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METRICS FOR SUSTAINABLE MANUFACTURING

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ABSTRACT

A sustainable manufacturing strategy requires metrics for decision making at all levels of the enterprise. In this paper, a methodology is developed for designing sustainable manufacturing metrics given the specific concerns to be addressed. A top-down approach is suggested that follows the framework of goal and scope definition: (1) goal - what are the concerns addressed and what is the appropriate metric type to achieve the goal (2) scope - what is the appropriate geographic and manufacturing extent. In this methodology, a distinction is made between environmental cost metrics and sustainability metrics. Utilizing this methodology, metrics focused on energy use, global climate change, non-renewable resource consumption, and water consumption are developed.

1 Introduction

Innovative strategies are needed to achieve sustainable processes technologies and industrial systems. “Green” technologies are often understood as those capable of meeting product design requirements while minimizing environmental impact. Minimizing impacts, however, is a necessary but not sufficient condition for a sustainability strategy.

Three important components of a sustainable manufacturing strategy are: (1) selection and application of appropriate metrics for measuring manufacturing sustainability, (2) completion of comprehensive, transparent, and repeatable life-cycle assessments (LCA), (3) adjustment/optimization of the system to minimize environmental impacts and cost based on the chosen metrics and the LCA [1]. This paper focuses on the first of these goals, and discusses the development of appropriate metrics for industrial processes and manufacturing systems. Metric selection and development is a critical component in a sustainable manufacturing strategy as it enables decision making on all aspects of manufacturing from tool choice to system configuration.

For the purposes of this paper “sustainability” is understood as the ability of an entity to “sustain” itself into the future without impacting the capacity of other entities in the system to sustain themselves. This definition involves consideration of three main drivers: economics, society, and the environment. The first of these, economics, has traditionally been the focus of the manufacturing research community. Societal concerns have been addressed by researchers as they relate to increased profit, however additional social metrics to be considered include poverty, gender equality, nutrition, child mortality, sanitation, health, education, housing, crime, and employment [2]. Aggregated indices that provide a broad value for “wellbeing” or “environmental sustainability” have also been developed [3]. While these social and aggregate metrics are valuable to make broad decisions, they may not allow for granular insight and decision making within the manufacturing enterprise.

This paper specifically discusses metrics related to the environment and environmental sustainability, although the procedure for metrics development is applicable across other areas as well. Environmental metrics are a useful starting point for dis-

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cussions of sustainability as they often map to societal and economic concerns. Moreover, reducing environmental impacts can reduce costs in ways that are unrealized by simple cost analysis; for example, by energy cost savings and the reduction of abatement costs. Societal concerns, such as health and sanitation, may also be addressed through reduced environmental impacts. Additionally, climate change is an environmental concern that is postulated to have serious societal implications.

Environmental sustainability has been previously assessed based on the availability and use of resources (such as coal, water, or oil usage) as well as environmental impact (pollution, toxicity, climate change) [4, 5]. Although the consideration of environmental impacts is important for the evaluation of environmental sustainability, environmental metrics do not necessarily indicate whether a level of emissions or consumption is actually sustainable. For this reason, we group metrics as either cost or sustainability indicators. Cost metrics indicate a measured value (ex: dollars, tons of CO_2, joules of energy) per functional unit of a process, good, or service. Reducing the "cost" of goods is valuable for sustainability, but it does not indicate whether the rate of consumption or emissions have achieved a level that can be continued indefinitely. Sustainability metrics indicate the performance of a system or process in maintaining a sustainable level of a specific resource (such as air, or clean water).

A challenge in selecting metrics for sustainable manufacturing is that it is not an inherently intuitive process. Unlike economic metrics, such as unit cost or part quality, sustainability metrics are not necessarily related to the function of the part being manufactured. Additionally, a complete picture of environmental impact and sustainability requires numerous metrics. However, time and cost considerations limit the number of possible metrics that can be practically considered in a manufacturing analysis. Choosing an appropriate set of metrics is critical as this choice will impact the conclusion of the analysis. For example, Schweimer et al. conducted an environmental life-cycle assessment of automobile manufacturing and found that 81% of CO_2 emissions occur during the vehicle use phase, 88% of non-methane VOC (volatile organic carbon) emissions occur in the fuel production phase, and 83% of dust emissions occur during the vehicle manufacturing phase [6]. Hence, the least sustainable phase of the automobile manufacturing process can be identified only based on the goal of the assessment (that is, if the goal was to minimize VOC emissions, CO_2 emissions, or dust emissions). For efficiently selecting metrics it is very important to have the utmost clarity on the goal of the environmental assessment and the aspects that are important for a specific industry or world region.

