Steel	18.3	3,629	381	1,568	221
Secondary Mild Steel	18.3	3,012	267	951	107
High-Strength Steel	13.2	2,670	279	1,184	164
Primary Aluminum	9.5	2,786	219	1,716	136
Secondary Aluminum	9.5	1,618	143	548	60
CFRP	2.9	1,187	82	860	57

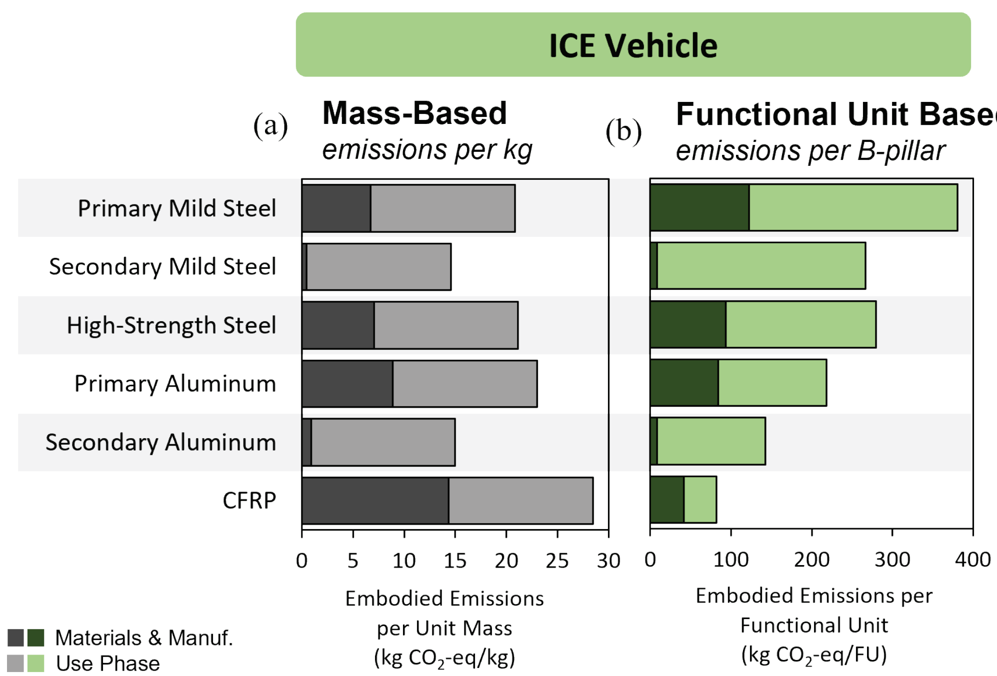


Figure 25. Comparison of life cycle energy and emissions results through the use phase for B-pillars of different materials in an internal combustion engine (motor gasoline) vehicle application, on a (a) mass basis (per kg of material); and (b) functional unit basis (per B-pillar)

