Evaluating Supply Chain Sustainability

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Lifecycle analysis (LCA) techniques can be used to quantify the environmental performance of a product, process, or service. This article describes several LCA methods and their application to supply chains.

Whether managing existing supply chains or developing new products and services, companies are increasingly concerned about their environmental footprint, including natural resource consumption and waste generation. To fully understand product sustainability, a business must consider not only its own operations, but also its entire network of suppliers, customers, and supporting resources. This article describes the methods and challenges of lifecycle assessment — a comprehensive approach for quantifying the environmental sustainability of supply chains, from raw material acquisition to end-of-life material recovery.

The expanding scope of corporate sustainability

Over the last decade, environmental sustainability has evolved from an obscure fringe concept to a mainstream concern at the highest levels of corporate governance. This dramatic shift is partly due to changes in the business environment — anxieties over climate change and energy security, increased pressures from stakeholder advocacy groups, and regulatory directives that oblige companies to consider the environmental impacts of their products and operations.

Another key force driving the adoption of sustainability principles has been a growing understanding of its influences on competitiveness and shareholder value creation. As early as the 1980s, companies like 3M began to see a connection between cleaner production and operational efficiency, and began to proactively modify their production processes and technologies to generate less pollution and waste. Common pollution prevention practices include better housekeeping, more-efficient use of resources, elimination of toxic or hazardous substances, process simplification, source reduction, and recycling of process wastes.

By the 1990s, many companies had taken the next logical step — applying these concepts to the full product lifecycle and incorporating environmental awareness into their product development processes. Through programs such as Responsible Care (the global voluntary initiative under which chemical companies work to improve their health, safety and environmental performance, and to communicate with stakeholders about their products and processes), the concepts of product stewardship and corporate citizenship emerged, signifying a broad commitment by companies to environmental and social responsibility. Leading companies, such as SC Johnson, Kimberly-Clark, and Xerox, have adopted design for environment strategies, which include eliminating toxic constituents, reducing packaging, conserving energy, utilizing renewable materials, extending product life, and facilitating end-of-life recovery.

Today, the financial community has recognized that sustainability contributes to shareholder value not only through cash flow improvement, but also through improved asset utilization, customer satisfaction, and brand recognition. Corporate sustainability is defined by the Dow Jones Sustainability Indexes as a business approach that creates long-term shareholder value by embracing opportunities and managing risks that derive from economic, environmental and social developments. This view combines market-oriented innovation and value creation with traditional cost reduction and environmental, health and safety management practices.

In search of strategic advantage, many global companies are expanding the scope of their sustainability initiatives to encompass their full supply chains. A commitment to supply chain sustainability requires awareness of the full product lifecycle, ranging from the conduct of upstream suppliers to the disposition of obsolete products. For example, companies like HP and Walmart have implemented green purchasing policies to ensure that their suppliers adopt sustainable business practices. As multinational firms extend into emerging markets, globalization and outsourcing have only accentuated the importance of corporate environmental and social responsibility in supply chain management. Meanwhile, recurrent incidents of product contamination have heightened customer concern about product quality and integrity.

The expanding scope of corporate sustainability concerns has gradually led to a broader scope of environmental assessment — going beyond the process or facility fenceline to the full range of enterprise and supply chain operations. As illustrated in Figure 1, broadening the system boundaries eventually encompasses the entire product lifecycle, and extends beyond industrial operations to the supporting economic and ecological systems. Understanding the interdependencies among these systems and, in particular, quantifying the value of ecosystem services — such as carbon sequestration and nutrient cycling — has become the new frontier of sustainability assessment *(1)*.

The complexity and global reach of modern supply networks, which may involve hundreds of suppliers and customers, make it challenging to measure and manage their performance. In particular, with regard to both financial and environmental performance, lifecycle analysis tools are needed to support business decision-making regarding new product introduction, supplier selection, capital investment, supply chain operations, and product take-back processes. Some companies have adopted new techniques for lifecycle cost analysis, which quantify indirect or hidden costs across the lifecycle of a facility, product, or process. Similar approaches have been used in the defense, construction, information technology, and other industry sectors to capture the total cost of ownership.

This article focuses on a class of analytic methods, called lifecycle assessment (LCA) techniques, used to quantify the environmental performance of a product, process, or service. While costs can be measured in dollars, environmental impacts are more elusive — they cannot be measured with a single indicator and often cannot be measured at all. In recent years, both the academic and business communities have turned to LCA as a methodology for expanding the scope of sustainability considerations across the supply chain. However, application of LCA requires significant training and has many hidden pitfalls, so it must be used with caution.