In this paper we present a methodology for selecting sustainability and environmental metrics. We then apply our methodology to understand key metrics in the areas of energy use, greenhouse gas emissions, and resource consumption. We conclude with a discussion on the need for more rigorous development of sustainability metrics and the potential application areas for these metrics.

2 Related Work

Much of the work characterizing environmental impacts of manufacturing processes and systems has focused on energy consumption patterns. While we will argue that energy consumption is not necessarily a proxy for environmental impact, it is a critical component in any overall sustainability strategy. Gutowski et al. [7] presented a seminal overview of the status of environmentally benign manufacturing technologies in the United States, and compared them to technology in Europe and Japan. The report discussed the competitiveness of US manufacturing practices and identified areas of focus for the US manufacturing industry to improve its environmental impact. Westkamper et al. [8] argued the need for a sustainable manufacturing strategy and discussed several approaches for life-cycle management and its application in sustainable manufacturing. Durham [9] highlighted the need for environmental management of the entire manufacturing cycle, taking into account both global and local effects and the consumption of materials in all parts of the cycle. O'Brien [10] argued that industry had to play a pivotal role in ensuring sustainable development in society and stressed the need for sustainable production systems to this end.

There has also been extensive work in the manufacturing community in characterizing the impacts of specific manufacturing processes and technologies. Dahmus and Gutowski [11] presented a detailed analysis of the environmental impact of machining, taking into account the material removal process as well as the use of cutting fluid and other consumables. Jeswiet et al. [12] proposed a calculated carbon emission signature for correlating electrical energy use to the greenhouse gas emissions of a number of traditional manufacturing processes. Morrow et al. [13] presented a detailed study comparing the environmental impacts of tool and die machining using conventional and laser-based processes. They identified the complex economic and environmental tradeoffs that needed to be made in selecting the most suitable processes for different types of mold designs. Roman et al. [14] investigated the water and energy consumption of industrial cleaning processes. Jayal et al. [15] investigated the relative health risks associated with mist versus flood cooling. Zhao et al. [16] considered methods to filter and recycle used cutting fluids. Nasr et al. [17] have done extensive work characterizing and understanding the remanufacturing of goods. Dornfeld and Wright [18] identified "wedge technologies" to enable the implementation of green manufacturing, where a wedge technology is one that is both scalable and offers a net environmental benefit when implemented.

Our work is motivated by the need to provide manufacturing engineers and scientists a set of tools with which they can better design and characterize sustainable manufacturing systems.

A robust set of metrics will enable the vision outlined by researchers in the field, and will help integrate the specific advances in manufacturing technology into the broader framework of sustainable production systems.

3 Metric Selection Methodology

We propose the following 4-part methodology to determine appropriate metrics for a sustainable manufacturing strategy. Metrics are identified based on the particular concerns being addressed in the sustainability study. Colloquially, we are looking for "the right tool for the right job" as it is difficult to conceive an absolute "best" metric for sustainable manufacturing. Additionally, this methodology is intended to be flexible and modular over time, which is important given that the effectiveness of the metric is determined only by its usefulness in a specific context. Determination of appropriate metrics is inherently influenced by current "social value, knowledge horizons, and individual perspectives" [19]. Figure 1 shows an overview of the metric selection process.

