Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

Direct Thermal Energy Conversion Materials, Devices, and Systems

Materials for Harsh Service Conditions

Process Heating

Process Intensification

Roll-to-Roll Processing

Sustainable Manufacturing - Flow of Materials through Industry

Waste Heat Recovery Systems

Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF ENERGY

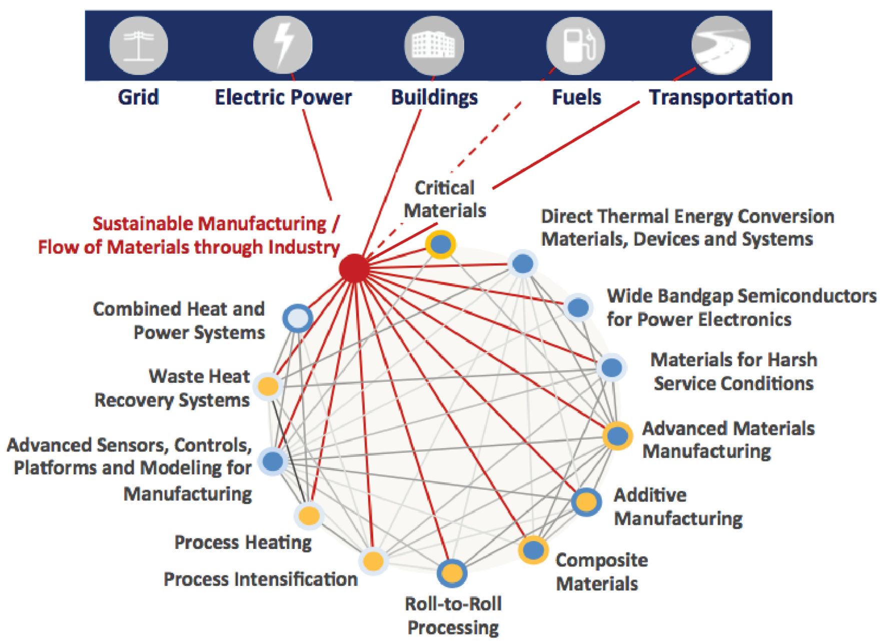
Quadrennial Technology Review 2015

Sustainable Manufacturing-Flow of Materials through Industry

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Sustainable Manufacturing-Flow of Materials through Industry is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections

- **Critical Materials:** materials substitution
- **Process Heating:** shared ownership of equipment to maximize production intensity
- **Materials for Harsh Service Conditions / Advanced Materials Manufacturing:** materials to increase durability or facilitate re-use
- **Combined Heat and Power / Process Intensification:** modular equipment design for easier reconfiguration, upgrade and repair
- **Additive Manufacturing:** distributed manufacturing; raw material minimization
- **Composite Materials:** lightweight materials manufacturing for life-cycle energy savings
- **Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing:** smart technologies to enable track and trace of materials through the life cycle
- **Waste Heat Recovery:** optimization of heat flows to maximize production intensity and minimize waste heat losses

Representative Extra-Chapter Connections

- **Electric Power:** management of water and energy resources
- **Buildings:** recycling and materials substitution/ minimization
- **Fuels**: biofuels and renewable feedstocks
- **Transportation**: Lightweight materials, batteries, recycling of materials

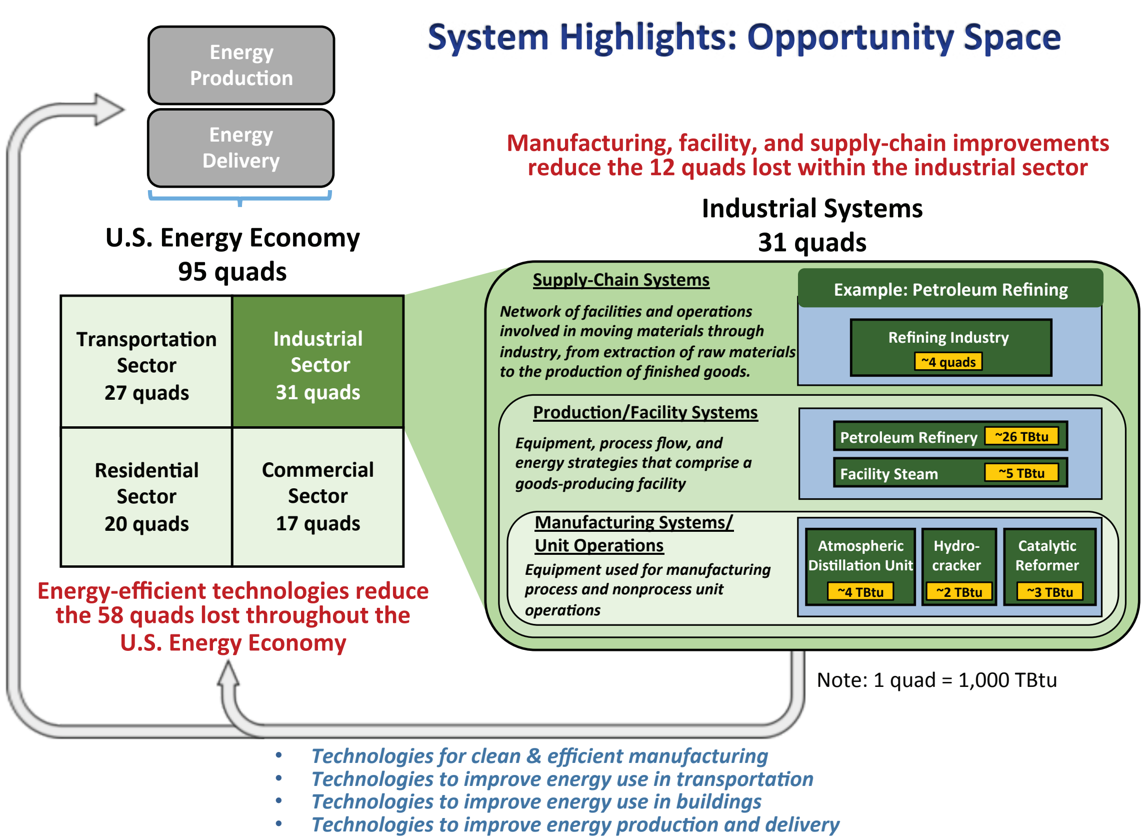
Introduction to the Technology/System

The industrial sector produces goods and services for consumers by using energy to transform materials into intermediate and finished products. Manufacturing systems have traditionally been designed based on a linear model starting with raw materials extracted from nature and ending at disposal in a landfill at the end of the product's useful life. A circular economy redirects this approach by providing opportunities to re-manufacture and reuse end-of-life consumer products, leading to more efficient use of materials.[1,2] By analyzing the pathways and transformations that occur as materials cycle from nature through manufacturing systems, consumer use and reuse phases, and back to nature through de-construction, de-manufacture and/or disposal, we can begin to better understand the material requirements, opportunities for reuse, and the associated use of energy and production of byproducts, waste products, and emissions to air, water, and soil.

Supply Chain and Material Flow Analysis

Energy savings opportunities exist within the industrial sector itself, but this sector also enables energy savings opportunities for the greater U.S. economy. Energy waste within the industrial sector totals roughly 12 quadrillion Btu (quads)[3] and originates at scales ranging from individual manufacturing processes (the smallest scale), through the entire supply chain system (the largest scale) (Figure 6.L.1). At the smallest scale, energy savings opportunities can be found by examining specific manufacturing systems or processes. These processes have their own energy and material efficiencies, often independent of any other surrounding or connected system (e.g., energy efficiency improvements can be achieved through use of improved motors or an enhanced coating to improve flow).

Figure 6.L.1 Opportunity space in evaluating the industrial sector.[4]



At the intermediate scale, opportunities can be found by examining production or facility systems, where different equipment and processes work together in a single facility, or closely aligned groups of facilities, to produce a product. These different processes can be optimized to maximize the energy and material efficiency of the facility(ies). This kind of optimization is being fostered through the U.S. Department of Energy (DOE) Better Plants Program[5] for state-of-the-art technologies. These small and medium scale opportunities generally encompass what can be called 'sustainable manufacturing'. The U.S. Environmental Protection Agency (EPA) defines sustainable manufacturing as the "creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources."[6] This technology assessment describes opportunities to support more sustainable manufacturing.

At the largest scale, supply chains are a system of organizations, people, activities, and information that transform natural resources, raw materials, and components into finished products for consumers.[7] The entire supply chain system must be examined to uncover energy (and other resource) savings opportunities. Knowing which part of the supply chain has the largest energy demand helps identify where to seek solutions to reduce the overall energy demand of the system. Some products have more extensive and complicated supply chains than others. This is typical of high technology products that include a large number of materials and associated processes to achieve specific performance requirements. The industrial sector, as the portion of the economy responsible for producing goods, is heavily impacted by supply chains. In many cases, an efficient supply chain can enhance the competitiveness of the industrial sector while also minimizing negative environmental impacts.

Supply chains are often global. Imports and exports of commodities and finished products are subject to ever-changing market conditions that react to new market competition, geopolitical issues, increases in costs, and other factors. Breaks in supply chain linkages can disrupt production on a global scale. Where supply chains are limited to a regional scale, there are often improved opportunities for the supplier and the customer to communicate directly about needs, specifications, and capabilities, and to collaborate on opportunities across parties. Further, advanced manufacturing technologies may provide advantages for different supply chain paradigms—for example, additive manufacturing may encourage more decentralized/distributed manufacturing.

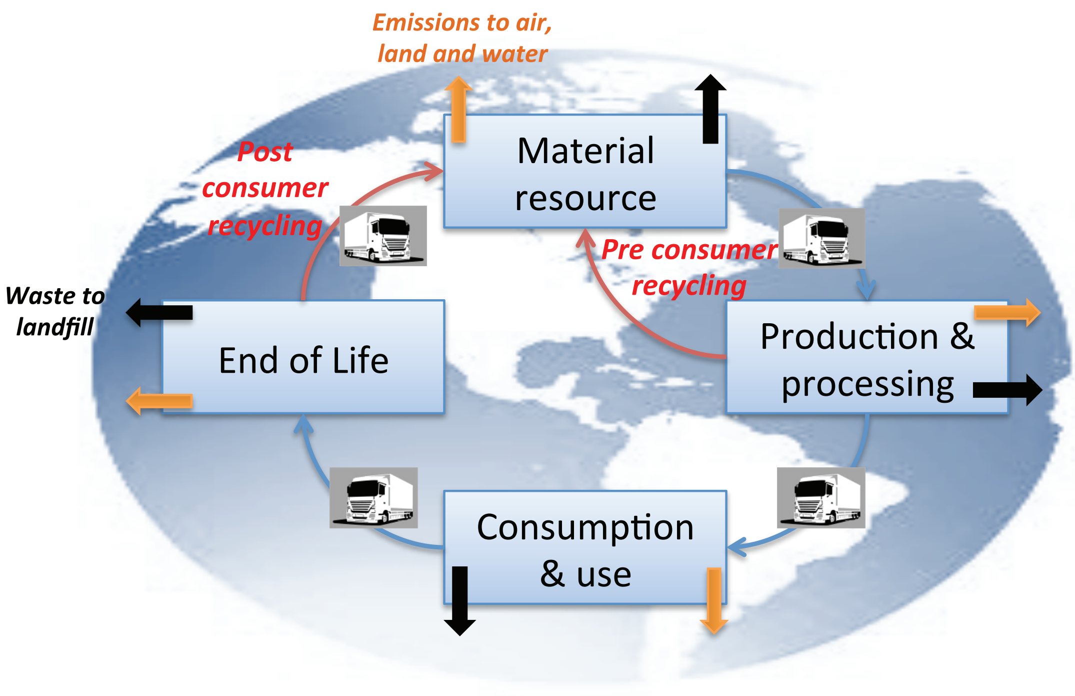
Figure 6.L.1 illustrates how the industrial sector links with the rest of the economy; consideration of this entire system from production through end-use then offers significant opportunities for reducing overall energy consumption. Analyzing these opportunities begins with understanding how technologies in the overall manufacturing supply chain produce products and services for the transportation, buildings, and industrial sectors. This analysis continues with evaluating how material flows and life cycle impacts span the economy and trying to understand the level and significance of the impacts occurring within the full system (depending on how the full system boundaries are defined, such as extraction through production, extraction through use, extraction through end of life, etc.). As an example, in the buildings sector there has been an emphasis on reducing operational energy, but energy efficiency alone provides an incomplete picture of the energy footprint attributable to buildings. As energy efficiency of new buildings continues to improve, the embodied energy of building components (the supply chain component) in a full building analysis becomes an increasingly important factor in the total life cycle impact of the building sector.

The transportation sector also provides some interesting and unique scenarios to better understand the importance of life cycle energy impacts. Most of the impacts in the transportation sector are related to operational energy demands (use phase). However, use of lightweight materials for the vehicle structure to reduce weight and associated operational energy demand is currently of interest and starting to show up in the marketplace (e.g., aluminum and carbon fiber in automobile panels and other components). Lightweight materials are generally more energy intensive (higher embodied energy) and more expensive to produce than conventional materials, so this trend has not moved rapidly and research to minimize the energy intensity and cost of lightweight materials is ongoing.[8] Looking at where the impacts occur in the supply chain will help to identify opportunity areas for energy reduction and cost for transportation products.

The study of material and energy flows is foundational to the field of industrial ecology and to the field's major analytical approaches—material flow analysis (MFA) and life cycle assessment (LCA). MFA tracks material usage on a large scale and is defined as a systematic assessment of the flows and stocks of materials within a system defined in space and time.[9] Flows include extraction, recycling, utilizing stocks, waste, and consumer products. The World Resources Institute (WRI) has done a series of MFA studies that cover global flows, industrial economy flows, and flows in the U.S.[10,11,12] The intent of the studies was to help shape policies to create a more efficient economy.

LCA is an accounting of the inputs (resources and materials) and outputs (products, emissions, and waste) (Figure 6.L.2), and the resulting impacts to human and environmental health (i.e. acidification, toxicity, resource depletion) for a specified system (see also Chapter 10 and the Supplemental Information for Chapter 10). LCA typically defines the scope of the system as cradle-to-gate (raw material extraction to just before leaving the facility gate), cradle-to-grave (raw material extraction to disposal), gate-to-gate (coming into a facility and leaving the facility), or cradle-to-cradle (from raw material extraction through product use and then recycling into the materials for a new product, reflective of a circular economy). An inventory is conducted of the inputs (including all energy, materials, water, and other resources) and outputs (including all gaseous, liquid, and solid wastes, as well as the products) within the system boundary. This inventory is translated into impacts on ecological and human health using established impact assessment methodologies. To date, DOE has largely focused on life cycle energy impacts when evaluating emerging advanced manufacturing technologies and products, but a comprehensive evaluation requires life cycle evaluation of all the inputs and outputs and the associated environmental impacts. There are a variety of different impact assessment methodologies that have been developed and are being utilized by researchers across the globe. For example, TRACI (Tool for the Reduction and Assessment of Chemicals and other environmental Impacts),[13] developed by the EPA, is a methodology considered relevant to the U.S. context. TRACI evaluates a range of impacts from those with ecological importance (e.g., eutrophication, eco-toxicity, and global warming), to those with human health implications (e.g., cancer and other diseases), to those associated with resource depletion (e.g., fossil fuel use).

Figure 6.L.2 High-level schematic representing the accounting for an LCA. The thin interior arrows (red and blue) represent movement of materials within the life cycle system. The thick orange arrows represent emissions to air, soil, and water, and thick black arrows represent waste products sent for disposal. The orange and black arrows, which are associated with opportunities to reduce energy and environmental impacts, represent the inputs and outputs for the system evaluated in an LCA approach.



Although one of the original LCAs was conducted in the 1960s by the Coca Cola Company to evaluate their packaging,[14] the use of LCA is still not widespread today. Greater use of LCA is primarily limited by the difficulty and expense of collecting and managing the data required to conduct the analysis. The data that are freely available are typically industry averages and may have limited value for an individual organization seeking to use LCA to improve their operations. Despite these difficulties, researchers have been successful in using LCA to improve products and processes in important areas. Additionally, the International Panel on Climate Change (IPCC) 5th Annual Report (AR5) for Working Group III (WGIII) utilized LCA much more extensively than in the past, to quantify positive and negative impacts of mitigation technologies and measures for greenhouse gas (GHG) emissions as well as evaluating use of water, land, and metal resources.[15]

Technology Assessment and Potential

Between 1975 and 2000, U.S. per capita materials consumption is estimated to have grown 23% and total material consumption is estimated to have grown 57% to 6.5 billion metric tonnes (gigatonnes, GT) in 2000.[16] In 2005, the United States used nearly 20% of the global primary energy supply and 15% of globally extracted materials. This 15% of the globally extracted materials equates to 8.1 GT of U.S. domestic material consumption (which is defined as domestic extraction plus imports minus exports). At roughly 27 metric tonnes (MT) per person per year, U.S. per capita material use is higher than most high-income countries and is approximately double that of Japan and the U.K.[17] The United States and other developed economies, as well as developing economies, currently have a linear economic structure in which materials used to make products are mostly disposed of at their end-of-life without being recycled or otherwise reused. As material demands continue to increase due to population growth and increasing wealth, there has been some transition toward a circular material economy, where products are being reused and recycled at end-of-life (see Figure 6.L.2).[18] This thinking is closely tied to the concept of material efficiency. Material consumption reflects the input side of the problem. On the output side, the United States generated close to 2.7 GT of waste in 2000.[18] This waste generation has increased 26% since 1975, with a 24% increase in the harmful waste products (radioactive compounds, heavy metals, and persistent organic chemicals). The 3.8 GT of remaining materials (6.5 GT consumption minus 2.7 GT of waste) can be attributed to material stocks in the form of buildings and other infrastructure.