Lifecycle assessment methodology

LCA refers to a collection of modeling methods that seek to rigorously analyze the environmental implications of a product, process, or service from a full lifecycle perspective. Resources are consumed and wastes or emissions are generated at each stage of the lifecycle, from natural resource extraction through material processing, transportation, manufacturing or assembly, distribution, customer use, and eventual recycling or disposition. The objective of LCA is to estimate the net energy or material flows associated with a product lifecycle, as well as the associated environmental impacts *(2)*. By understanding these flows, companies can develop strategies to reduce their adverse impacts in ways that are cost-effective, and potentially even profitable.

The first standard methodology for LCA, developed by the Society for Environmental Chemistry and Toxicology in the early 1990s, involved the following steps:

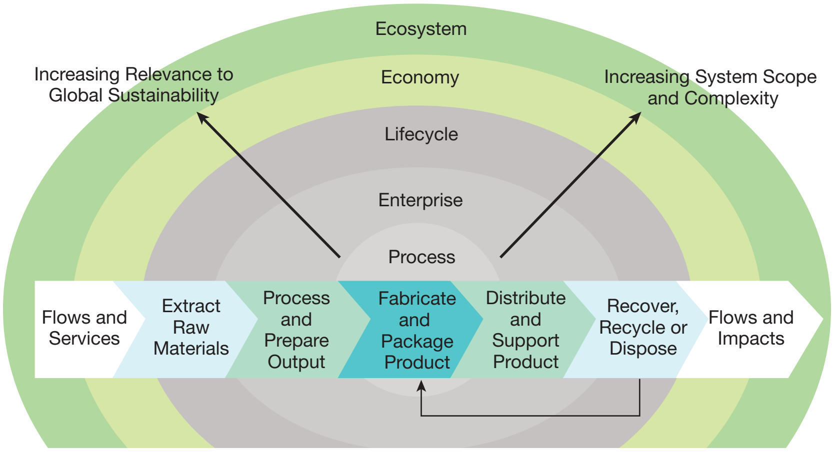
1. *Goal and scope.* Define the product, process, or activity to be assessed and the goal, scope, and system boundaries of the assessment. For comparative studies, it is important to define the functional unit of comparison.

2. *Lifecycle inventory.* Develop a system-wide inventory of the environmental burdens by identifying and quantifying energy and materials used and wastes released to the environment at each stage of the lifecycle.

3. *Lifecycle impacts.* Assess the impacts of the energy and materials consumption and waste releases on the environment and/or human health.

4. *Interpretation.* Evaluate the results and implement opportunities for improvement.

The original LCA methodology has been updated and standardized through guidelines developed by the International Organization for Standardization (ISO 14040:2006 and ISO 14044:2006). These guidelines ensure that all assumptions are transparent, that the system boundaries and



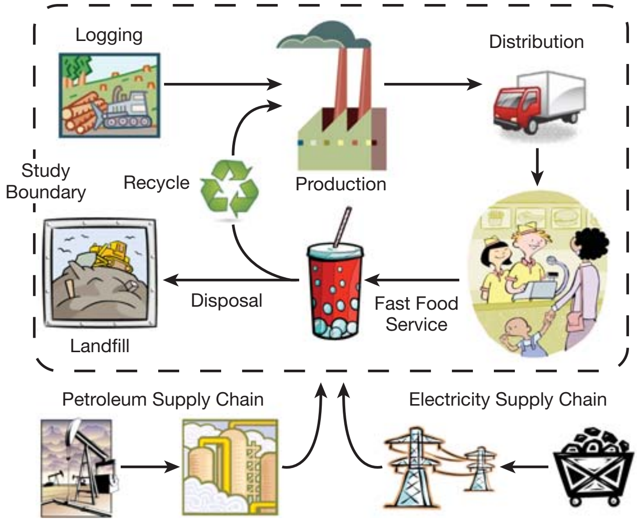
▲ **Figure 1.** The breadth of system boundaries for supply chain analysis may vary considerably.

functional unit of analysis (*i.e.*, product or service value delivered) are clearly defined, and that data quality, uncertainty, and gaps are clearly stated.

LCA has frequently been applied to compare alternative technologies or materials for common consumer products. Figure 2 illustrates a simple lifecycle model that can be used to compare disposable paper cups with cups made of polystyrene foam. The paper cup lifecycle is divided into five major stages — raw material extraction, production (involving multiple process steps), distribution, customer use, and end-of-life. Some fraction of used paper cups will be recycled back into the paper production chain, and the rest will be landfilled. A similar model can be constructed for polystyrene cups, except that the raw material stage involves chemical production rather than logging. One key assumption is the equivalent functional unit — in this case, the paper vs. polystyrene cups are equivalent, but an analysis of grocery bags might assume that two plastic bags equal one paper bag in terms of grocery-carrying capacity.

