Flow of Materials through Industry / Sustainable Manufacturing
Technology Assessment

Contents

1. Introduction to the Technology/System

Industrial systems are built on the exchange of materials and energy between producers and consumers (Schaffartzik et al. 2014, Gutowski et al 2013). The industrial sector produces goods and services for consumers by using energy to extract and transform raw materials from nature. By analyzing the pathways and transformations that occur as materials pass from nature to consumer use and back to nature through disposal, we can begin to better understand the material requirements, as well as the associated use of energy and production of byproducts, such as emissions to air, water, and soil.

1.1 Supply chain and material flow analysis

Energy savings opportunities for the industrial sector equate to 31 quads of energy. This can be found at different levels or scales starting from the manufacturing systems (the smallest scale), through the supply chain system (the largest scale) (figure 1). On the smallest scale, opportunity can be found through examining specific manufacturing systems or processes. These processes have their own energy and material efficiencies; independent of any other surrounding or connected system (i.e. energy efficiency improvements can be achieved through use of improved motors or an enhanced coating to improve flow). At the medium scale, opportunities can be found through examining production or facility systems, where different equipment and processes are working together in a single facility to produce a product. The facility system can be optimized to maximize the energy and material efficiency at that specific facility site through optimizing activity through from part of the process to the next. This kind of optimization is being supported through the better buildings/better plants program. The small and medium scale opportunities are generally covered under what can be call 'sustainable manufacturing'. The US 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" (www.epa.gov/sustainablemanufacturing/). At the largest scale, opportunities need to be found by examining the supply chain system that links different industries and facilities together and support each other. The supply chain system is typically global, but where it is regional, there are better opportunities to take advantage of industrial ecologies and for system improvements to have greater impacts (i.e. a supply chain that is predominantly local will have reduced transportation requirements). Additionally, there are better opportunities for the supplier and the customer to communicate directly about needs and specifications and capabilities and to collaborate on opportunities for improvement for both parties. In a global supply chain, it is necessary to have strict specifications so suppliers will be able to provide the desired product. On a national level, with national level energy goals, knowing which part of the supply chain has the largest energy demand can help with hotspot analysis to look for solutions to reduce the overall energy demand of the system. The supply chain system and tools to evaluate it are discussed throughout this section. In this context, these scales do not include evaluating the use phase or disposal/reuse of a product which can have significant impacts.

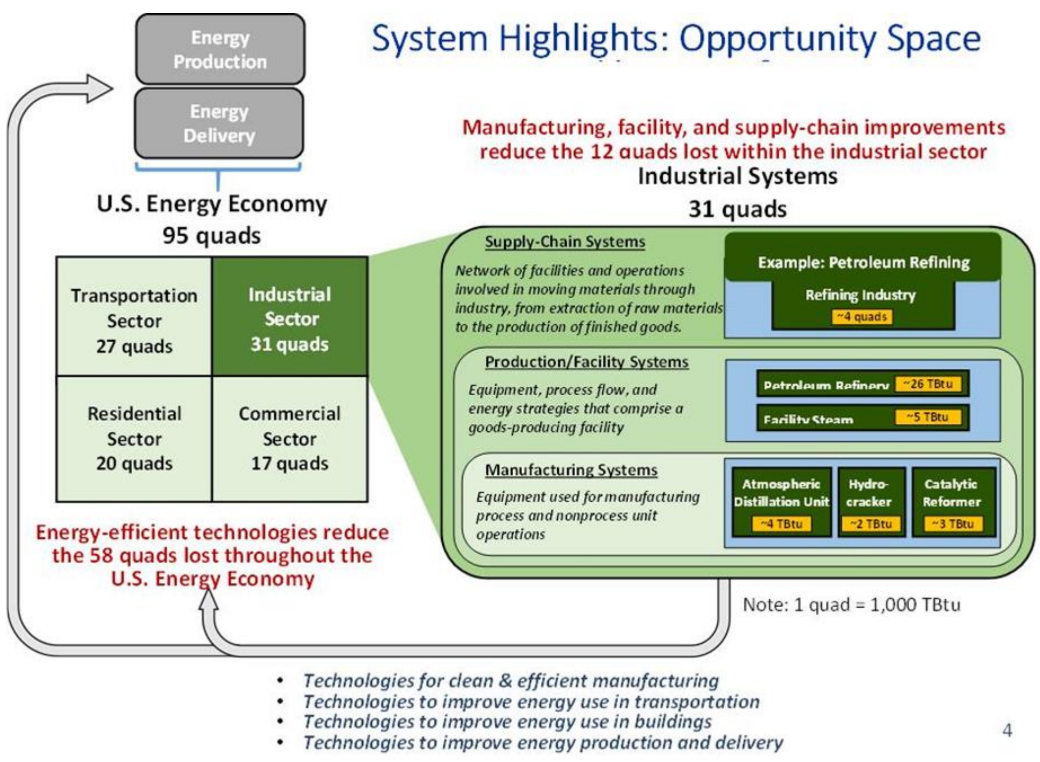


Figure 1: Opportunity space in evaluating the industrial sector.

An understanding of the supply chain supports analysis of all technologies. In the buildings sector, there has been an emphasis on reducing the operational energy. With the significant improvements in building energy efficiency over the last couple of decades, a shift to reducing the embodied energy of building components (the supply chain component) in a full building analysis can help to minimize the total life cycle impact of the building sector. The transportation sector also provides some interesting and unique scenarios. Most of the impacts in the transportation sector are related to operational energy demands (use phase). However, application of lightweight materials to minimize operation impacts is currently of interest and starting to show up in the market place (aluminum, carbon fiber). Lightweight materials are generally more energy intensive (higher embodied energy), so this trend has not moved rapidly and research to minimize the energy intensity of lightweight materials is ongoing. Looking at where the impacts are occurring in the supply chain will help to identify opportunity areas for energy reduction for transportation products.

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. US per capita materials consumption is estimated to have grown 23%, and total material consumption grew 57% between 1975 and 2000 (WRI, 2008).

Global material use is an important consideration for potential improvements to industrial process energy efficiency. Gutowski et al. (2013) identify that it will require a 75% reduction in average energy intensity of material production to meet IPCC climate goals by reducing global energy use by half from 2000 to 2050, while at the same time developing countries achieve a standard of living equivalent to the current developed world.

A supply chain can be thought of the system of company-level energy and material flows The supply chain system is a system of organizations, people, activities, information and resources involved in moving a product or service from the supplier to the customer. These activities transform natural resources, raw material and components into a finished product for the consumer (Nagurney 2006). It is what links all different parts of industry together and shows how materials are flowing through the industrial sector. These flows and links are important to understand because breakages in the links can interrupt the flow of materials and disrupt production. In this global economy, flows are coming from and running to many different countries and are subject to the market fluxes. Fluxes in the market can be from new market competition, geopolitical issues, increases in costs, or other reasons.

The supply chain reflects the products and associated processes required to produce a specific commodity or end product that can trace back to extraction of materials from the ground. Some products have much more extensive and complicated supply chains than others. This is typical of highly complex systems that have a high number of material components or materials that are highly processed to achieve specific performance requirements. The industrial sector, as a sector that is responsible for the production of all the products utilized in the economy, is heavily impacted by the supply chain. A supply chain that is efficient, has minimal negative impacts and provides jobs will enhance the industrial sector.

Material flow analysis (MFA) is a methodology for evaluating material usage in a product system as is defined as a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberer, 2004). The World Resources Institute (WRI) has done a series of MFA studies that cover global flows, industrial economy flows and flows in the US. The intent of the studies was to help shape policies to create a more efficient economy. The MFA helps to evaluate the quantity of material consumed and waste generated. Figure 2 illustrates the methodology used by WRI to account for the material flows.