The Greenhouse Gas (GHG) Protocol, developed by World Resources Institute (WRI) and World Business Council on Sustainable Development (WBCSD), sets the global standard for how to measure, manage, and report GHG emissions. The GHG protocol evaluates carbon emissions under 3 categories or scopes.[19] Scopes 1 and 2 reflect emissions from direct (fuel) and indirect (electricity) energy usage; scope 3 covers other indirect emissions, such as the extraction and production of purchased materials (Figure 6.L.3). The IPCC AR5 report (Figure 6.L.4)[20] indicates that scope 1 (direct) and scope 2 (indirect) emissions in the baseline scenarios will continue to rise in projections to 2100. However, the IPCC AR5 does not cover the associated scope 3 emissions. Huang et al.[21] found that 75% of carbon emissions are from scope 3 sources, indicating that the supply chain is an opportunity space to reduce emissions. This was confirmed by a recent pilot study conducted by Quantis and the WRI on their new GHG protocol accounting tool[22] that accounts for emissions from all three scope sources. Dahmus[23] also looked at opportunities in the supply chain and found that the next step to improving energy efficiency is to examine resource consumption in the supply chain. The cases evaluated by Dahmus suggest that the market would respond to appropriate incentives and move toward reducing resource consumption and the associated environmental impacts.

Figure 6.L.3 Overview of the GHG protocol scopes and emissions across the value chain (GHG protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard).[24]

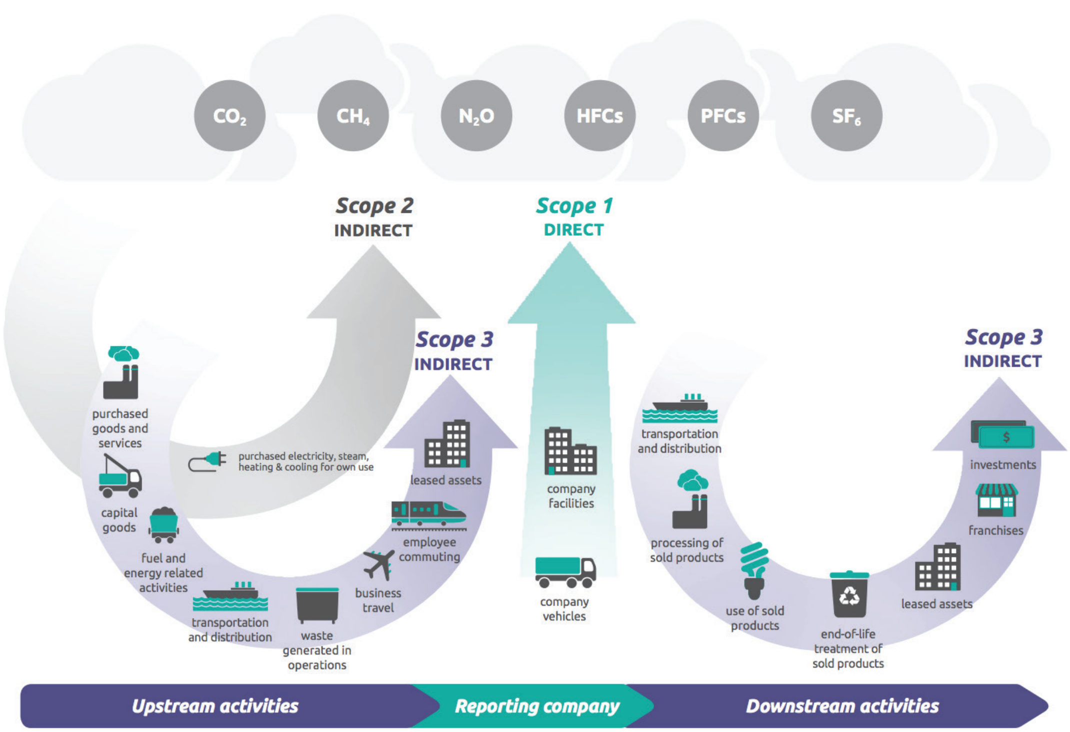
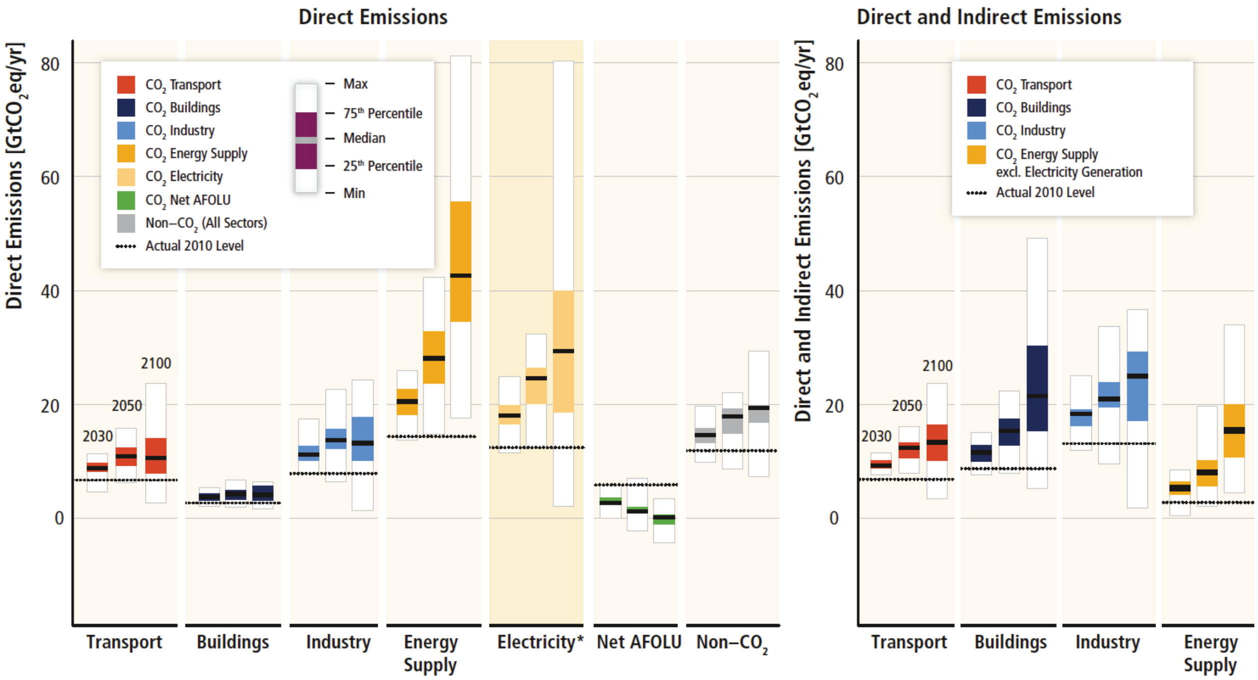


Figure 6.L.4 Baseline scenarios from WGIII IPCC AR5 suggest rising GHG emissions in all sectors, except the land use sector.[25] AFOLU represents emissions from agriculture, forestry and other land use.

Credit: IPCC 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom and New York, NY: Cambridge University Press, p. 65. Accessed April 2016, http://ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_technical-summary.pdf.



The exchange of materials and energy frequently crosses international borders. As a result, the analysis of material use in an economy should be placed in an international context. This is relevant considering the growth of materials production and use by emerging and developing economies. Gutowski et al.[26] projected that meeting IPCC goals to reduce global energy use by half from 2000 to 2050, while at the same time enabling developing countries to achieve a standard of living equivalent to the current developed world, would require a 75% reduction in the average energy intensity of material production. Other models predict a doubling of global resource use by 2050.[27]

In addition to the growth in material consumption, global demand for engineering materials has increased by a factor of four over the last half century and is projected to continue to increase with the growing global population (Figure 6.L.5a and b). Table 6.L.1 provides U.S. plant level estimates of the increased energy demand between 2010 and 2050 for these key engineering materials assuming the application of state-of-the-art technologies, which amounts to over 2.8 billion GJ (3.2 quads) of energy demand. With implementation of cutting edge technologies and additional research breakthroughs, these efficiencies can still be improved but face hard limits based on theoretical (and practical) minima. As a result, reductions in GHG emissions from these industries will largely need to come through use of other strategies.

Figure 6.L.5 a) Normalized demand for five key engineering materials from 1960 – 2005.[28] b) IEA forecasted range of increase in future demand for aluminum, paper, steel, plastic and cement compared to 2005.[29]

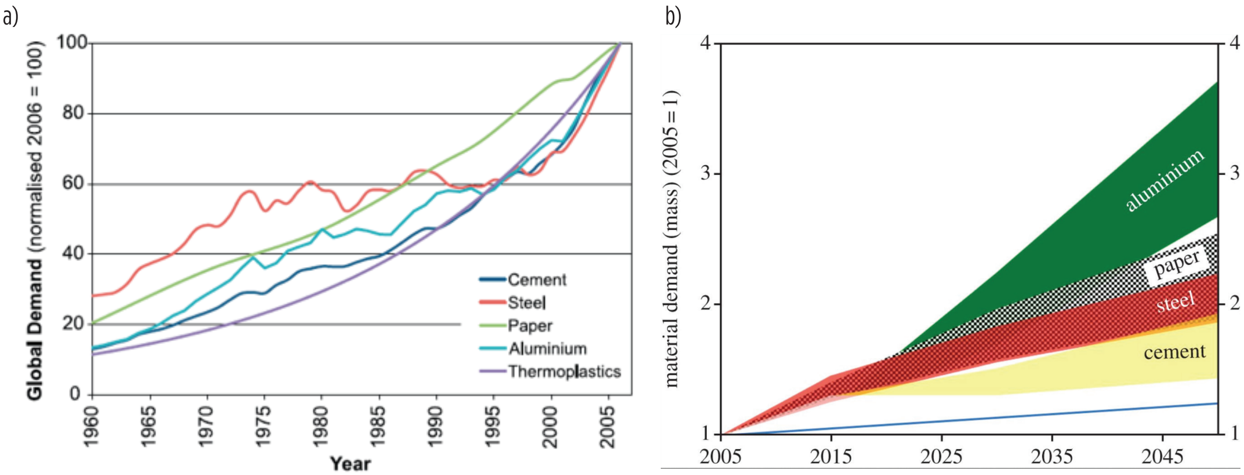
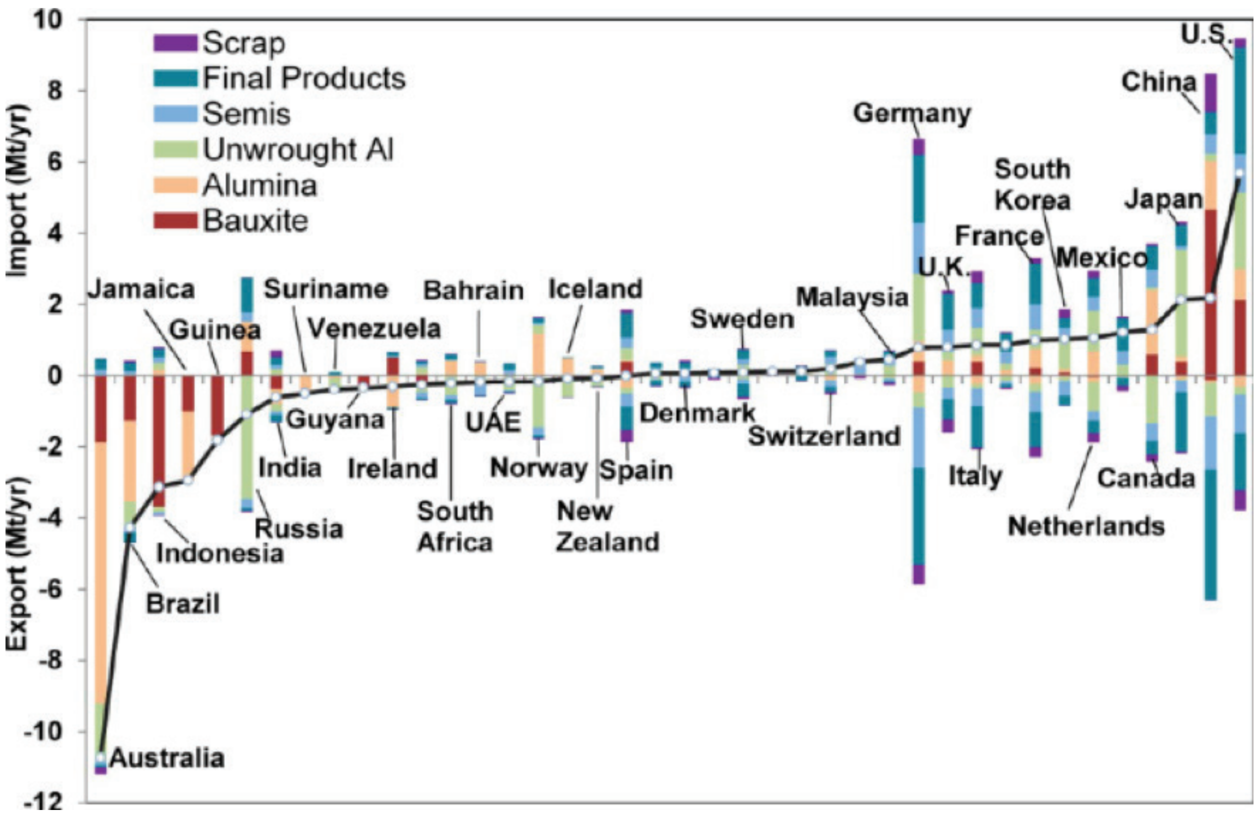


Table 6.L.1 Estimated increase in U.S. facility level energy demand from 2010 – 2050 associated with the approximate minimum projected increase in global material demand estimated by Gutowski et al[30] (from Figure 6.L.5b) applied to the U.S. market and applying state-of-the-art technologies (as evaluated by the DOE Industrial Bandwidth Reports). These estimates assume static recycling rates and that the global increase in demand would proportionally increase demand in the U.S. market.

	Approximate range of material demand increase from 2010 to 2050[a]	Process	State of the art energy intensity (2010)[b]	2010 Production[c]	Projected 2050 facility energy demand (low estimate)
			GJ/MT	million MT	million GJ
Aluminum ingot	225 – 325%	Primary	19.4	1.7	75.5
		Secondary	2.0	1.3	5.5
Steel	150 – 200%	Basic Oxygen Furnace	18.0	38.7	1,045
		Electric Arc Furnace	1.9	61.3	172.9
Paper and paperboard	200 – 215%		7.7 – 18.0	75.3	1,535.7
TOTAL ENERGY DEMAND					**2,834**

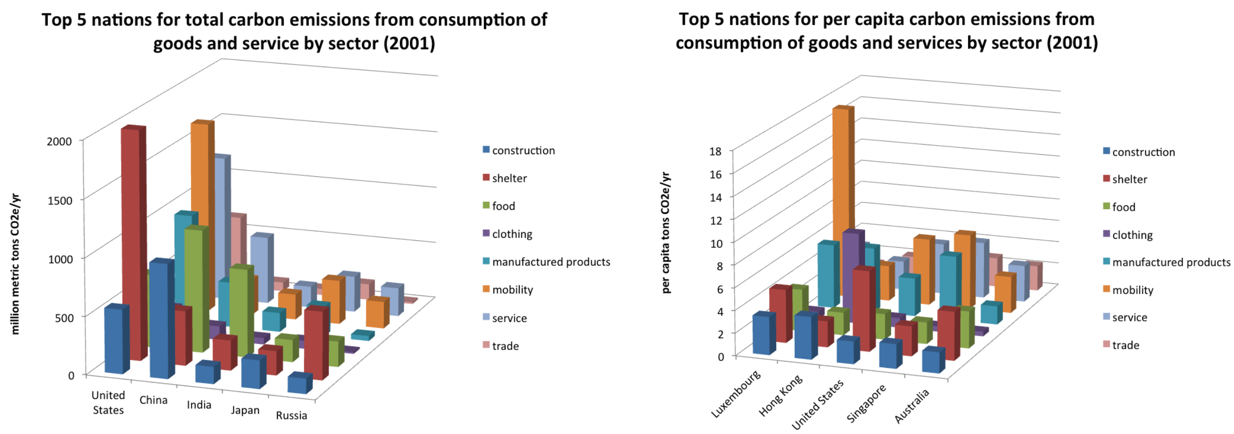
[a] Material demand increase are approximations from the Gutowski et al. analysis (Figure 6.L.5.b)
[b] State of the art energy intensities are from the DOE industry bandwidth report analyses[31,32,33]
[c] Production values are based on values pulled from multiple sources[34,35,36]

Figure 6.L.6 International trade of aluminum in bauxite, alumina, unwrought aluminum, semi-manufactured products, final products, and scrap in 2008. The countries are sorted by total net imports from left to right (the dark curve represents total net trade). All values are aluminum metallic equivalent in Mt/yr.[37] Semi-manufactured products are products that have not been completely assembled and are shipped to have final assembly in the country where it will be sold.