Traditional LCA studies have been based on bottom-up analysis — detailed characterization of selected industrial processes within the supply chain. Because data collection can become burdensome, a critical issue is establishing the scope of the study in order to keep it manageable. In Figure 2, for example, the study boundary excludes the production of fuel and electric energy, relying instead on published data. LCA studies typically do not collect data on secondary supply chain components, such as truck manufacturing and maintenance, as well as infrastructure maintenance. They may also exclude secondary manufacturing inputs, such as catalysts, cleaning agents, and auxiliary supplies.

These practical scoping decisions can lead to omissions or assumptions that may introduce significant error. Alternative top-down methods (discussed later) overcome this problem by expanding the study boundary and using industry-average estimates of material and energy flows. These newer methods offer a more streamlined approach and deliver more complete, albeit approximate, results.

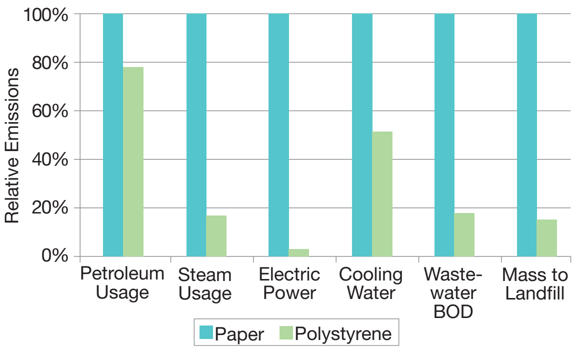


▲ **Figure 2.** The study boundary for the paper cup LCA excludes detailed analysis of the production of fuel and electric energy.

Inventory assessment

Development of a lifecycle inventory involves step-by-step analysis of each process within the study boundary (logging, production, etc.) in order to estimate the resources consumed and the waste or emissions generated. The resources typically analyzed include different types of energy and materials, and accounting for resource flows in a supply network often requires allocation of the environmental burdens based on relative mass or cost. Rapidly renewable energy (*e.g.*, wind power) and materials (*e.g.*, wood) have traditionally been regarded as resource-neutral, since they can be replaced through ecological processes, whereas consumption of nonrenewable resources depletes the available stock. Some more-recent LCA methods account for the use of water and other ecological goods and services that are necessary for continued availability of renewable resources.

Consider again the paper vs. polystyrene cup example. Many environmental advocates have campaigned against the use of polystyrene because it is derived from petrochemicals, arguing that paper is preferable because it is a renewable resource and is biodegradable. In fact, the city of Portland, OR, banned polystyrene cups even though paper cups were more expensive. However, early lifecycle inventory studies comparing uncoated paper cups with polystyrene suggested that paper had higher environmental burdens. For example, Figure 3 compares several categories of resource consumption and emissions on a relative scale *(3)*. A more-recent, more-comprehensive study funded by the American Chemistry Council found that a 16-oz polystyrene cup is roughly equivalent to a paper cup, but slightly preferable when the paper cup is combined with a corrugated paper sleeve *(4)*. In



▲ **Figure 3.** A lifecycle inventory allows comparison of disposable cups made of paper and polystyrene foam. Source: *(3)*.

general, LCA studies often yield conflicting or inconclusive results, and are highly dependent on specific assumptions such as the end-of-life recycling rate.

Impact assessment

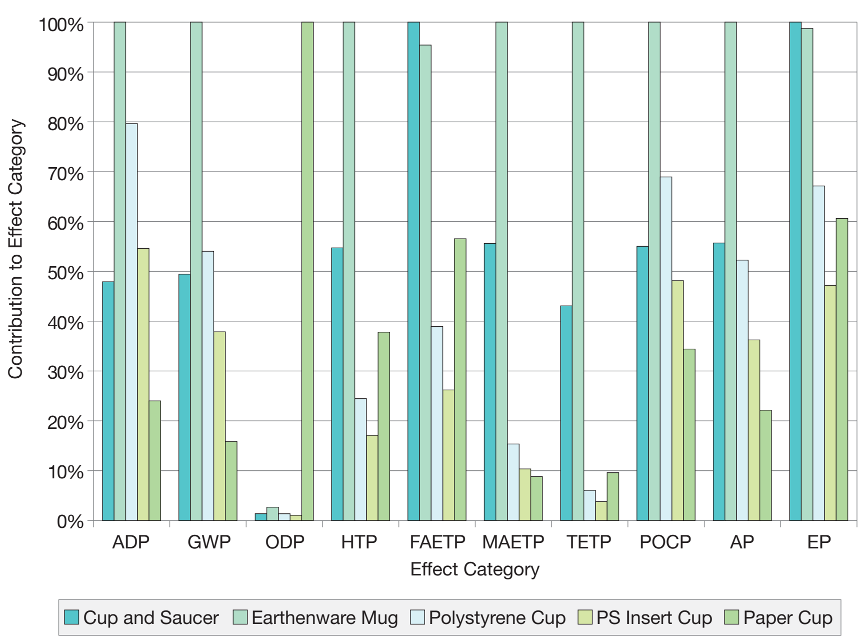
Within the LCA framework described above, the most-challenging step is characterization of the impacts associated with resource use and environmental emissions during each lifecycle stage. These impacts may include environmental, health or safety impacts on humans and ecosystems, as well as economic impacts such as land use restriction and resource depletion. Moreover, impacts may be local, regional or global in nature.

