Use Sustainability Metrics to Guide Decision-Making

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Sustainability provides a framework for integrating environmental, social and economic interests into effective business strategies.

In recent years, many companies have adopted the concept of sustainable development as a core business value. Although sustainability can be defined in many ways, its underlying premise is that economic well-being is inextricably linked to the health of the environment and the success of the world's communities and citizens.

For those businesses that have recognized the need to embrace sustainable development, the next step is to understand how to implement it. Putting this concept into operation requires identifying practical indicators of sustainability and understanding how they can be measured over time to determine if progress is being made. Sustainability metrics are designed to consolidate key measures of environmental, economic and social performance.

The development of metrics that relate environmental and economic performance for production processes is an excellent way for many companies to begin to incorporate the goal of sustainability into management decision-making. Linking the business concept of creating value with environmental performance is termed "eco-efficiency." A management strategy that incorporates eco-efficiency strives to create more value with less impact. It enables more-efficient production processes and the creation of better products and services, while reducing resource use, waste and pollution along the entire value chain *(1)*.

The metrics presented here are designed to meet the following criteria:

- simple — not requiring large amounts of time or manpower to develop
- useful to management decision-making and relevant to business
- understandable to a variety of audiences, from people in operations to finance to strategic planning
- cost-effective in terms of data collection
- reproducible — incorporating decision rules that produce consistent and comparable results
- robust and non-perverse — indicating progress toward sustainability when improvement has in fact been made
- stackable along the supply chain so they are useable beyond the particular fenceline for which the calculation was performed
- protective of proprietary information — preventing the back-calculation of confidential information.

Basic metric construction

Five basic indicators of sustainability are:

- material intensity
- energy intensity
- water consumption
- toxic emissions
- pollutant emissions.

Complementary metrics within each of these categories can be developed as the need for further areas of decision support arises. A common temptation in designing metrics is to take into consideration too many factors. Measurements that combine too many components are actually less versatile and less useful for making comparisons across products and industries. Therefore, it is best to have a core set of simple, widely applicable metrics and to construct complementary metrics to meet the needs of specialized industries. Examples include greenhouse gas emissions as a complementary metric within the category of pollutant emissions, packaging as a complementary material-intensity metric, and water added to products as a complementary water-consumption metric.

Each metric is constructed as a ratio, with impact, either resource consumption or pollutant emissions, in the numerator and a representation of output, in physical or financial terms, in the denominator. To calculate the metrics, all impact numerators and output denominators are normalized to one pound of product. Expressing the metrics as ratios protects proprietary information and provides a way to relate environmental and economic performance.

Measurements for the third dimension of sustainability, social performance, can also be incorporated through the use of ratios. Efforts are underway to develop denominators that capture important indicators of societal benefit. Societal metrics present greater challenges however, because they tend to be values-laden, as well as place- and time-dependent.

The three output denominators are: mass of product, dollars of revenue, and dollars of value added. These denominators yield metrics that are useful at the plant operations level, as well as from the standpoint of strategic business planning. Mass of product is expressed in pounds, and is the mass of product plus the mass of saleable co-products per pound of product. When no co-products are produced, the mass denominator equals one. Revenue is expressed in dollars, and is the revenue obtained for one pound of product plus the revenue obtained for the co-products produced per pound of product. The revenue denominator is based on the market prices of the product and saleable byproducts or co-products. Value-added is expressed in dollars, and is the revenue minus the cost of raw materials and utilities per pound of product. This denominator is particularly useful because it simultaneously captures reductions in costs and increases in net benefits, and it is not as susceptible to market vagaries as the revenue denominator.

The fenceline of the manufacturing facility serves as the boundary for the calculation of metrics for chemical production processes. Sources of data include process flowsheets, Toxic Release Inventory (TRI) reports and financial reports. Many companies are also engaged in initiatives such as pollution prevention and waste minimization, which provide additional information.

Use of the metrics as indicators of sustainability follows the simple rule that *the lower the metric the more effective the process.* A lower metric indicates that either the impact of the process is less (the numerator is smaller) or the output of the process is more (the denominator is larger). The rule that lower is better can be used to evaluate the relative performance of manufacturing processes in terms of impact per unit output.

