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# Measuring and Communicating Sustainability through Eco-Efficiency Analysis

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Eco-efficiency analysis promotes an understanding of the economic and environmental trade-offs over products' lifecycles, and supports informed, strategic decision-making in all areas of a business, from spurring innovative product development to promoting credible marketing claims.

Many companies have realized the importance of sustainability as a critical business success factor — that what is good for the environment and society can also be good for their financial bottom line. By prioritizing sustainability as a key strategic focus and managing it similar to other parts of the business, such as marketing and sales, leading companies have been able to better identify and manage risks, enhance brand value and corporate reputation, and, more importantly, facilitate clear, measurable value creation throughout the supply chain.

Sustainable development has been defined as the balance of economic success, ecological protection, and social responsibility. To effectively manage sustainability, a company must be able to measure or otherwise quantify sustainability in each of those pillars. Eco-efficiency analysis (EEA) harmonizes two of these pillars — the economy and the environment. EEA is a comprehensive, science-based approach that provides information about the relationship between a product's or technology's economic benefits and its impacts on the environment along the entire supply chain and throughout all of its lifecycle stages. A new three-pillar, socio-eco-efficiency analysis tool, known as SEEBALANCE, integrates social metrics into the eco-efficiency analysis (but is beyond the scope of this article) (1).

BASF has completed more than 400 EEA studies for a diverse range of products, including chemical intermediates, consumer and personal-care products, vitamins, packaging materials, adhesives, and renewable-based products. As a

strategic tool, EEA provides the necessary data to support internal investment and product portfolio decisions. Just as importantly, it helps customers and other external stakeholders manage the proliferation of eco-confusion by presenting a large amount of complex data in a clear and easily understood manner.

This online article, a longer version of the article by the same name that appears in the December 2010 issue of *Chemical Engineering Progress*, describes the eco-efficiency analysis method and presents three examples that demonstrate how the tool and study results have contributed to strategic and informed decision-making and effective communication. Additional case studies are available at the BASF website, [www.basf.com/group/corporate/en/sustainability/eco-efficiency-analysis/projects/index](http://www.basf.com/group/corporate/en/sustainability/eco-efficiency-analysis/projects/index), and at [www.nsf.org/business/eco\\_efficiency/analyses.asp?program=EcoEff](http://www.nsf.org/business/eco_efficiency/analyses.asp?program=EcoEff).

## The eco-efficiency method

Eco-efficiency analysis (2, 3) involves measuring the lifecycle environmental impacts and lifecycle costs for product alternatives that provide a defined level of output. The eco-efficiency methodology is a comparative analysis — it does not determine the sustainability of a product, but rather compares the sustainability of one product relative to that of other alternatives. Thus, a product identified as most eco-efficient in one analysis may be a less eco-efficient alternative when compared with other options for a different application.

An eco-efficiency analysis requires that:

- the products or processes under evaluation must

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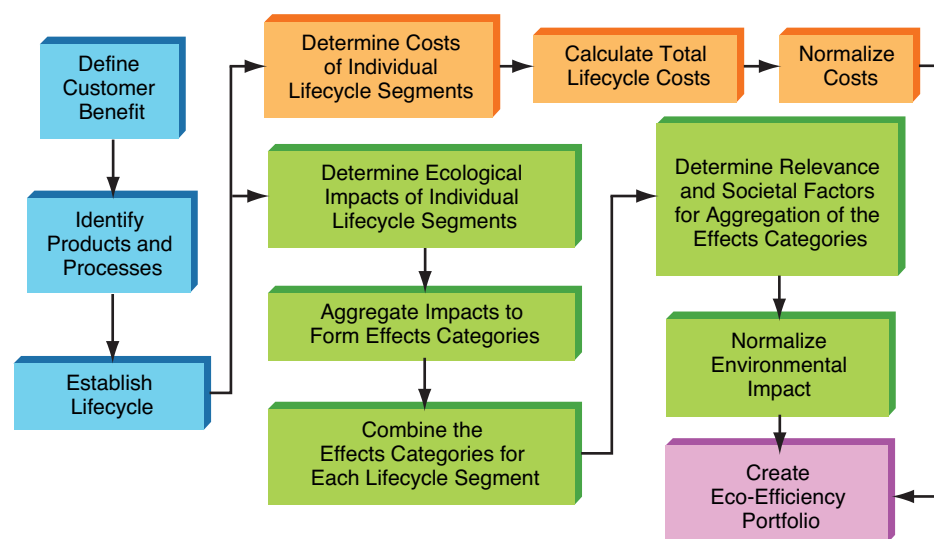
have the same defined functional unit or provide the same customer benefit

- the alternatives considered should cover at least 90 % of the relevant market
- the entire lifecycle is considered
- both an environmental and an economic assessment are carried out.

The BASF eco-efficiency method is based on the required and optional phases of the ISO 14040 and ISO 14044 standards for lifecycle assessments (LCA) (4). In addition to the requirements of the standards, it includes enhancements that allow for expedient review and decision-making at all business levels.

The general process for conducting an EEA is depicted in Figure 1 and involves the following steps:

1. Define the total cost from the customer's viewpoint.
2. Prepare a specific lifecycle analysis for all product or process options according to the rules of ISO 14040 and ISO 14044.
3. Determine the impacts on the health, safety, and other risks to people.
4. Assess the use of land over the entire lifecycle.
5. Calculate relevance factors for specific weighting.
6. Weight the environmental factors with societal factors.
7. Determine the relative importance of the environment vs. the economy to the analysis.
8. Create an eco-efficiency portfolio.
9. Analyze the appropriateness, quality, and sensitivities of the data.
10. Conduct scenario analyses for further interpretation of the results.



▲ **Figure 1.** Eco-efficiency analysis is a systematic methodology for comparing the environmental and economic aspects of alternative products or processes.

## Define the customer benefit, alternatives, and system boundaries

The first step of the EEA is to define the goal and scope of the study. In this step, the customer benefit, or functional unit of comparison, as well as the alternatives, are identified.

The functional unit provides the reference point for comparing the economic and environmental inputs and outputs for each alternative. It should include clear performance criteria as well as spatial and temporal limits. Because the eco-efficiency method is a comparative analysis, it should consider as many alternatives in the marketplace or in development as possible that can perform the same function.

The scope of the EEA is defined by the specific elements of the production, use, and disposal phases of the product's lifecycle that will be considered, and the relevant system boundaries (e.g., cradle-to-grave or cradle-to-cradle boundary conditions). The same lifecycle stages must be considered for each alternative. Any lifecycle stage that is identical for every alternative can be excluded from the analysis because its impact on each alternative will be the same. However, any excluded factors must be examined to determine whether their inclusion would change the overall analysis.

## Determine economic impacts

EEA assesses the full economic impact of a product or process over its lifecycle to determine an overall total cost of ownership for the defined customer benefit. The specific approach used to conduct a lifecycle cost (LCC) analysis will depend on the customer benefit selected and the system boundaries and alternatives considered.

Cost accounting needs to include initial costs and all future cost impacts or benefits of the products, as well as any costs associated with an environmental impact (e.g., disposal of hazardous waste). Either constant (real) or nominal monetary values can be used for cost accounting, but they cannot be mixed in the analysis. In addition, the final cost analysis can be calculated at a point in time, or it can account for the time value of money, in which case a net present value (NPV) or similar metric needs to be determined.