The assessment of impacts is problematic because the complex physical and chemical phenomena that determine the fate and effects of substances released to the environment are not well-understood. Despite much continuing scientific research, knowledge in this arena remains fragmentary and largely theoretical. In some cases, such as greenhouse gas emissions or energy consumption, the impacts are cumulative and broadly distributed, but in other cases, such as mercury emissions or water consumption, the impacts are highly localized and dependent on specific environmental conditions.

Traditional methods for environmental impact assessment are not appropriate for product development purposes because they are detailed and site-specific, whereas LCA is applied at a broader system level. Lifecycle impact assessment uses simplified models that provide relative measures of impact within broad categories. These categories reflect midpoint indicators of potential impact rather than final endpoints corresponding to predicted impacts. For example, the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), developed by the U.S. Environmental Protection Agency (EPA) and widely used in North America, uses CFC-11 equivalents per kg of emissions as a midpoint indicator of ozone depletion potential, rather than assessing the ultimate effects on humans and other organisms of increased exposure to ultraviolet radiation *(5)*. Based on such indicators, it is possible to use simplified impact assessment coefficients to derive relative comparisons of design options in terms of their potential adverse effects on humans or the environment. Assessing the actual risks of such effects requires more detailed environmental risk assessment methods.

An example of impact assessment results is presented in Figure 4, which compares a variety of options, including both reusable and disposable drinking cups. This particular analysis uses an assessment methodology developed in the Netherlands *(6)* and considers the following midpoint categories:

- *abiotic mineral resources depletion potential (ADP)* — indicates consumption of nonliving raw materials (*e.g.*, crude oil, iron ore) relative to the existing stock in the Earth's crust
- *global warming potential (GWP)* — indicates emissions of greenhouse gases (GHGs) expressed in CO_2 equivalents; combustion of renewable materials (*e.g.*, paper) is considered carbon-neutral
- *ozone depletion potential (ODP)* — indicates emissions of ozone-depleting substances (*e.g.*, chlorofluorocarbons), expressed in CFC-11 equivalents
- *human toxicity potential (HTP)* — indicates potential risk to humans resulting from emissions of toxic substances, accounting for their probable fate in the environment and estimated toxic concentration levels
- *freshwater aquatic eco-toxicity potential (FAETP)* — indicates potential risk to freshwater organisms resulting from emissions of toxic substances, accounting for their probable fate in the environment and estimated toxic concentration levels
- *marine aquatic eco-toxicity potential (MAETP)* — indicates potential risk to marine organisms resulting from emissions of toxic substances, accounting for their probable fate in the environment and estimated toxic concentration levels
- *terrestrial eco-toxicity potential (TETP)* — indicates potential risk to terrestrial wildlife resulting from emissions



▲ **Figure 4.** An impact assessment compares the potential adverse effects on humans or the environment. Source: *(6)*.

of toxic substances, accounting for their probable fate in the environment and estimated toxic concentration levels

• *photochemical ozone creation potential (POCP)* — indicates potential for smog formation due to sunlight acting on pollutants (*e.g.*, volatile organic compounds [VOCs], carbon monoxide) in the presence of nitrogen oxides, expressed in acetylene (C_2H_2) equivalents

• *acidification potential (AP)* — indicates potential for adverse effects on vegetation, aquatic life, and human property due to deposition of acidating emissions (*e.g.*, SO_2, NOx), measured in SO_2-equivalents

• *eutrophication potential (EP)* — indicates potential adverse effects of excessive levels of macronutrients (*e.g.*, nitrogen, phosphorus) resulting in increased biomass production and oxygen depletion (*e.g.*, the formation of dead zones), expressed in phosphate (PO_4) equivalents.