Calculating the metrics

Material intensity is expressed as pounds of material wasted (not converted to desirable product) per unit output. This metric is calculated by subtracting the mass of product and saleable co-products from the mass of raw materials input to the process. Water and air are not included in the calculation of the material metric unless hydrogen or oxygen from water or air become part of the molecular make-up of the product. In these cases, the stoichiometric requirement of hydrogen or oxygen is included, which ensures that the material metric will be positive.

Energy intensity is expressed as Btus per unit output. It is a measure of the net fuel-energy consumed to provide the heat and power requirements for the process. Energy inputs to the process include natural gas, fuel oil, steam and electricity. Pounds of steam or kilowatt-hours of electricity input to the process are converted to Btus of fuel energy using the efficiencies of steam generation and power generation and transmission. The conversion to fuel energy is performed in all cases, whether electricity and steam are imported or generated onsite. (The benchmark-metric calculations used an average efficiency of 80% for steam generation and 31% for electricity generation and transmission. These efficiencies correspond to fuel energy estimates of 1,350 Btu/lb of steam and 11,000 Btu/kWh of electricity.) Steam or electricity that is exported from the process is credited in the metric by subtracting the exported energy in terms of fuel energy from the fuel energy consumed in the process.

For many processes, fuel energy consumption provides the most useful energy-intensity metric for benchmarking performance and tracking progress. This metric captures process improvements, such as enhanced heat recovery, better heat integration or higher production capacity. It also reflects improved efficiencies of power and steam generation through technologies such as cogeneration.

For processes in which more energy is recovered from an exothermic reaction than is needed to run the unit operations, net fuel-energy consumed is negative. Although negative metrics are still useful measurements, their value as indicators is limited. Comparison of a negative metric with a positive metric still follows the rule that lower is better — *i.e.,* the negative metric is better than the positive one. Comparison of two negative metrics with mass denominators also provides a reliable indication of the more-favorable process. However, comparison of two negative metrics with either financial denominator can be misleading, as the metrics appear to improve (become more negative) as revenue or value-added diminishes.

A complementary energy-intensity metric can be used to track performance of processes for which net fuel-energy consumed is negative. This metric is obtained by including the energy released in the chemical reaction as an energy input to the process. The metric is calculated by summing the net fuel-energy consumed as described above and the negative heat of reaction ($\Sigma\Delta H_{f,R} - \Sigma\Delta H_{f,P}$, where $\Delta H_{f,R}$ and $\Delta H_{f,P}$ are the enthalpy of formation of the reactants and products, respectively, at standard conditions). Because this calculation yields a positive metric, regardless of whether the fuel energy consumed is negative, the metric with any one of the three output denominators can be used to evaluate performance over time or to compare two processes.

Water consumption is expressed as gallons of fresh water, excluding rainwater, consumed per unit output. This metric includes evaporation and misting losses from cooling water (7% of cooling water usage is the default if no data are available), water vapor vented to the atmosphere, water lost through waste treatment or disposal, and water lost through deep-well injection. Rainwater is not included in the core water metric because rainfall quantities are site-specific. A complementary metric for rainwater losses may be a useful measurement for some facilities.

Toxic emissions are expressed as pounds of toxic material emitted by the process per unit output. Chemicals are considered toxic if they are listed by the U.S. EPA as chemicals that must be reported on the Toxic Chemical Release Inventory Form (Form R) under Section 313 of the Emergency Planning and Community Right-to-Know Act. Emissions of criteria pollutants as defined in the Clean Air Act are also included in this metric.

Pollutant emissions are expressed as pounds of pollutants emitted by the process per unit output. This metric is calculated based on the sum of pollutant equivalents (rather than the mass of pollutants *per se*). For example, substances that have a eutrophication effect in receiving waters are expressed as mass of phosphate equivalents. Several pollutant effects are calculated for the pollutant metric: air acidification, water eutrophication, ozone depletion, acidification of fresh water, and salinity in freshwater. These effects can be summed in a single metric, or expressed as separate complementary metrics.