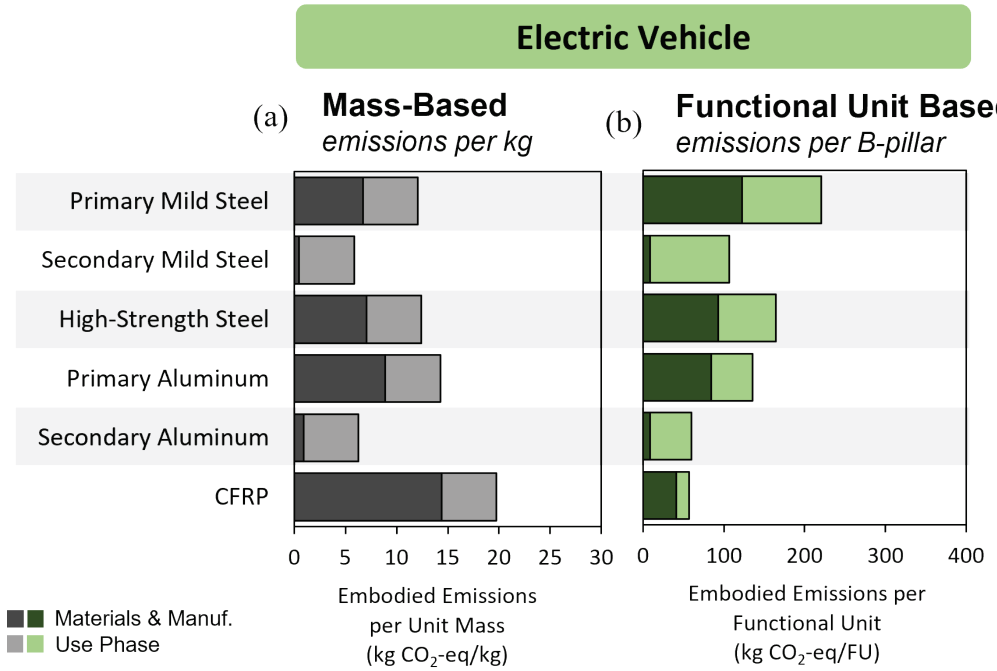


Figure 26. Comparison of life cycle energy and emissions results (through the use phase) for B-pillars of different materials in an electric vehicle application, on a (a) mass basis (per kg of material); and (b) functional unit basis (per B-pillar)

Overall, the results of this analysis suggest that secondary aluminum and CFRP B-pillar designs may minimize life cycle emissions in both ICE vehicle and EV implementations compared to baseline steel and other material options. However, there are some differences in material ranking results for the ICE and EV applications. This observation highlights the importance of good assumptions about the vehicle use case in materials comparisons. Use phase energy consumption and emissions are much higher for the ICE vehicle compared to the EV, and as a result, lightweighting has a much stronger benefit (kilogram for kilogram) in the ICE scenario in terms of life cycle energy and greenhouse gas emissions. Composites and other lightweight materials are therefore likely to offer the highest emissions benefits in scenarios with long vehicle lifetimes and high energy-related emissions in the use phase (e.g., an ICE vehicle consuming motor gasoline). Direct benefits of lightweighting may be lower in scenarios with shorter vehicle lifetimes or low energy-related use phase emissions (though there may be additional indirect benefits of component lightweighting, such as the ability to downsize the engine and/or battery). Careful accounting for such tradeoffs, including sensitivity analysis in the design phase, can help with opportunity identification to enhance environmental performance at the component level.

5.8 Results Synthesis and Next Steps

The comparisons in Figure 25 and Figure 26 provide useful information for decision-making, however, it is important to keep in mind that the analysis just presented was focused on a limited set of environmental metrics and performance criteria. The stoplight matrix of Figure 27 notes some additional considerations that may be important to a decision-maker, including repairability and recyclability at the end of the B-pillar's lifetime. The Transportation and Product Use phases have been combined in the stoplight matrix for this case study because the transportation phase (i.e., transportation of raw materials or finished component to the automotive plant) is expected to have a small impact compared to the use phase (i.e., lifetime travel by the vehicle in which the B-pillar is installed). Since energy and emissions impacts in both phases are strongly influenced by the B-pillar's mass, considerations for these phases are similar.

	Raw Materials	Manufacturing	Transportation & Product Use	End of Life
Mild Steel (Primary)	virgin raw materials	moderate manufacturing energy & emissions	heavy; easy to repair and work with	repair; recycle
Mild Steel (Secondary)	recycled scrap raw material	very low manufacturing energy & emissions	heavy; easy to repair; may be lower quality than primary	repair; recycle
Advanced High Strength Steel	virgin raw material	moderate manufacturing energy & emissions	some lightweighting; may be difficult to weld	recycle; may be more difficult to repair than mild steel
Aluminum (Primary)	virgin raw materials	moderate manufacturing energy & emissions	moderate lightweighting; non-weldable	recycle; may be more difficult to repair than mild steel
Aluminum (Secondary)	recycled scrap raw material	low manufacturing energy & emissions	moderate lightweighting; non-weldable	recycle; may be more difficult to repair than mild steel
CFRP	petroleum-based feedstock	very high manufacturing energy & emissions	greatest lightweighting; non-weldable	landfill; minimal or no repairs possible

Figure 27. A "stoplight matrix" summarizing potentially significant considerations in each phase of the product life cycle for a B-pillar of different materials.