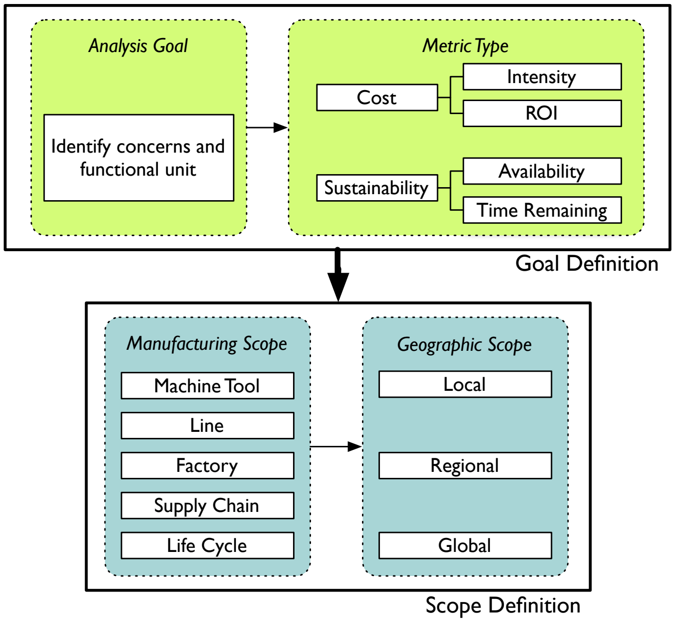


Figure 1. Metric selection methodology

It should be noted that this methodology follows the ISO 14040 standards on life-cycle assessment [20]. The four main steps of life-cycle assessment are goal and scope definition, inventory analysis, impact assessment, and interpretation of results. With this methodology we are essentially performing the first step of ISO14040 as it is relevant to metric selection. Steps 1 and 2 define the metric's goal, while steps 3 and 4 determine scope.

Step 1: Goal Definition - Determine the goal of the assessment. This first step requires an understanding of the sustainability concerns driving the effort. This means that the metric selection needs to be driven by the objective of the sustainable manufacturing strategy. Additionally, at this stage the functional unit for the assessment should be determined.

Furthermore, if a technology is new, or requires the processing of new materials that are poorly understood, then a comprehensive sustainability assessment employing a suite of metrics may be necessary. However, if we are studying specific impacts or the consumption of particular resources, then it is adequate to only highlight these concerns. Care should be taken to not overly simplify the assessment goals; however with enough information, simplification and scope reduction at this stage can be useful in reducing the time and costs needed for the sustainability assessment.

Step 2: Goal Definition - Choose a metric type. Generally, metrics for manufacturing decision making can be classified as either "cost" or "sustainability" indicators. Here, these categories are further broken down into four distinct metric types (summarized in table 1).

The first two metric types are analogous to familiar cost metrics. First are the *intensity* metrics, which indicate the cost per functional unit. Second are *return on investment* metrics that indicate the percent savings of a particular investment relative to the input required for the investment.

The third and fourth metric types are based on sustainability concerns relative to resource availability. Use of resources that are considered "renewable" can be characterized by an *availability factor*, which indicates consumption relative to replenishment rates. The availability is the "amount of resource use" relative to the "total resource availability". This is comparable to machine tool availability metrics used in measuring the efficiency of manufacturing systems.

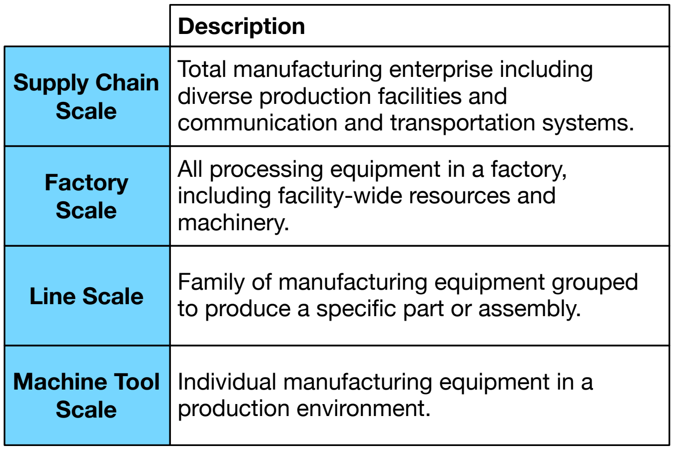
Decision metrics for non-renewable resources is an area requiring further research; however one way to quickly understand the risk associated with using non-renewable resources is by calculating the *time remaining* of the resource given current consumption patterns and available reserves. Because this value does not enable decision making at all levels of production, it highlights the need for metrics to understand non-renewable resource consumption.

Step 3: Scope Definition - Determine the manufacturing scope of the assessment.

While it is always important in the development of green technologies to consider the life cycle of the technology – which includes material extraction and conversion, industrial facilities usage, process consumables usage, manufacturing process impacts, supply chain and transportation impacts, product use, and end of life – decision making often must occur on a smaller scope

Table 1. Overview of Metric Types. (Impact: monetary or environmental cost; LC: total life cycle; BAU: business as usual; Investment: replacement for BAU; Use: rate of consumption; Stock: amount available for consumption; SA: sustainable available stock.)