Greenhouse gas emissions are expressed as pounds of carbon dioxide equivalents emitted per unit output. This metric is a complementary metric under the category of pollutant emissions. It includes carbon dioxide equivalents emitted from the treatment of waste streams and the burning of fuel needed to generate the energy for the process. Carbon dioxide emissions resulting from the generation of electricity and steam are included in this metric, even though these emissions occur outside the fenceline of the process when electricity or steam is purchased rather than generated onsite. This prevents the misleading outcome of purchased electricity appearing to create fewer emissions than electricity that is generated onsite.

Applications of sustainability metrics

Once a company has constructed metrics for its processes, the measurements can be used in numerous ways to guide improvements in operations. The following examples illustrate applications of the metrics. These examples present metrics calculated using data from SRI International's Process Economics Program (PEP), and do not represent any particular company or facility.

Benchmarking performance

The use of metrics for benchmarking enables managers to determine where the greatest opportunities for improvement exist in their current operations. Benchmark values, such as those developed using PEP data *(2)*, are useful for gauging the performance of chemical processes.

The Formosa Plastics complex at Point Comfort, TX, served as a pilot facility for developing metrics from company data and for testing the usefulness of the PEP benchmark metrics. The facility is a modern, integrated chemical plant whose products include polypropylene, ethylene glycol, linear low-density polyethylene, high-density polyethylene, polyvinyl chloride and caustic. The PEP benchmark metrics and the Formosa product metrics were in approximately the same range. Several of the facility metrics were more favorable, indicating that in some instances the relatively new, integrated plant was able to achieve a more efficient use of resources and generate less pollution than the PEP processes, which are based on production at separate facilities.

Internal best practices and industry studies can also serve as sources for benchmark values. When comparing metrics for benchmarking or other purposes, it is essential that both sets of measurements be based on the same decision rules and boundaries.

Tracking progress

The ability to measure progress over time is critical to the success of sustainability initiatives. Metrics provide a cost-effective means for tracking how well a company is doing in the key impact areas and for communicating that information to a variety of audiences.

Table 1 illustrates a hypothetical example of tracking metrics for terephthalic acid production when fuel energy consumption is reduced 30%, for example through improvements in plant systems or the installation of a cogeneration unit. The metrics calculated per pound of product reflect the 30% improvement in energy intensity and a 24% improvement in the greenhouse-gas emissions metric. (The greenhouse gas metric also includes emissions for waste treatment, as well as energy production, so the measurement does not improve a full 30%.) The remaining metrics calculated per pound of product do not change, since impacts in these areas have not been affected and the output denominator has not changed. Metrics calculated with the revenue denominator follow the same trend, reflecting the reduced impact in energy intensity and greenhouse gas emissions.

The value-added denominator reveals improvement in all categories. Because lower energy consumption translates to lower production costs, the value-added for the process has increased. Metrics for material intensity, water consumption

Table 1. Tracking improvement over time — metrics for terephthalic acid production via oxidation of p-xylene.

		Per Pound of Product		Per Dollar of Revenue		Per Dollar Value-Added	
Metric	**Unit**	**Baseline Metrics**	**Improved Energy**	**Baseline Metrics Efficiency**	**Improved Energy**	**Baseline Metrics Efficiency**	**Improved Energy Efficiency**
Material	lb	0.13	0.13	0.45	0.45	0.94	**0.90**
Energy	kBtu	6.15	**4.30**	21.5	**15.0**	44.9	**30.2**
Water	gal	3.09	3.09	10.8	10.8	22.5	**21.6**
Toxics	lb	0.011	0.011	0.037	0.037	0.078	**0.075**
Pollutants	lb	0.0008	0.0008	0.003	0.003	0.006	**0.005**
CO_2	lb	0.92	**0.70**	3.22	**2.46**	6.72	**4.94**

Improved metrics are shown in bold.

and toxics improve slightly because of the improved value-added denominator. The metrics for energy intensity and greenhouse gas emissions reflect improvements both in impact reduction and in value-added, and show improvements from the baseline of 33% and 26%, respectively.

The full complement of metrics (using all three denominators) is a valuable data set for measuring progress from several perspectives. The metrics calculated as impact per pound of product provide information that is a direct function of the process operations. These metrics are particularly useful to decision-makers focusing on environmental performance and process improvements. Metrics calculated with the financial denominators incorporate information relative to the selling price of the product and the cost of production, yielding important information for strategic business decisions.