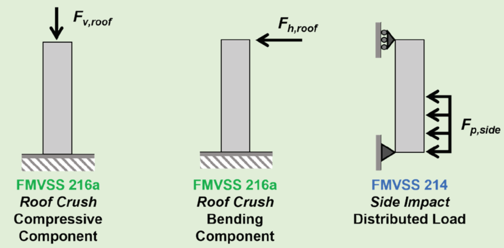
Based on the results of this case study (including the additional considerations noted in the stoplight matrix), we can identify the following next steps to expand on this analysis:

- Conduct an in-depth analysis of the end-of-life phase of the product life cycle for each B-pillar material to better understand capabilities and current practices for recycling or other end-of-life processing for B-pillars of different materials.
- Perform sensitivity analysis on key assumptions in this analysis, particularly vehicle lifetime and energy-related emissions for grid electricity.

- Perform a full LCA (on fully-designed B-pillars of different materials and of mixed-material designs) to confirm and better understand the screening results of this initial analysis and explore impacts in additional environmental categories.

A summary of the analysis for this case study is given in Table 29.

Table 29. Framework-Based Analysis Summary for the B-Pillar Case Study

Shipping Pallet Case Study: Analysis Summary		
Analysis Step		**Case Study Outcomes**
1	Define the Application and Analysis Scope	**Analysis objectives:** In this screening analysis, our goal is to compare the environmental performance of B-Pillar materials for ICE vehicle and EV applications.  **Study boundaries:** cradle-to-use **Selected environmental metrics:** embodied energy; embodied emissions
2	Define the Functional Unit	**Functional Unit:** the mass of a 1000-mm-long, 120-mm-wide structural B-pillar for a light-duty vehicle that can safely support the vehicle and provide occupant protection under rollover conditions (U.S. FMVSS 216a) and side-impact conditions (U.S. FMVSS 214).
3	Identify Candidate Materials	**Candidate materials:** primary mild steel; secondary mild steel; advanced high-strength steel; primary aluminum; secondary aluminum; CFRP composite
4	Derive Expression for Minimum Required Functional Unit Mass	**Functional unit mass:** $$m_{FU} = \rho L w t_{min}$$ where ρ = density, L = length of B-pillar, w = width of B-pillar, and t_{min} = the minimum thickness of a B-pillar meeting all constraints (i.e., the maximum value of t_{min} from equations 14, 17, and 20)
5	Gather Material & Environmental Data	*See Table 20 and Table 22*
6	Calculate Required Mass	*See Table 24*
7	Assess Environmental Performance	*See Table 25, Table 27, and Table 28*
8	Synthesize Results & Plan Next Steps	**Key findings:** The benefits of lightweight materials in the vehicle use phase may be counteracted by penalties in the materials and manufacturing phases, so a life cycle perspective is essential. This analysis shows that a CFRP composite B-pillar may minimize life cycle emissions in a conventional ICE vehicle application whereas secondary aluminum may have lower life cycle emissions for an EV. These findings are strongly influenced by vehicle assumptions such as lifetime kilometers traveled. **Next steps:** analyze the end-of-life phase to better understand end-of-life impacts; perform sensitivity analysis on key assumptions; perform a full LCA (on fully-designed B-pillars of shortlisted materials) to assess impacts more accurately and explore effects in environmental impact categories not yet considered.