A global economy moves many materials and products across international borders. For example, production of a laptop might require materials extracted from sites all over the world, transported to Asia for assembly in several facilities, and finally transported to the United States for distribution and sales to the end consumer. Liu and Muller[38] provide an analysis of anthropogenic aluminum flows and found that Germany, China, and the United States are the largest importers (Figure 6.L.6). Chen and Chen[39] evaluated global energy consumption through an analysis of embodied energy. The U.S., as the world's largest materials consumer, is also the largest embodied energy importer. China is projected to overtake the U.S. in 2027 as the largest total embodied energy consumer, but will still remain behind the United States on a per capita basis.[40] In terms of carbon emissions, Hertwich and Peters' global multi-regional input-output analysis (based on 2001 global trade data)[41] found that the United States is the largest emitter of CO_2e (equivalent emissions) from the consumption of goods and services and the third largest on a per capita basis (Figures 6.L.7), with mobility and shelter being the largest consumption categories (derived from the Global Trade, Assistance, and Production industry sectors). The CO_2e emissions represented by the "mobility" category are primarily attributable to fuel consumption for vehicles, but also includes emissions from production of vehicles and air and land transport services. The shelter category covers the operation and maintenance of residences. Note that the Hertwich and Peters study is based on 2001 data and the ranking of nations has since likely shifted (especially with regards to China); however, as of this writing no comparable analysis has updated these data.

Figure 6.L.7 Top five nations for total (left) and per capita (right) annual carbon emissions by sector for the production and consumption of good and services (scope 3 emissions) based on a global multi-regional input-output model for the year 2001 in terms of million metric tons CO_2e.[42]



Some accounting for social impacts in international supply chains has begun, but there is currently no consideration of GHG emissions embodied in traded goods or services. Peters et al.[43] evaluated the trend in supply chain carbon emissions associated with traded products and services between different regions. Peters et al. found that carbon impacts from imports had increased almost three-fold between 1990 and 2008 and that the production of the goods and services are primarily occurring in non-Annex B nations (i.e., developing nations as defined by the Kyoto Protocol) and they are being primarily shipped to Annex B nations (i.e., developed nations). China, Brazil, and India dominate production for non-Annex B nations (Figure 6.L.8). The imports to Annex B nations have been primarily in the non-energy intensive manufacturing sector which the analysis classified as covering production of products like textiles, electronics, furniture, and cars (Figure 6.L.9). The analysis considered energy intensive industries to produce materials such as cement, steel, and pulp and paper. In 2012, Japan completed a governmental pilot project for carbon footprinting of products and transitioned to a long term program to identify carbon hotspots and provide information to companies and consumers.[44] Since 2008, Grenelle Environment in France has worked to develop a system to help manufacturers evaluate ecological, economic, energy, and social changes, including energy consumption and carbon footprints. These are continuing to evolve.[45]

Figure 6.L.8 The balance of emissions embodied in trade (BEET, in terms of MT CO_2) for six aggregated regions from 1990 – 2008. The BEET for the U.S. is primarily in imports from China and the Rest of non-Annex B nations, with a fraction of exports to Europe.[46] The dotted line represents net emissions transfers for the Annex B with non-Annex B nations and the solid black line represents the transfer with the rest of the world.

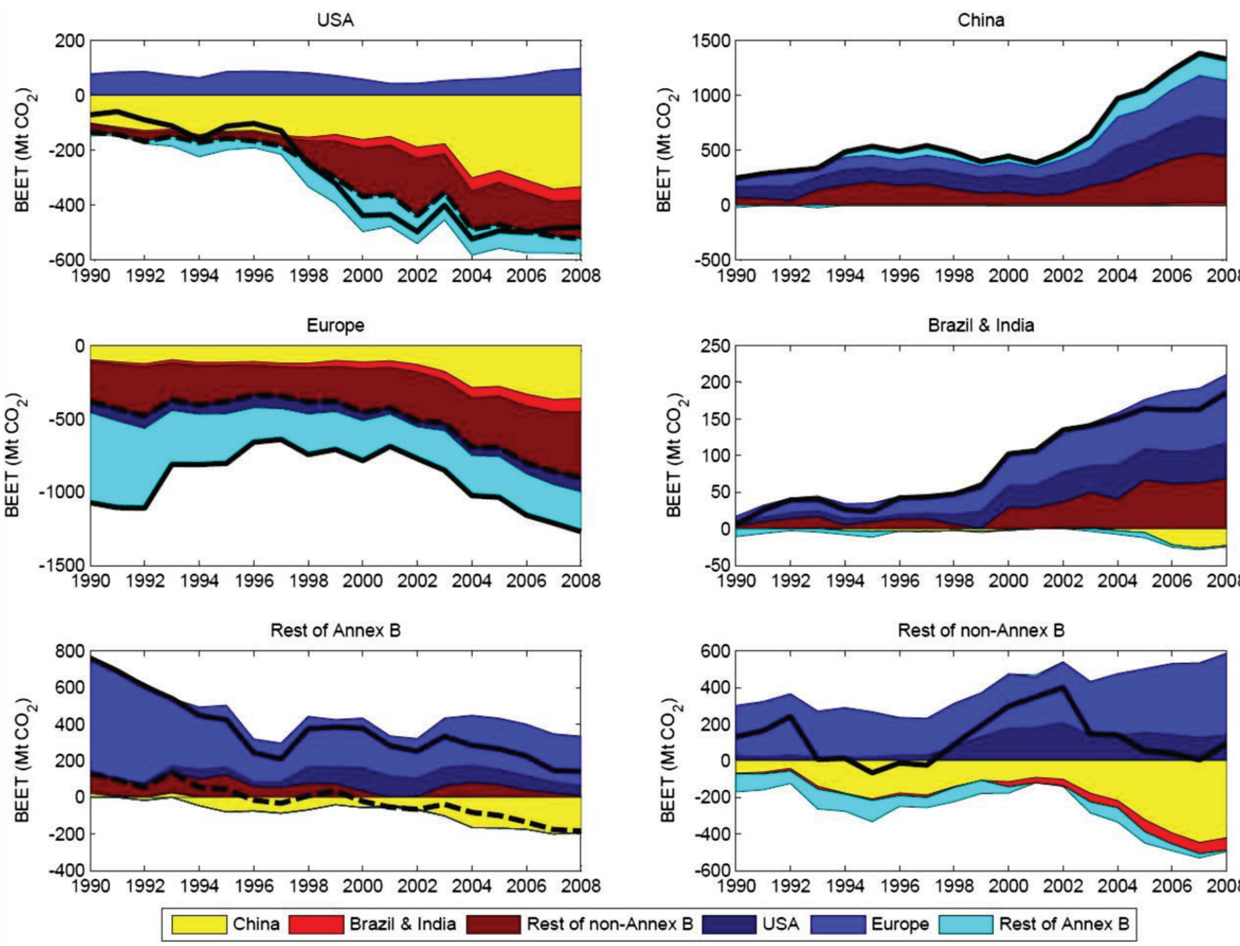
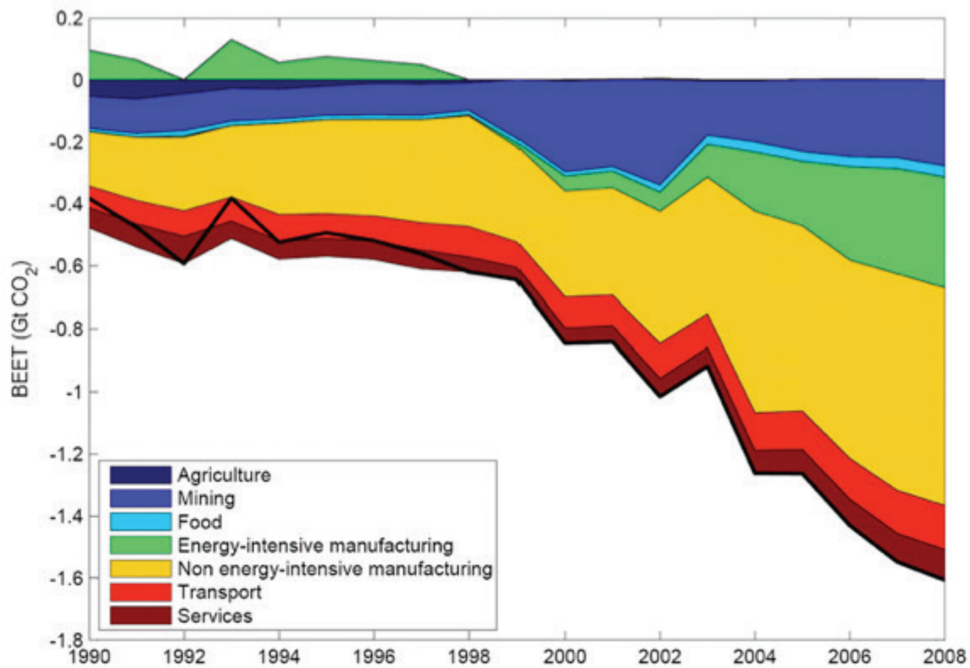


Figure 6.L.9 The balance of net emission transfer via international trade between Annex B and non-Annex B nations (developed and developing nations, respectively as defined by the Kyoto protocol) by sector. BEET (GT CO_2) represents the emissions from the production of exports minus the emissions in other countries from the production of their imports. Annex B nations on a net basis have been primarily importing products from non-Annex B nations and this has been predominately from non-energy-intensive manufacturing.[47]



Methods to Reduce Impacts: Energy and Material Efficiency

Varying concepts to address the broader scale impacts of the industrial sector have been developed over the last few decades. Energy efficiency has been a major focus of analysis and efforts, resulting in steady improvements in the ability to produce more with less energy. Many of these efforts have targeted specific industries, facilities, and processes, and were focused on areas that had potentially large impacts due to high energy intensity or high demand. Including a focus on the supply chain can support the evaluation of specific technologies, and can also identify areas of interest that may not be considered high energy intensity or high demand for individual processes, but that are pervasive and therefore have the potential for significant energy efficiency improvements.

The idea of material efficiency[49] takes this a step further and recognizes that energy is required to produce commodity products; therefore, reducing the amount of material required for manufacturing and processing can result in net energy savings—whether direct (realized at the manufacturing facility), indirect (realized elsewhere in the supply chain), or both. This concept is demonstrated by additive manufacturing (AM). While the manufacturing energy intensity of AM is currently very high compared to conventional manufacturing techniques, reduced material demand (lower "buy-to-fly" ratio) and lower product weight can provide energy savings during material production and product use (see the Technology Assessment 6.A *Additive Manufacturing* for case studies). Material efficiency can also help ease the demand for critical materials and minimize the use of imported materials (e.g., lithium) and energy intensive materials, as discussed in the Technology Assessment 6.F *Critical Materials*. Allwood et al.[50] examine further opportunities and actors for material efficiency, many of which are outlined in Table 6.L.2. Due diligence would need to be done on any material efficiency strategy to assess other impacts (as listed later in Table 6.L.3).

Table 6.L.2 Strategies for Material Efficiency with Different Pathways, Actors, and Examples of Enabling Technologies.

Strategy	Pathways	Description	Examples and Enabling Technologies	2015 QTR Chapter and Technology Assessment (TA) Representative Connections	Actors
Alternative material approaches[D] *(Identify potential material substitutes for different applications)*	Critical material substitution	Non-critical material in place of critical materials	Ferrite magnets in place of rare earth element based permanent magnets; system-level substitutions such as induction motors that do not require permanent magnets at all	6.F Critical Materials	Designers
	Biomass substitution	Biobased materials in place of nonrenewable resources	Biofuel substitution for petroleum based fuels and chemicals; use of bioproducts	6.F Critical Materials	Designers
	Energy intensive material substitution	Lower-embodied-energy materials in place of high-embodied-energy materials	Super-vacuum die casting process using a new magnesium alloy;[A] Materials Genome Initiative to develop new materials;[G] blended cement geo-polymers[F]	6.B Advanced Materials Manufacturing	Designers
Use products for longer[D] (*Use products for full lifetime; extend lifetime of products)*	Property improvement for increased productivity or longer life[D]	Improving the properties of materials and products to facilitate use for longer lifetimes	Improving heat transfer to increase WHR efficiency*; improving properties to make some materials suitable for AM*; boosted capacitors;[B] Lithium sulfur batteries;[B] real-time corrosion sensing; self-healing materials; protective coatings; increase life of WHR equipment	6.H Materials for Harsh Service Conditions 6.M Waste Heat Recovery	Designers; Producers
	Re-sale[D]	Re-sale of used goods that have not yet reached the end of their useful life	Consignment stores and secondhand merchants; sale of used cars; re-sale of used equipment and electronics	N/A	
	Design for longer life[D]	Designing more robust products that last longer	Longer-lasting lighting;[H] batteries with long cycle life; cyber-physical systems that can be upgraded to delay obsolescence	3.A Cyber and Physical Security 3.C Electric Energy Storage 6.H Materials for Harsh Service Conditions	Users
	Design for repair or re-manufacture[D]	Designs that allow products to be repaired, rebuilt as original, re-made, upgraded or retrofitted	Remanufacturing of automotive components; joining technologies for materials that are not easily welded; refurbishment of equipment and electronics; retreading tires; building renovations	8.D Lightweight Automotive Materials	Designers; Producers; Users

Table 6.L.2 Strategies for Material Efficiency with Different Pathways, Actors, and Examples of Enabling Technologies, continued.

Strategy	Pathways	Description	Examples and Enabling Technologies	2015 QTR Chapter and Technology Assessment (TA) Representative Connections	Actors
Use products for longer[D] (*Use products for full lifetime; extend lifetime of products*)	Modularity[D]	Designs that are modular and allow for easier upgrades, reconfiguration, and repairs	Modular fuel cells; micro-turbine units; battery packs (BMW I3); smaller processing equipment; modular consumer electronics[C]	6.D Combined Heat and Power Systems 6.J Process Intensification	Designers; Users
	Re-use[E]	Products that can be re-used repeatedly	Re-usable shipping containers; building scaffolding and construction equipment; re-usable glass containers[F]	N/A	Designers; Users
	Lightweighting[D]	Designs utilizing lighter weight materials and overall products	Additive manufacturing; lower cost lightweight metals production; lower cost and lower energy carbon fiber production process[A]	6.A Additive Manufacturing 8.D Lightweight Automotive Materials	Designers; Producers
Do without or with less products or resources[D] (*Reduce or eliminate overall material demand*)	Dematerialization[D]	Designs allowing for disassembly; tessellation; digital replacing physical services; design to optimize material usage and ease of manufacturing[E]	Consolidation of multiple sub-parts into a single component; less feedstock demand via more precise chemistry; thinner films and coatings;[F] smart manufacturing technologies to enable track & trace of materials (through the full life cycle of product), and associated data management and data analytics to utilize the data	6.A Additive Manufacturing 6.C Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing 6.J Process Intensification 6.K Roll-to-Roll Processing	Designers
	Yield improvement[D]	Reducing material loss during processing	Membrane coating for the black liquor-to-fuel concentration process;[A] coating material to reduce surface deposits in ethylene production;[A] hybrid system for industrial wastewater treatment and reuse ;[A] combined microbial reverse electrodialysis technology with waste heat recovery to convert effluents into electricity and products;[A] additive manufacturing; near net-shape processing	6.A Additive Manufacturing 6.B Advanced Materials Manufacturing 6.J Process Intensification 6.K Roll-to-Roll Processing	Designers; Producers

Table 6.L.2 Strategies for Material Efficiency with Different Pathways, Actors, and Examples of Enabling Technologies, continued.

Strategy	Pathways	Description	Examples and Enabling Technologies	2015 QTR Chapter and Technology Assessment (TA) Representative Connections	Actors
Do without or with less products or resources[D] (*Reduce or eliminate overall material demand)*	Distributed manufacturing	Paradigm shift for how materials and supply chains work	Additive manufacturing to enable on-demand manufacture of parts closer to point of need; "Maker-Shops "; distributed (forecourt) production of hydrogen at the fueling station; co-located operations throughout the supply chain;	6.A Additive Manufacturing 6.C Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing 7.D Hydrogen Production and Delivery	Producers
	Recycling / recovery	Reduce the need for virgin material by increasing the rate of recycling, recovery, and reuse	Lightweight metals recycling;[B] critical materials recovery from consumer electronics (Critical Materials Institute); alloy management	6.F Critical Materials Ch. 5 (Section 5.6.4 – Embodied Energy) Ch. 10 (Section 10.2.3 Analysis Tools and Metrics)	Designers; Producers; Users
	Operation at or near capacity	Sharing ownership and/or use of manufacturing equipment and facilities; manufacturing to maximize capacity utilization and minimize energy intensity	Siting near materials/energy resources (e.g. near water sources to reduce energy in pumping and water losses); utilizing furnaces more intensively to reduce overall energy intensity; adjustable-speed drives to reduce energy consumption to match load during non-peak operation	6.I Process Heating 6.N Wide Bandgap Semiconductors for Power Electronics	Users
Use products more intensively[D] (*Maximize utilization of products)*	Shared use	Shared ownership and use of products; rent as needed	Car shares (e.g., Zipcar®); public libraries; scientific user facilities	6.J Process Intensification	Producers
	Products as service	Customer pays for service while manufacturers or third parties retain ownership	Automobile leasing; equipment rental with integrated service plans (e.g., office copiers; internet routers; portable event stages)	N/A	Producers; Users

A[51] B[52] C[53] D[54] E[55] F[56] G[57] H[58]

Accounting for resource or material use is an important way to evaluate the efficiency of technologies and manufacturing processes. The concept of "reduce, reuse, and recycle" has been part of the popular lexicon for many years, with recycling at the forefront of efforts. Reducing material use, however, has a large untapped potential to reduce energy consumption early in the supply chain and in product manufacturing. Inefficient material production and manufacturing processes result in excess in-plant scrap and represent opportunities to improve material use intensity. Some industries have taken significant steps to reduce manufacturing scrap. For example, the garment industry uses computer programs to determine how to best cut the fabric to minimize scrap; this programming optimizes the material in the bolt to cut small items (belts, pockets, etc.). For the aluminum and steel industries, in-plant scrap is reusable and often contains fewer contaminants than post-consumer scrap. However, in-plant scrap requires processing before it can be reused, and there is a cost and energy associated with this additional processing—although still less than the requirements to produce virgin material.