Metric Type	Units	Metric Formulation
Intensity: cost or environmental impact per unit of production	$\frac{Value}{Unit}$	$\frac{Impact_{Investment}}{Functional\ Unit}$
% Return on Investment: amount not emitted/consumed relative to amount emitted/consumed	$\frac{Savings}{Investment}$	$\frac{Impact_{BAU} - LC_{Investment}}{LC_{Investment}}$
Sustainability - Availability Factor: fraction of available resources consumed	$\frac{Used}{Available}$	$\frac{Use_{Investment}}{SA - Use_{GeographicRegion} + Use_{BAU}}$
Sustainability - Time Remaining: for resources being consumed faster than replenished	$Time$	$\frac{Stock_{GeographicRegion}}{Use_{GeographicRegion}(1 - RecyclingRate)}$



	Description
Supply Chain Scale	Total manufacturing enterprise including diverse production facilities and communication and transportation systems.
Factory Scale	All processing equipment in a factory, including facility-wide resources and machinery.
Line Scale	Family of manufacturing equipment grouped to produce a specific part or assembly.
Machine Tool Scale	Individual manufacturing equipment in a production environment.

Figure 2. Scales of decision making in a manufacturing system

within the larger process (see Figure 2). Decision making in a manufacturing enterprise can take place at many different levels, therefore the scope of application should be understood when using the metric formulations given above. For example, when investigating the manufacture of a product, the eventual use and end of life of that product need not be considered, unless decisions during the manufacturing stage have an impact on the use phase, or the end of life (see Figures 3).

The following levels of analysis scope are identified:

Machine Tool Scale: At this scale, decisions specific to one machine tool or a small family of tools are taken. The decisions are usually made regarding the fundamental process technology. Control of lubrication systems and MQL is an example of decisions for sustainable manufacturing at this level. Metrics at this scale reflect the functionality of the machine tool (ex: emissions per minute or energy consumption per part). The “ripple” effects of decisions taken at this scale must be considered by analyzing subsequent manufacturing operations (example: using MQL could necessitate additional cleaning operations).

Line Scale: This scale includes the set of machine tools and support equipment that are logically organized into a manufacturing line or cell. Final and intermediate products are created at this scale and metrics need to be relevant to the entire scope of this scale including support equipment and machinery.

Factory Scale: Here the entire factory is incorporated and metrics at this scale need to capture the impact of the facility itself on the environment. For example, the total water and energy consumptions of a semiconductor facility must take into account HVAC and clean-room systems [21].

Supply Chain Scale: This level looks at the manufacturing enterprise including its entire supply chain. At this scale, metrics need to be selected to capture the interrelationships between discrete geographical entities in the system. The effect of the complex transportation and communication networks prevalent in manufacturing systems also need to be accounted for [22]. The metrics at the factory and supply chain scales also need to comply with local, national, and international standards because an economic cost can be associated with these. For example, in the United States emissions not known to be an environmental

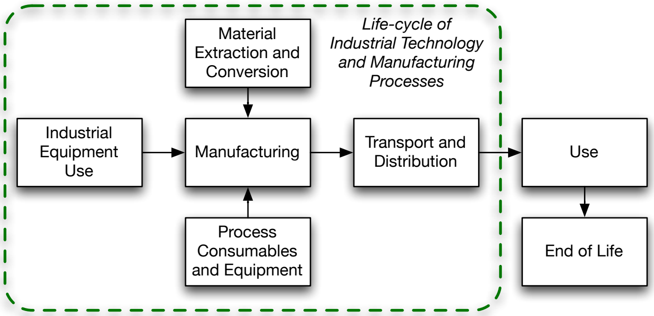


Figure 3. Life-cycle of a manufacturing process

hazard at the time can be later subject to large fines through the Superfund program [23].

Life Cycle Scale: The final level goes beyond the supply chain to include product use and end of life decisions. This will incorporate supply chains associated with consumables throughout the use-phase, operational and maintenance impacts, as well as end of life reverse logistics, recycling, re-use, and disposal.

Note that each scale incorporates the effects of lower scales [24]. For example, the supply chain scale includes all the factories throughout the system, plus transportation and logistics. The factory scale includes all of the product lines as well as extraneous factory requirements such as HVAC and overhead. The line scale includes all machines in the line plus transport between machinery. Given the complexity of decision making across these scales, it is critical to clearly identify at which scale (or scales) the sustainability metrics are going to be applied. It may not be possible to select a metric that is relevant or applicable across all the scales. For example a metric of local water availability cannot be readily applied across a global supply chain.