6. Conclusions

Materials selection can provide a major opportunity for improving a product's environmental performance. Substitution of standard materials with "greener" options can lower a product's environmental impact while still meeting key application requirements. In environmentally motivated product design decisions, it is important to recognize that environmental impacts are strongly affected by specifics of the product and its use case. The quantity of material required to satisfy application requirements will depend not only on material properties, but also on application constraints including how long and how intensively the product will be used; and what types of thermal, mechanical, or other operational demands it will be subjected to over its lifetime. Such information is critical for an accurate determination of the overall environmental impact of a particular materials selection in a product. Correct accounting of such details, including assessment of data quality and uncertainty, is foundational to life cycle assessment and life cycle thinking.

In this report, we presented a design-integrated framework for comparing the environmental performance of different materials fairly in the context of a specific application. At the core of this methodology, simplified mechanical models empower analysts with physics-based functional units that can be expressed symbolically as a function of material properties relevant to the application (such as density, elastic modulus, thermal conductivity, and yield strength). This allows any combination of materials to be "tried out" in an application to assess its potential environmental performance—before committing to a specific product design or material concept. Three worked case studies (an insulation panel, a shipping pallet, and an automotive B-pillar component) were included as illustrative examples of the methodology:

- In the residential insulation case study, we found that paper wool (where feasible) offers significant life cycle emissions reductions compared to benchmark fiberglass batting insulation. Polymer foam insulation materials may also offer cradle-to-gate benefits, but a deeper analysis of the end-of-life phase is necessary to better understand the potential harms from landfilling of polymer foam insulation products.
- In the shipping pallet case study, we demonstrated that wood stringer pallets minimize life cycle emissions for applications that involve light-duty loads and short-haul travel. Wood block pallets minimize life cycle emissions for heavy-duty, long-haul applications. No alternative pallet materials considered here offered a life cycle environmental benefit. However, tradeoffs between materials depend strongly on the specific use case for the pallet, including lifetime, pallet management approach, and expectations for typical dynamic loads. A longer-haul and/or heavier-duty application than the ones considered in this report might result in life cycle benefits for a lightweight aluminum pallet.
- In the automotive B-pillar case study, we showed that benefits of lightweight materials in the vehicle use phase may be counteracted by penalties in the materials and

manufacturing phases. Analysis showed that a carbon-fiber composite B-pillar may minimize life cycle emissions in a conventional ICE vehicle application, whereas aluminum offers similarly low cradle-to-use emissions in an EV. Tradeoffs are strongly influenced by vehicle assumptions such as lifetime kilometers traveled and (particularly for electric vehicles) the electric grid mix.

All three case studies highlighted a common theme in life cycle assessment and environmental analysis: assumptions (particularly those related to a product's expected use case) are important. For example, a carbon fiber B-pillar may offer the best life cycle environmental performance if the B-pillar lasts the lifetime of the vehicle (over 160,000 kilometers) without repair—but a steel or aluminum B-pillar may be superior if the component is likely to require repair or replacement. Likewise, the best material for a shipping pallet designed for single use may not be the same as the best material for a shipping pallet expected to deliver hundreds of product loads over its service life. Further, it is important to recognize that data collected from different sources or using different methods (e.g., facility-specific "foreground" data vs. industry-average "background" data; process-level vs. facility-level data; or lab-scale data vs. commercial-scale data) are often not directly comparable. If using mixed data in comparisons, methodological differences and associated uncertainties must be addressed thoughtfully.

The integration of green principles into product conceptualization and engineering should ideally start at the earliest possible stage of product design to maximize environmental benefits. Early-stage LCA/LCT implementation necessitates an approach that is simple to use and amenable to a process of iteration to update and improve assumptions as the product, its intended use case, and its marketplace matures. Careful consideration of data sources and data quality is particularly important—especially when environmental impact information is being used to make comparisons across materials and products. The framework and case studies presented here may be valuable as a resource for life cycle thinking in the context of engineering decisions and product design.