The complexity of some products provides challenges for recycling of minor metals. These challenges are multi-faceted: the minor metals may occur in low concentration in the product; the presence of a valuable material may be required to make the overall recovery economically viable; and the product design may or may not make the minor metal components accessible to facilitate recovery. Considerations regarding recycling need to be incorporated into product design to facilitate recovery. For example, vehicle electronics are typically not recycled since they are dispersed throughout the vehicle and not easily reclaimed prior to the vehicle being shredded for recycling. On the consumer end, while recycling has become commonplace for some products, (i.e. cell phones, batteries) mechanisms may be required to help bring other products back into the recycling stream rather than being discarded.[59] More intensive use and longer life of products can be affected by designers and users. Users are driven by a number of factors in their decisions to replace products. These factors, as defined by Allwood and Cullen,[60] are degradation, inferior, unsuitable, and unwanted, and relate to the product's performance and value. Based on these factors, users may replace a product before its end-of-life if it is no longer useful for their circumstance (sports car replaced with a minivan), or if it is not current (upgrading to the newest computer or cell phone). These are social choices and understanding the drivers around social behavior can inform decision makers trying to improve society's material efficiency.

The European Union (EU) has acknowledged that materials are a finite resource and that existing trends in material efficiency will not be adequate to reduce the overall material intensity of the EU economy, as the rate of resource efficiency improvements has been outpaced by the rate of economic growth. In a 2011 roadmap, the EU investigated the benefits, risks, challenges, and costs of implementing material efficiency measures.[61] Risks associated with resource scarcity included reduced competitiveness and supply security issues; these risks can be mitigated by increased material efficiency. Benefits of strong resource efficiency include improved productivity, growth and job creation, environmental health and resilience benefits, and macroeconomic stability. The report indicated that adaptation to resource megatrends over time will require structural economic change, and will involve updating technologies, innovation, and skills—all of which have associated transitional costs. These costs will depend on how well change is predicted and managed, the pace of change, and the flexibility of the economy to be able to adapt, to include technological innovations. The importance of sustainable production has also been identified in UNEP's global sustainability goals.[62]

Life Cycle Assessment

Energy and material intensities are good metrics to work with while evaluating next generation technologies. However, there is always a risk of burden shifting when substituting one technology for another. Burden shifting occurs when the reduction of impacts in one stage of the life cycle, geographic location, or impact category result in increased impacts elsewhere. One example of this trade-off occurs when a reduction in energy demand to produce a product also causes an increase in the product's use phase energy demand (e.g., a smaller heat exchanger on an air conditioner reduces material use and manufacturing energy demand, but results in lower efficiency and higher energy demand in operation). Another example of burden shifting might be when a reduction in fossil fuel demand during the use phase is associated with an increase in eco-toxicity impacts during the manufacturing phase (e.g., manufacture of advanced batteries for electric vehicles can result in toxic waste but reduces fossil fuel demand in the use phase of the vehicles).

LCA enables the researcher/analyst to understand the entire system associated with a product or process, from extraction to end of life (disposal/reuse/remanufacture/recycle) and to look for solutions that minimize all negative impacts across all life cycle stages. LCA evaluates all of the resource, chemical and product inputs and outputs associated with a clearly defined system (see Figure 6.L.2). Those inputs and outputs are characterized and connected with certain types of midpoint impacts (problem oriented) and associated endpoint impacts (damage oriented) (Table 6.L.3 column 1 and column 5). Some LCA's will provide results only to the inventory stage (e.g., GHG emissions); more sophisticated LCAs will provide results evaluated through the midpoint and others will provide results at the endpoint stage that are aggregated to ecosystems (impacts to species lifetime), human health (daily adjusted life year [DALY]) and resources (in terms of $). Assessments looking at the endpoint can have increased subjectivity and uncertainty and conclusions can vary significantly based on the perspective of the analyst and the goal of the study. The EPA TRACI impact methodology provides guidance only through the midpoint, where the foundation is scientifically objective.

LCA is already used by industry to perform process improvements to reduce waste, increase efficiency, reduce toxics, and save costs across their products' life cycles. Results of LCAs do not necessarily provide definitive solutions to these problems, but the results can support better-informed decisions by helping to identify where trade-offs, such as burden shifting, occur. Some of the typical impacts and contributing factors examined with LCAs are listed in Table 6.L.3. The different metrics are utilized either individually or in combination depending on the goal of the analysis. The multi-criteria analysis provides perspective of the pros and cons of different scenarios across the multiple metrics evaluated. The case study below on Industrial Environmental Accounting describes examples of this type of LCA analysis being applied in industry to better quantify the sustainability of its products.

Table 6.L.3 Typical Impacts that can be Evaluated by and Associated Damages that can be Informed by LCAs.[63,64]

Problem Impact Category (Midpoint)	Scale	Representative chemical and physical inventory contributors (Inventory)	Common characterization	Description of possible damages / (Endpoints)
Acidification	Regional; Local	Sulfur Oxides (SO_x) Nitrogen Oxides (NO_x) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_3) Hydrogen Sulfide (H_2S)	Acidification potential	Building corrosion; water body acidification; vegetation effects; soil effects; plant, animal, and ecosystem effects
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates (NO_3) Ammonia (NH_3)	Eutrophication potential	Algal blooms; hypoxia; the depletion of oxygen in the water, which may cause death to aquatic animals; plant, animal and ecosystem effects; odors and recreational effects; human health impacts
Photochemical smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical oxidant creation potential	Smog; decreased visibility; eye irritation; respiratory tract and lung irritation; vegetation damage; human mortality
Terrestrial toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents; radioactive elements	LC50*; marine sediment eco toxicity; ionizing radiation	Decreased production and biodiversity and decreased wildlife for hunting or viewing
Aquatic toxicity	Local	Toxic chemicals with a reported lethal concentration to fish; radioactive elements	LC50*; freshwater aquatic toxicity; marine aquatic toxicity; ionizing radiation	Decreased aquatic plant and insect production and biodiversity; decreased commercial or recreational fishing
Global warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global warming potential; climate change	Polar melt; soil moisture loss; forest loss/change; change in wind and ocean patterns; coastal area damage; agricultural effects; plant and animal effects
Stratospheric ozone depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone depletion potential	Increased ultraviolet radiation; skin cancer; cataracts; material damage; immune system suppression; crop damage; other plant and animal effects
Human health	Global; Regional; Local	Toxic releases to air, water, and soil; radioactive elements	LC50*; ionizing radiation; respiratory effects	Increased morbidity and mortality
Non-renewable Resource depletion	Global; Regional; Local	Quantity of minerals used; Quantity of fossil fuels used	Resource depletion	Decreased resources for future generations

*LC50 – lethal concentrations that will kill 50% of populations in a single exposure.

Table 6.L.3 Typical Impacts that can be Evaluated by and Associated Damages that can be Informed by LCAs,[63,64] continued.

Problem Impact Category (Midpoint)	Scale	Representative chemical and physical inventory contributors (Inventory)	Common characterization	Description of possible damages / (Endpoints)
Land use	Global; Regional; Local	Land modifications	potential; abiotic depletion	Loss of terrestrial habitat for wildlife and decreased landfill space; effects on threatened and endangered species (as defined by proxy indicator)
Water use	Regional; Local	Freshwater used or consumed	Land availability; agricultural land occupation; urban land occupation; natural land transformation; land use change	Loss of available freshwater from groundwater and surface water sources; water scarcity or stress on watershed/region; loss of drinking water for communities and businesses
Ecosystem quality	Local	Eco toxicity; acidification; eutrophication; land use	Freshwater shortage	Effects on species diversity, especially for vascular plants and lower organisms
Fossil fuel depletion	Global; Regional; Local	Quantity of fossil energy resource utilized	potential; water footprint	Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects
Cumulative energy demand	Global	Quantity of renewable and non-renewable energy used	Energy footprint	Accounting of total energy demand across life cycle

*LC50 – lethal concentrations that will kill 50% of populations in a single exposure.

Several federal agencies and offices are also utilizing multiple LCA metrics to evaluate environmental impacts. For example, the DOE Bioenergy Technology Office (BETO) is evaluating life cycle GHG emissions, water use, energy use, land use, and air quality impacts[65] for the biofuels program. The DOE Office of Fossil Fuels develops LCAs on fossil and alternative fuel technologies and provides publicly-available life cycle inventory (LCI) data.[66]

The EPA National Risk Management Laboratory (NRML) is using LCA to evaluate environmental impacts in different issue areas (e.g. nanotechnology, sustainable materials management, Li-ion batteries, and biofuels). As described earlier, EPA maintains an impact assessment methodology (TRACI).[67] The USDA is also using LCA to evaluate the impacts of biofuels and has developed an agriculture LCI database based on data in the National Agriculture Library (NAL).[68]

The National Institute of Standards and Technology (NIST) provides two LCA software tools for the buildings industry: Building for Environmental and Economic Sustainability (BEES) and Building Industry Reporting and Design for Sustainability (BIRDS). BEES allows designers, builders, and product manufacturers to compare life cycle impacts of 230 building products.[69] BIRDS relies on a hybrid LCA approach to allow users to compare the construction, operation, and decommissioning impacts of eleven different building types.[70]

The Department of Defense (DoD) has started to look at multiple types of impacts in their sustainability analysis for their updated acquisition program.[71] Multi-criteria analysis is utilized to select the best scenario or option based on the full range of criteria being evaluated. The sustainability analysis includes both LCA and life cycle cost analysis (LCCA) and covers impacts to the mission, human health and the environment. The DoD program methodology evaluates four resource categories (– energy, chemicals and materials, water, and land), which are in turn connected to 23 impact categories related to resource availability, human health impacts, ecological health impacts, water use efficiency, land degradation, and global environmental health. The DoD goal is to analyze alternatives for meeting mission requirements to support informed decisions making for sustainable systems and lower total ownership costs (defined as a sum of internal costs (to DoD), external costs (to society and the environment), and contingent costs [risks]). As an example, one DoD study compares the total cost of using a chromated coating system for equipment compared to a non-chromated coating system. A chromated coating system is much more effective in protecting equipment but is highly toxic to humans and the environment, and therefore its use requires extensive (and costly) protective measures and additional hazardous waste management. A non-chromated coating system requires more frequent applications, but without the extensive protective measures.

Technologies are frequently selected for an application without full consideration of positive and negative impacts.[72] Some examples of negative externalities include: air pollution from burning fossil fuels that causes damages to crops, buildings, and public health;[73,74] water pollution from industrial effluent; and costs of managing the long term risks of disposal of chemicals, which may remain permanently hazardous. Examples of positive externalities include reductions in GHG emissions from driving an electric vehicle and may improve local air quality, leading in turn to better public health. These impacts are not commonly internalized into prices.

Although historical practice has tended towards the adoption of new technologies without fully understanding their potential negative impacts, a growing number of studies have evaluated multiple impacts associated with emerging technologies. Jungbluth et al.[75] performed an LCA of photovoltaic (PV) power plants based on twelve different grid connected PV systems in Switzerland for the year 2000. The study provided insight as to the different types of potential environmental impacts as well as the associated life cycle stages. The analysis results provide insights about what kinds of impacts are occurring in which stage of the life cycle. For example, for the system that Jungbluth et al. evaluated, climate change impacts are primarily from the silicon purification process but significant contributions also come from wafer sawing, panel production, and plant installation. Contributions to eco-toxicity are primarily from the plant installation, but there are also significant contributions from panel production and wafer sawing.

A life cycle inventory study of PV systems by Fthenakis et al.[76] evaluated energy payback times (EPBT), life cycle GHG emissions, criteria air pollutant emissions, and heavy metal emissions for mono- and multi-crystalline silicon (Si), cadmium telluride (CdTe), and high concentration PV (HCPV) using III-V multijunction cells. A comparison of life cycle cadmium (Cd) emissions against other electricity and fuel consumption sources was also done for the PV technologies, natural gas, nuclear, and hydropower; results showed that all of these supplies emitted less than 1 g Cd/GWh. However, hard coal, lignite, and oil had cadmium life cycle emissions of 3.1, 6.2, and 43 g Cd/GWh respectively. The analysis looked primarily at the differences between PV technologies which are important to help provide insight about which PV technology may have the lowest overall impact. However, a broader comparison of PV technologies against all electricity production technologies is also important to understand the implications of broadly implementing PV technology for electricity generation. Additionally, it is helpful to apply impact assessments to the life cycle inventories to provide context for what kinds of impacts the life cycle emissions have (see Table 6.L.3).

In 2014, Bergesen et al.[77] conducted a study on cadmium indium gallium selenide (CIGS) and CdTe thin film PV power generation, evaluating a range of impacts compared to the 2010 average U.S. electric grid. The goal of the study was to identify potential benefits and trade-offs from using U.S.-manufactured and -deployed thin-film PVs to mitigate GHG emissions in the long term. In addition, the study evaluated the impact of potential improvements in technology efficiency, module material efficiency, and recycling. Additionally, the study looked at the impact of a broader change in the background economy based on an IEA Blue map scenario where global energy-related GHG emissions are cut in half by 2050 presuming heavy deployment of carbon capture and storage (CCS). The results for both PV technologies indicated potential reduced impacts in all assessed categories except metal depletion and land occupation (equal impact) (Figure 6.L.10). Implementation of the potential improvements indicated there could be reduction in global warming, metals depletion, and carcinogen impacts as well (Figure 6.L.11).

Figure 6.L.10 Environmental and resource impacts of ground-mounted CIGS (left graphic) and CdTE (right graphic) thin-film PVs from 2010 and 2030 normalized to those of the 2010 U.S. electricity grid mix in scenarios evaluated by Bergesen et al.[78] No end-of-life recycling is included in the 2010 scenario, but the 2030 scenario includes recycling of aluminum, copper and steel. The logarithmic scale is necessary to display large variations in impacts relative to the U.S. grid. The 2030 scenario is based on an International Energy Agency (IEA) scenario ("BLUE Map")[79] with increased renewable electricity generation; in this scenario, it is assumed that global energy-related GHG emissions are cut in half by 2050, and that carbon capture and storage (CCS) systems are used in fossil facilities. The environmental impacts of the two different PV technologies are not significantly different in the context evaluated in this study.

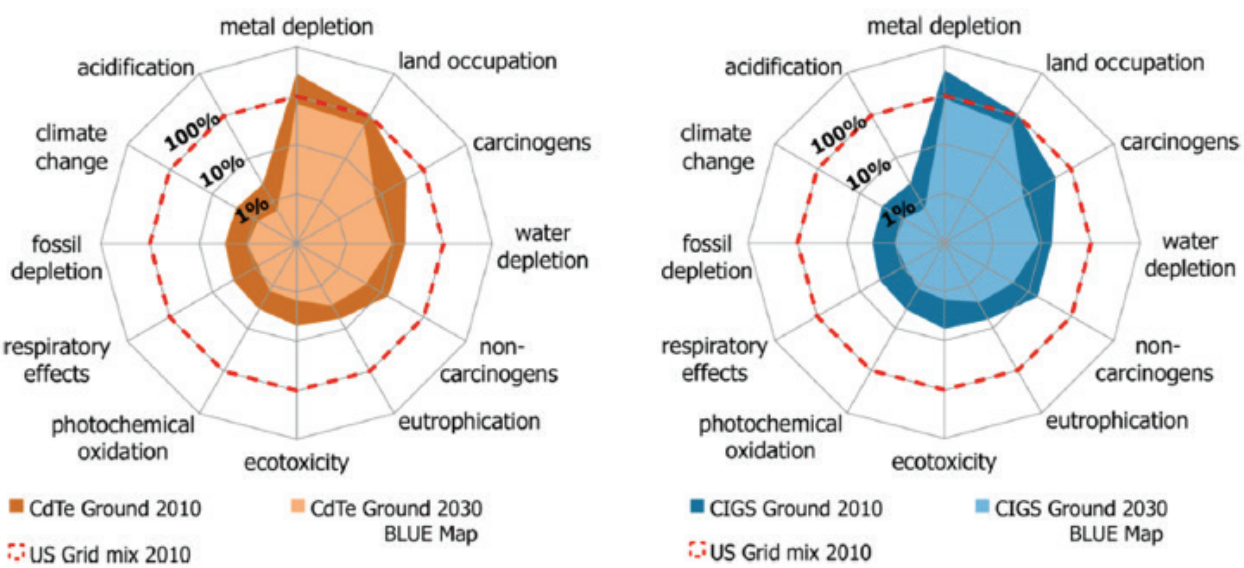
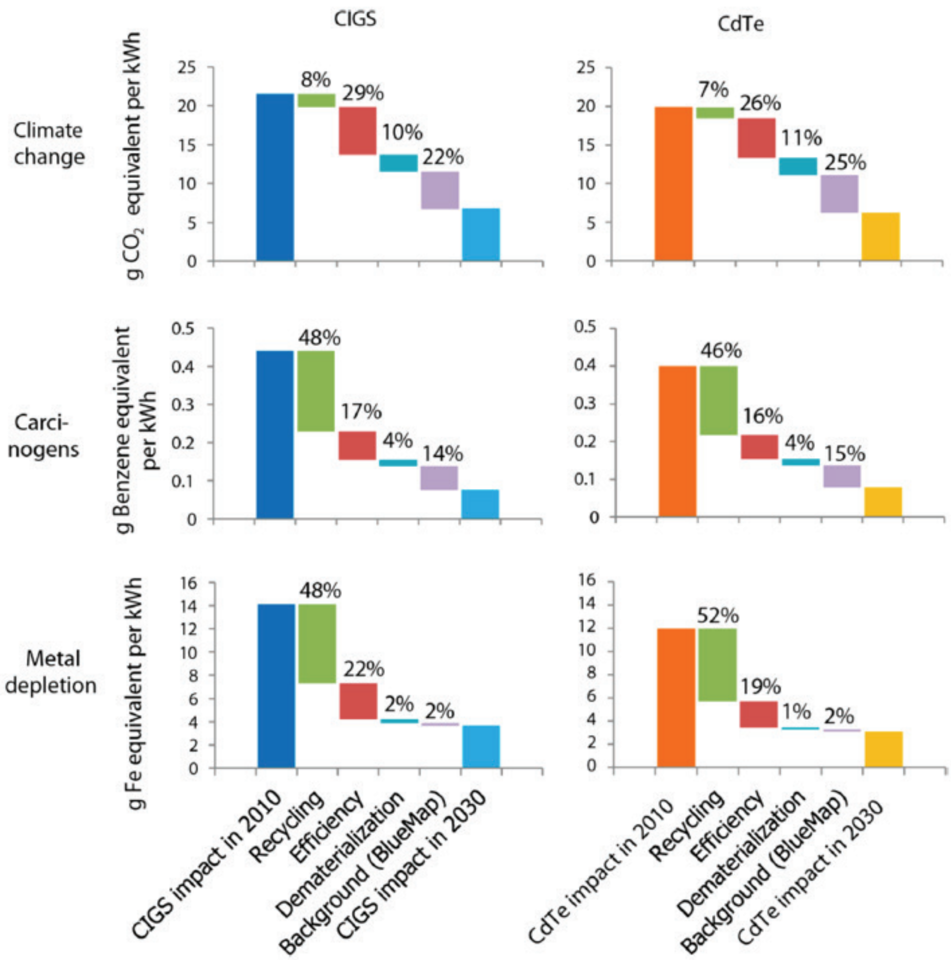