Metrics at the lowest scale tend to be customized for specific process technology (such as consumable consumption rates) and local environmental conditions for sustainability. Metrics at the higher scales can be broad-based enough to be applied at the lower scales (such as carbon emissions or energy consumption), but not necessarily vice-versa.

Step 4: Scope Definition - Determine the geographic scope of the assessment. While in some cases the manufacturing scope defines the geographic scope of the assessment, this is not always necessarily true. For example, a sustainability metric based on energy use can be related to either global energy resources or local energy infrastructure capacity. Depending on the goal of the assessment, the appropriate geographic scope can be determined. Choosing a metric requires understanding the geographic range of the environmental concern. Environmental impacts may be highly localized or globalized. For example, greenhouse gas emissions can affect global climate change regardless of where they are released. However, if electricity supply is scarce in one location, excessive use of electricity elsewhere is neither harmful nor helpful to the local scarcity.

4 Metrics Development Examples

To demonstrate the previously described methodology, metrics aimed at concerns of energy, greenhouse gas emissions, water use, and non-renewable resources are discussed in the following sections. Each section is structured to answer the question: what is the appropriate scope for this goal, and what might a metric look like given this goal and scope.

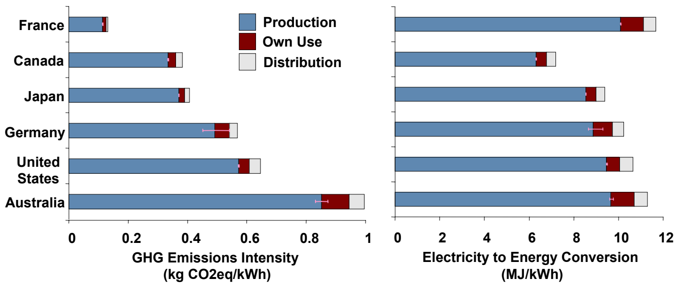


Figure 4. Electricity greenhouse gas emissions and energy use [1,25]

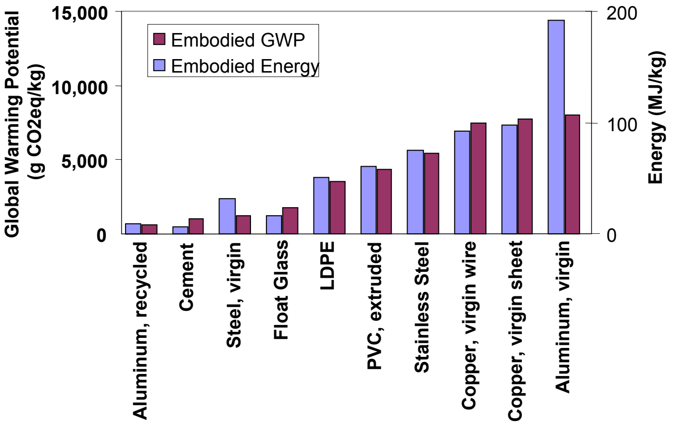


Figure 5. Materials embodied energy and CO2 emissions from New Zealand LCA [26]

4.1 Energy Metrics

Table 2 explores some possible energy metrics, where the scope of the energy metric varies depending on the context and source of energy; it can be considered a renewable or non-renewable resource on a local or global scale. For example, if the concern is global coal availability, then only the energy use attributable to coal should be studied. Or, if an energy metric is used to address concerns of energy independence then only regional energy use needs to be considered.

In recent reports and studies, energy metrics have been used as a proxy for greenhouse gas (GHG) emissions. While energy is preferred to GHG emissions because it is considered a more straightforward quantity to measure, it does not allow for a true understanding of greenhouse gas emissions. Even in the case of ostensibly using the same amount of electricity for the same activity in multiple places, there can be a large difference in the GHG emissions associated with the electricity source. To illustrate this point, Figure 4 shows the CO2-equivalent emissions (global warming potential) associated with a kWh of electricity demanded from the grid for selected countries and U.S. states

Table 2. Energy Metric Examples.