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Appendix A. Selected Results from DOE Manufacturing Energy Bandwidth Studies

Table A-30. Summary of Fourteen *Manufacturing Energy Bandwidth Studies* Published Between 2015 and 2017 (industries ordered from largest to smallest 2010 energy consumption in the United States)

Bandwidth Study Industry *and Major Processes Assessed*	Citation	Industry Energy Consumption, TJ (TBtu)			
		2010[a]	SOA[b]	PM[c]	TM[d]
Chemicals *Production processes for 74 individual chemicals.*	(DOE 2015a)	3,399 (3,222)	2,591 (2,456)	1,350 (1,280)	-782 (-741)
Petroleum Refining *Alkylation; atmospheric crude distillation; catalytic hydrocracking; catalytic reforming; coking/visbreaking; fluid catalytic cracking; hydrotreating; isomerization; vacuum crude distillation*	(DOE 2015b)	3,351 (3,176)	2,908 (2,756)	2,071 (1,963)	178 (169)
Pulp and Paper *Liquor evaporation; pulping chemical preparation; wood cooking; bleaching; paper drying; paper machining (wet end)*	(DOE 2015c)	2,226 (2,110)	1,736 (1,645)	1,580 (1,498)	1,418 (1,344)
Food and Beverage *Grain and oilseed milling; sugar manufacturing; fruit and vegetable preserving; dairy product manufacturing; animal slaughtering and processing; beverage production*	(DOE 2017e)	1,303 (1,235)	948 (899)	805 (763)	-2 (-2)
Iron and Steel *Agglomeration; cokemaking; ironmaking via blast furnace (BF) and direct reduction ironmaking (DRI); steelmaking via basic oxygen furnace (BOF) and electric arc furnace (EAF); casting and rolling*	(DOE 2015d)	1,054 (999)	801 (759)	643 (609)	402 (381)
Plastics and Rubber Products *41 plastic and rubber product manufacturing (shaping) processes for 11 polymeric materials*	(DOE 2017j)	287 (272)	196 (186)	173 (164)	-1 (-1)
Cement *Crushing/grinding; clinker pyroprocessing with cooling; finish grinding; cement storage and packaging*	(DOE 2017i)	258 (245)	193 (183)	187 (177)	68 (64)
Glass *Manufacturing of flat glass, container glass, glass fiber wool, glass fiber textiles, and specialty (pressed and blown) glass*	(DOE 2017h)	209 (198)	145 (137)	128 (121)	9 (9)
Aluminum *Raw material beneficiation; reductant production; primary metal production (electrolysis, casting); secondary material production (processing, melting and casting); semi-finished shape production (hot rolling, cold rolling, extrusion)*	(DOE 2017a)	52.3 (49.6)	38.6 (36.6)	26.7 (25.3)	12.3 (11.7)
Glass Fiber Reinforced Polymer (GFRP) Composites *Glass fiber production (batching, melting, fiberization, finishing); resin production; composite product forming*	(DOE 2017f)	32.5 (30.8)	25.4 (24.1)	16.2 (15.4)	-0.1 (-0.1)

Bandwidth Study Industry ***and Major Processes Assessed***	**Citation**	**Industry Energy Consumption, TJ (TBtu)**			
		2010[a]	**SOA[b]**	**PM[c]**	**TM[d]**
Advanced High Strength Steel (AHSS) *Agglomeration; cokemaking; ironmaking (BF); steelmaking via BOF and EAF; casting and rolling*	(DOE 2017d)	23.9 (22.7)	16.0 (15.2)	12.8 (12.1)	9.0 (8.5)
Carbon Fiber Reinforced Polymer (CFRP) Composites *Carbon fiber production (polymerization, spinning, oxidation/carbonization, finishing); resin production; composite product forming*	(DOE 2017g)	5.7 (5.4)	4.4 (4.2)	0.8 (0.8)	-0.1 (-0.1)
Titanium *Primary metal production ($TiCl_4$ process, sponge production, melting); secondary ingot processing; semi-finished shape production*	(DOE 2017c)	1.9 (1.8)	0.6 (0.6)	0.6 (0.6)	0.1 (0.1)
Magnesium *Raw material preparation; primary metal production (electrolysis, ingot production); secondary metal processing/production; semi-finished shape production*	(DOE 2017b)	1.3 (1.2)	1.3 (1.2)	1.1 (1.0)	0.4 (0.4)

[a] 2010 = estimated energy consumption for this industry in the United States in 2010 (latest available data year at publication time for the studies), based on typical manufacturing practices.