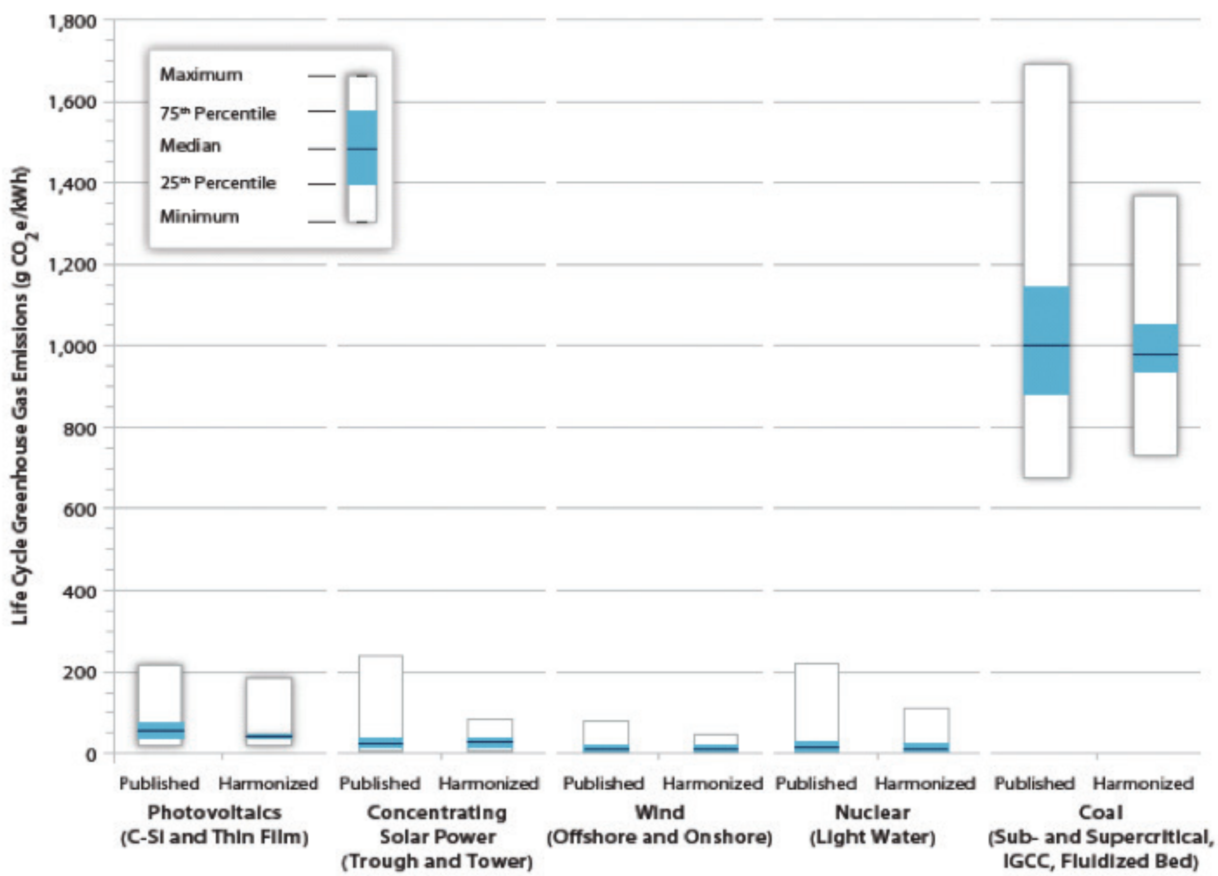
Figure 6.L.11 Impact reductions by technological improvement categories from 2010 to 2030 for climate change, carcinogens, and metal depletion for CIGS and CdTe ground-mounted systems. The two charts show how technology improvements can reduce the associated life cycle impacts of PVs as a result of each category of technological improvement: balance of system (BOS) recycling, efficiency, dematerialization, and background changes. The dark blue bar (for the CIGS system) and the orange bar (for the CdTe system) represent the quantified climate change, carcinogen and metal depletion impacts for each technology in 2010. The green, red, turquoise and purple bars represent the reductions in impacts associated with those specific technology improvements (listed on the horizontal axis). The light blue bar (for the CIGS system) and the yellow bar (for the CdTe system) represent the quantified impact on the resulting systems in 2030 after adoption of the evaluated technology improvements and the adjusted background economy. These background impacts are based on an IEA scenario ("BLUE Map") where global energy-related GHG emissions are cut in half by 2050.[80]



Results reported in the literature evaluating different types of renewable technologies have varied significantly. NREL has conducted harmonization studies of power generation technologies to bring some of the GHG results reported in the literature into some alignment.[81] These harmonizations adjust the results from the different references to a common set of boundary conditions (to include all life cycle stages: materials, transportation, construction, operations, and end of life) and operating parameters. (e.g., capacity factors, solar irradiation, operating lifetimes). As an example, the harmonization study for PV evaluated C-Si and thin film systems using 17 different references with 46 different estimates. These harmonized estimates determined that life cycle GHG emissions from these PV systems can range from 900 – 2143 g CO_2e/kWh with a median value of 1700 g CO_2eq/kWh which have a reduced variation as compared to the unharmonized as-published data (see Figure 6.L.12).

The harmonized results present carbon emissions on a kWh basis and include all the life cycle stages. The results are for existing technologies and do not reflect adoption of next generation technologies that are not present in the current market. The harmonized data has been used in evaluating GHG impacts for the range of the DOE EERE power vision studies (e.g., Wind Vision,[82] SunShot Vision,[83] Renewable Portfolio Standard (RPS) benefits analysis[84]), to understand the GHG emissions implications of increased deployment of renewable technologies.

Figure 6.L.12 Harmonized Life Cycle GHG Emissions for PV, CSP, Wind, Nuclear and Coal Power Generation Technologies.[85]



	Photovoltaics	Concentrating Solar Power	Wind	Nuclear	Coal
Estimates	46	36	126	99	164
References	17	10	49	27	53

Vehicle technologies are rapidly evolving and understanding the impacts of the next generation vehicles requires evaluation of many factors that contribute to the life cycle impacts. The vehicle itself is a complex system to evaluate and the vehicles exist and are operated in a complex ecosystem. The DOE report, *Using Natural Gas for Vehicles*,[86] exemplified this complexity. The report evaluated the energy and associated GHG emissions impacts in scenarios utilizing natural gas (NG) to fuel vehicles. The analysis evaluated vehicle fuel life cycle efficiency, at what stages in the fuel life cycle energy is lost, as well as where in the fuel life cycle the related GHGs are being emitted (Figure 6.L.13). The analysis compared three different vehicle technologies powered by NG. The compressed natural gas vehicle (CNGV) is an ICE vehicle running on CNG. The fuel cell electric vehicle (FCEV) is powered by a hydrogen fuel cell, with the hydrogen being generated from NG. The plug-in vehicle (PEV) is powered by electricity generated from a NG power plant.

This analysis showed that while the CNG supply chain (well to pump) has relatively low energy losses, the operation of the CNVG vehicle has significant loss resulting in it being overall the least efficient of the vehicle types evaluated. The FCEV vehicle and supply chain are overall more efficient than the CNGV, but the losses in the FCEV supply chain are greater than for the CNVG primarily due to energy losses at the steam methane reforming (SMR) plant. The PEV vehicle and supply chain were the most efficient of the three technologies due to the efficient vehicle operations. However, the losses in the PEV supply chain were greater than the other two vehicle supply chains due to energy loss at the NG power plants. The carbon emissions for each scenario parallel the energy efficiencies, with the highest carbon emissions occurring in the CNGV scenario followed by the FCEV and the PEV having the lowest carbon emissions. With the bulk of the carbon emissions for the FCEV and PEV scenarios occurring in the supply chain there is greater opportunity to reduce carbon emissions through application of CCS technologies. This is not possible in the CNVG scenario since the bulk of the emissions occur during vehicle operation for which there are no foreseeable on-board CCS technologies and there would be a significant weight penalty for the on-board storage of CO_2 and associated CCS equipment.

Figure 6.L.13 Fuel Life Cycle Efficiency (a) and Fuel Life Cycle GHG Emission (b) for Natural Gas Power Vehicles.[87]

a)

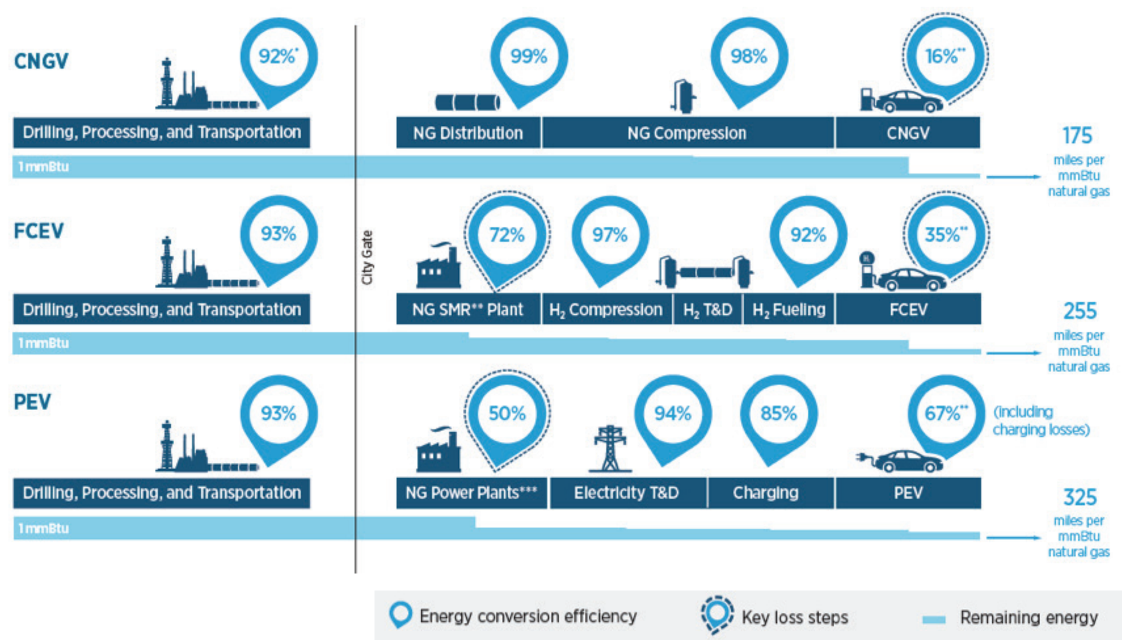
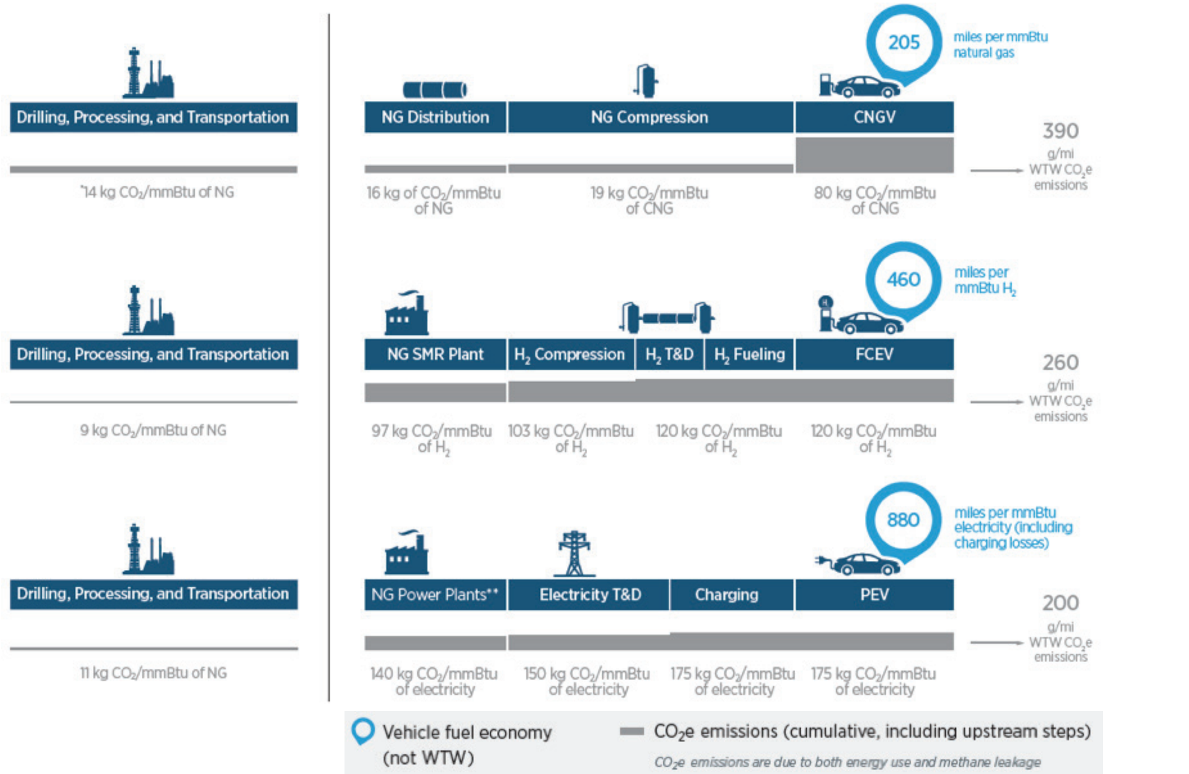


Figure 6.L.13 Fuel Life Cycle Efficiency (a) and Fuel Life Cycle GHG Emission (b) for Natural Gas Power Vehicles,[87] continued

b)



The next logical step in evaluating next generation vehicle technologies would be to look beyond the energy and associated carbon impacts and evaluate a range of environmental impact criteria (see Table 6.L.3). The vehicle manufacture, operations, and fuel supply chain are all critical parts of the ecosystem. The assumptions about the source of energy for vehicles contribute a large part to the energy and carbon impacts; for conventional internal combustion engine vehicles (ICEVs), the fuel is a critical component, while for electric vehicles (EVs), the source of electricity is important.