Scenario (Goal)	Geographic Extent (Scope)	Metric Type	Possible Metric Formulation
Understand local energy consumption as it relates to local energy supply	Local	Availability	$\frac{EnergyUse_{Investment}}{EnergyCapacity_{Local}-EnergyUse_{Local}+EnergyUse_{BAU}}$
Understand how a new investment can reduce energy use from the local grid	Local	Return On Investment	$\frac{EnergyUse_{BAU}-EnergyUse_{LC-Investment}}{EnergyUse_{LC-Investment}}$
Understand time remaining until known stocks of oil are consumed; assuming current consumption rates	Global	Time Remaining	$\frac{OilStocks_{Global}-OilUse_{Global}}{OilUse_{Investment}}$

[1] [25]. The difference in these values shows that there is no straightforward conversion between energy and greenhouse gas emissions. Another example of the inappropriateness of energy to represent GHG emissions is seen in Figure 5 where embodied energy and CO2 data from a life-cycle assessment of building materials in New Zealand [26] are shown – note that the ratio between CO2 and energy consumed for the different materials is not consistent.

4.2 Greenhouse Gas Emissions

Given recent concerns over global climate change, metrics based on greenhouse gas emissions are extremely relevant; and because greenhouse gas emissions contribute to global climate change, this goal has a global scope.

Greenhouse gas metrics can be constituted as either an intensity factor, a return on investment, or a sustainability availability factor. Intensity factors are of the form $\frac{GHG}{unit}$ and availability is relative to earth's ability to absorb and utilize the emissions.

The greenhouse gas return on investment metric (GROI) has been suggested previously by Reich-Weiser et al. [27] to determine the fastest route to mitigating climate change. GROI (equation 1) can be used to evaluate tradeoffs between two opportunities and indicates the amount of greenhouse gases saved from the "business as usual" case for every unit of greenhouse gas emitted by the "investment". A positive GROI indicates that the investment is a net GHG saver and a negative GROI indicates that it is preferable to maintain business as usual.

$$GROI = \frac{GHG_{BAU} - GHG_{Investment}}{GHG_{Investment}} \tag{1}$$

Here, GHG_{BAU} is the life-cycle greenhouse gas emissions of the current technology. For a machine tool this includes emissions associated with both the manufacture and use-phase of the tool (including the electricity emissions and embodied greenhouse gas emissions of consumables). The life-cycle greenhouse gas emissions have to be amortized over a functional unit such as dollars of revenue or amount of material processed (this functional unit will be the same as used in $GHG_{Investment}$).

$GHG_{Investment}$ is the greenhouse gas emissions from installing or utilizing a new technology. This is where tradeoffs such as make-versus-buy (for a product) or replace-versus-keep (for a machine tool) come in to play. These are the emissions associated with the alternative to the product assessed in GHG_{BAU}. For example, if a decision is being made between the purchase of two alternate machine tools, then GHG_{BAU} and $GHG_{Investment}$ are the life-cycle greenhouse gas emissions of alternative machine tools amortized over the functional unit.

4.3 Water

Water is of vital importance for human life and its availability is expected to change as climate change progresses [28–30]. Recent events in the United States concerning water scarcity have also highlighted the importance of water use reduction and minimization [31].

The use of water occurs in three ways, by:

1. Withdrawal, where water is removed from a natural water system. Some of this water may be returned to the river, lake, or groundwater source it was removed from, but it is almost always altered in some way, either by temperature increase or pollution.
2. Consumption, where water becomes unavailable to the water system from whence it came. All water remains within the global "water cycle" so this water may end up as rainfall somewhere else, but rainfall elsewhere may not be particularly useful to the community or ecosystem whose water was consumed.
3. Pollution, where water becomes unfit for use by nature or society; however this water often does continue to be used

leading to health and ecosystem damage downstream. Certain types of pollution may make water unfit for only a select number of uses.

As water is a renewable resource, the value of the rate of renewal must be incorporated in the chosen metric. While a return on investment metric could calculate the water savings achieved by a new investment relative to the business as usual case, this will not indicate how the change relates to local water scarcity. It may be that in one community the marginal water savings from implementing a new technology has a large impact on water scarcity, while elsewhere water is abundant and the savings are negligible. Additionally, the goal of a water metric is to understand water scarcity and the manufacturer's role in promoting or preventing water scarcity, which is a local issue because water is not easily transported and freshwater supplies are not interconnected.

For these reasons, a renewable resource metric is suggested to characterize these nuances: the water availability factor (WAF) (equation 2). Calculated as the amount of water consumed relative to the renewable water supply in a region, this factor is the fraction of available water impacted by use.

$$WAF = \frac{WaterUse_{Local-Investment}}{RenewableWaterSupply_{Local} - WaterUse_{Local}} \tag{2}$$

4.4 Non-Renewable Resources

The use of non-renewable resources is linked with economic costs as the increased effort required to obtain scarce resources – along with the economics of supply and demand – can drive material prices higher. Therefore understanding resource scarcity when choosing materials can indicate the potential scale-up opportunities for a product or process, as well as the long-term feasibility of production.