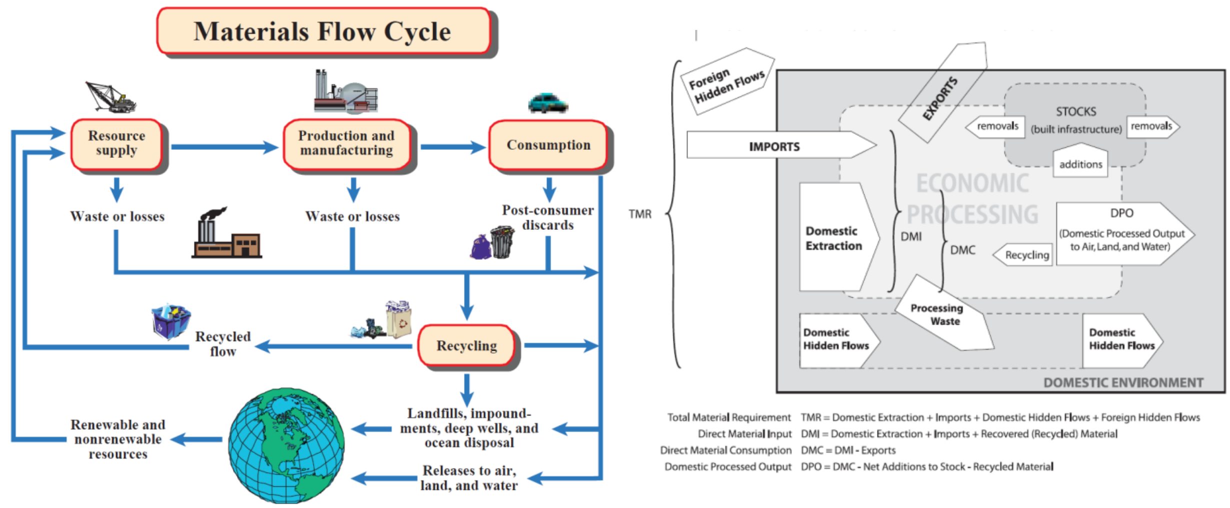


Figure 2: Process flow diagrams to understand the material flow cycle. WRI uses the methodology in the RH figure to account for material flows in their analyses.

The life cycle assessment (LCA) methodology is able to evaluate systems from cradle-to-gate (extraction to the facility gate), cradle-to-grave (extraction to disposal), cradle to cradle (extraction through recycling) or gate to gate (just at the facility) (figure 3) and looks to understand all the inputs and outputs associated with the system. This includes chemical emissions to soil, air and water that can negatively affect both human and ecological health as well as resource depletion (i.e. water and minerals). An inventory is conducted to account for all the inputs and outputs in the system and then translated using established impact assessment methodologies to understand the effects on human health and the ecology. The US Environmental Protection Agency (USEPA) has developed an impact assessment methodology (figure 3) that is considered relevant to the US context call the Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) (USEPA 2012). TRACI evaluates a range of impacts from those with ecological impacts (i.e. eutrophication, ecotoxicity and global warming), to those with human health implications (i.e. cancer and noncancer) to resource depletion (i.e. fossil fuel use, water use and land use).

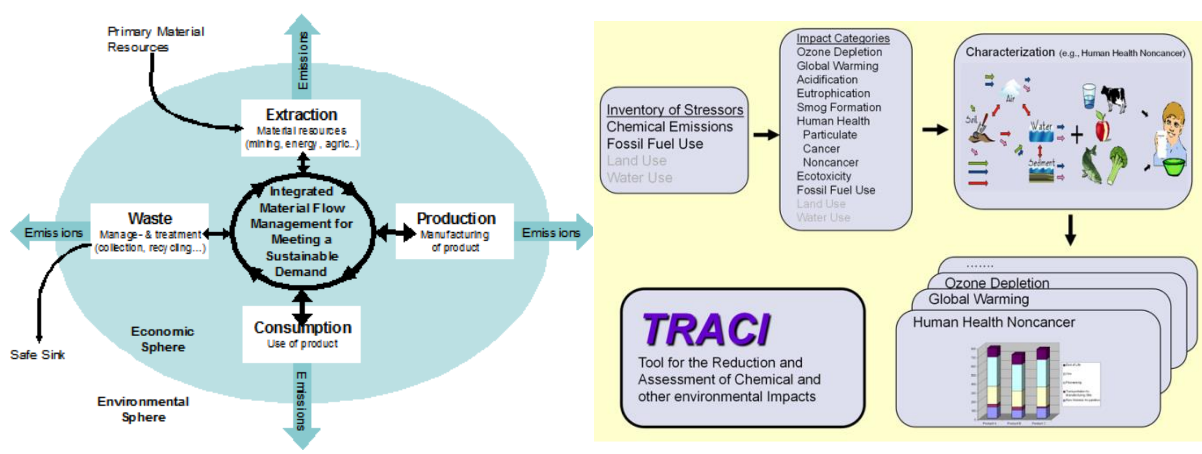


Figure 3: Schematics representing the accounting for life cycle assessment. The RH figure continues from the inventory accounting to the impact assessment for the TRACI methodology.

The LCA and MFA methodologies are well established globally in industry, academia and government as tools for process improvement, hotspot analysis and identifying cost reduction opportunities. The LCA methodology is primarily limited by data availability. The data that is freely available is typically industry averages. Data access and / or development is typically very costly. There are established ISO standards (14040, 14044) for conducting LCAs and the LCA research community continues to improve the methodology for dynamic analysis, geographic specificity, more thorough and detailed impact assessments and broader capability to understand market impacts. Despite the continuing evolution of the methodology, researchers have been able to utilize LCA to improve upon products and processes. One of the original LCAs conducted was by the Coca Cola Company looking at its packaging system in the 1960's. They were evaluating moving from glass to plastic bottles and the results of the study helped shape their packaging decisions.

The LCA methodology has evolved to allow the development of environmental product declarations, carbon footprints, water footprints and other labeling initiatives. ISO standards have also followed to provide guidance on the development of environmental product declarations (EPD) (ISO 14025). Additionally, the European Union (EU) has developed some additional product environmental footprint (PEF) standards that expand on the ISO requirements (EC ND).

2. Technology Assessment and Potential

2.1 Material flows

In 2005 the US used nearly 20% of the global primary energy supply and 15% of globally extracted materials, equivalent to 8.1 gigatons. However, at roughly 27 metric tons (MT) per person, US per capita material use is higher than most high-income countries and is approximately double that of Japan and the UK (Gierlinger and Krausmann, 2012). The US and most of the world has utilized a linear material economy for most of history. A linear material economy is one where materials are used to make products and then the product is disposed of at end of life in a landfill. With growing population and increased quality of life the demand for products has increased and a transition has begun to a circular material economy, where products are being reused and recycled at end of life. This thinking is closely tied to the concept of material efficiency.

The MIT Environmentally Benign Manufacturing (EBM) group has looked at what impact this growth might have. In addition to the growth in US material consumption, global demand for engineering materials has increased by a factor of four over that last half century (figure 4). With the projected growth in the population also continuing to increase, this global demand is expected to continue.

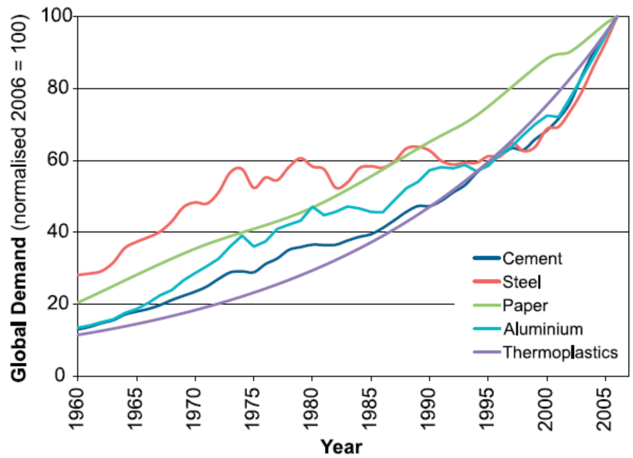
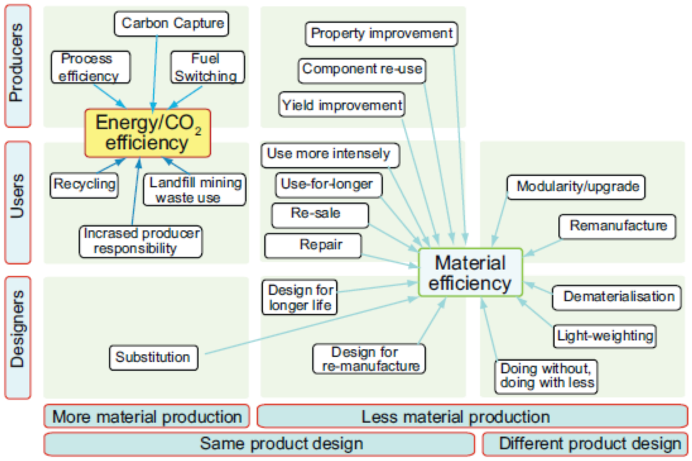


Figure 4: Normalized demand for five key engineering materials from 1960 – 2005. (Allwood et al., 2010).