The economic metrics normally considered for each

alternative include the costs of raw materials, labor, energy, capital investment, maintenance activities, transportation, illnesses and accidents, and waste disposal, among others. When all the costs are identified and accounted for, they are summed and combined in appropriate units (*e.g.*, dollars or euros) without additional weighting.

This rigorous accounting of lifecycle cost impacts can identify the economic benefits of a product in its use and application and help manufactures better understand their economic value proposition. It can also uncover hidden costs and cost-intensive areas of the lifecycle that present opportunities for optimization.

### Determine environmental impacts

Businesses and consumers alike are bombarded with “green” product claims and such terms as carbon footprint, embodied energy, and recycled or biobased content. Whether these claims accurately reflect the overall environmental impact caused by a product over its entire lifecycle is often unclear.

Rather than focusing on just a few individual metrics or considering only a portion of a product’s lifecycle, the eco-efficiency method measures, at a minimum, 11 environmental impacts in six main categories: energy consumption, resource consumption, emissions (to air, water, and land), land use, toxicity potential, and risk potential.

Data acquisition and calculation are performed according to the requirements of ISO 14040 and ISO 14044 for each impact category as defined by the study’s scope, boundary conditions, and customer benefit. This process is known as the inventory analysis stage.

The second analysis stage, impact assessment, starts by systematically classifying and characterizing all the information gathered during the inventory analysis. The environmental impacts are then aggregated using normalization and weighting schemes for each impact category.

### Characterize environmental impacts

*Energy impacts* are expressed in terms of primary energy sources, such as oil, gas, coal, lignite, biomass, nuclear power, and hydro power. The cumulative amount of energy consumed during the lifecycle of each alternative is measured and typically expressed in megajoules per unit of customer benefit (MJ/CB), then converted back to the appropriate primary energy source. Fossil fuels are included before production and renewable energy before its harvest or use. The consumption of the individual primary energy sources is also included in the raw material or resource consumption category.

*Resource consumption* considers key materials consumed during the lifecycle of each alternative. The amounts of the different raw materials used are aggregated into a

common unit of consumption, such as kg, by applying weighting factors that take into account each material’s exploitable reserves (for example, as identified by the U.S. Geological Survey) and its current level of consumption by society (all uses). In this way, higher weightings are applied to materials that are either scarce or have a very high consumption rate. Renewable raw materials produced through sustainable management practices are considered to have a theoretically infinite reserve and thus would have a weighting factor of zero.

One resource in particular — fresh water— is the subject of much interest and political debate. Of specific interest in eco-efficiency analysis is the need to understand the impacts of each alternative on the quality and availability of this valuable, and in some areas limited, resource. Advanced methods that incorporate a more-rigorous approach to assessing the use and impacts of water consumption are under development. For instance, the method proposed by Pfister *et al.* (5) assesses damages to three areas of protection: human health, ecosystem quality, and resources.

*Emissions* are divided into emissions to air, water, and land (soil). The air emissions inventory is classified into four subcategories: global warming potential (GWP), ozone-depletion potential (ODP), photochemical-ozone (summer smog)-creation potential (POCP), and acidification potential (AP). Some air emissions, such as methane, can be included in more than one subcategory.

Weightings are applied to each emission to permit aggregation within each subcategory. For example, global warming potential is expressed as the total amount of CO<sub>2</sub> equivalents emitted into the atmosphere, so the GWP of a particular substance is expressed relative to that of CO<sub>2</sub> (which is set at 1). The GWP of methane is 25 (6) — that is, every 1 kg of methane emitted to the air is equivalent to 25 kg of CO<sub>2</sub> emissions. POCP values are compared relative to that of ethene (POCP = 1), which is more than 140 times as potent as methane, whose POCP is only 0.007.

The water emissions inventory includes chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen, hydrocarbons, heavy metals, chloride, sulfates, ammonium, phosphates, total suspended solids (TSS), and total dissolved solids (TDS), among other pollutants. The concept of critical volumes, or critical limits, is used to characterize discharges. Wastewater regulations set a statutory limit, or critical load, for each pollutant; the greater the hazard posed by a substance, the lower its limit.

This step of the EEA determines the amount of uncontaminated water needed to dilute a water emission to meet the statutory limits. For example, if the legal limit for COD is 75 mg/L, the factor is 1/75, or 0.013; for a more-potent contaminant with a legal limit of 1 mg/L the factor would be 1. Each identified water emission is multiplied by its cor-

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responding dilution factor, and these values are aggregated over the lifecycle to determine a single number — the critical water volume — for each alternative.

The statutory threshold limits used in the BASF model are based on the German wastewater ordinance. The wastewater constituents are common pollutants with well-established toxicity, so the limits should be similar across various geographies. In addition, this regulation considers many different types of water emissions (*e.g.*, eutrophication, heavy metals, etc.), whereas most other models consider only a few.

The solid-waste inventory analysis considers wastes that will end up in a landfill (cradle-to-grave); materials that are recycled (cradle-to-cradle) are not counted in this category. Wastes are categorized as either municipal (household trash), hazardous (per the U.S. Resource Conservation and Recovery Act (RCRA) definition of hazardous waste), construction (nonhazardous materials generated during building or demolition activities), or mining (nonhazardous earth or overburden generated during raw-material extraction activities). A weighting factor that accounts for the wastes' varying impact potentials is applied to each waste type based on typical disposal costs. All weightings are normalized to the municipal waste category, which is assigned a value of 1. The impacts are then summed to obtain an overall impact, which is expressed as kg of municipal waste equivalents per unit of customer benefit (kg/CB).

*Land use* is becoming more prominent in lifecycle assessments, although there is much debate about how to incorporate land use as an impact category in LCA, and no one methodology has been universally adopted. The EEA methodology quantifies the effects that various land transformations, land occupations, and land restorations have on biodiversity, as measured by specific indicators. This approach is more robust than a previous technique based only on the naturalness of an area and the specific use of the land. It is adapted from an approach proposed by Köllner and Scholz (7) that employs a land-use characterization factor, called the ecosystem damage potential (EDP). Inventory data for this analysis are available in some LCA databases such as SimaPro 7.

The two remaining environmental categories — toxicity and risk — are normally not assessed in LCA because they are not covered by the ISO standards. However, EEA includes them in order to provide a more-comprehensive evaluation of the environmental impacts of products.

*Toxicity potential* focuses on the human toxicity of the final product as well as all of the reactants and chemical precursors required during its manufacture and ultimate disposal. The general framework for performing this analysis is described in Ref. 8. The EEA methodology classifies the possible adverse human health effects of a

material by assigning points based on the appropriate Risk Phrases (R-phrases) as defined in Annex III of the European Union Directive 67/548/EEC, which deals with dangerous substances.

The R-phrases related to human health effects (others deal with flammability, explosivity, toxicity to flora and fauna, etc.) have been broadly grouped into six categories that reflect the severity of each toxic effect relative to one another, as shown in Table 1. Less-severe risks, such as irritating to eyes or skin (R-36 and R-38), are scored lower than more-hazardous risks, such as toxic by inhalation (R-23) and may cause cancer (R-45).