The results in Figure 4 suggest that reusable mugs have a larger environmental impact, mainly because of the energy required to clean them after each use. However, the differences between paper and polystyrene are mixed; for example, paper appears to have higher impacts for ozone depletion and human and wildlife toxicity, while polystyrene scores higher in global warming and mineral resources depletion. It is difficult to reach definitive conclusions in light of such trade-offs.

Weighting schemes

A common practice in environmental assessment is to use scoring or weighting techniques to aggregate various specific performance measures. Thus, the ten individual scores listed above (ADP, GWP, etc.) could be combined into a single number. However, this practice is not recommended because the results may be misleading.

Weighting schemes may reflect a variety of different considerations, including:

• values of different stakeholder groups (*e.g.*, customers vs. community)

• relative importance of environmental impacts (*e.g.*, human health vs. ecology)

• internal business priorities (*e.g.*, strategic advantage).

For example, the ISO 14040-43 guidelines for lifecycle assessment include an intricate scheme for quantifying the impacts of substance emissions: classification of substances according to their effects (*e.g.*, carcinogens), characterization of their collective impacts based on environmental exposure and effect modeling, normalization of the effects relative to a benchmark, and weighting of effect scores based on relative importance. Such schemes may conceal policies and value judgments that can skew the results in unintended ways. Therefore, it is important to maintain the ability to drill down in order to understand how specific data contribute to the overall score.

Limitations

The LCA methodology just described has several limitations:

• Rigorous application of LCA requires specialized expertise and training, and can involve considerable time and expense.

• Process-level data are difficult to obtain and may have large uncertainties, especially with new technologies that have not been in widespread use.

• LCA requires assumptions and subjective judgments that may be difficult to validate, and therefore results from different investigators cannot be readily compared.

• System boundaries must be drawn, but important stages in the upstream supply chain or downstream product use chain may be inadvertently omitted.

• Inventory assessment alone is inadequate for meaningful comparison, yet impact assessment is fraught with scientific difficulties.

• Conventional LCA does not account for ecosystem goods and services (*e.g.*, biomass provision, nutrient cycling) and the impacts of renewable resource use, nor does it compare the results against the biocapacity or availability of such resources.

Notwithstanding these limitations, with appropriate definition of system boundaries LCA can be a useful tool for identifying the environmental advantages or drawbacks of various design options, thus supporting product-development decisions *(7)*. Sensitivity analysis can be helpful in determining whether the findings are dependent on any key data inputs or assumptions. However, caution should be exercised in using the results of such analyses for external marketing and communication, such as comparative product claims.

Lifecycle footprint methods

Because of the limitations of LCA, many companies have turned to footprint indicators as a less complex and more meaningful way to measure their environment performance. The term footprint has become popular in the environmental lexicon, but it is used so loosely as to be virtually meaningless. Most practitioners think of an environmental footprint as an aggregate measure of the total burden that a company, a household, or a community places on the environment. Some have interpreted this in terms of a single metric, such as a carbon footprint, while others have interpreted it as a collection of indicators representing different environmental burdens (*e.g.*, energy use, solid waste, air emissions). In the latter case, plotting these indicators on a spider-web chart enables a company to track its progress over time as the footprint shrinks toward zero.

Various study boundaries commonly used for footprint analysis are depicted in Figure 5. For example, an energy consumption footprint may include only nonrenewable energy sources (*e.g.*, petroleum-based fuels, coal, nuclear) or may include renewable sources (*e.g.*, solar, wind, geothermal). A material footprint may analyze total mass throughput, may focus only on consumption of input materials, or may focus on wastes, which in turn may include solids, liquids, and/or airborne emissions. Note that a carbon footprint focuses on just one type of airborne emissions, greenhouse gases. Furthermore, a material footprint may include only products purchased within the economy, may include consumption of materials derived from ecological sources, such as biomass (*e.g.*, grass, wood, fish), or may include ecological resources that are not consumed but can be degraded (*e.g.*, water).

A more-challenging task is quantifying the environmental footprint of a company or other entity in terms of the ecosystem goods and services that are required to support its operations. For example, one technique uses land area as an indicator, but it is difficult to capture many important ecosystem services, such as climate regulation, water purification, and pollination. New scientific methods based on lifecycle exergy consumption (discussed later) make it possible to quantify all of the indicators shown in Figure 5 within a common framework.