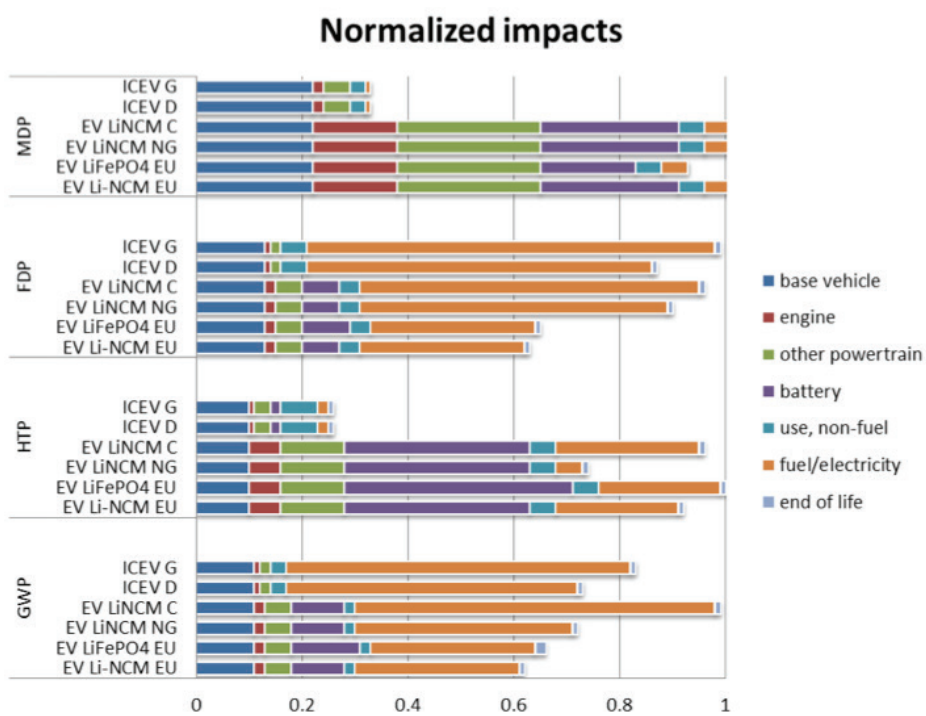
A study by Hawkins et al.[88] provides an example of a multi-criteria comparative scoping LCA that evaluates a first generation EV and a corresponding conventional ICEV in the European context. The study included a sensitivity analysis to evaluate the impact of modest variations in the grid mix powering the electric vehicles. The study covered ten different impact categories including global warming potential (GWP), human toxicity potential (HTP), fossil resource depletion (FDP), and mineral resource depletion (MDP) (see Figure 6.L.14 for the GWP, FDP, and HTP normalized results by life cycle stage and component). The scenarios evaluated in this particular study (specific to the early EV technologies and certain grid assumptions) indicate that there can be a potential burden shifting of impacts. The EV scenarios have lower impacts for FDP and GWP (except for the NG and carbon sourced electricity generation scenarios). The GWP impacts from the EV scenarios can be attributed to electricity demand from vehicle operation that is being powered by the EU electric grid, natural gas powered electricity and solely coal powered electricity. In alternative scenarios where a heavily decarbonized grid is in place, the GHG impacts from EV operations would be significantly reduced , as shown in the main QTR report, Figure 8.2 on page 279 (note, however, that this figure does not include GHG emissions resulting from the production of the materials in and manufacture of the EV); this could also potentially significantly reduce FDP by EVs. The ICEV scenarios evaluated have lower impacts for HTP and MDP. The increase in MDP for EVs has been cited in other EV studies due to the dependence on metals of varying availability. The study did not focus heavily on the MDP component, so the results for MDP are more uncertain than for other impact categories. These MDP results will also be significantly impacted by the use of used EV batteries in secondary markets, such as for grid storage. Both MDP and HTP impacts can be significantly reduced by improvements in life cycle management from mining through recycling that can be instituted as this sector develops.

The Hawkins et al. study illustrates the importance of the background data used. Collection and usage of primary data (rather than averages) could reduce uncertainty in results and provide better insight in many cases. Conducting sensitivity analyses to understand potential impacts associated with decarbonizing the grid, lightweighting of vehicles, and adopting next generation battery technologies will help to understand what kind of scenarios will lead the industrial sector to improvements across multiple impact areas. Additionally, multi-criteria analysis can also provide insight on the advantages and disadvantages of next generation technologies. For example, the Hawkins study might suggest there is a research need around the reduction of toxic impacts from battery technologies, or that large-scale near-term deployment of EVs with a heavily carbonized grid at present may show limited GWP benefits, but would enable large GWP benefits as the grid is decarbonized over time. Providing decision makers and investors with a full understanding of the range of potential impacts of next generation technologies can lead to better informed decisions. Multi-criteria analysis can also help identify hotspots in the life cycle of next generation technologies that may be areas of needed R&D. Any single scenario analysis is constructed based on assumptions that can affect the results and LCA results cannot be fully understood without a clear understanding of the assumptions used.

A harmonization approach can help to better understand the impacts under a common context, which is especially important for multi-criteria analysis. The harmonization work illustrated in Figure 6.L.12 demonstrates how studies by different authors with different context can result in a wide range of results. For vehicle technologies, it would be useful to expand the analysis of well-to-wheels petroleum use and GHG emissions for 2035 mid-sized cars (QTR Chapter 8 (Figure 8.2), to a multi-criteria analysis that includes the full life cycle of the vehicle technologies, across multiple fuel, electricity grid and end of life options. More broadly, this approach could be utilized to evaluate a wide range of end use technologies to understand the full environmental implications.

Figure 6.L.14 Life cycle impacts of first generation electric vs conventional vehicles (as defined by Hawkins et al.[89]) normalized to the largest total impacts attributed to life cycle stage or vehicle component production. As shown in Figure 8.2, page 279, of the main QTR report, the GWP of EVs will significantly decline as the grid is decarbonized, and this could also significantly reduce the FDP of EVs. The MDP and HTP impacts of EVs can be significantly reduced by improvements in life cycle management from mining through recycling that can be instituted as the EV industry develops.
[Key: Global warming potential (GWP), human toxicity potential (HTP), mineral resource depletion potential (MDP), fossil resource depletion potential (FDP), internal combustion engine vehicle (ICEV), electric vehicle (EV), lithium iron phosphate (LiFePO4), lithium nickel cobalt manganese (LiNCM), natural gas sourced electricity (NG), coal sourced electricity (C), European electricity mix (EU)].[90]

Credit: Hawkins, T. R., Singh, B., Majeau-Bettez, G. and Strømman, A. H. (2013), Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology, 17: 53–64. doi: 10.1111/j.1530-9290.2012.00532.x



See also Figure 8.2 of the main QTR report for potential GHG impacts of various fuel and electricity supplies.

The Corbière-Nicollier et al. comparative LCA study[91] evaluated glass fibers (GF) and a bio-fiber equivalent made from China reed (CR) fibers for reinforcement in plastics, including a sensitivity analysis of the assumed life time and plastic composition. The study evaluated the two materials utilized in plastic transport pallets. The results (Table 6.L.4) indicate that the CR pallet had lower impacts in all categories than the GF pallet. A sensitivity analysis showed that increasing the percentage of fiber in the pallet (both for GF and CR) increases the strength of the pallet. However, the CR pallet showed a greater decrease in energy with the increase in fiber content and improved strength.

Table 6.L.4 Impact assessment results per pallet for a glass fiber (GF) reinforced plastic transport pallet compared to a China reed (CR) fiber reinforced pallet, using the CML92[92] impact assessment methodology.[93]

Impact per pallet (unit)	GF-reinforced pallet	CR-reinforced pallet
Human toxicity (kg 1,4 dichlobenzene$_{eq}$)	21	9
Terrestrial ecotoxicity (kg 1,4 dichlobenzene$_{eq}$)	5250	4500
Aquatic ecotoxicity (kg 1,4 dichlobenzene$_{eq}$)	1.1	0.67
Greenhouse gas emissions(kg CO_{2eq})	75	40
Ozone formation (kg ethylene$_{eq}$)	0.21	0.13
Acidification (kg SO_{2eq})	0.65	0.43
Eutrophication (kg PO_{4eq})	0.068	0.063
Energy (MJ)	1400	720

Current AMO Approaches

The DOE Advanced Manufacturing Office (AMO) has been developing a series of tools for holistic analysis of next generation technologies. The goal of understanding the life cycle energy and carbon impacts of these technologies has required the ability to analyze energy impacts that occur outside of the industrial sector. The Materials Flows through Industry (MFI) tool[94] has been developed to evaluate the energy and carbon impacts of the supply chain. In addition, the Life Cycle Industry GreenHouse gas Technology and Energy through the Use Phase (LIGHTEnUP) tool[95] allows analysts to examine a next generation technology or material and evaluate the impacts in the industrial sector as well as the use phase in the industrial, buildings, and transportation sectors.

Deep dive analyses have also been conducted by Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL)/Northwestern University around lightweight materials, natural gas feedstock potential, application of wide bandgap semiconductors (see Technology Assessment 6.N *Wide Bandgap Semiconductors for Power Electronics*), additive manufacturing (see Technology Assessment 6.A *Additive Manufacturing*), process intensification (see Technology Assessment 6.J *Process Intensification*), and other technology areas of interest to AMO.

Additive manufacturing (AM) is a method of three-dimensionally printing an object. As opposed to subtractive methods of manufacturing (i.e. machining/milling), AM can increase the material utilization efficiency by enabling optimized part designs, such that equivalent or better performance can be achieved with less material. Further, AM can significantly reduce materials waste during the manufacture of the part. Analysis of the life cycle energy impacts of particular products finds that AM has the potential to reduce energy use and environmental emissions. For example, in a case study of aircraft brackets made by additive manufacturing,[96] an optimized design results in a bracket that is 65% lighter [2.4 lbs to 0.84 lbs] than a conventionally designed bracket, saving 93% of the raw materials required to manufacture the bracket [19.22 lbs to 1.26 lbs]. These material savings came from the combined effect of reduced manufacturing scrap and an optimized AM design enabling a lighter-weight finished component. The new design contributed to the freight & distribution energy savings due to less material being transported to the manufacturer, to the final customer, and for end of life recycling/disposal. The lightweight part also provided use phase energy savings due to reduced fuel requirements for the aircraft, resulting in a total life cycle energy savings of 66% compared to the conventional part. For further details of this and other additive manufacturing case studies, see the Technology Assessment 6.A *Additive Manufacturing*.

An energy bandwidth analysis for lightweight structural materials is ongoing[97] to explore opportunities for energy savings associated with the use of aluminum, advanced high strength steel, magnesium, titanium, carbon fiber composites, and glass fiber composites. The analysis is specifically looking at applications for automotive lightweighting, compressed gas storage, wind turbines, and aerospace and other transportation applications. While research in reducing the energy demands for producing lightweight structural materials is important, much of the energy savings opportunities for lightweight products exist in the use phase (typically outside the industrial sector). The LIGHTEnUP tool has been used to evaluate lightweighting scenarios through the use phase. The Technology Assessment 6.E *Composite Materials* includes a text box with details of a specific analysis of utilizing lightweight materials to replace steel for light duty vehicles. In addition, the Recycling Carbon Fibers for High-Volume Automotive Applications text box in this technology assessment explores the energy impacts of utilizing recycled carbon fiber in light duty vehicles.

Recycling Carbon Fibers for High-Volume Automotive Applications

Recycling is a critical component of sustainable manufacturing. The 6.E Composite Materials Technology Assessment identified carbon fiber (CF) lightweighting of the U.S. light-duty vehicle (LDV) fleet as a promising opportunity to reduce net U.S. energy consumption across the manufacturing and transportation sectors.[98] Using the LIGHTEnUP[99] life cycle analysis (LCA) tool, a case study compared the manufacturing and use-phase energy impacts of a hypothetical low-energy carbon-fiber reinforced polymer (CFRP) manufactured with an alternate precursor to the current energy intensive conventional polyacrylonitrile (PAN)-precursor-based CF. That case study concluded that lightweighting the U.S. LDV fleet using current CFRP manufacturing processes yields a net energy savings eventually, as use phase energy savings from the lightweighted LDV stock accumulate over time. However, lightweighting the U.S. LDV fleet using hypothetical low-energy CFRP parts—if commercially available — could yield net energy savings immediately due to the assumed low energy intensity of these parts. This case study expands upon the Composite Materials Technology Assessment by assessing the impact of recycled CF, again using the LIGHTEnUP LCA tool.

For consistency, this case study applies the same assumptions as the case study presented in the QTR 6.E *Composite Materials Technology Assessment* with additional accounting for recycled CF (recycled CF is assumed to come from retiring LDVs at the end of their lifetime [13 years]).[100] The majority (~60%) of virgin CF's embodied energy intensity is associated with precursor conversion into final, long-filament CF tows. In contrast, recycled CF only requires heat, mechanical, or chemical processing to separate the resin from the CF in the original CFRP part, which lowers recycled CF's energy intensity to an estimated 80 MJ/kg—about 92% lower than current PAN CF (1150 MJ/kg) and 79% lower than the hypothetical low-energy CF (388 MJ/kg). Based on recycling technologies available today,[101] most recycled CF is anticipated to be short-length CF with lower mechanical performance properties (e.g., fiber strength and modulus) compared to virgin CF. This might restrict their use to a limited set of applications where the loading conditions, geometry, and other factors are safe and within engineered specifications, and also may motivate R&D to better preserve recycled CF properties to more closely match those of virgin CF and to recover and recycle a portion of the polymer matrix.

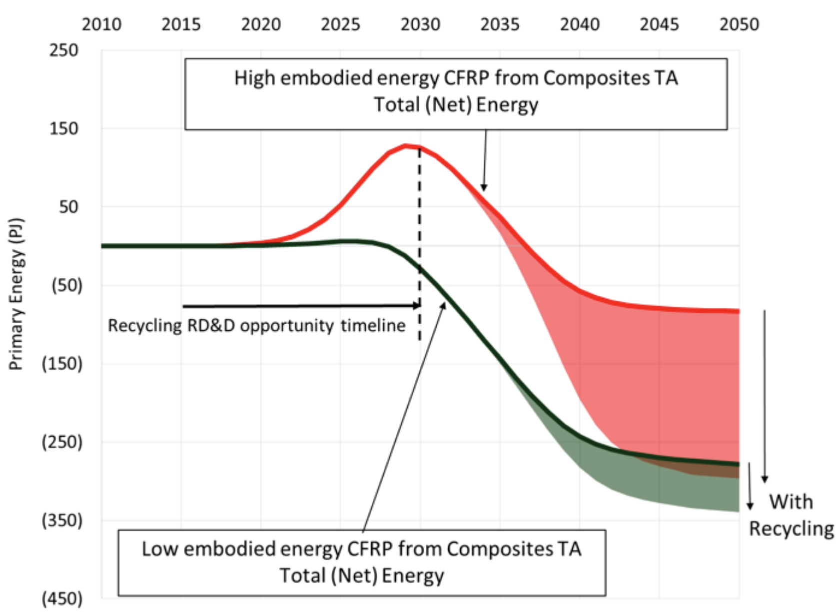
Figure 6.L.15 shows net energy results of the high- and low-energy intensive CFRP from the composite materials TA (solid curves) with recycling (shaded areas). For simplification, this figure only shows the total (net) energy impacts, including the manufacturing sector's increased production

Recycling Carbon Fibers for High-Volume Automotive Applications, continued

of CFRP parts, the steel manufacturing sector's reduction of steel, and the transportation sector's lightweighted LDV fuel savings.

This scenario assumes perfect recycling, specifically that: 1) the CF will be harvested from all retiring LDVs; 2) the recycled CF's embodied energy will be much lower than virgin CF's embodied energy (79 – 92% lower as defined above); and 3) the new parts manufactured from recycled CF meet safety and engineering performance specifications. Achieving widespread penetration of recycled composites in vehicles will require successful RD&D in the technologies that will enable low-embodied-energy, cost-effective CF recycling. The Composite Materials Technology Assessment (and this case study) assumes that CFRP parts will start showing up in LDVs by 2017, with a gradual accumulation of CFRP parts in the fleet after that introduction year. Based on a historical average LDV lifetime of 13 years, a typical 2017 lightweighted LDV would be retired in 2030. However, it is important to note that changing consumer choices, vehicle designs, and vehicle ownership paradigms could result in shorter vehicle lifetimes in the future. Cost- and performance-effective CF recycling add an important contribution to sustainable manufacturing's goals of lowering net energy consumption and associated emissions.

Figure 6.L.15 Net life cycle energy impacts of replacing a 110-kg steel part with a 39-kg CFRP part in the U.S. LVD fleet, based on four replacement scenarios: high embodied energy CFRP (with and without recycling) and low embodied energy CFRP (with and without recycling). The low embodied energy CFRP offers immediate energy savings upon introduction. Recycled CF provides energy savings in both cases as CF is harvested from retiring lightweighted LDVs and recycled into new LDV parts. For the current high-energy CFRP manufacturing scenario (red curve), recycling has a substantial net energy reduction (red shaded area), more than doubling (150%) the net energy savings by 2050 compared to a no-recycling scenario. For the hypothetical low-energy CFRP manufacturing scenario (green curve), recycled CF provides a net energy reduction of about 20% by 2050 (green shaded area) compared to a no-recycling scenario.[102]



Evaluating material efficiency broadens the scope of energy efficiency analysis from evaluating only fuel use to evaluating the use of all materials. All materials have an energy intensity associated with their production (i.e., an embodied energy), and the reduction in the overall material demand to produce final products would reduce associated energy consumption.

Aluminum recycling is a well-known example of material efficiency improvements. While reducing the initial material demand would be the best option, utilizing pre- and post-consumer scrap is still less energy intensive than using virgin materials. Figure 6.L.16 illustrates the U.S. supply chain energy demand for four scenarios to produce aluminum ingot:

- Scenario A is a U.S. baseline with the current average mix of 40% primary and 60% secondary aluminum utilizing the modern Hall-Héroult smelting technology for the current market demand of 7.3 million MT (excluding imports; see Figure 6.L.17).
- Scenario B reflects the increased demand for aluminum in 2050 to 16.4 million MT (2.25 X increase; see Figure 6.L.5).
- Scenario C reflects an increased use of secondary aluminum in 2050, switching to a 30% primary/70% secondary aluminum ratio.
- Scenario D reflects an improved material efficiency of 20% from scenario C (13.1 million MT). The increase in material demand will have a significant impact, which will be only partially offset by use of recycling and 20% material efficiency improvements.