If only one R-phrase applies to the substance, that substance is assigned to the appropriate group. If, however, multiple R-phrases apply — other than weak or local effects (Group 1 or 2) or for the same effect caused by multiple exposure routes (*e.g.*, oral and dermal) — its score is upgraded to that of the next higher level. In general, a substance is upgraded only one level, regardless of how many R-phrases apply.

If R-phrases have not been specifically identified for a chemical but a material safety data sheet (MSDS) exists, health effect information obtained from the MSDS can be used to estimate the appropriate R-phrases. In cases where limited or no toxicological information exists for a substance, possible toxic effects may be estimated based on toxicological data for related substances, structure-activity relationships, and data from preliminary tests; such estimation requires consultation with toxicologists and expert judgment.

After the inventory analysis phase identifies all of the chemicals utilized by each alternative, an overall toxicity score is developed for each lifecycle stage by multiplying the quantity of each material by its respective toxicity score. Weighting factors are applied to each chemical's toxicity score based on the safety standards with which the manufacturing facility complies (*e.g.*, the minimum required by regulations or higher self-imposed or industry-imposed standards), the material's vapor pressure, whether the material is handled in an open or closed system, and whether nanoparticles are present.

The scores are also adjusted based on the lifecycle stage in which the substance is present. Scores for materials encountered in the production phase, where plant operators are normally protected by personal protective equipment (PPE) and U.S. Occupational Safety and Health (OSHA) regulations, are given lower weight than use-phase scores, since consumers are typically less protected and less knowledgeable about the hazards of exposure to the materials. In this regard, the EEA goes beyond consideration of only the hazards.

Although not part of a standard EEA, eco-toxicity can



Table 1. Toxicity potential is scored using a system based on the R-phrases defined by Annex III of European Union Directive 67/548/EEC.		
Group	Description	Score
1	Weak effects	100
	R36: Irritating to eyes R38: Irritating to skin R66: Repeated exposure may cause skin dryness or cracking R67: Vapors may cause drowsiness and dizziness	
2	Local effects	300
	R21: Harmful in contact with skin R22: Harmful if swallowed R34: Causes burns R35: Causes severe burns R37: Irritating to respiratory system R41: Risk of serious damage to eyes R42: May cause sensitization by inhalation R43: May cause sensitization by skin contact R62: Possible risk of impaired fertility R65: Harmful: may cause lung damage if swallowed	
3	Acutely toxic, irreversible effects, reproductive toxicity suspected	400
	R20: Harmful by inhalation R24: Toxic in contact with skin R25: Toxic if swallowed	
4	Severe irreversible effects, reproductive toxicity	550
	R23: Toxic by inhalation R27: Very toxic in contact with skin R28: Very toxic if swallowed R29: Contact with water liberates toxic gas R31: Contact with acids liberates toxic gas R33: Danger of cumulative effects R39: Danger of very serious irreversible effects R48: Danger of serious damage to health by prolonged exposure R60: May impair fertility R63: Possible risk of harm to the unborn child R64: May cause harm to breast-fed babies R68: Possible risk of irreversible effects	
5	Carcinogenic	750
	R26: Very toxic by inhalation R32: Contact with acids liberates very toxic gas R40: Limited evidence of a carcinogenic effect R45: May cause cancer R46: May cause heritable genetic damage R49: May cause cancer by inhalation R61: May cause harm to the unborn child	
6	Only by combination of groups	1,000
+1	Upgrade for additional "strong" effects (all except those of Groups 1 and 2 and additional exposure routes)	

be integrated into the analysis if the nature of the products (e.g., detergents) or the type and amount of water emissions warrants. Eco-toxicity potential is determined by the European Union Risk Ranking System (EURAM) (as described in Ref. 9), which is essentially a scoring system based on the principles of environmental risk assessment (*i.e.*, risk as the product of hazard and exposure). Generally, substances are ranked based on their intrinsic properties (e.g., physicochemical and eco-toxicological data) and their ultimate fate in the environment. The eco-toxicity score is combined with the human-health toxicity score through a weighting system, and the two are combined into an overall toxicity impact score.

*Risk potential*, the final impact category, is based on both quantitative and semi-quantitative data.

The quantitative data deal mainly with workplace accidents and occupational illnesses. Materials identified in the inventory analysis are linked with workplace-safety statistics for the industries that produced them through one of the standard industrial classification systems, such as Nomenclature Générale des Activités Économiques (NACE) or the North American Industrial Classification System (NAICS). This information is combined with industrial production data to develop a quantitative correlation, such as the number of fatal working accidents per unit of material produced.

The semi-quantitative portion of the risk category deals mainly with physical hazards such as flammability and other unique properties (e.g., mold resistance) of the materials, and considers both the probability of a hazard occurring and the severity of the consequences should it occur. Risks can be compared and ranked using a traditional risk matrix or simply the product of severity multiplied by likelihood of occurrence. For example, one approach first characterizes a risk qualitatively as very low, low, medium, high, or very high, and then assigns the corresponding numerical value from 1 to 5 to allow semi-quantitative comparisons to be made.

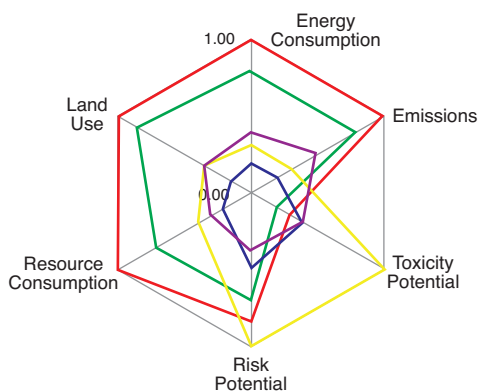
The two risk factors are calculated and summed over the production, use, and disposal lifecycle stages to produce a total score for each alternative.

### Normalization, weighting and aggregation

After all of the environmental impacts in each of the six categories for each alternative over the defined lifecycle have been classified and characterized, the data must be presented clearly in a way that will facilitate understanding and comparison. This involves data normalization, weighting and aggregation.

The first normalization is quite simple and applies to all the main environmental categories except emissions (which requires additional weighting steps to aggregate the subcategories, as discussed later). For each category (other

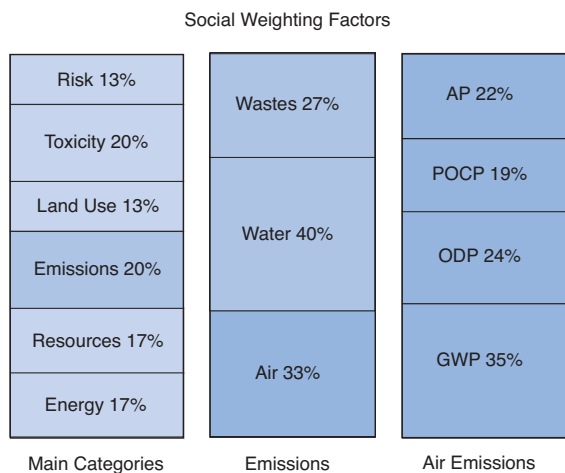
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▲ **Figure 2.** The environmental fingerprint provides a clear picture of the relative impacts of the alternatives.

than emissions), the summed lifecycle impact data (e.g., total energy consumption per customer benefit (MJ/CB) or overall toxicity potential score) are normalized relative to the alternative with the highest impact in that area. The least-favorable alternative (i.e., the one with the highest impact) is assigned a value of 1, and the other alternatives are valued proportionately. After normalization, the relative environmental impacts for the various alternatives can be compared graphically on a plot called the environmental fingerprint (Figure 2), where each color represents a different alternative.