To further complicate matters, the scope of a footprint analysis can vary enormously based on the chosen lifecycle boundary. A materials or energy footprint may be confined to the direct operations of a company or facility, it may extend to indirect activities associated with purchased goods or services, or it may encompass the full breadth of ecosystem goods and services. In published environmental reports, many companies quantify their environmental footprint in terms of direct consumption of resources and direct generation of waste and emissions. Efforts have begun, however, to include the broader supply chain footprint using lifecycle analysis methods.

Carbon footprint. A carbon footprint can be calculated by taking an inventory of the total greenhouse gas emissions for a company, facility, product, community, family, or any other entity. The Kyoto Protocol identifies six GHGs: carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Each GHG has a global warming potential (GWP) that can be expressed in terms of equivalent CO_2 *(8)*. Carbon footprints can be expressed in either absolute terms, *i.e.*, CO_2-equivalent metric tons per year, or in normalized terms, *e.g.*, CO_2-equivalent kg per sales dollar, per kg of product output, per employee, or per square foot of space. Carbon footprints are typically organized in terms of three successively broader scopes, covering the following GHG sources:

• *scope 1* — fuel combustion in vehicles or facilities that are directly owned and/or controlled

• *scope 2* — purchased electricity from fossil fuel combustion

• *scope 3* — other indirect sources of GHG emissions (*e.g.*, waste disposal, business travel).

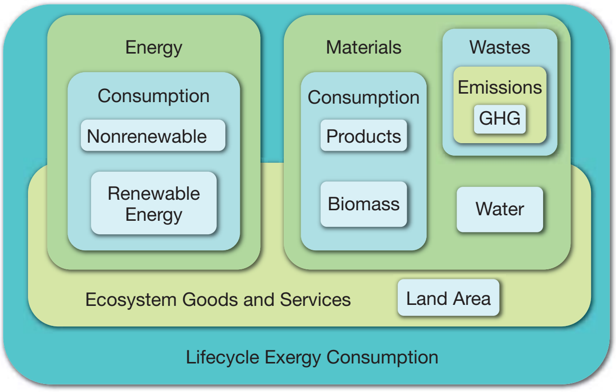
The accepted practice for Scope 3 sources is to allow considerable latitude in the inclusion of lifecycle emissions *(9)*. Most carbon footprints address primarily Scope 1 and 2 emissions, so the carbon-neutral label may be misleading. If a company were to consider all of the energy expended in the supply chain to provide purchased goods and services, its overall carbon footprint could be as much as 10 to 20 times larger.

The GHG Protocol, a joint effort of the World Business Council for Sustainable Development and the World Resources Institute, has launched a new initiative to produce international standards for product lifecycle accounting and corporate value chain accounting that is expected to be released in 2010. These standards will help to achieve greater precision and uniformity in the estimation of Scope 3 GHG emissions using lifecycle inventory methods.

Materials footprint. A mass-balance approach called material flow analysis (MFA) is widely used in Europe, Japan, and other nations to estimate the total material and waste burdens generated by an economic system or a specific enterprise *(10)*. MFA calculates the mass of materials entering and leaving a defined system, and provides several useful footprint indicators:

• *per capita material consumption.* Studies have shown that supporting the lifestyle of the average European requires a direct material consumption of about 44 kg/d, or close to 100 lb/d. The majority of these materials are construction minerals, fossil fuels, and biomass from agriculture.

• *total material requirements.* This measures the additional burdens of indirect hidden flows, including mining wastes and other discarded materials that are carried along with the direct material inputs but generate no economic value and may disturb the natural environment. For the aver-



▲ **Figure 5.** Environmental footprint indicators may be developed based on various LCA study boundaries.

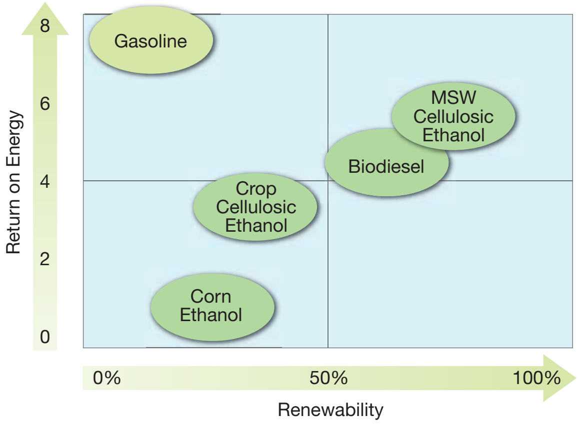
age European, this is estimated to be about 220 kg/d.

• *material intensity.* This is the ratio of material flow to total value produced. MFA studies suggest that the European Union economy has become more eco-efficient, since material intensity slowly declined from about 1.2 kg/€ in 1992 to about 1 kg/€ in 2000 *(11).* However, absolute material consumption continues to increase due to economic growth.