The material consumption reflects the front side of the problem. On the back side, the US generated close to 2.7 B MT of waste in 2000. 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). Huang et al. (2009) found that 75% of carbon emissions are from scope 3 sources[1] indicating that the supply chain is an opportunity space to reduce emissions. This figure was confirmed by a recent pilot study conducted by Quantis on the new GHG protocol accounting tool[2]. Dahmus (2014) also looked at opportunities in the supply chain and found that the next step to improving energy efficiency is to look at resource consumption in the supply chain. The cases evaluated by Dahmus (2014) suggest that the market would respond to appropriate incentives and move toward reducing resource consumption and the associated environmental impacts. Looking at the supply chain and resource consumption provides an opportunity to evaluate the entire system to understand where there are hotspots and which issues are pervasive. The field of industrial ecology looks at this problem from a slightly different perspective in that they are looking to link different industries in a common location to optimize utilization of waste products from one industry as a resource for another.

The next step after maximizing energy efficiency in the supply chain is to implement maximum material efficiency. Allwood et al. (2011) looks at this issue and the opportunities. Figure 5 illustrates the opportunities of energy efficiency compared to material efficiency. The opportunities affect different parties (producers, users, designers).

[1] The GHG protocol evaluates carbon emissions under 3 categories or scopes. Scopes 1 and 2 are reflecting direct (fuel) and indirect (electricity) energy usage; scope 3 looks at other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity transmission and distribution losses, outsourced activities, and waste disposal.
[2] Accounts for emissions from scope 1, 2 and 3 sources.



Strategies for material efficiency
Light weight design
Reducing yield loss
Diverting manufacturing scrap
Reusing components
Longer life products
More intense use

Figure 5: Material efficiency contrasted with energy efficiency around different actors and solution spaces, and strategies for material efficiency (Allwood et al. 2011).

Varying concepts to address the broader scale impacts of industrial society have been developed over the last few decades. LCA is a methodology that has been in use for several decades and provides a holistic approach to understanding the impacts of a product or process from cradle (extraction) to grave (end of life). LCA involves an accounting of all the inputs (resources and materials) and outputs (chemical emissions, waste, products) for the entire life cycle and linking them to impacts to human health and the environment. Environmental engineering (initially called sanitary engineering) refers to the integration of science and engineering principles to improve the natural environment, to provide healthy water, air, and land for human habitation and for other organisms, and to clean up pollution sites. Environmental engineering looks to address the issue of energy preservation, production asset and control of waste from human and animal activities (waste and waste water management) and emerged as a field in response to concern over widespread environmental quality degradation from water and air pollution impacts. Life cycle engineering (LCE) is another methodology described by Alting and Legarth, 1995 as the art of designing the product life cycle through choices about product concept, structure, materials and processes, and life cycle assessment (LCA) is the tool that visualizes the environmental and resource consequences of these choices. Life cycle design (LCD) utilized the concept of design for service that looks at ease of repair, disassembly and recycling, and addresses issues related to the end of life (EOL) of products. Sustainable production has the intent of providing products that are designed, produced, distributed, used and disposed with minimal (or none) environmental and occupational health damages, and with minimal use of resources (materials and energy) (Alting and Jorgensen (1993). Design of the Environment (DfE) (www.epa.gov/dfe/) is a USEPA program and label to reduce the presence of harmful chemicals in products that can migrate into the environmental and have harmful human and environmental health impacts. Design for deconstruction and disassembly (DfD) or life cycle building is a concept for designing buildings to maximize flexibility, reuse, disassembly and to minimize construction waste and energy costs which is included the in USEPA definition of a green building (USEPA, NDa). In addition to these concepts and methodologies, there is also green engineering, green chemistry, closed loop manufacturing, environmental benign manufacturing, eco-design, life cycle management, sustainable engineering, and life cycle design. There is some overlap between the different methodologies, with differences coming from how the methodologies are focused and which fields they are applied to.

Historical efforts have targeted specific industries, facilities and processes and were focusing on areas that had potential large impacts due to the higher energy intensity or high demand from those areas. These were low hanging fruit. Shifting focus to the supply chain can both support the evaluation of specific technologies, but also identify areas of interest that while may not be considered high energy intensity or high demand for individual processes, they are pervasive through the system and have opportunity for significant energy efficiency improvements. Additionally, the idea of material efficiency (Allwood et al. 2013) takes this a step further and recognizes that there is energy required to produce commodity products and that reducing the amount of material required to produce different products, not only in the production process (reduction of industrial scrap) but also in the product itself (light-weighting), there is significant opportunity for energy reduction. This concept is in play for additive manufacturing (AM). While the energy intensity of AM is currently very high, the benefits from reduced material demand (lower buy to fly ratio) and product weight results in energy savings both from the material production and the end use of the product (see AM technology assessment). Material efficiency could also help ease the demand of critical materials and minimize the reliance on foreign material imports (i.e. lithium) and minimizing energy intensive material usage (see critical materials technology assessment).

The EU (EC 2001) has also looked at the material efficiency issue and has reported on the opportunities, risks, challenges and costs of implementing material efficiency measures. The report covered EU competitiveness, jobs, productivity, environmental impacts and resiliency. The report acknowledges that materials are a finite resource and that existing trends in material efficiency will not be adequate to reduce the material intensity of their economy. Risks include reduced competitiveness and supply security implications. Benefits included improved productivity, growth and job creation, environmental health and resilience benefits and macroeconomic stability. Costs would come from exposure to the risks and volatilities of resource scarcity and shocks and competitive advantage shifting to developing countries with less locked into physical infrastructure and institutional rigidities. Adaptation to resource megatrends over time will involve structural economic change and will involve updating of technologies, innovation, skills which will have transitional costs. These costs will depend on how well change is predicted, the pace of change, and the flexibility of the economy.

2.2 Global Flows/Materials-Energy-Emissions Embodied in Trade

In a global economy there are materials and products moving across boarders for just about every type of product. Production of a laptop requires material extraction from all over the world, transport to Asia for assembly in different facilities and final transport to the U.S. for distribution and sales to the end consumer. There is starting to be some accounting for social impacts (i.e. labor abuses) in international production lines, but no accounting for carbon impacts associated with imported products. Australia implemented a carbon tax in 2012, but then repealed it in 2014 (Taylor and Hoyle, 2014). In 2012, Japan completed a governmental pilot project for carbon footprinting of products and transitioned to long term program to identify carbon hotspots and provide information to companies and consumers[3]. Since 2008, the French have been working on developing a system to inform the consumer of product carbon footprints. These efforts have gone through several stages and are continuing to evolve. Some carbon accounting in life cycle assessment has tried to highlight the offshoring of carbon emissions. This is a large issue with biofuels from Brazil that are impacting the rain forests and increasing carbon emissions

[3] http://www.pef-world-forum.org/initiatives/country-governmental-initiatives/japan/

due to land use change. There are not currently any carbon import taxes. There are also some studies looking at the embodied energy in trade. Liu and Miller (2013) provide some analysis around flows of anthropogenic aluminum with Germany, China and the US being the largest importers (figure 6 below). Chen and Chen (2011) evaluated global energy consumption through an analysis of embodied energy. The US, as the world 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 US on a per capita basis.

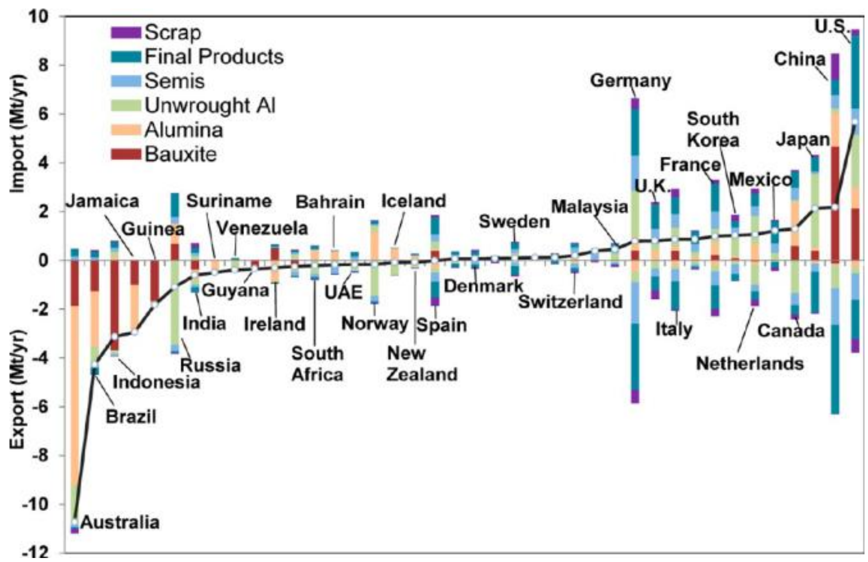


Figure 6: International trade of aluminum in bauxite, alumina, unwrought aluminum, semis, final products, and scrap in 2008. The countries are sorted by total net import from left to right (the dark curve represents total net trade). All values are aluminum metallic equivalent in Mt/yr (Liu and Muller, 2013).