The environmental fingerprint makes it easy to visualize the trade-offs between alternatives by clearly showing where certain alternatives perform well and where their performance is less desirable. However, to clearly understand each alternative's overall environmental impact and thus which impact categories drive the results of the analysis, an additional weighting procedure is required to



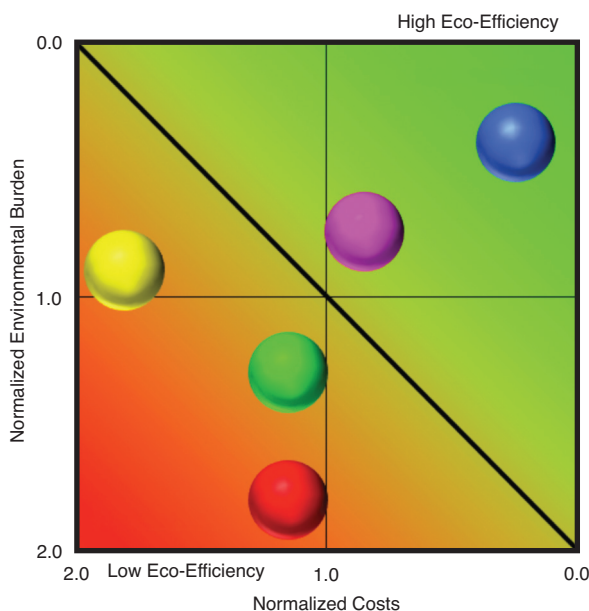
▲ **Figure 3.** Social weighting factors, such as those for emissions impacts, incorporate society's opinions on the importance of each impact into the EEA.

combine the normalized results reflected in the environmental fingerprint into one single score. This weighting process incorporates both scientific relevance factors and societal weighting factors.

The relevance factors help put into context the significance of each environmental impact for the individual eco-efficiency analysis. They are unique for every EEA, and they differ depending on the specific results of the analysis and the region of the world in which the analysis applies. The relevance factors reflect the level to which an alternative's impact in a particular category, for example, emissions or energy consumption, contributes to the total impact from that category in the EEA's geographic region. Each factor is calculated by dividing the alternative's impact (determined during the inventory, classification, and characterization phase) by the total burden that impact category imposes on the region. Such data are typically available in various publicly available statistical databases. This approach allows high environmental burdens to be more heavily weighted than relatively low burdens.

The societal weighting factors are used in conjunction with the environmental relevance factors to account for society's opinion on the importance of each environmental impact. They are derived from the results of third-party market research and polling, and they are constant for each analysis, but they should be updated periodically to reflect society's changing views.

For example, global warming potential (GWP) is currently receiving much attention as a key air emission. Not long ago, however, air emissions related to ozone depletion



▲ **Figure 4.** The eco-efficiency portfolio summarizes the calculations of environmental and economic impacts on a single plot.

or acid rain were gaining more notoriety. Figure 3 presents typical social weighting factors, with each column reflecting society's view of the importance of each impact category relative to the others.

The geometric mean of the environmental relevance factor and the societal weighting factor is calculated as an overall weighting factor for each impact category. The results of the normalization step (the environmental fingerprint) are multiplied by these overall calculation factors and summed over the six categories to represent the final environmental impact for each of the alternatives evaluated.

Although the environmental impact assessment and cost calculations are separate steps of the eco-efficiency analysis, the goal is to present both findings in a balanced way that supports clear understanding and facilitates strategic decision-making. This is accomplished through the eco-efficiency portfolio. After a final weighting step (described in more detail in Ref. 10) that takes into consideration whether the environmental or cost impacts are more influential in driving the results of the analysis, each alternative's environmental impact score is combined with its normalized economic impact (discussed earlier) on a biaxial plot, as illustrated in Figure 4. Each circle represents one alternative, with its cost coordinate shown on the horizontal axis and its environmental impact on the vertical axis. The graph reveals the eco-efficiency of the products or processes considered relative to each other. Since both environmental impact and costs are equally important, the most eco-efficient alternative is the one with the largest perpendicular distance from the diagonal line in the direction of the upper-right quadrant. The least eco-efficient alternatives are located in the lower-left section, reflecting higher environmental burden and higher lifecycle costs.

The dynamic nature of the eco-efficiency model allows scenario and sensitivity analyses to be conducted easily by varying the study parameters. The results can then be plotted to create revised portfolios that provide further decision-making support.

The following examples (and the case study accompanying the online version of this article at [www.aiche.org/cep](http://www.aiche.org/cep)) demonstrate how EEA has been used to compare the relative sustainability of alternative products, to support strategic decision-making and permit clear, credible communication with external stakeholders.

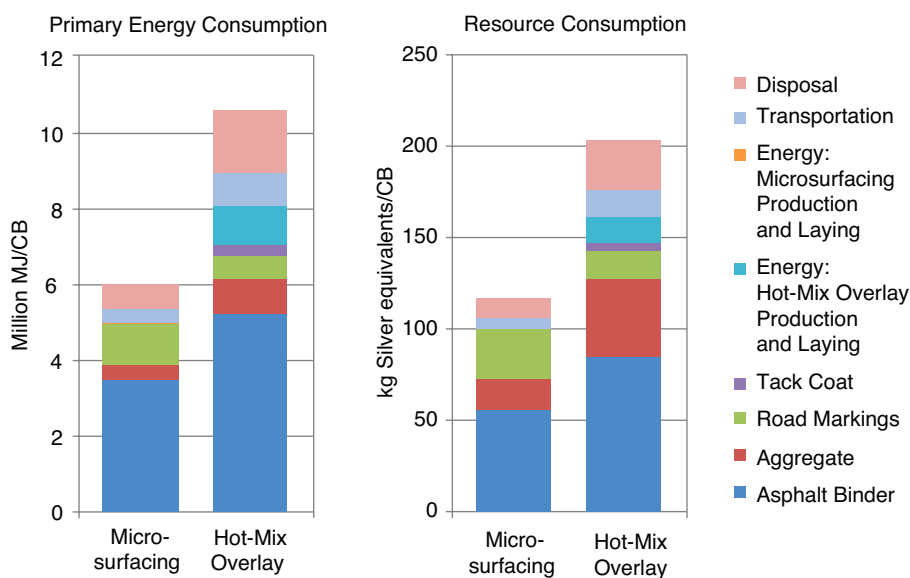
### Example 1: Preserving asphalt roads

Pavement preservation is the systematic scheduling of nonstructural maintenance to protect engineered road pavements and extend their service life. Challenges include determining which pavement-preservation technologies and materials are the most eco-efficient, on what basis to make the comparison, and what metrics best define the sustainability of road construction materials.