Figure 6.L.16 Supply chain energy demand for a U.S. market demand of aluminum ingot for four scenarios. Scenario A is a baseline market demand for 2009 (7.3 million MT).[103] Scenario B reflects the projected increased demand in 2050 (16.4 million MT) based on Gutowski et al.[104] projections (Figure 6.L.5). Scenario C reflects an increased use of secondary aluminum in 2050 (30% primary/70% secondary aluminum ratio; 16.4 million MT). Scenario D is a 20% increase in material efficiency with increased secondary aluminum for 2050 (13.1 million MT).[105]

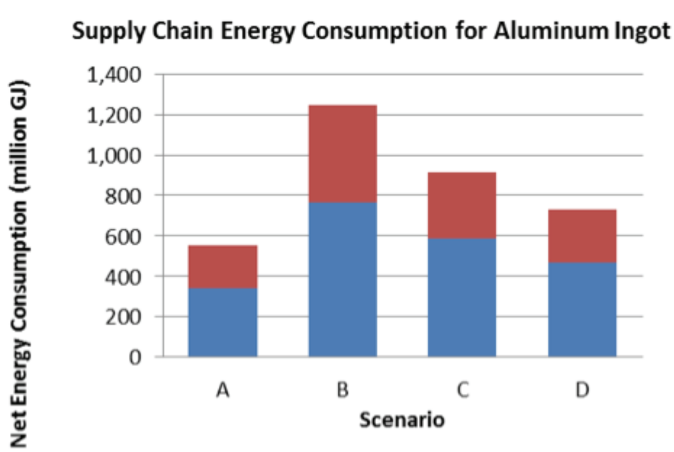


Figure 6.L.17 Aluminum flows (million MT) through the U.S. and Canadian economies in 2009. The green color represents secondary aluminum flows, the red represent primary aluminum flows, yellow represents imported and exported finished product flows, and the brown represents waste and scrap exports that are not utilized within the industrial sector and represent opportunities to optimize the aluminum materials usage.[106]

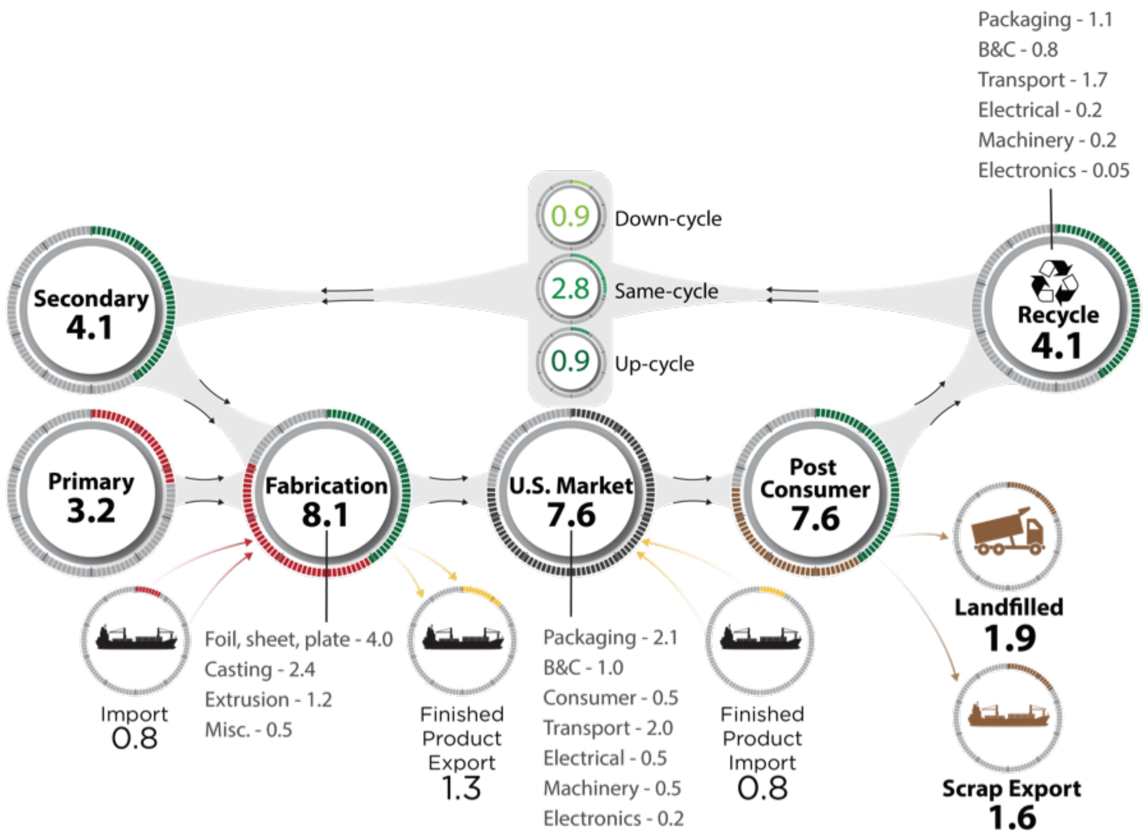


Table 6.L.5 Energy Demands for Primary and Secondary Aluminum Ingot at the Facility and for the Supply Chain from raw material to the aluminum ingot commodity.

	Energy Demand (GJ/MT)		
	Primary Aluminum Ingot Production	Secondary Aluminum Ingot Production	Current mix of Primary (40%) and Secondary (60%) Ingot Production
FACILITY ENERGY DEMAND	GJ/MT	GJ/MT	GJ/MT
Current Typical[A]	55.6	6.5	26.1
State-of-the-Art[A]	42.4	3.1	18.8
Thermodynamic minimum[A]	21.6	0	8.6
SUPPLY CHAIN ENERGY DEMAND[B]			
Typical average	134	22	66.8

A-Lightweight Materials Bandwidth Study[107]
B-MFI tool[94] calculation

Between 2010 and 2014, the recovered pre-consumer scrap grew from 1.6 million MT to 1.9 million MT.[108] There is embodied energy associated with this scrap that could be saved by increasing material efficiency (discussed previously in the section on Material Efficiency). This could come from multiple activities. With increased recycling (use of both pre- and post-consumer secondary aluminum) the facility energy savings total up to 47.9 GJ/MT for every metric ton of primary aluminum replaced by secondary aluminum (assuming there is sufficient availability of secondary material and the ability for 1:1 substitution of secondary aluminum for primary aluminum). This option is currently somewhat limited due to the mix of alloys in secondary aluminum.[109] The amount of secondary aluminum used depends on the purity of aluminum required for the final product. There is a need for technology improvement R&D in the metals separations processes to be able to more easily and cost effectively recover metals at the required quality levels. Further, there is a need for mechanisms to reduce the number of alloys in the market or to be able to sort and separately manage the different types of alloys.

The current supply chain energy (extraction through production) for aluminum ingot (which averages around 40% primary aluminum and 60% secondary aluminum for total aluminum use (see Figure 6.L.17) equates to 67 GJ/MT with the majority of that energy demand coming from alumina, anode, and smelt production. If the primary/secondary ratio shifted to 30% primary/70% secondary, the supply chain energy demand would decrease by about 11 GJ/MT. The current supply chain energy demand can range between 22 GJ/MT for secondary aluminum to 134 GJ/MT for primary aluminum (Table 6.L.5). The strategies for component reuse, longer product life, and more intensive use can also result in decreased total demand. Implementing state-of-the-art technologies as identified by the lightweight materials structural bandwidth reports[110] at the facility could achieve savings of around 13.2 GJ/MT for primary aluminum production and 3.4 GJ/MT for secondary aluminum production.

Future United States and global demands for aluminum are forecast to increase significantly over the coming decades, due in part to the lightweighting capabilities of aluminum in the transportation sector (see discussion of lightweighting in the transportation sector in the Introduction of this technology assessment, bottom of page 3).With the 2.25 – 3.25 projected global increase in demand for aluminum (Figure 6.L.5), the fabrication demand would be upwards of 18 million MT (from a 2009 baseline, Figure 6.L.17). This increase (with 40% primary/60% secondary distribution) would result in a facility level energy demand increase for aluminum ingot of around 477 million GJ with current technologies and 344 million GJ with practically achievable technologies. From the other side of the supply chain, 54% of the post-consumer aluminum is recycled. However, the other 46% is landfilled (1.9 million MT) and exported as scrap (1.6 million MT). This is a simplified assessment and more extensive analysis would be required to identify methods to increase the recovery and utilization of the material and would require additional alloy management in the supply chain. The alloy management issue causes significant down-cycling of aluminum and requires sweetening or addition of virgin aluminum to the recycled product to achieve the necessary specifications and quality. R&D is needed to identify improved waste separation technologies and/or to design for deconstruction which will help provide cleaner lines of recycled product that do not need to be sweetened or down-cycled.[111]

The cost effectiveness of materials efficiency improvements to industry is strongly dependent upon a combination of standardization and optimization. Material efficiency leans toward optimization and can come at the expense of standardization. This can equate to increases in costs, such as labor. Allwood and Cullen[112] determined that more complicated product designs that used less material required more labor to manufacture. Development of technologies that can help bring the standardization and manufacturing efficiency for material efficient design will help to bridge the gap without increasing the cost.

Program Considerations to Support R&D

Current Activities around Sustainable Manufacturing

Efforts are ongoing across multiple agencies and organizations to improve the knowledge base for how to implement sustainable manufacturing. NIST has developed a Sustainable Manufacturing Indicator Repository (SMIR)[113] with the intent of helping companies measure their sustainability performance. The National Science Foundation (NSF) made a five year award[114] for the Sustainable Manufacturing Advances in Research and Technology Coordination Network (SMART CN).[115] Related to this award, NSF also hosted a workshop in 2013 to develop a roadmap for sustainable manufacturing and in 2015 an additional workshop was held to review the main challenges in advanced manufacturing, prioritize urgent research needs, and suggest strategies for implementing sustainable advanced manufacturing. Most recently, AMO hosted a sustainable manufacturing workshop in January 2016,[116] aiming to better understand the connection between energy use in industry and sustainable manufacturing technology opportunities. Sessions during the workshop focused on alternative feedstocks, end of life management, material-water-energy relationships, sustainable design decision making, and waste reduction. The Department of Commerce (DOC) through the International Trade Administration also has a Sustainable Manufacturing Initiative[117] and a website to serve as an information portal for U.S. companies to understand what the DOC and other agencies are doing to support sustainable manufacturing in the U.S. The USEPA website for sustainable manufacturing[118] provides information on how to develop a business case for sustainable manufacturing, a clearing house of resources, case studies, tools, and information about federal programs. Internationally, there are efforts and resources available through the Organization for Economic Cooperation and Development,[119] the United Nations Environment Program,[120] and the United National Industrial Development Organization.[121] Universities doing research in this area include Purdue University's green manufacturing program,[122] University of California, Berkeley's Laboratory for Manufacturing and Sustainability and Sustainable Manufacturing Partnership (SMP) program,[123] and Duke University's Center for Sustainability and Commerce.[124] The extent of these activities might be considered an indicator of the increasing awareness of the value of sustainable manufacturing. Much of the work is diverse in focus (metrics, technologies, toolkits, partnerships) and also in the early stages of development and deployment. The uptake in industry is still limited, indicating that there is much work to be done to characterize and communicate the value proposition for industry. The AMO workshop was attended by experts across multiple industries and they found that while some issues are common across industries, many are very industry specific and process specific.

DOE Analysis

DOE's work strengthens U.S. energy security, environmental quality, and economic vitality through enhanced energy efficiency and productivity. This has been achieved through a series of mechanisms that include manufacturing demonstration facilities, technology deployment, investment in innovative manufacturing processes and next generation manufacturing, and analysis of life cycle energy impacts.

Energy intensity opportunities have traditionally been a key focus of AMO and DOE in general. Carbon intensity issues, shown in Table 6.L.6, have become more relevant with the concerns of global warming and the impact of the industrial sector. Material efficiency opportunities, summarized in Table 6.L.2, have often been outside of the scope of traditional DOE analysis and have not been as thoroughly investigated. These opportunities may be more challenging to pursue because they focus on life cycle stages that may span multiple economic sectors, but may ultimately change the way advanced technologies are developed and evaluated.

Table 6.L.6 Energy and Carbon Reduction Opportunities in the Industrial Sector

Energy Intensity	Carbon Intensity
Process Intensification	Feedstock Substitution
Electrotechnologies (especially for Process Heating)	Green Electrification
Combined Heat and Power	Green Chemistry
Waste Heat Recovery	Carbon Capture and Storage
Supply Chain Integration	Biomass-based Fuels
Advanced Sensors, Controls, Platforms, and Modeling	
Roll-to-Roll Processing	
Advanced Materials	
Additive Manufacturing	

The LCA and supply chain analysis methodologies can be used in evaluating technologies of interest to understand and minimize the externalized impacts and the material efficiency associated with the supply chain. Multi-criteria analysis methods and system optimization can be used to incorporate this additional impact information into the decision making process. The increasing focus on water scarcity due to drought impacts in the western U.S. and stressed aquifers from over-withdrawals indicates the pressing need to consider the connections between water and energy, and how LCA can help inform energy decisions by also taking into account water impacts. At a minimum, having an understanding of the environmental impacts of a technology investment can minimize the risk of investing in a technology with significant negative environmental impacts. The material efficiency space indicates that there are multiple strategies (Table 6.L.2) that could be pursued in the R&D space to not only reduce energy demands in the U.S. economy, but also to move DOE R&D to a new model that is holistic in nature. This new model would help to minimize local, regional, national, and global negative environmental impacts and would look for solutions that optimize the use of natural resources. The use of LCA in advancing the strategies outlined in Table 6.L.2, deployed either individually or jointly, can help ensure that measures deployed to reduce energy impacts in the U.S. economy do not inadvertently shift burdens elsewhere, such as by increasing energy impacts in other sectors, geographical locations, or life cycle stages—or by decreasing energy usage at the expense of human or environmental health.

Some cities and regions are already incorporating a geographic dimension into analyses used to assess the carbon impacts for their region. A geographically explicit LCA of a next generation technology or material could examine a scenario where a new technology is deployed in a facility in a certain city or region to assess how the technology impacts the energy/carbon/environmental footprint of that region (and of other regions). Part of the challenge for conducting LCAs is getting the data to support it. Reliable geographically specific LCI data is currently very limited and the methodology to do geographic analysis of the life cycle impacts is not fully developed, but is being explored by LCA researchers.

The National Renewable Energy Laboratory (NREL) conducted a life cycle air emissions inventory analysis[125] of the implementation of the Renewable Fuels Standard (RFS)[126] and evaluated the life cycle inventory of air emissions on the county level of biofuels feedstock production for DOE's Bioenergy Technology Office. The analysis is able to identify regions where implementation of the RFS could either further impact or push counties into a non-attainment status of the USEPA National Ambient Air Quality Standards. Adding the geographic component to LCA allows researchers to try and answer questions like: Where can technologies be deployed without damaging the ecosystem of the region? Which regions are more resilient? What emissions associated with a technology need to be better controlled to limit damage to the region where they are located? This kind of analysis could be applied to deployment of next generation technologies in order to identify and quantify pollutant emissions associated with the deployment of the technology that could be detrimental to certain regions.

Critical Materials

The availability of critical materials is a significant concern for industry and is being researched at the Critical Materials Institute.[127] The institute has four main focus areas: diversifying supply, developing substitutes, improving recycling and reuse, and cross-cutting research. The availability of critical materials is partly a supply chain problem and represents one of the risks of a vulnerable supply chain. The use of LCA in the development of substitutes will help select lower impact alternatives. Minimizing material demand through applying material efficiency would also reduce the risk. Recycling and reuse at the end of life is challenging, but for materials with a limited supply and a high demand, this also will help reduce the need for virgin materials.

Existing research has looked at the global supply of lithium as a constraint for the widespread deployment of electric vehicles due to the limited supply,[128] the impacts of recycling lithium-ion batteries,[129,130] how recycling could affect the life cycle energy and air quality impacts of lithium-ion batteries,[131] and implementation of an economic and sustainable recycling system for lithium-ion battery end-of-life management.[132] Critical materials are discussed in depth in the technology assessment 6.F *Critical Materials*.

Direct and Indirect Impacts

The supply chain can be affected both directly and indirectly by adoption of next generation technologies or materials. Lightweighting of a product changes the demand for materials coming into the manufacturing facility as well as the product weight leaving the facility. This results in overall reduced transportation fuel demands. An increase in product durability and lifetime across the economy would likely reduce the amount of new products being consumed and therefore the overall demand. Increased quality control can have impacts through several mechanisms. Improved information exchange between manufacturers and suppliers could result in higher quality products and reduced in-plant waste for defective components. A higher quality product would also feasibly result in higher consumer satisfaction and fewer product returns, and might also result in increased market share and higher demand, reducing the sale of lower quality products. Improved industry-supplier information exchange could also result in opportunities to identify process improvements and thus streamlining of the system. Material availability is a large concern for materials that are in high demand, have restricted sourcing, or are from geopolitically unstable regions with obvious risks to the supply chain. Identification and minimization of material availability bottlenecks in the supply chain are useful for creating a resilient supply chain.

Risk, Uncertainty and Other Considerations

Risks in the supply chain are grouped here into five different categories: technical, regulatory, economic and competitiveness, environmental, and security. Technical risks are associated with problems that can occur with information exchange, technology failure, and underperformance. These can result from incorrect application of specifications or lack of precision. Regulatory risks are inherent in all industries and are not addressed here. Economic risks are associated with the cost of capital, technology, energy, resources, operations, etc., and are associated with the competitiveness of the technology in associated markets. A material in high demand can drive up the cost and reduce availability. This can be especially important for critical materials. Environmental risks can be due to emissions from a process that degrades the environment (air, water, and soil) and can potentially be harmful to humans and the biosphere. Security risks are associated with the dependence on a material from a politically unstable region, extreme events such as weather or earthquakes, damage to infrastructure, and others. There are also regulatory challenges associated with shifting to next generation materials for some industries. For increased use of secondary materials, there has to be a shift in industry in terms of developing broader markets for secondary materials as well as management of different alloys both on the production side as well as on the recycling side.