2.3 Methodologies to reduce impacts across the life cycle

The impacts of the system can be covered under several categories: energy efficiency, material efficiency and life cycle impacts.

2.2.1 Energy efficiency

Choi Granade et al. (2009) provided a detailed analysis of the opportunity space around energy efficiency. Energy efficiency has been the focus of analysis and efforts for the last few decades and has made steady improvements in the ability to produce more with less energy. The report indicated opportunities for further savings worth more than $1.2 trillion and reducing US energy consumption by 9.1 quads by 2020. This would equate to 1.1 GT per year of greenhouse gas reductions. The report suggests that there is opportunity to reduce projected end use consumption in 2020 by 23% and primary energy consumption by 26%. The report additionally looks at the challenges for achieving improved energy efficiency and some strategies and solutions. . The energy efficiency arena is one that DOE has worked in extensively and continues to do so.

2.2.2 Material efficiency

Accounting for resource or material use is another way to evaluate the efficiency of technologies and manufacturing processes. Sustainability initiatives have looked at the concept of “reduce, reuse and recycle" for many years. Recycling has been on the forefront of these efforts. The reduction of material usage however has large opportunities in reducing energy consumption early in the supply chain and reducing extraneous processing to make use of non-optimal usage of material in manufacturing. The amount of in-plant scrap that is produced reflects the inefficiency of the process. Some industries have taken significant steps to reduce this scrap. The garment industry uses computer programs to determine how to best cut the fabric to minimize the in plant scrap; this programming optimizes the material in the bolt to include small items (belts, pockets, etc.). This optimization minimizes to amount of scrap generated and generally material not pre-measured is waste. White cotton is typically the only material scrap that can be recycled (for high quality paper). For the aluminum and steel industries, in plant scrap is reusable and is of higher quality than post-consumer scrap. However, in-plant scrap still requires additional processing to reuse and there is a cost and additional energy associated with this additional processing.

The aluminum industry produces over 900K MT of in-plant scrap. There is embodied energy associated with this scrap that could be saved by increasing material efficiency (discussed previously in section 2.1). This could come from multiple activities. With increased recycling (use of secondary aluminum) the saving amounts to up to 38 GJ/MT for every metric ton of primary aluminum replaced by secondary aluminum. The current supply chain energy for aluminum (which averages 68% primary aluminum and 32% secondary) equates to 45 GJ/MT with the majority of that energy demand coming from alumina (33%) and anode (25%) production. If the primary/secondary ration shifted to a 40/60 ration, the supply chain energy demand would decrease to 34 GJ/MT. With a light weighting and reduced yield loss strategy, the initial demand is decreased and the savings amounts to up to 57 GJ/MT. The strategies for reusing components, longer product life and more intense use also can result in decreased total demand.

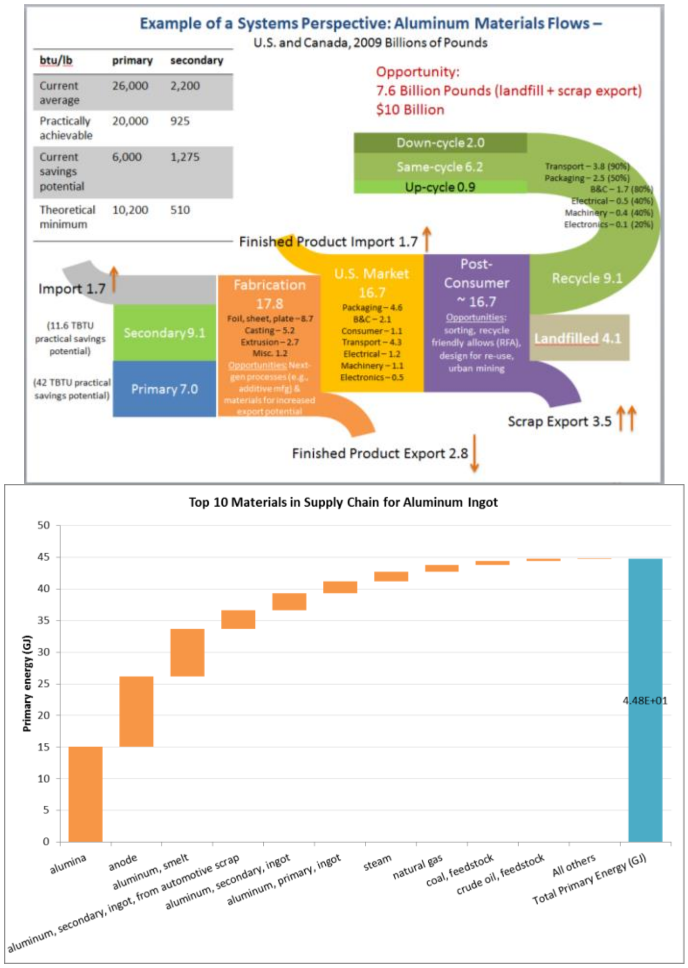


Figure 8: Aluminum flows through economy (DOE AMO 2013) and the most energy intensive materials in aluminum supply chain.

The argument can be made that energy efficiency is really just material efficiency but applied only to fuel materials. Material efficiency would broaden the scope from just fuels to all materials. As all materials have an energy intensity associated with their production (embodied energy), reduction in the overall material demand for producing final products would result in a reduction in energy consumption associated with the production of these products.

Additive manufacturing (AM) is a methodology that increases the material efficiency of production. Combined with analysis of the life cycle impacts of a particular product, advanced manufacturing has the potential to significantly reduce energy use and environmental emissions. The following case studies demonstrate the ability of additive manufacturing to reduce embodied energy and use phase energy through increased material efficiency. In the first case study, additive manufacturing is used to reduce the raw material required to produce an aerospace bracket by 95%. This results in a 95% reduction in the energy used in raw material production and part manufacturing, and a 13% reduction in total life cycle energy.

In the second case study, additive manufacturing is used to not only reduce the material required to produce the bracket by 93% but also to enable a new design that weighs 65% less than the original. In addition to a 93% reduction in energy for raw material production and part manufacturing, the new lightweight design reduces use phase energy by 65% and total life cycle energy by 66%. The new design also contributes to the transportation energy savings due to less mass being transported to the manufacturer, to the final customer, and for end of life recycling/disposal.

Aluminum recycling is a well-known example of applying material efficiency. 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 9 looks at the supply chain energy demand for four scenarios evaluating aluminum ingot. The energy savings from material efficiency are scaled to the efficiency improvements. The energy savings for the increased use of secondary aluminum is 38 GJ/MT.

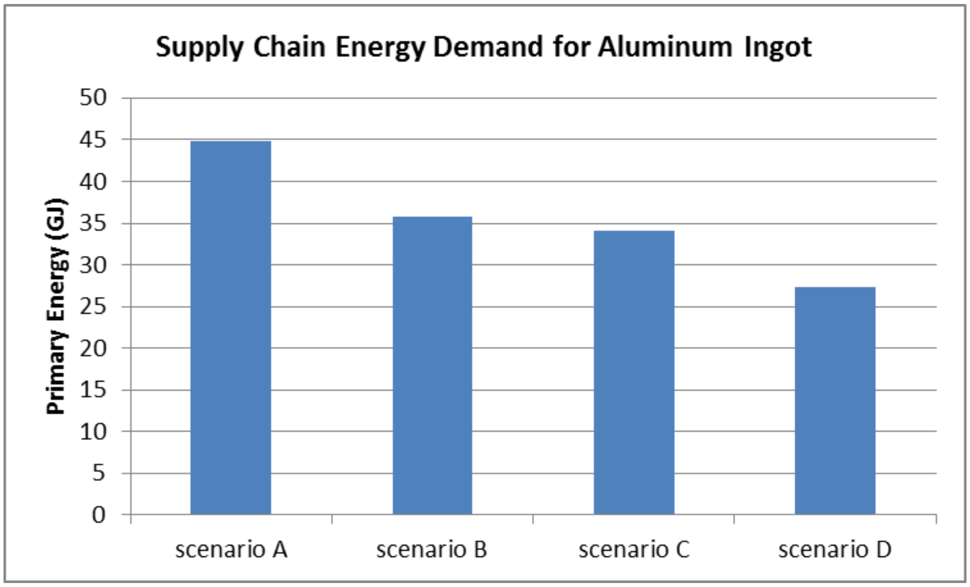


Figure 9: Supply chain energy demand for aluminum ingot for four scenarios. Scenario A is a baseline business as usual for 1000 kg. Scenario B is a 20% improved material efficiency (decrease in buy to fly ratio; 800 kg) from the baseline. Scenario C is the increased use of secondary aluminum (40/60 primary to secondary aluminum ratio; 1000 kg). Scenario D is a 20% increase in material efficiency with increased secondary aluminum (800 kg).