This example compares the relative eco-efficiencies of two common pavement-preservation technologies for urban roads — a polymer-modified asphalt-emulsion-based microsurfacing technology and a 2-in. polymer-modified hot-mix overlay (also known as mill-and-fill). The study evaluates the environmental and economic impacts associated with maintaining a 1-mi stretch of a 12-ft-wide lane of urban road using best engineering practices over a lifetime of 40 years. The specific issue is whether it is more sustainable to install a more-durable layer that contains 10% recycled content but requires more materials and extensive road work (the hot-mix overlay, with an average life of 11 yr), or to use a less cost- and resource-intensive maintenance technology more frequently to achieve the same desired road performance (microsurfacing, which typically lasts 6 yr).

Figure 5 shows that microsurfacing consumes about 40% less primary energy and fewer resources than hot-mix overlays over the 40-yr lifecycle of the road. Hot-mix overlays have higher impact scores due to their higher bitumen content and hotter production and application temperatures, as well as the higher fuel requirements for transporting larger volumes of materials to and from the job site.

Detailed results that reveal how the individual system



▲ **Figure 5.** Microsurfacing consumes less primary energy and fewer resources than hot-mix overlays over the lifecycle of the road.

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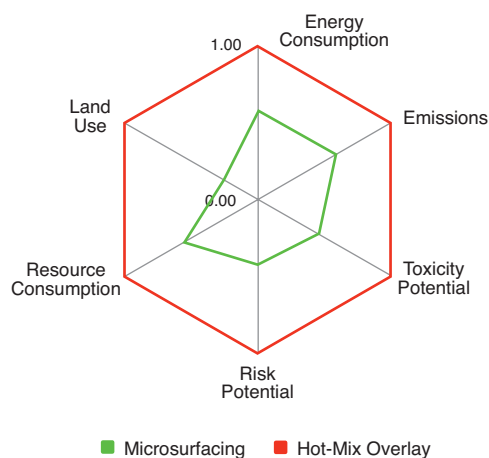
components contribute to the overall impact category are essential for informed decision-making. For instance, road markings have a surprisingly significant environmental impact over the lifecycle of microsurfacing. Thus, to further improve the overall eco-efficiency of microsurfacing, it may be necessary to consider optimizing other aspects of the technology.

The environmental fingerprint in Figure 6 illustrates the benefits of microsurfacing over hot-mix overlay. These advantages can be directly attributed to its more-efficient use of resources, its lower energy consumption, and its lower total emissions. Its better environmental profile combined with its reduced lifecycle cost (25% less than hot-mix overlay) places microsurfacing at a clear eco-efficiency advantage in the base-case analysis.

Sensitivity analyses are useful for assessing how the study results may differ if key assumptions are changed. In this EEA, increased durability and increased recycled-material content are examined in more detail. Even if the durability of hot-mix overlay is extended to 17 yr (Figure 7) or the overlay's recycled asphalt pavement (RAP) content is increased to 40% with no corresponding beneficial changes to the microsurfacing assumptions, microsurfacing still has the clear advantage in both cases.

Stakeholders of LCA or eco-efficiency studies who are not as well-versed in the common units of measurement (e.g., grams of SO<sub>2</sub> equivalents for assessing acidification potential or megajoules for energy consumption) may not appreciate the significance of the impacts. Thus, communicating the results in more common terms is essential to effective communication and ultimately facilitating strategic review and decision-making.

For example, the advantages of microsurfacing over hot-mix overlay identified in the microsurfacing study, which



▲ **Figure 6.** The environmental fingerprint shows that the impacts of microsurfacing are lower than those of hot-mix overlays in all impact categories.

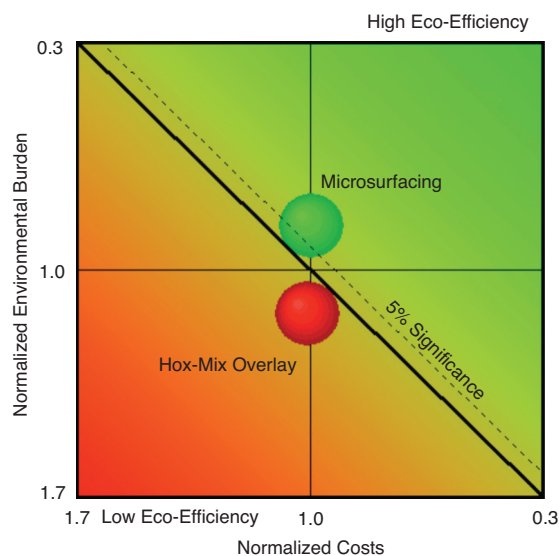
focused on only a 1-mi stretch of urban road over 40 yr, could be expressed in more commonly understood equivalencies, such as:

- resource savings of 1,200,000 lb less material required and 34 tons less material sent to landfill
- improved energy efficiency, with oil consumption reduced by more than 280 bbl per lane-mile and savings equivalent to the annual energy consumption of 110 U.S. homes (11)
- a smaller carbon footprint, equivalent to taking more than 20 cars off the road or the amount of carbon sequestered annually by more than 22 acres of pine forest (12).

## Example 2: Are biobased materials green?

Many consumers and businesses alike question whether biobased materials are more sustainable than traditional petroleum-based products. This EEA compares conventional petroleum-based products with polyol manufacturing routes utilizing renewable or natural oils, such as soy and castor. The customer benefit is defined as the production, use, and disposal of one million board-feet (1 MM BF) of high-quality furniture foam with a density of 1.8 lb/ft<sup>3</sup>. (A board-foot is a 1 ft × 1 ft × 1 in. block.) The analysis considers processes to make a conventional polyol derived from petroleum (Pluracol 50), a castor-oil-based polyol (Balance 50), and a soy-oil-based polyol (Balance 80). Study assumptions include:

- polyols are formulated such that there are no differences in the foam manufacturing process or the scrap rates generated
- foams are derived from a reaction of the polyol and toluene diisocyanate (TDI); the amounts of catalyst, addi-



▲ **Figure 7.** Extending the life of the hot-mix overlay from 11 yr to 17 yr does not enable it to overtake microsurfacing on the eco-efficiency portfolio.



tives, and isocyanate required for each alternative are the same

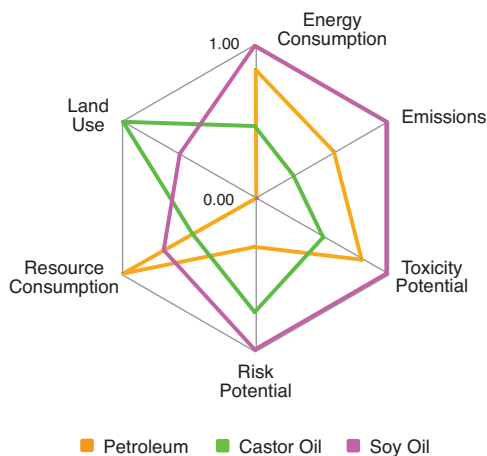
- the necessary manufacturing equipment is in place, so no capital investment is required
- polyols are delivered by railcar
- energy supplied to maintain the proper polyol viscosity is included
- performance and durability of the finished foams (the use phase of the lifecycle) are identical for all three polyols
- each foam's ability to be recycled, reused, or recovered is the same.