Table 2. Comparing alternative production processes — metrics for hexamethylenediamine production.

Metric	Unit*	Hydrocyanation of Butadiene	Electrohydrodimerization of Acrylonitrile
Material	lb/$VA	1.44	**0.17**
Energy	kBtu/$VA	**59.4**	92.1
Water	gal/$VA	16.2	**15.4**
Toxics	lb/$VA	0.0023	**0.0000**
Pollutants	lb/$VA	0.81	**0.008**
CO_2	lb/$VA	**8.85**	13.2

* $VA = dollar value-added
More-favorable metrics are shown in bold.

Evaluating processes

Metrics are a useful decision-support tool for evaluating alternative processes for the manufacture of a given product. Testing the effect of a new process on each metric reveals which impacts can be reduced and which ones may present increased risks. Metrics provide a simple means for identifying issues early, before they become major problems.

Table 2 presents the metrics for two hexamethylenediamine (HMDA) manufacturing processes. The two sets of metrics clearly show the trade-offs for these processes. The hydrocyanation process has lower energy-intensity and greenhouse-gases metrics, but its material-intensity, water-consumption and pollutants metrics are higher than those for the electrohydrodimerization process.

In a similar fashion, metrics provide a means for comparing resource consumption and pollutant emissions for the manufacture of various products. Table 3 shows metrics for several processes calculated from PEP data. The processes for methanol, chlorine and phosphoric acid are the most energy intensive per dollar value-added in terms of net fuel-energy consumed. The relatively high impacts of producing phosphoric acid, combined with the low value-added for the process, result in metrics that are in some cases several orders of magnitude higher than those of the other processes. The toxics and pollutants metrics for the production of acrylonitrile are relatively high compared to the other processes.

Comparing the metrics for various processes serves to highlight those areas, such as high energy intensity or toxics emissions, that pose potential business risks. Companies can use such information in a number of ways. GlaxoSmithKline, for example, has developed a system based on metrics for evaluating chemistries used in the production of pharmaceuticals *(3)*. Other companies may use metrics to evaluate their products in terms of the impacts and value-added associated with their production, discovering which products are most likely to satisfy stakeholders' concerns and meet environmental objectives and which products may present continuing or future business risks.

Stacking along the supply chain

An important characteristic of the metrics is that they are stackable — that is, they can be combined (or stacked) to calculate environmental impact per pound of product over the series of processes that comprise a supply chain. The figure illustrates how metrics for ethylene, chlorine, vinyl chloride and polyvinylchloride (PVC) can be stacked to obtain metrics for the production of PVC, beginning with

Table 3. Comparing impact per dollar value-added for various processes.

Product (Production Process)	Material (lb/$VA*)	Energy (kBtu/$VA*)	Water (gal/$VA*)	Toxics (lb/$VA*)	Pollutants (lb/$VA*)	CO_2 (lb/$VA*)
Methanol (Reforming natural gas)	0.60	155.6	42.5	0.013	0.000	19.40
Acetic Acid (Carbonylation of methanol)	0.39	15.9	7.88	0.00069	0.000	2.44
Terephthalic Acid (Oxidation of p-xylene)	0.94	44.9	22.5	0.078	0.006	6.72
Acrylonitrile (Ammoxidation of propylene)	4.68	59.5	32.0	0.14	0.22	13.71
Chlorine (Electrolysis of NaCl)	0.16	127.8	9.62	0.000	0.0036	18.94
Phosphoric Acid (Dihydrate wet process from phosphate rock)	318.1	253.6	208.2	4.21	0.000	37.70

* $VA = dollar value-added

naphtha and brine. The metrics calculated with the mass denominator can be readily combined. Impact per dollar value-added can also be calculated for a supply chain by combining the value-added denominators along the chain in the same way that impact per pound of product is stacked. The stacked impact numerator (impact per pound of product) over the stacked value-added denominator (dollar value-added per pound of product) results in supply chain metrics expressed as impact per dollar value-added.

Expressing the metrics as stackable units enhances their versatility and usefulness as decision-making tools. The metrics for entire supply chains, as well as specific processes, can be compared and evaluated. In addition, once a supply chain has been constructed from the individual metrics, the processes within the chain that have the greatest environmental impact can be identified. This allows companies to better target areas for improvement within their own facilities, or make more informed decisions concerning their choice of suppliers.