Similarly, by drawing the boundary around an enterprise or a specific product system, MFA can be used to measure its material intensity. However, reliance on mass flow indicators can be deceptive for several reasons. First, not all materials are equal in terms of their environmental impacts, and MFA does not distinguish materials in terms of toxicity or other properties. Second, MFA often does not account for the hidden environmental burdens associated with imported materials. In an economy where global sourcing is increasingly the norm, the question of allocating accountability for these upstream material flows remains challenging.

Land area footprint. A technique called ecological footprint uses land area (hectares) as a metric for estimating the productive capacity needed to support both resource consumption and waste absorption for a specified economic activity, such as power generation *(12).* This footprint can be interpreted as the burden placed on the carrying capacity of ecosystems, which is the maximum amount of replenishment per unit time that they can support without impairment. The worldwide carrying capacity is estimated to be 2.1 hectares per capita, of which 1.6 hectares are land-based ecosystems such as forests, pastures, and arable land and 0.5 hectares are ocean areas.

The average ecological footprint per capita is estimated to be 12.3 hectares in the U.S., 7.7 hectares in Canada, and 6.3 hectares in Germany. Hence, it is often stated that it would take more than three planet Earths to support the world's population if they all adopted the lifestyle of a developed nation. The average footprint for all nations is estimated to be 2.8 hectares per capita, suggesting that humanity has already overshot global capacity and is depleting the available stock of natural capital.



▲ **Figure 6.** The Eco-LCA tool was used to compare the renewability and return on energy of alternative automotive fuels.

Although it has been used primarily at a national level, ecological footprint analysis can be applied at any level of granularity, from an entire nation to a single individual. Thus, it offers a method for estimating the ecological burden associated with economic enterprises, supply chains, or communities *(13).*

Water footprint. The water footprint of a product or an entire enterprise can be defined as the total annual volume of fresh water that is used directly in operations and indirectly in the supply chain *(14).* This is sometimes called virtual water.

Some industries, such as food processing, use large quantities of water. Even businesses that use very little water for manufacturing may still have a substantial supply-chain water footprint if their raw materials come from agricultural sources. For example, the footprint for cotton garment manufacturers includes a large amount of irrigation water. In addition, consumers who launder those garments use a considerable amount of water over the product lifecycle, and this can be considered part of the footprint from an extended producer responsibility perspective. In the U.S., nearly 25% of all fresh water use is process water for steam turbines in electric power generation, and this may often be the largest component of a company's water footprint. The water footprint of common foods can range from about 1,000 L per kg of grain to about 16,000 L per kg of beef *(15).*

Water use can be measured in terms of water volumes consumed, *i.e.*, evaporated, and/or polluted per unit of time. Thus, water that is simply borrowed, as in hydroelectric power generation, does not count as usage.

The water footprint can be split into three elements:

• *blue water* — the volume of fresh water that was evaporated from surface water or ground water resources

• *green water* — the volume of fresh water that was evaporated from rainwater stored in the soil as soil moisture

• *gray water* — the volume of polluted water, calculated as the volume of water that was required to dilute pollutant discharges in order to meet water quality standards.

Unlike greenhouse gases, the ecological or social impact of a water footprint depends not only on the volume of water used, but also on the geographic locations and timing of the water use. Water-stressed or arid regions are more vulnerable to water use, especially during dry seasons.

Streamlined LCA

Many LCA practitioners have turned toward simplified LCA tools that provide results more quickly and with less effort, but also with less precision. Especially in the early stages of product development, such tools may be more appropriate for rapid design iteration. Alternative approaches have emerged that are more comprehensive and more streamlined, although less fine-grained than conventional LCA. For example, Carnegie Mellon Univ. developed a tool that uses aggregate input-output data to model the entire economy from a top-down perspective *(16).*

Such advanced methods are a useful complement to detailed, bottom-up LCA. In particular, since streamlined LCA requires only basic data about resource inputs, it is helpful in assessing new products when emissions data are not yet available. Streamlined methods can also be combined with detailed methods through hybrid LCA studies, which embed a focused LCA for specific industrial processes within a broader envelope representing the rest of the economy.

Ohio State Univ. (OSU) has developed an online, streamlined LCA tool called Eco-LCA that combines an economic input-output model of 488 sectors of the U.S. economy with an ecological resource consumption model based on exergy analysis. Eco-LCA enables immediate assessment or comparison of proposed designs based on an approximate bill of materials, and can display a variety of lifecycle indicators, ranging from a simple carbon or water footprint to a comprehensive ecosystem goods and services consumption profile. With support from the National Science Foundation, a public version of the Eco-LCA tool is available free of charge at www.resilence.osu.edu.