The relative impacts for the six environmental categories are shown in the environmental fingerprint in Figure 8.

Castor-based polyol consumes less energy and fewer resources, produces fewer total emissions, and its toxicity potential is lower. However, it requires more land than the other alternatives because it has the highest biobased content (up to 100%), and the agricultural practices associated with castor oil production from the castor bean plant have a relatively low yield (oil/acre). Unlike the soy-based alternative, the castor-based polyol requires little or no fertilizer.

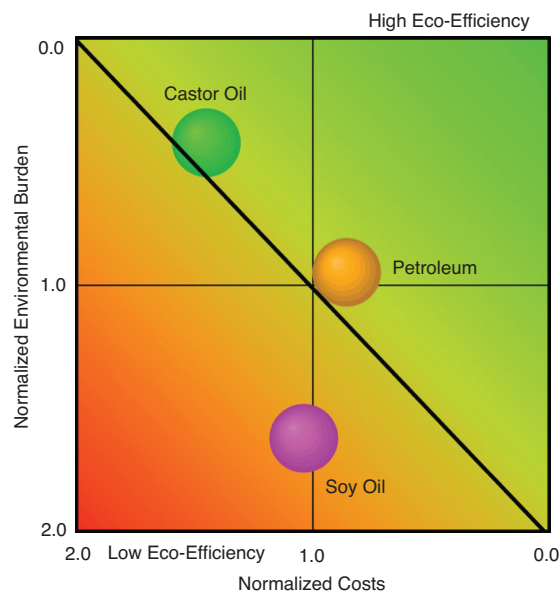
Figure 9, the eco-efficiency portfolio, combines the six individual environmental-impact categories into a single relative environmental impact. The petroleum-based polyol and castor-based polyol have similar overall eco-efficiencies (*i.e.*, they are about the same distance above the diagonal line). Castor-based polyol has a higher cost, but it clearly has the lowest environmental impact. Petroleum-based polyol has the lowest cost, but it also has a higher environmental impact than castor-based polyol. Soy-based polyol has an intermediate cost, but a much higher environmental impact than both of the alternatives.

The polyol raw material production accounts for a significant portion of the environmental impact over the life-

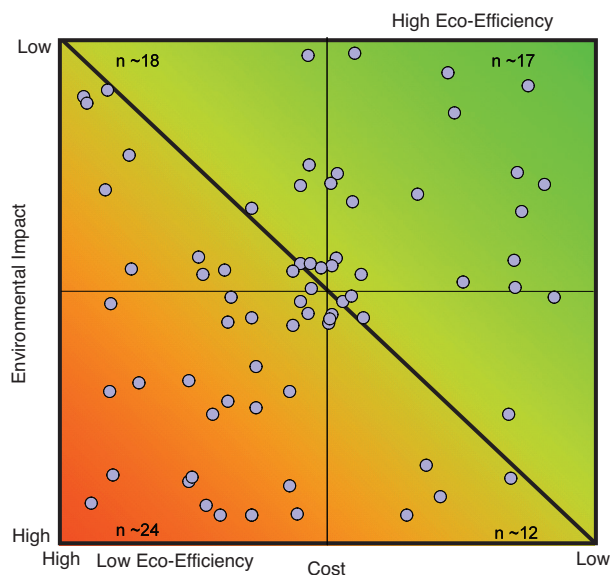


▲ **Figure 8.** This environmental fingerprint depicts the relative raw material and energy inputs for the petroleum- vs. bio-based polyol comparison.

cycle (production, use, and disposal) of 1 MM BF of flexible foam. Replacement of petroleum-derived propylene oxide with renewable raw materials, such as castor oil (a non-food-based feedstock) or epoxidized soy oil, does not necessarily result in a more eco-efficient foam. For example, soy-based polyol has a high energy impact because it is more viscous at room temperature and must be heated prior to foam produc-

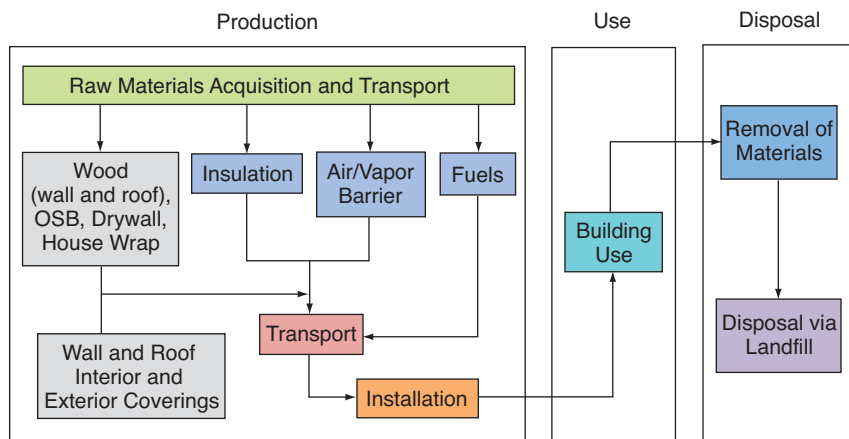


▲ **Figure 9.** The eco-efficiency portfolio for the polyol EEA depicts the relative environmental and economic impacts of the petroleum-, castor-, and soy-oil-based processes.



▲ **Figure 10.** An eco-efficiency portfolio comparing a wide range of applications reveals that eco-efficiency scores of biobased products vary significantly.

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▲ **Figure 11.** The system boundaries for the residential insulation study encompass the production, use, and disposal phases of the insulation's lifecycle.

tion. In addition, both biobased formulations have higher land-use requirements associated with the farming and harvesting of the materials.

More than 32 other eco-efficiency studies comparing 71 biobased products provide additional insights into the relative sustainability of bio- vs. petroleum-based products. The analyses cover a diverse range of products and markets, including automotive plastics and plastic packaging, building and construction materials (e.g., insulation and roofing), fuels (diesel and biodiesel), flooring (wood and vinyl), coatings, and nutritional and animal-feed supplements. As shown in Figure 10, no definitive generalization can be made about the eco-efficiency of biobased products — sometimes they have high eco-efficiency scores, but other times their eco-efficiency scores are low. This comparison clearly shows that before claims or comparisons can be considered credible, rigorous analysis needs to be performed on a case-by-case basis in order to fully understand all the economic and environmental impacts and benefits associated with each product.

### Example 3: Residential insulation systems

This example highlights the risks associated with making strategic decisions based on claims or comparisons that consider only individual environmental attributes or that do not consider the entire lifecycle. It also highlights the importance of not extrapolating the results of one study to other locations or product applications. In addition, it shows the performance of a product can be more significant in determining its environmental impact than the inputs required to produce it.