2.2.3 Minimizing Externalities

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 moving from one technology level to the next. Burden shifting is when trying to reduce the impacts in one stage of the life cycle, geographic location or impact category and having that result in an increase elsewhere. An example might be if a reduction in energy demand in the manufacture of a product results also results in an increase in the energy demand through the use phase of the product; or a reduction in fossil fuel demand during the use phase results in an increase in ecotoxicty impacts during the manufacturing phase. The life cycle approach allows the researcher/analyst to understand the entire system associated with a product or process, from cradle/extraction to grave/end of life/disposal/recycling and to look at all the different types of impacts that are occurring in each life cycle stage and look for a solution that minimizes all impacts across all life cycle stages. When looking at individual impacts, LCA can help find solutions that will minimize impacts across all life cycle stages and feasibly across the economy. LCA is used by industry to do process improvements to understand where in the life cycle the impacts are occurring and to use the information to reduce waste (cost), increased efficiency (cost), and reduce toxics (cost). It also helps to understand that reductions of impacts in one part of the life cycle might result in an increase in another, but achieves a net savings.

Some commonly utilized sustainability metrics are listed in table 1. 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 Nike analysis utilizes a range of criteria to understand the sustainability of their products (text box 1).

Table 1: Typical impacts that are evaluated with life cycle assessment. (Pre 2014, USEPA 2006)

Impact Category	**Scale**	**Chemical and physical contributors (examples)**	**Common characterization**	**Impact description / Endpoints**
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, longer seasons, forest loss/change, and change in wind and ocean patterns.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depletion Potential	Increased ultraviolet radiation.
Acidification	Regional; Local	Sulfur Oxides (SO_x) Nitrogen Oxides (NO_x) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification potential	Building corrosion, water body acidification, vegetation effects, and soil effects.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication potential	Algal blooms, hypoxia, the depletion of oxygen in the water, which may cause death to aquatic animals.
Photochemical smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical oxidant creation potential	Smog, decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage.
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 and decreased commercial or recreational fishing.
Human Health	Global, Regional, Local	Toxic releases to air, water, and soil; radioactive elements	LC50; ionizing radiation; respiratory effects	Increased morbidity and mortality.
Resource depletion	Global, Regional, Local	Quantity of minerals used; Quantity of fossil fuels used	Resource depletion potential; abiotic depletion	Decreased resources for future generations.

Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications	Land availability; agricultural land occupation; urban land occupation; natural land transformation; land use change	Loss of terrestrial habitat for wildlife and decreased landfill space.
Water Use	Regional; Local	Water used or consumed	Water shortage potential; water footprint	Loss of available water from groundwater and surface water sources.
Ecosystem Quality	Local	Eco toxicity + acidification + eutrophication + land use		
Cumulative Energy Demand	Global	Quantity of renewable and non-renewable energy used	Energy footprint	

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

References

Different federal agencies are also evaluating different environmental impacts. DOE BETO is evaluating greenhouse gases, water use, energy use, land use, and air quality impacts for the biofuels program. The DOE Office of Fossil Fuels does full LCAs on the different fossil fuels and develops life cycle inventory data that is publicly available (http://www.netl.doe.gov/research/energy-analysis/life-cycle-analysis). The USEPA 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). NRML has also developed and are maintaining an impact assessment methodology that is specific to the US context. The USDA has also been using LCA to evaluate the impacts of biofuels and have developed a life cycle inventory (LCI) library based on data in the National Agriculture Library (NAL) (http://www.lcacommons.gov/). The Department of Defense (DoD) has started to look at multiple types of impacts in their sustainability analysis for their updated acquisition program (Yaroschak, 2012). The sustainability analysis includes both LCA and life cycle cost analysis (LCCA) and covers impacts to the mission, human health and the environment. Figure 10 lists the broad range of specific life cycle impacts being assessed. The DoD goal is to analyze alternatives for meeting mission requirements and make informed decisions that result in sustainable systems and lower total ownership costs which are defined a sum of internal costs (to DoD), external costs (to society and the environmental) and contingent (risks). One of the DoD studies compared 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 requires extensive (and costly) protective measures when applying and the requirement of additional hazardous waste management. Utilization of a non-chromated coating system require more frequent applications, but without the extensive protective measures. A spider diagram analysis was utilized to select the best scenario or option based on the full range of criteria being analyzed (example in figure 11).

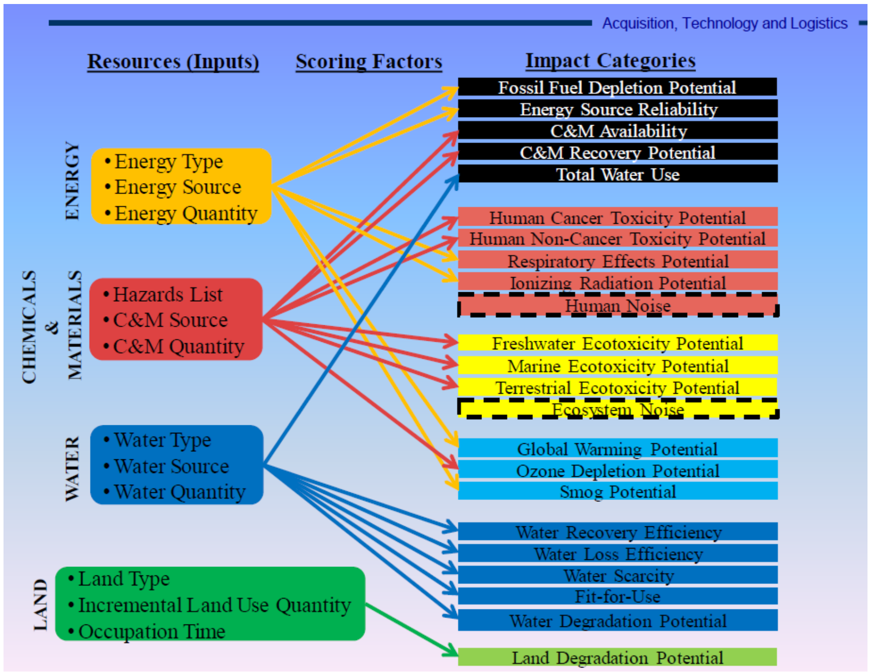


Figure 10: resources and impacts covered under the DoD Acquisition, Technology and Logistics sustainability assessment program (Yaroschak 2013)

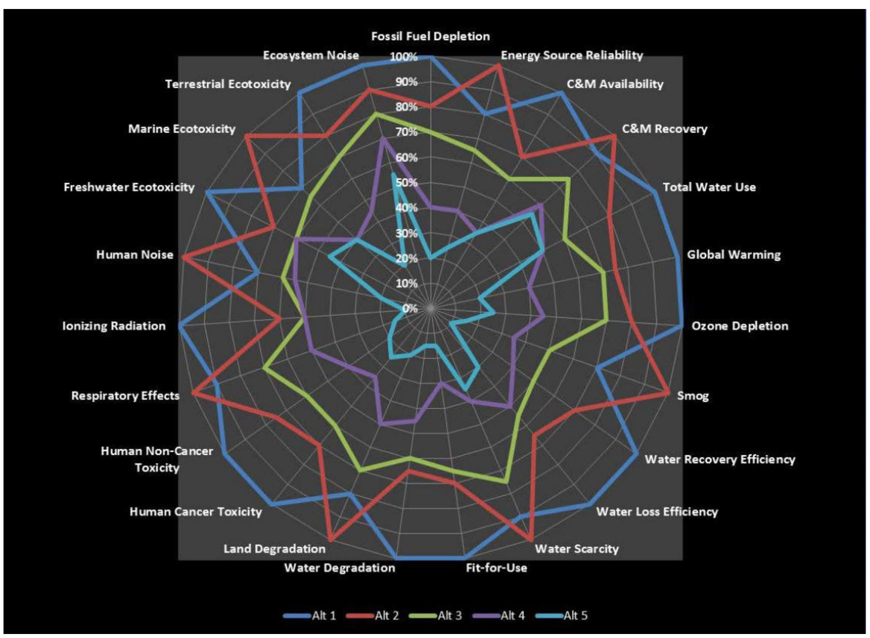


Figure 11: The DoD sustainable acquisitions program analysis spider diagram analysis (Yaroschak 2013)

Many of the impacts evaluated by LCA are considered externalities. An externality is the cost that affects a party who did not choose to incur that cost (Buchanan et. al 1962). Externalities by definition can have a positive or negative effect. Manufacturing activities that cause air pollution impose health and clean-up costs on the whole society, whereas the neighbors of an individual who chooses to fire-proof his home may benefit from a reduced risk of a fire spreading to their own houses.