As with any modeling analysis, uncertainty is high when evaluating the life cycle impacts of technologies. This is due to data availability, data quality issues and uncertainty in parameters, and propagation of uncertainties in scenarios and models, which can be exacerbated in highly complex systems. Uncertainties can be partially managed through sensitivity analyses.

Social behavior can influence opportunities for implementing multiple material efficiency strategies (Table 6.L.2, where actors include users). Allwood and Cullen[133] found that some improvements in material efficiency can be achieved through improved systems, but that a part is also limited by social habits and economic constraints. Successful implementation of material efficiency strategies will require understanding of the potential technology improvements, the economics of the strategies, and associated social behavior expectations. Research to inform decision makers should include all three components.

Industrial Environmental Accounting

Different forms of environmental accounting are occurring within the industrial sector. Many companies are publishing sustainability performance reports that cover their global environmental, social and economic performance. There are also a wide range of different environmental labeling systems in the market looking to evaluate the sustainability of industries, products, and companies. For example, the Ecolabel index has identified 463 ecolabels in 199 countries and 25 industry sectors; it also looks at what is covered under the label, how it was developed, who manages it, and how the label evaluates compliance.[134]

In 2015, the UNEP published a report on climate change commitments of subnational Actors and Businesses.[135] The report evaluated impacts from different company level climate change initiatives. UNEP estimates that almost 25% of the top 1000 largest GHG emitting companies are participating in some sort of initiative, some of which have emissions reductions targets with methodologies to evaluate emissions and some do not.

Some industries are choosing to develop type III environmental product declarations (EPD) which present quantified environmental information on the life cycle of a product that enables comparisons with other products with the same function (type III indicates that declarations are externally reviewed and intended for an external audience). ISO 10425 provides the standard for these declarations and the windows industry recently completed their product category rules to define what needs to be included in a windows EPD.[136,137]

In 2007, Shaw Industries commercialized a nylon carpet recycling technology (partially funded by AMO) that has from 2007 – 2011 kept 200 million pounds of carpet out of landfills and reduced energy use by approximately 450 billion Btus.[138]

The Sustainable Apparel Coalition (SAC) developed the Higg Index that allows brands, retailers, and facilities of all sizes to measure their environmental, social, and labor impacts and identify areas for improvement.[139] Nike utilizes a Material Sustainability Index (MSI) methodology (related to the SAC Higg Index) for evaluating the sustainability of their products. They are using a multi-criteria LCA based approach that looks at the life cycle stages from the design of the product through re-use (as their end of life option). The criteria are grouped and weighted and cover different aspects of chemical impacts, energy and GHG intensity, water and land use, and physical waste. Some companies have also compared newer products to older products across different criteria, such as energy, GHG, water, and waste.[140] There is an online tool that allows users to do product comparisons with varying material input options.[141,142]

Case Study: Better Buildings Water Savings Initiative – Voluntary Commitments to Measuring and Improving Water Utilization

As drivers such as population growth and climate change increase pressure on fresh water resources, both at the local and global level, manufacturers are seeking ways to incorporate more efficient and sustainable water use into their operations. This sustainable water use is driven from both an environmental perspective and from a business perspective. The former links manufacturers to the environment in which they operate and ensures that their operations do not adversely impact fresh water availability within their community. Further, water use requires energy and chemicals, both of which carry their own environmental footprint. Sustainable water use also benefits the business model by reducing the costs of water and the costs of the energy and chemicals to use the water, as well as providing operational resiliency. Manufacturers recognize that the communities in which they operate provide an unwritten license to draw from and dispose to local water sources. This license can be revoked if the facility is seen as harming the local water resources with consequences as severe as forcing facilities to shut down. In India, this has already become a reality as a bottling plant was shut down over concerns regarding its use of groundwater and the quality of the effluent.[143] Further, as water scarcity becomes exacerbated by changing climate, manufacturers are recognizing that suitable access to freshwater may not be guaranteed in the future.

The most recent USGS data on water use in the U.S. reported manufacturers consumed approximately 21 billion gallons per day from both municipal and self-supplied sources, with approximately 75% of use attributable to the latter.[144] While agricultural and thermoelectric power water use constitute 81% of U.S. water use, manufacturing water use represents 31% of water use from the remaining sectors. More importantly, there appears to be ample room for reductions in water use. The Pacific Institute estimated the potential for a 39% reduction in water use by industries (excluding agriculture) in California.[145]

In response to the environmental and business costs of water use and a call from manufacturers for greater assistance in implementing water reduction efforts, the DOE Better Buildings program established a Water Savings Initiative in 2015 to partner with companies to explore ways to expand their sustainability efforts to include water in addition to energy. Partners set water savings goals, track progress, and showcase water saving solutions. Currently, eight companies are participating in this new initiative: Cummins, Ford Motor Company, General Motors, HARBEC, Nissan North America, Saint-Gobain, Toyota Motor Engineering and Manufacturing North America, and United Technologies Corporation. In the program's first year, partners saved enough water to offset the average annual water use of 3,000 households.

Partners are demonstrating a wide array of approaches to achieving water savings, ranging from basic techniques such as identifying and fixing leaks, to complex strategies such as developing methods to incorporate the "true cost of water" when evaluating capital improvements. Employed by Cummins, the true cost of water incorporates all costs and risks associated with using water at a facility, including costs associated with water volume, treatment, discharge, chemicals, energy, and the business risk associated with losing access to water. Another novel approach is being demonstrated by HARBEC. HARBEC, whose sustainability achievements already include carbon neutrality, has established a water savings goal to eliminate municipal water from all process uses. To achieve this goal, HARBEC has installed a rainwater collection pond to serve process cooling loads. In addition to reducing water

Case Study: Better Buildings Water Savings Initiative – Voluntary Commitments to Measuring and Improving Water Utilization, continued

costs, HARBEC has been able to take cooling towers offline, also reducing the use of water treatment chemicals. Partners are also reporting innovative advances to improve process efficiency and reduce water use. For example, Ford reported implementing near dry machining, also known as Minimum Quantity Lubrication (MQL), to reduce water use associated with machining. As opposed to "wet machining" which floods the tool with fluids and water to cool parts being machined, MQL uses a fine spray of oil applied directly to the part. The MQL process cut in half the water use per engine at the Cologne Engine Plant between 2011 and 2012 and is estimated to save 280,000 gallons of water per year at a typical production line. In addition to water savings, Ford reports that MQL also reduces energy costs, oil purchases, and improves indoor air quality.

Water reuse is another common practice reported by partners for achieving water savings. Understanding water quality requirements is central to this practice. Potable water is generally not required for all water uses in a manufacturing facility. Use of primary or secondary treatment water can reduce water costs, and energy costs if water is treated on site. Technologies for treating water for reuse include membrane separation (e.g. reverse osmosis), ion exchange, filtration, biological treatment, and others. The selection of the appropriate technology will depend on the pollutant streams in the water and the required level of treatment. Further savings can be achieved through process changes, such as cascading water. This involves using wastewater from one process directly as the intake for another process that has lower water quality requirements. Cooling towers, chilled water systems, boiler systems, and process uses are applications where recycled/reused water may be suitable for use without impacting production. Water savings can be significant from implementing water recycling/reuse. For example, Frito-Lay's manufacturing plant in Casa Grande, AZ, was able to install a process water treatment plant (PWTP) to recycle 75% of the plant's water use and save 100 million gallons of water per year. The PWTP uses a combination of technologies including membrane bioreactors, granular activated carbon, UV disinfection, and low pressure reverse osmosis membranes. Reuse water is used and reclaimed from several cleaning operations, including potato, corn, and equipment washing.[146] In another example of the significant savings achievable through water reuse, Intel combined technology advancements and process efficiency to save two billion gallons of water, or 25% of its total water withdrawals, in 2010. Intel achieved these savings by improving the efficiency of the process for producing Ultrapure Water (UPW) from requiring two gallons of water to produce one gallon of UPW to now requiring 1.25 to 1.5 gallons of water to produce one gallon of UPW. Further, effluent UPW from the wafer cleaning process was used for other industrial processes and irrigation.[147]

Sustainable water use extends beyond the manufacturing facility's boundary, and opportunities for lessening environmental impact also exist upstream of the facility. Availing of these opportunities better connects the manufacturing facility to the community in which it operates. All seven partners polled listed environmental stewardship/corporate sustainability as a driver for establishing water reduction targets. Additional opportunities for using recycled water exist for manufacturing facilities located in wastewater districts with the capability of providing recycled water to customers (e.g. water treated to a standard less than potable). Such a scenario can reduce energy consumption at the wastewater treatment plant, as well as freshwater consumption and overall water costs at the manufacturing facility. As of

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2012, 31 states had rules, regulations, or guidelines addressing supplying purchased recycled water to industrial facilities including manufacturing facilities, power plants, and fossil fuel extraction.[148] In California in 2009, municipal wastewater facilities delivered 15,300 million gallons of recycled water to industrial facilities (excluding agriculture).[149] Challenges to greater adoption include infrastructure costs and identification of recycled water uses within manufacturing facilities. However, when implemented, the freshwater reduction impact can be significant; the West Basin Municipal Water District supplies 5.8 million gallons per day of single pass and 2.4 million gallons per day of second pass reverse osmosis water to the Chevron refining facility in El Segundo, CA.[150]

Despite the successes of the partners, many challenges to integrating water management efforts into sustainability efforts exist. Through the Water Savings Initiative, several barriers to better understanding water use at a manufacturing facility within the context of the local environment have been identified. A significant barrier is the ability for manufacturers to monitor water use within their facility. While water use is generally tracked at the facility level, water use by end uses is generally less understood. Establishing water performance metrics, baselines, predictive models, and identifying water saving actions are all hindered by the lack of insight into equipment or process-level water use. Further, tracking facility-level water can be complicated by lack of water metering on unbilled sources (e.g. onsite surface and ground water sources) and water discharge. Adding further complexity to data issues on manufacturing water use is a lack of standardization on how to track water use, including sources to track and where to place metering. Guidance on best practices for tracking water use and lower cost metering solutions could help manufacturers increase their water management efforts.

Manufacturers participating in the Water Savings Initiative are demonstrating that more efficient use of water is a critical element of a comprehensive sustainability effort that can also improve the bottom line. In order to advance sustainable water use within the manufacturing sector, there is a need for greater information on manufacturing water use, sharing of best practices strategies for achieving reductions, greater access to water saving technologies, and improved understanding of the impacts of a facility's water use outside of its fence line.

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24.4 quads Manufacturing Sector = 5.2 quads feedstock energy +19.2 quads excluding feedstock energy

19.2 quads Manufacturing Sector = 12.4 quads of energy losses (onsite and offsite) + 6.9 quads of applied energy

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Acronyms

AM	Additive manufacturing
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
BAU	Business as usual
BEES	Building for Environmental and Economic Sustainability
BEET	Balance of emissions embodied in trade
BETO	Bioenergy Technology Office
BOF	Basic oxygen furnace
BOS	Balance of systems
CCS	Carbon capture and storage
Cd	Cadmium
CdTe	Cadmium telluride
CF	Carbon fiber
CFC	Chlorofluorocarbons
CFRP	Carbon fiber reinforced plastic
CH_3Br	Methyl bromide
CH_4	Methane
CHP	Combined heat and power
CIGS	Copper indium gallium selenide
CNG	Compressed natural gas
CNGV	Compressed natural gas vehicle
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CR	China reed
C-Si	Crystalline silicon
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EAF	Electric arc furnace
ENTSO-E	European Network of Transmission System Operators for Electricity
EPBT	Energy payback time
EPD	Environmental product declaration
EU	European Union

EV	Electric vehicle
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FDP	Fossil resource depletion potential
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
g/mi	Grams per mile
GF	Glass fiber
GHG	Greenhouse gas
GJ	Gigajoule
GT	Gigatonnes
GWh	Gigawatt hour
GWP	Global warming potential
H_2	Hydrogen
H_2S	Hydrogen sulfide
HCFC	Hydrochlorofluorocarbons
HCl	Hydrochloric acid
HCPV	High concentration photovoltaic
HF	Hydrofluoric acid
HTP	Human toxicity potential
ICEV	Internal combustion engine vehicle
IPCC	Intergovernmental panel on climate change
IEA	International energy agency
ISO	International organization for standardization
KG	Kilogram
kWh	Kilowatt hour
LC50	Lethal concentrations that will kill 50% of populations in a single exposure.
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LDV	Light duty vehicle
$LiFePO_4$	Lithium iron phosphate
LIGHTEnUP	Lifecycle Industry GreenHouse gas Technology and Energy through the Use Phase
LiNCM	Lithium nickel cobalt manganese

m^2	Square meters
MDP	Mineral resource depletion potential
MFA	Material flow analysis
MFI	Materials Flows through Industry
mi	Miles
MMBTU	Million british thermal units
mpgge	Miles per gallon gasoline equivanet
MQL	Minimum quantity lubrication
MSI	Material Sustainability Index
MT	Metric tons
NAAQS	National Ambient Air Quality Standards
NAL	National Agriculture Library
NG	Natural gas
NH_4	Ammonia
NIST	National Institute of Standards and Technology
NMHC	Non-methane hydrocarbon
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NREL	National Renewable Energy Laboratory
NRML	National Risk Management Laboratory
ORNL	Oak Ridge National Laboratory
PAN	Polyacrylonitrile
PEF	Product environmental footprint
PEV	Plug-in electric vehicle
PMFP	Particulate matter formation potential
PO_4	Phosphate
POFP	Photochemical oxidation formation potential
PV	Photovoltaic
PWTP	Process water treatment plant
QTR	Quadrennial Technology Review
R&D	Research and development
RFS	Renewable Fuel Standard
Si	Silicon

SMR	Steam methane reforming
SO_x	Sulfur oxides
TA	Technology assessment
TAP	Terrestrial acidification potential
T&D	Transmission and distribution
TETP	Terrestrial ecotoxicity potential
TRACI	Tool for the Reduction and Assessment of Chemicals and other environmental Impacts
UCTE	Union for the Coordination of the Transmission of Electricity
UK	United Kingdom
UPW	Ultrapure water
U.S.	United States
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S Geological Survey
WBG	Wide band gap
UV	Ultraviolet
WHR	Waste heat recovery
WRI	World Resource Institute
WTW	Well to wheel
YR	Year

Glossary

Annex B nations	Countries with emission-reduction commitments in the Kyoto Protocol
Btu	British thermal units
Burden shifting	Occurs when the reduction of impacts in one stage of the life cycle, geographic location, or impact category result in increased impacts in another.
Buy to fly ratio	The ratio of raw material purchased to manufacture a product to the amount of material in the final product. The phrase “buy to fly” emerged from the aerospace industry.
Critical materials	Materials with a high demand in industry, but a global supply that is unstable or uncertain due to one or more risk factors. Certain substances provide essential capabilities, such as light emission or magnetism, and when the supply of one of these substances is at risk, it becomes a “critical” material. The DOE has identified five rare earth elements – neodymium, europium, terbium, dysprosium and yttrium – as critical materials essential for America’s transition to clean energy technologies. The DOE has identified two additional elements, lithium and tellurium, as “near-critical” materials. These non-rare-earth materials play an indispensable role in emerging energy storage and battery technologies, such as hybrid and electric vehicles, wind turbines, and photovoltaic thin films. (Reference: CMI fact sheet https://cmi.ameslab.gov/materials/factsheet)
Embodied energy	The sum of all the energy required to produce a good or service, considered as if that energy was incorporated or 'embodied' in the product itself; it is an accounting method which aims to find the sum total of the energy necessary to produce a product (cradle to gate).
End of life	Stage of a product’s life cycle when it is no longer used for its intended application and is recycled or disposed of.
Environmental product declaration	A standardized way of quantifying the environmental impact of a product or system. Declarations include information on the environmental impact of raw material acquisition, energy use and efficiency, content of materials and chemical substances, emissions to air, soil, and water, and waste generation. Product and company information is also included. An EPD is created and verified in accordance with the International Standard ISO 14025.
Externalities	A cost or benefit that affects a party that did not choose to incur that cost or benefit.
Greenhouse Gas Protocol	Developed by World Resources Institute (WRI) and World Business Council on Sustainable Development (WBCSD), sets the global standard for how to measure, manage, and report GHG emissions.
Life cycle assessment	An accounting of the inputs (resources and materials), outputs (chemical emissions, waste, products), and impacts to human and environmental health (i.e. acidification, toxicity, resource depletion) for a specified system.

Life cycle cost analysis	Method for assessing the total cost of facility ownership taking into account all costs of acquiring, owning, and disposing of a product system.
Life cycle impact assessment	Stage of an LCA that characterizes the life cycle inventory data into impacts.
Life cycle inventory	Detailed tracking of all the flows in and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water, and land by specific substance.
Material efficiency	The use of material resources per unit output for a product system.
Material flow analysis	An analytical method to quantify flows and stocks of materials or substances in a well-defined system (also referred to as substance flow analysis (SFA)).
Non-Annex B nations	Developing nations without emission reduction goals in the Kyoto Protocol.
Product environmental footprint	Product environmental footprint meeting the specific criteria set out by the European Commission (http://ec.europa.eu/environment/eussd/smgp/product_footprint.htm).
Quad	One quadrillion (10^{15}) British thermal units (Btu)
Scope 1 emissions	Carbon emissions from direct energy use (combustion of fuel).
Scope 2 emissions	Carbon emissions from indirect energy use (electricity).
Scope 3 emissions	Indirect carbon emissions from the activities in the supply chain (extraction and production of purchased materials).