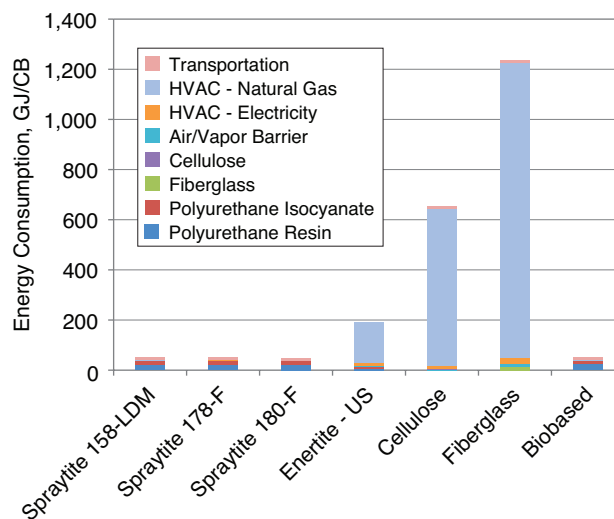
This study quantifies the differences in lifecycle environmental impacts and total lifecycle costs of various insulation systems for residential buildings in the U.S. — specifically

a single-story home in four different locations in three distinct climate zones. Considering four unique regions provides a more-comprehensive picture of the effects of regional material and energy costs, as well as regional climate conditions.

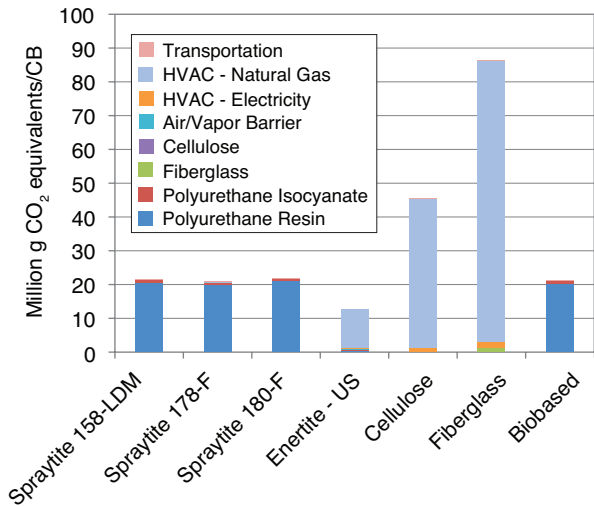
The alternatives considered in this analysis include both open-cell (Enertite) and closed-cell (Spraytite) spray polyurethane foams (SPFs), fiberglass, and cellulose. The spray foams are petroleum-based products that require the use of blowing agents during installation, which can range from water (for the open-cell foam) to various hydrofluorocarbons (HFCs) (for the closed-cell foam). These blowing agents help to give closed-cell foams their superior insulating capability

(R-values of 6.6–6.9/in. vs. 3.4–3.7/in. for the other alternatives), but also contribute to climate change due to their inherent global warming potential.

Closed-cell foams, unlike the other conventional insulation systems, can also function as an air-and-vapor-barrier system and help to increase the structural integrity of a wall and roof. Closed-cell spray foams are the only alternative classified by the U.S. Federal Energy Management Agency (FEMA) as being highly resistant to floodwater damage. The fiberglass and cellulose are derived primarily from nonpetroleum-based raw materials, and in most cases contain a significant amount of recycled content. Figure 11 depicts the specific boundary conditions considered for the



▲ **Figure 12.** The relative primary-energy requirements to heat and cool the house over its lifecycle exceed the energy embodied in the insulating materials.



▲ **Figure 13.** On the basis of relative energy consumption, blowing agents account for nearly 95% of the greenhouse gas emissions of the closed-cell spray foams.

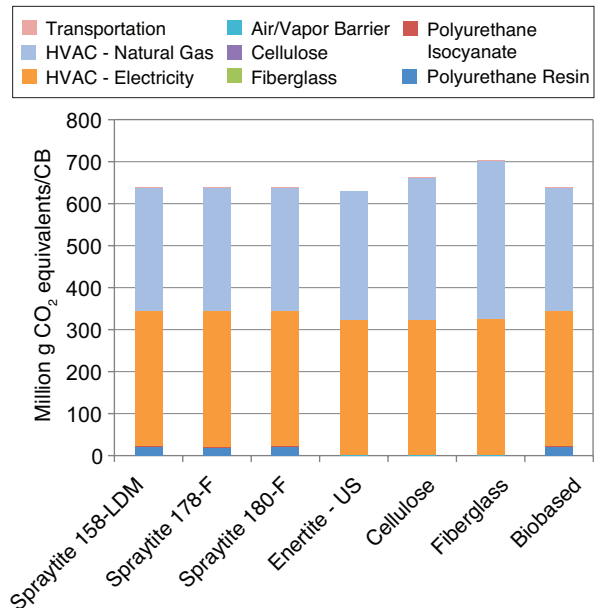
assessment; the areas shaded in gray are excluded from the analysis because they are identical for all of the alternatives.

Because this is a comparative study, it uses a differential analysis of the energy needed to heat and cool the home over its lifecycle. That is, the difference between the energy consumed by each alternative and that consumed by the best-performing option is used to calculate the heating, ventilation, and air conditioning (HVAC) impacts for natural gas (heating) and electricity (cooling). For the base-case scenario (Newark, NJ), the closed-cell foam is about 3% more energy-efficient than the open-cell foam, 11% more efficient than cellulose, and 21% more efficient than fiberglass.

Figure 12 shows that energy consumption for heating and cooling the house over its lifecycle contributes significantly more to the overall energy impact than the embodied energy of the insulation alternatives. This highlights the importance of considering lifecycle impacts when determining the true environmental impacts of products. If only the embodied energy of the insulation material was considered, the energy impact comparison would be quite different, as the approximate primary-energy requirements to produce each type of insulation material are:

- closed-cell SPF: 85 MJ/kg = 45,000–48,000 MJ/CB
- open-cell SPF: 70 MJ/kg = 21,000 MJ/CB
- fiberglass: 46 MJ/kg = 24,500 MJ/CB
- cellulose: 4 MJ/kg = 3,100 MJ/CB

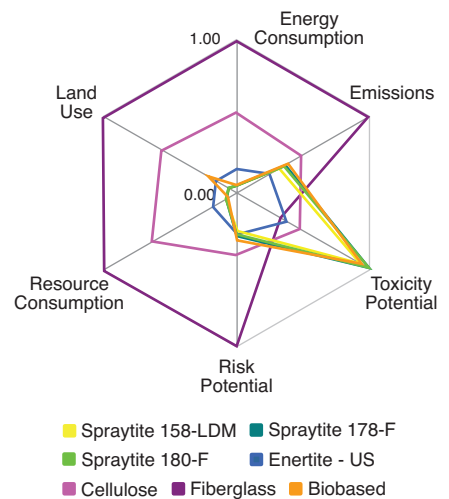
Thus, the superior insulating and air-barrier performance of spray foams, specifically the closed-cell spray foams, offset the higher energy impact of their manufacturing, transportation, and installation. Cellulose, although its embodied energy is extremely low, does not fare as well in overall energy consumption because it allows much more air



▲ **Figure 14.** When absolute energy consumption over the home's lifecycle is considered, blowing agents contribute only about 3% of the GHG emissions.

infiltration than the spray foams do.