Society has historically adopted new technologies without understanding the ultimate hazards (Commoner, 1969). Some examples of negative externalities include:

- Air pollution from burning fossil fuels causes damages to crops, (historic) buildings and public health (Torfs et al. 2004; Rabl et al., 2005). Air pollution from a coal-fired power plant can present a health hazard to the neighboring community. These neighbors can suffer additional asthma, bronchitis, and even premature mortality as a result of producing electricity by burning coal.
- Anthropogenic climate change as a consequence of greenhouse gas emissions from burning oil, gas, and coal. The social cost of carbon is projected to start at $25-30 per mt CO2e if CO2e concentrations are stabilized at 450 parts per million.
- Water pollution by industries that adds effluent, which harms plants, animals, and humans.
- The costs of managing the long term risks of disposal of chemicals, which may remain permanently hazardous, is not commonly internalized in prices. The USEPA regulates chemicals for periods ranging from 100 years to a maximum of 10,000 years, without respect to potential long-term hazard. The industrial sector uses a wide range of chemicals and hazardous waste management is a common issue.

Examples of positive externalities include:

- Construction and operation of a manufacturing facility contributes to job opportunities for the surrounding community and money spent in that area by the workers. This is an externality that Congress and the administration are actively concerned with and job growth is regularly tracked.
- Driving an electric vehicle reduces dispersed GHG emissions and improves local air quality leading to better public health.

Motor vehicles cause air, nose and water pollution, traffic delays and accidents; it requires infrastructure for roadways, signage, and fuel delivery. Delucchi (2000) accounted for the social costs associated with different aspects of air pollution, human health, water pollution, noise and climate change with total costs ranging from $38-546 billion dollars for US motor vehicle usage ($1991).

The NRC (2009) reports climate change damages from the production, distribution and use of energy at between $1 – 100 per ton of CO2e based on emissions in 2009. The range is partly to do discount rate assumptions and partly due to assumptions about future events. Without emissions controls, damages are on the higher end of the range. Non climate damages (which were not evaluated comprehensively) were a small fraction of climate damages.

There are many studies that look at multiple impacts associated with emerging technologies. Jungbluth (2005) performs a life cycle assessment of photovoltaic (PV) power plants based on twelve different grid connected PV system in Switzerland for the year 2000. The study provides insight as to the different types of environmental impacts as well as the associated life cycle stages. Figure 12 provides insights about what kinds of impacts are occurring in which stage of the life cycle. For example, fossil energy demand is dominated by the silicon purification process, and ecotoxicity is predominantly from the production of BOS components, but also has significant contributions from panel production and wafer sawing. The eco-indicator 99 (H, A) and (I, I) presents analysis that combines the impacts into a single score that is weighting the impacts from the different categories. The (H, A) score reflects a methodology that weights energy resource usage higher, where the (I, I) score weights metal resource usage higher.

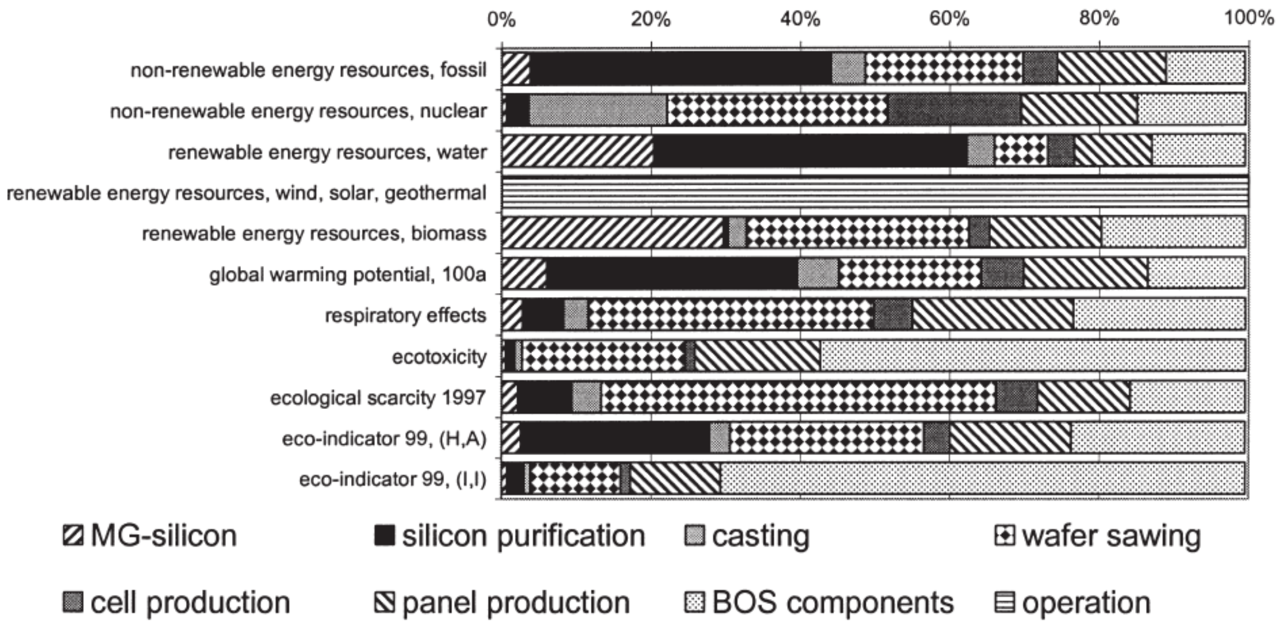


Figure 12: Share of process stages for Swiss grid-connected, 3 kWp slated roof installation with a polycrystalline silicon panel evaluated with different LCIA method. (Jungbluth, 2005).

The Hawkins et al. (2012) study evaluated the life cycle assessment of an electric vehicle compared to a conventional one and evaluated a range of impacts. Figure 13 shows the environmental impacts associated with the different scenarios by life cycle stage. In this analysis, the EV scenarios do not appear to provide significant benefits in any impact category except for fossil resource consumption and photochemical oxidation (ozone) formation.

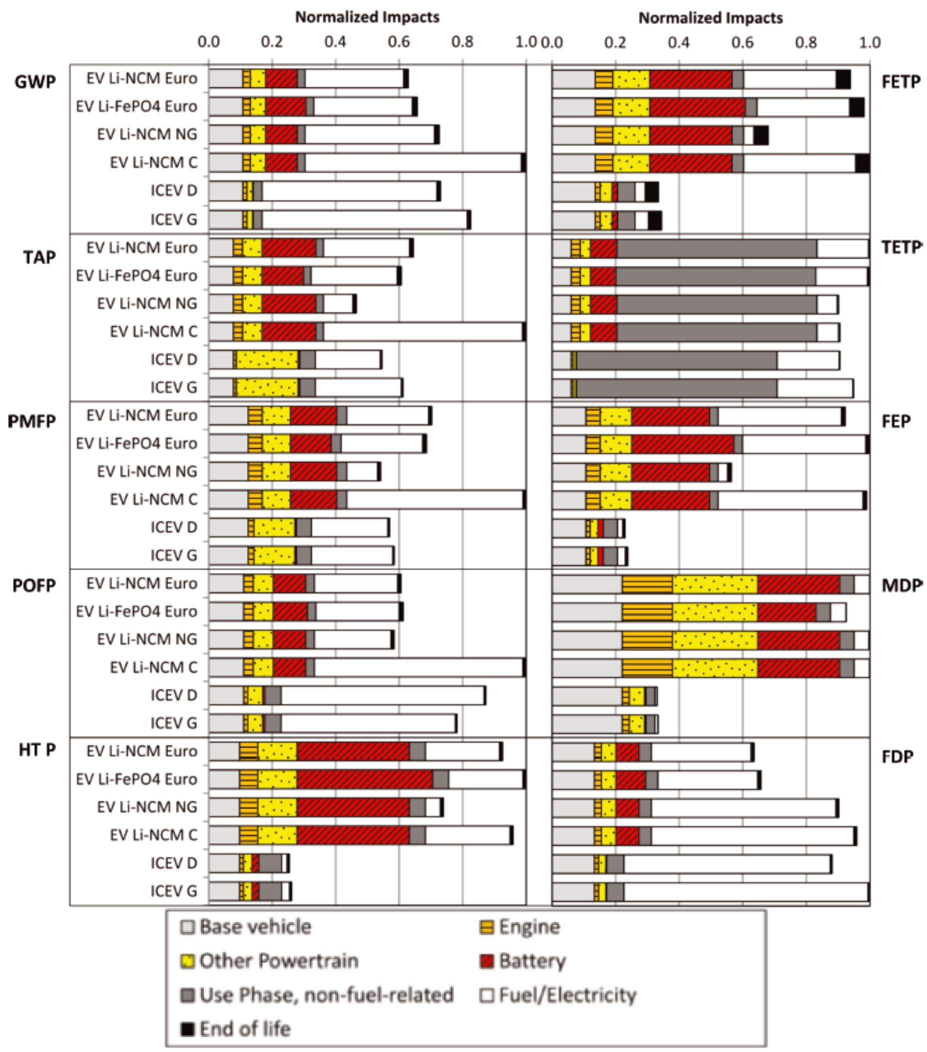


Figure 13: Impacts of vehicle production normalized to the largest total impacts[Global warming (GWP), terrestrial acidification (TAP, particulate matter formation (PMFP), photochemical oxidation formation (POFP), human toxicity (HTP), freshwater toxicity (FETP), terrestrial eco-toxicity (TETP), freshwater eutrophication (FEP), mineral resource depletion (MDP), fossil resource depletion (FDP), internal combustion engine (ICEV), electric vehicle (EV), lithium iron phosphate (LiFePO4), lithium nickel cobalt manganese (LiNCM), natural gas (NG), European electricity mix (Euro)] (Hawkins et al. 2012).