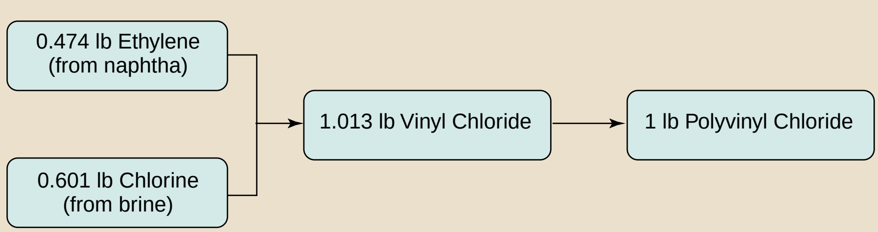
Calculating metrics for facilities

Product-based metrics provide useful information that can be compared with benchmark metrics or other product metrics and that can be stacked to evaluate supply chains as discussed above. In some cases, however, it may be more useful to calculate metrics for a facility, business stream or company rather than a product.

Evaluating facility performance can identify what practices result in the best performance and the greatest value-added per unit input. The information can also be valuable for identifying facilities that need to be improved or, in some instances, shut down because they are too outdated or inefficient.

Integrating metrics with other tools

The metrics provide excellent data with which to begin utilizing a set of integrated decision-support tools that can provide guidance for decision-makers. This toolbox includes practical minimum-energy requirements, lifecycle inventories and total cost assessment (TCA). Although each



Metric	Material (lb/lb PVC)	Energy (kBtu/lb PVC)	Water (gal/lb PVC)	Toxics (lb/lb PVC)	Pollutants (lb/lb PVC)	CO_2 (lb/lb PVC)
Ethylene × 0.474	0.039	1.473	0.433	0.00027	0.00006	0.207
Chlorine × 0.601	0.007	5.050	0.380	0.00000	0.00014	0.748
Vinyl Chloride × 1.013	0.206	4.966	2.129	0.00000	0.00356	0.756
Polyvinyl Chloride	0.049	3.935	0.619	0.00203	0.00000	0.546
PVC Supply Chain	**0.300**	**15.424**	**3.561**	**0.00230**	**0.00376**	**2.257**

Figure. Stacking metrics for the PVC supply chain.

tool provides a mechanism for incorporating sustainable development into business decisions, the significant power of the tools lies in their combination and integration *(4)*.

The practical minimum energy (PME) tool expands the energy intensity metric from one value to a series of levels, each of which corresponds to a category of process improvement and an economic criterion. Metrics linked with PME requirements provide a mechanism to identify energy-intensive processes and to evaluate the viability of energy reduction strategies.

The stackable characteristic of the metrics enables them to function as building blocks in a lifecycle inventory (LCI) or assessment (LCA). The purpose of performing an LCI is to identify the environmental impacts at each phase of a product's life. All input and output flows from raw material extraction through product manufacture, use and end-of-life are inventoried. An LCA is an organization of the flow into impact categories, such as material intensity or greenhouse gas emissions. The LCI and LCA tools are key to identifying the largest impacts in the lifecycle of a product.

TCA provides a method for considering the costs related to sustainability when choosing between alternative products or process designs. While comparing the metrics for two processes can highlight those areas that may pose potential risks, the TCA tool is used to determine the true cost of each alternative. By translating each measurement of impact into a cost, the TCA tool enables the five different types of impacts expressed by the metrics to be summed in terms of dollars, thus providing a single value with which to compare or evaluate alternative processes. Work is progressing on expanding this tool to determine societal costs along the lifecycle of a product. Capturing both current and potential future costs associated with the stacked metrics provides a more robust way of evaluating the viability of alternatives in terms of sustainability.

Closing thoughts

Putting the concept of sustainability into operation requires practical, cost-effective ways to assess performance and measure progress. The metrics presented here give managers simple yardsticks to calibrate how well their company is doing in terms of resource consumption and pollution emissions while extracting more value from their processes. The metrics support decision-making by providing a mechanism for benchmarking performance, tracking improvement over time, evaluating products and processes, and developing strategies for improvement. CEP

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