Closed-cell spray foams are not perceived to be as environmentally friendly as other insulation materials because of the blowing agents' inherent global warming potential. Figures 13 and 14 compare the GWPs of greenhouse gases (GHGs; e.g., CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, blowing agents) emitted over the various alternatives' lifecycles in relative and absolute terms. Fiberglass and cellulose have the highest carbon footprints. Considering relative energy consumption (Figure 13), the blowing agent constitutes almost 95% of the GHG emissions for the closed-cell spray foams. However, when the absolute lifecycle energy consumption is considered (Figure 14), the blowing agent for the closed-cell spray foams contributes only about 3% to the overall carbon footprint (or GHG emis-



► **Figure 15.** The environmental fingerprint compares the impacts of various types of home insulation for the base case (Newark, NJ).

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sions). Thus, the benefit of the blowing agent in promoting better energy efficiency far outweighs the environmental impacts of the foams' production, use, and disposal.

Figure 15 plots the relative impacts of each alternative for the Newark, NJ, base case as an environmental fingerprint. Fiberglass insulation has the highest environmental impact in all categories except toxicity potential, where it has the lowest impact. Although fiberglass has a whole-wall R-value similar to that of the alternatives, its higher air-infiltration rate leads to significantly higher fuel consumption and electricity use for heating and cooling. This requirement for the production and distribution of larger amounts of utilities contributes to fiberglass also having the highest risk potential (occupational illnesses and on-the-job accidents) of all alternatives. Cellulose insulation also has high environmental impacts in all categories except toxicity potential. Although its air-infiltration rate is lower than that of fiberglass, its higher air-infiltration rate relative to spray foams leads to its higher fuel and electricity consumption.

The three closed-cell SPF alternatives have the lowest overall environmental impact in the energy use, resource consumption, and land use categories, and they score well on risk potential and emissions. They have the lowest air-infiltration rates, which makes them the most energy-efficient alternatives. However, because they contain isocyanate, they have the highest toxicity potential. The biobased spray foam performs similar to the other closed-cell SPF's in all aspects except land use, where its larger impact is due to the land required to produce its renewable content. The open-

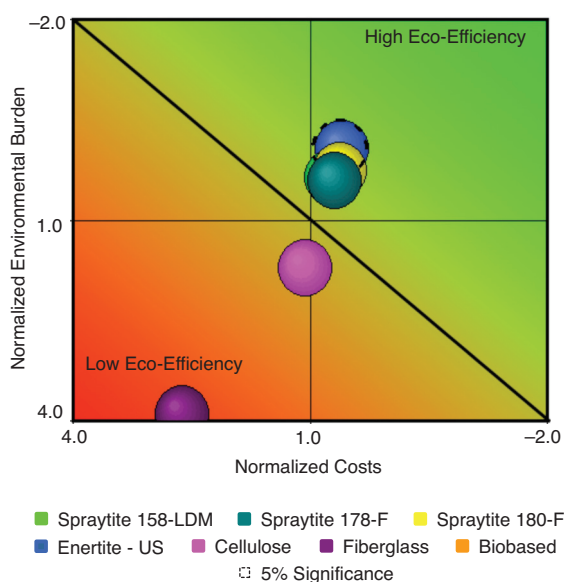
cell SPF has the lowest emissions and risk potential. It also scores well on toxicity potential and resource consumption, as well as energy consumption because of its low air-leakage rate and high whole-wall R-value.

The eco-efficiency portfolio (Figure 16) combines the six individual environmental-impact categories into a single relative environmental impact and a lifecycle cost impact. The open-cell SPF is the most eco-efficient alternative because of its combination of low environmental burden and low lifecycle cost. The four closed-cell SPF's have very similar eco-efficiencies, which are slightly lower than that of the open-cell SPF.

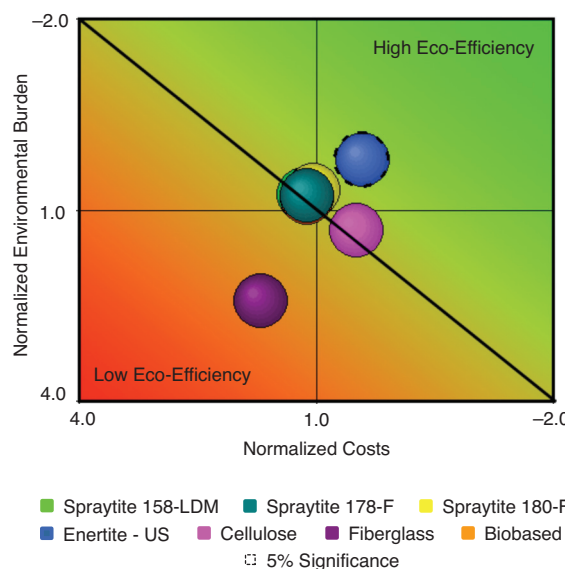
The spray foam alternatives have the lowest lifecycle costs because their normally higher installation costs are offset by the utility savings (relative to fiberglass and cellulose) during the use phase of the home's lifecycle. Fiberglass is the least eco-efficient alternative, followed by cellulose.

Figure 17 is the eco-efficiency portfolio for the same insulation materials in Tampa, FL. This southern city has the lowest overall energy consumption of the four locations considered, and energy consumption is dominated by cooling (unlike the heating-dominated climate zone of the Newark, NJ, base case). Furthermore, utility costs (as well as overall lifecycle costs) are lowest here.

In this scenario, the open-cell SPF has a better relative eco-efficiency compared to the base case (Figure 16). Because overall utility costs are lower, the initial installation costs have a more significant impact — improving the position of the open-cell SPF, cellulose, and fiberglass relative to the closed-cell SPF alternatives. The closed-cell



▲ **Figure 16.** The eco-efficiency portfolio combines the insulations' environmental impacts and economic impacts for the base case (Newark, NJ).



▲ **Figure 17.** In the eco-efficiency portfolio for Tampa, FL, the alternatives are clustered closer together, with relatively lower environmental and economic impacts.



SPFs and the cellulose alternatives have roughly equivalent eco-efficiencies. Cellulose has a lower lifecycle cost, while the closed-cell SPFs have lower environmental burdens.

The analysis also evaluated home insulation in the northern Midwest city of Minneapolis, MN, which has the highest utility demand. Here, the closed-cell alternatives become more attractive, and along with the open-cell SPFs are the most eco-efficient insulations.

### Final thoughts

Eco-efficiency analysis facilitates strategic decision-making along the entire value chain and enables companies to drive innovative product development toward bringing more sustainable products to the marketplace. The methodology identifies the factors whose optimization will directly translate into improvements in the company's product portfolio sustainability profile. A clear understanding of trade-offs helps to prevent inadvertently shifting environmental impacts from one area to another or between the economic and environmental pillars. By measuring the impacts on a system level and including a comprehensive approach to environmental impact assessment, it also safeguards against reaching potentially false conclusions, as can happen when only single metrics (e.g., carbon footprint, energy consumption) are considered.

Eco-efficiency analysis is also an effective communication tool. Since the entire lifecycle of a product is analyzed, the effects on customers along the supply chain can be quantified and evaluated, and a stronger strategic value proposition can be developed. Beyond communication with direct customers, EEA results can be used to educate and engage government agencies and nongovernmental organizations (NGOs).

In order to improve its overall competitiveness in the marketplace by identifying risks and opportunities early, as well as communicate how its products support a more sustainable future, a company must integrate lifecycle tools such as EEA into its business strategy and decision-making process.

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