The 2001 study by Corbiere-Nicolier et al conducted an LCA study to compare glass fibers to a bio-fiber equivalent made from the China reed (CR) fiber and conducted some sensitivity analysis around the assumed pallet life time and plastic composition. Figure 14 indicate that the CR pallet has lower impacts in all categories than the GF pallet. The results from the sensitivity analysis are show in figure 15. The CR pallet needs to have a lifetime of at least 2.2 years to match the energy impacts of the GF pallet. For the plastics composition, the increase in fiber increases the young’s modulus, but the CR pallet shows a greater decrease in energy demand with the increase in fiber than the GF pallet.

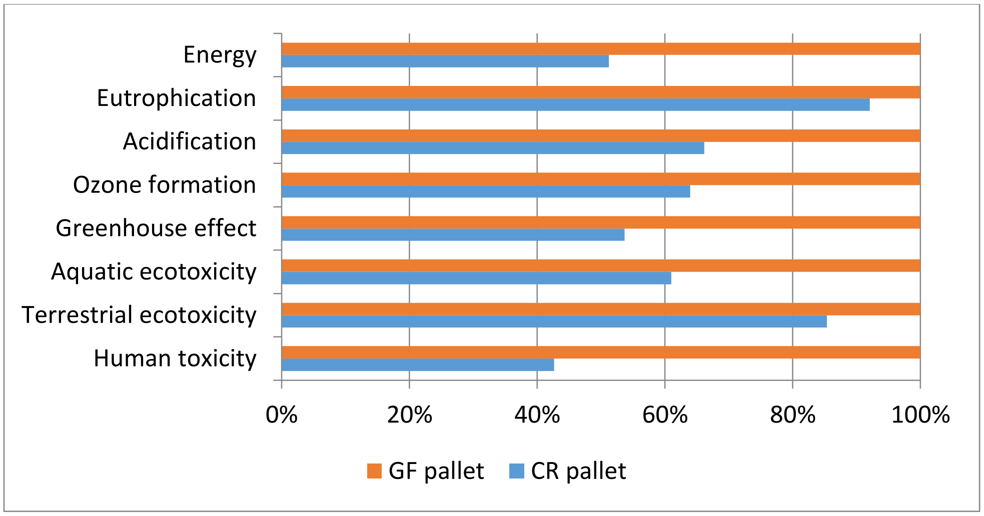


Figure 14: Impact assessment results for GF pallet compared to CR pallet using the CML92 (reference) methodology (Corbiere-Nicolier et al, 2001)

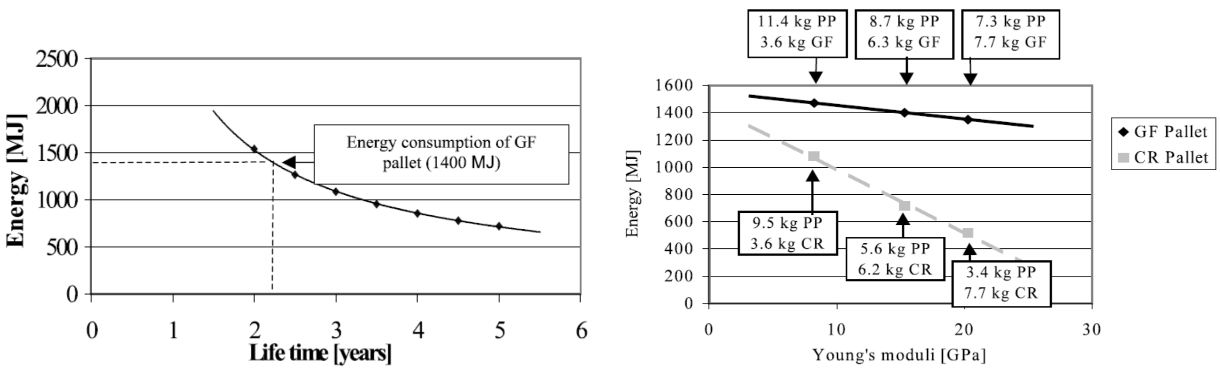


Figure 15: Pallet life time (a) and plastic composition (b) sensitivity results (Corbiere-Nicolier, 2001).

3. Program Considerations to Support R&D

3.1 Expanding boundaries of DOE analysis

DOE has looked to strengthen US energy security, environmental quality and economic vitality through enhanced energy efficiency and productivity. This has been achieved through a series of mechanisms to include manufacturing demonstration facilities, technology deployment, investment in innovate manufacturing processes and next generation manufacturing and analysis of life cycle energy impacts. Figures 16 and 17 represent the thinking around the use, energy and carbon intensities reduction opportunities for the industrial sector. Material efficiency is a mechanism that can affect all the intensities and the boundary of analysis needs to open up to include the supply chain.

Use Intensity	Energy Intensity	Carbon Intensity
Primary and non-destructive recycling	Process Efficiency	Feedstock substitution
Reuse and remanufacturing	Electro-Technologies	Green electrification
Material efficiency and substitution	Combined heat and power	Green chemistry
By-products	Process integration	Renewable Distributed Generation
Behavioral change	Waste heat recovery	Carbon, capture and sequestration
Product-Service-Systems	Supply chain integration	Biomass-based fuels

Figure 16. Reduction Opportunities in the Industrial Sector

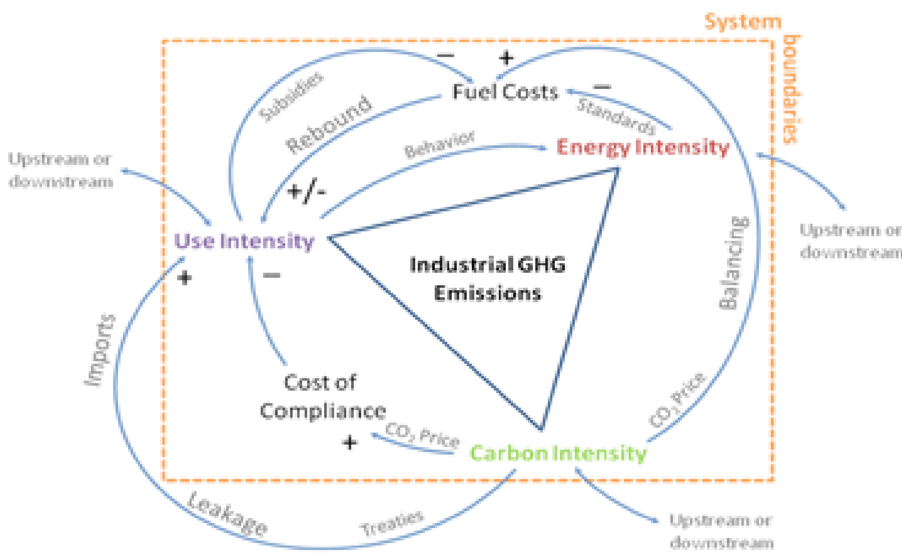


Figure 17. High level analysis framework

The LCA and material flow assessment 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. At a minimum, having an understanding of all the environmental impacts of a technology investment can minimize the risk of investing in a technology that can significantly negative environmental impacts.

3.2 Risk and Uncertainty, and Other Considerations

The risks in the supply chain can be grouped into five different categories (technical, regulatory, economic/competitiveness, environmental, security). The technical risks are associated with problems that can occur with information exchange, technology failure and underperformance. This can be from incorrect application of specifications or lack of precision. Regulatory risks are inherent in all industries and are not addressed here. Economic risk is associated with the cost of capital, technology, energy, materials, operations, etc. and is associated with the competitiveness of the markets. A material in high demand can drive up the cost and reduce availability. This can be especially important for critical materials. Environmental risk 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 ecology. Security risks are associated with the dependence of a material from a politically unstable region. There are also regulatory challenges around shifting to next generation materials for some industries. For increased up 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.