[b] SOA = hypothetical "state-of-the-art" energy consumption for this industry, assuming broad industry-wide adoption of state-of-the-art commercial technologies.

[c] PM = hypothetical "practical minimum" energy consumption for this industry assuming successful demonstration, commercialization and industry-wide adoption of promising (but pre-commercial) R&D technologies.

[d] TM = Theoretical thermodynamic minimum energy consumption for this industry, calculated using a Gibbs free energy approach based on required material transformations. (The thermodynamic minimum represents a lower bound on energy demand, and would typically not be achievable in commercial operations.)

Appendix B. Selected Results from DOE Manufacturing Energy Bandwidth Studies: Manufacturing Energy Intensities for Seven Structural Materials

Table A-31. Manufacturing Energy Intensities (Gate-to-Gate) for Seven Structural MaterialsBased on Data Reported in DOE's *Manufacturing Energy Bandwidth Studies*

Structural Material	Estimated Annual U.S. Production, kg/year (million lb/year)	Product Detail for Energy Intensity	Manufacturing Energy Intensity, MJ/kg (Btu/lb)			
			CT[a]	SOA[b]	PM[c]	TM[d]
Conventional Steel (DOE 2015d)	76,920 (169,570)	*Weighted Average of BF/BOF and EAF Steel; Hot Rolled*	10.6 (4,560)	8.4 (3,610)	6.8 (2,910)	4.9 (2,100)
Advanced High Strength Steel (AHSS) (DOE 2017d)	1,150 (2,530)	*BF/BOF Steel; Cold Rolled*	23.3 (10,020)	17.0 (7,310)	13.4 (5,760)	10.1 (4,330)
Aluminum (DOE 2017a)	8,410 (18,550)	*Weighted Average of Primary and Secondary Aluminum, Hot Rolled*	40.8 (17,540)	29.8 (12,800)	19.7 (8,480)	11.0 (4,590)
Magnesium (Das et al. 2017b)	54 (118)	*Weighted Average of Primary and Secondary Magnesium, Cast*	30.6 (13,140)	29.8 (12,800)	25.2 (10,810)	9.0 (3,870)
Titanium (Das et al. 2017c)	36 (80)	*Weighted Average of Primary and Secondary Titanium, Forged*	165 (70,840)	165 (70,840)	57.7 (24,820)	8.1 (3,490)
Carbon Fiber Reinforced Polymer (CFRP) Composites (DOE 2017g)	37 (82)	*50wt% Carbon Fiber / 50wt% Epoxy CFRP Composite, Resin Transfer Molded*	309 (132,620)	240 (103,070)	44.9 (19,320)	-2.9 (-1,240)
Glass Fiber Reinforced Polymer (GFRP) Composites (DOE 2017f)	1,420 (3,140)	*50wt% Glass Fiber / 50wt% Epoxy GFRP Composite, Resin Transfer Molded*	48.5 (20,870)	38.1 (16,370)	24.4 (10,480)	-0.1 (-60)

[a] CT = estimated energy intensity for this material in the United States at publication time for the studies, based on typical manufacturing practices.

[b] SOA = hypothetical "state-of-the-art" energy intensity for this material, assuming broad industry-wide adoption of state-of-the-art commercial technologies.

[c] PM = hypothetical "practical minimum" energy intensity for this material assuming successful demonstration, commercialization and industry-wide adoption of promising (but pre-commercial) R&D technologies.

[d] TM = Theoretical thermodynamic minimum intensity for this material, calculated using a Gibbs free energy approach based on required material transformations. (The thermodynamic minimum represents a lower bound on energy demand, and would typically not be achievable in commercial operations.)

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