Exergy analysis

Recent advances in LCA capture the material and energy flows in complex systems based on the laws of thermodynamics. *Exergy* is defined as the available work that can be extracted from a material. The exergy content of a fuel, for example, is essentially its heat content *(17).* All of the factors of industrial production — energy, materials, land, air, water, wind, tides, and even human resources — can be represented in terms of exergy flows. Therefore, exergy can be used as a universal indicator to measure eco-efficiency and sustainability in industrial-ecological systems *(18).*

This method has the unique capability to quantify the contributions of most ecosystem services, and is particularly useful for analyzing new technologies when detailed process-level data are nonexistent. It is also useful for aggregation of environmental impacts, since it correctly accounts for the differences in quality among various resources (*e.g.,* energy from sunlight is much lower in quality than electrical energy).

OSU incorporated exergy analysis into a comprehensive lifecycle assessment of bio-based fuels, funded by the National Science Foundation. This study uses a hybrid methodology, combining a detailed process model of ethanol production with the Eco-LCA model of the U.S. economy to represent commodity flows from outside the process boundaries. Figure 6 shows the results of such a study of biofuels in terms of renewability (percent from renewable sources) and return on energy (megajoules delivered per megajoule consumed over the lifecycle). This analysis indicates that the renewability of municipal solid waste is far greater than the renewability of corn ethanol, which requires energy-intensive harvesting. Gasoline has a far superior return on energy, although it is not renewable *(19).*

Integrated lifecycle thinking

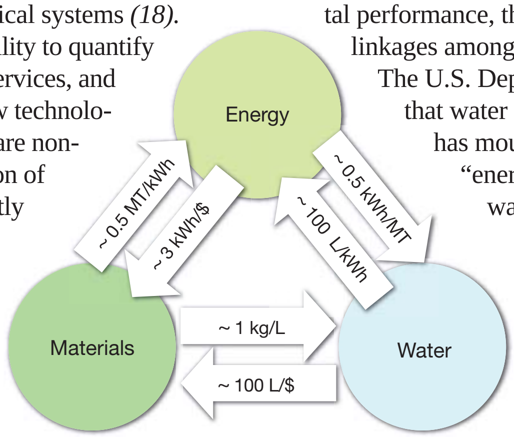
Lifecycle assessment methods can be challenging to apply, and may be inappropriate in situations where adequate data are not readily available. But lifecycle *thinking* is essential to a modern enterprise that wants to understand strategic risks and opportunities through its supply chain.

The use of streamlined LCA or footprint indicators may be sufficient to support strategic priority setting and business decision-making. For purposes of environmental performance measurement and stakeholder communication, simple and meaningful indicators such as material intensity are generally the most practical and useful.

For example, Coca-Cola has adopted a water stewardship strategy based on a water efficiency ratio, *i.e.*, liters of water per liter of product. The ratio has steadily declined to about 2.5 in 2007, and the company has announced a global goal of 20% improvement by 2012 from the baseline year of 2004. Coca-Cola's ultimate goal is to achieve water neutrality by returning water to nature equivalent to what it uses in its operations.

One of the shortcomings of traditional LCA is the separation of resources, emissions, and impacts into separate categories, as if they were independent. As companies gain a better understanding of their supply chain environmental performance, they are beginning to understand the linkages among different indicators of sustainability. The U.S. Dept. of Energy (DOE) has recognized that water and energy use are closely related and has mounted a major initiative to address this "energy-water nexus." In fact, the global water cycle is closely linked to the global carbon cycle, with vegetation playing a vital role through photosynthesis *(20).*

An extension of this integrative approach reveals the material-energy-water nexus, depicted in Figure 7. Materials are essential to the supply of both energy and water, and vice versa. In fact, the root cause



▲ **Figure 7.** The material-energy-water nexus illustrates the interdependence of essential natural resources.

of the enormous carbon footprint of the U.S. — over 7 billion metric tons per year — is material throughput, which drives the consumption of energy throughout the economy *(21)*.

Current efforts to improve supply chain sustainability focus on incremental efficiency gains, such as shorter transport distances and pooled urban distribution via common carriers. However, the real sustainability challenge is to reduce the growth of material requirements — to decouple economic well-being from resource consumption. What is needed is a paradigm shift from a material-based economy based on throughput, product delivery, and material wealth to a value-based economy based on knowledge, service delivery, and quality of life. Integrated lifecycle thinking will help companies to achieve breakthrough innovation, and to collaborate with governmental and nongovernmental organizations to realize the vision of a sustainable and prosperous society. CEP

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