Uncertainty is high with evaluating the life cycle impacts of technologies. This is due to insufficient data availability and data quality issues and especially in highly complex systems.

3.3 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 material demand of the commodity 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 the product durability and lifetime on an economy scale would feasibly reduce the amount of products being consumed and therefore the overall demand. Increased quality control can have impacts through several mechanisms. Improved information exchange between the industry and the supplies would 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, fewer product returns, although it might result in increased market share – higher demand. 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 geo-politically unstable regions with obvious impacts to the supply chain. Identification and minimization of material availability bottlenecks in the supply chain are useful to creating a resilient supply chain.

The supply chain can affect industry through shifts to demand response, on demand technologies and distributed manufacturing. This would feasibly reduce the quantities of material or product that might be ordered at any time, and have the orders distributed to smaller facilities or operations. With smaller orders going to more places, the transportation impacts would be increased.

3.4 Critical materials

The concern of availability of critical materials is a significant one for industry and is being researched at the Critical Materials Institute. 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 ensure that the substitute is a sustainable and less impactful alternative. Minimizing demand through applying material efficiency would also reduce the risk. Recycling and reuse at end of life is challenging, but for materials with a limited supply and a high demand signal, this also will help reduce the need for virgin materials.

Gruber et al. (2011) looked at the global supply of lithium as a constraint for the widespread deployment of electric vehicles due to the limited supply. While Dunn et al. (2012) and Gaines (2014) looked at the other side of the lithium problem in assessing the impacts of recycling lithium-ion batteries. Dunn et al. (2012) was evaluating how recycling could affect the life cycle energy and air quality impacts of lithium-ion batteries, while Gaines (2014) was looking at actions that would facilitate the implementation of an economic and sustainable recycling system for lithium-ion batteries for end of life management.

TEXT BOX – Nike Material Sustainability Index

Nike has developed a Material Sustainability Index (MSI) methodology that has also been adopted by the Sustainable Apparel Coalition on how to evaluate the sustainability of their products. They are using a multi-criteria LCA approach that looks at the life cycles stages from the design of the product through re-use (as their end of life option). The criteria is grouped and weighted and cover different aspects of chemical impacts, energy and greenhouse gas intensity, water and land use and physical waste. A spider diagram (figure 18) is used to help illustrate the final results. Figure 19 and 20 are examples of an evaluation of current products and a comparison against older products (Nike, 2012). There is an online tool that allows users to do product comparisons with varying material input options (www.nikeresponsibility.com/infographics/materials/).

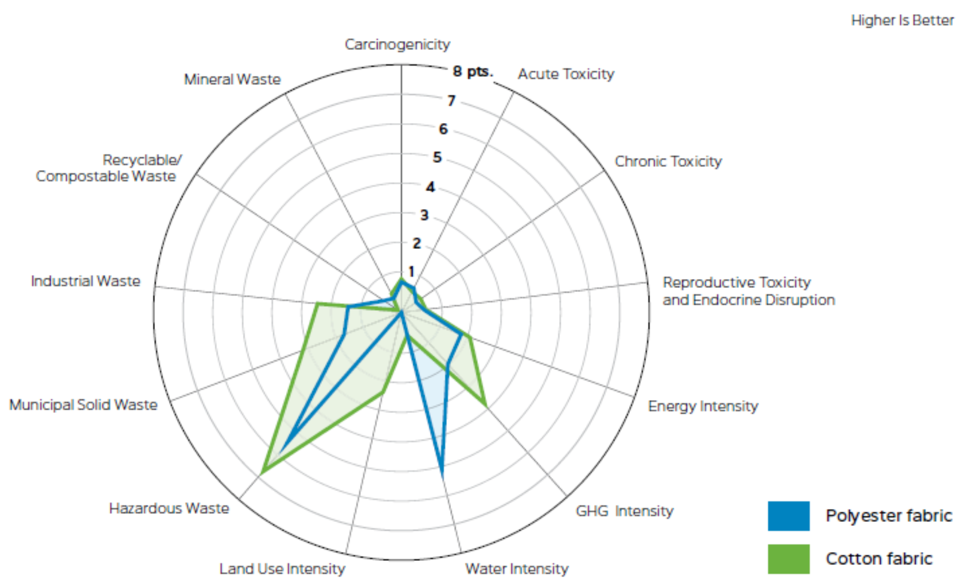


Figure 18: Comparison of environmental trade-offs between cotton and polyester from Nike MSI analysis.

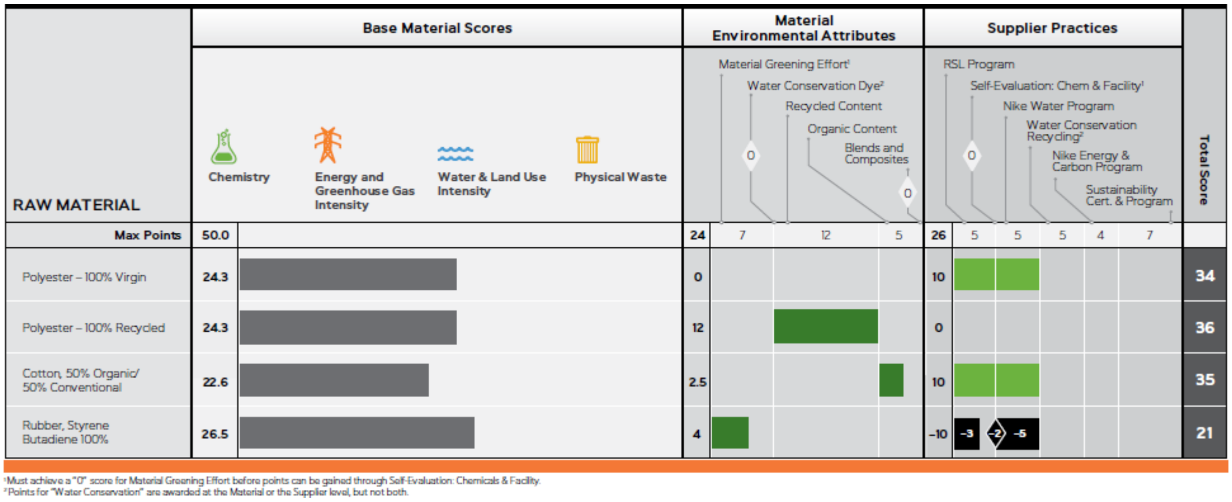


Figure 19: Nike Materials Sustainability Index scoring examples.

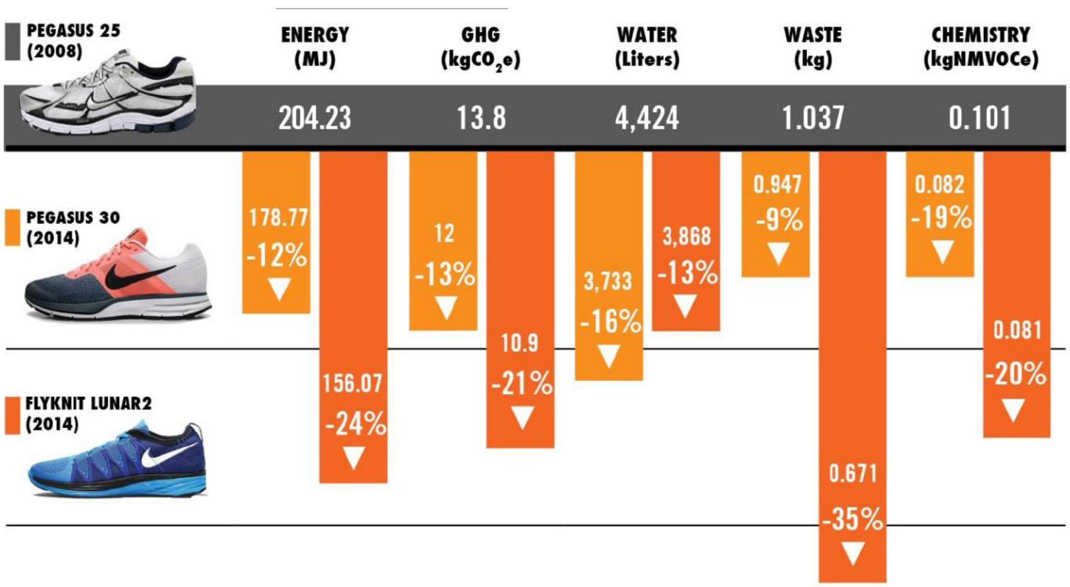


Figure 20: Sustainability metrics comparison of older products against new one

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