Data on resource availability is obtained using known geographical surveys and mining techniques from the U.S. Geological Survey [32]. This report also contains data on current global consumption rates and U.S. recycling rates. From this data, the number of years remaining – assuming today's consumption patterns and known stocks – can be determined, as shown in equation 3 and Figure 6.

$$Years_{Remaining} = \frac{Stock_{Global}}{AnnualUse_{Global}(1 - RecylingRate)} \tag{3}$$

Choice of manufacturing location may also influence the ease with which resources are acquired, and/or the distance (influencing flexibility, cost, and environmental factors) they must travel. The availability of Bauxite to be processed into Aluminum is a simple and relevant example of material availability.

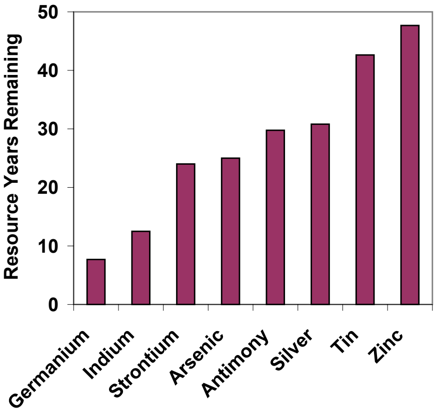


Figure 6. Years remaining of scarce resources according to U.S. Geological Survey [32]. Note: recycling is incorporated only for silver, tin, zinc, and germanium, and the availability of germanium ignores germanium stored in coal ash.

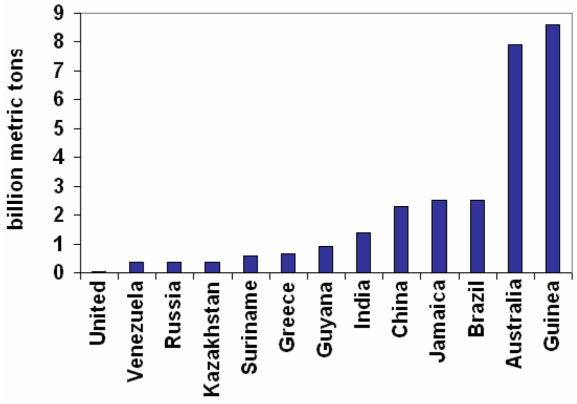


Figure 7. Bauxite Resource Availability with Current Mining Techniques [32]

Figure 7 shows the estimated bauxite reserve base, or bauxite extractable through current methods in different countries, according to the US Geologic Survey [32].

5 Discussion

Table 3 summarizes the metrics discussed in this paper. In addition to being used in life-cycle assessments of manufacturing technology, these metrics can also be applied to benchmark products and systems for use in investment-related decision making. For example, the intensity metrics for the extraction and processing of petroleum products can be applied as the baseline for comparing alternative energy technology investments. Recently there has been a move towards using a monetary value to esti-

Table 3. Summary of Metrics

Goal	Scope	Metric Type	Units	Metric Formulation
Energy Scarcity	Local	Availability	$\frac{Energy_{Used}}{Energy_{Available}}$	$\frac{EnergyUse_{Investment}}{EnergyCapacity_{Local}-EnergyUse_{Local}+EnergyUse_{BAU}}$
Energy Independence	Local	Return On Investment	$\frac{Energy_{Savings}}{Energy_{Use}}$	$\frac{EnergyUse_{BAU}-EnergyUse_{LC-Investment}}{EnergyUse_{LC-Investment}}$
Oil Scarcity	Global	Time Remaining	*years*	$\frac{OilStocks_{Global}-OilUse_{Global}}{OilUse_{Investment}}$
Climate Change	Global	Return on Investment	$\frac{GHG_{Savings}}{GHG_{Emissions}}$	$\frac{GHG_{BAU}-GHG_{Investment}}{GHG_{Investment}}$
Water Availability	Local	Availability	$\frac{Water_{Used}}{Water_{Available}}$	$\frac{WaterUse_{Local-Investment}}{RenewableWaterSupply_{Local}-WaterUse_{Local}}$
Material Scarcity	Global or Local	Time Remaining	*years*	$\frac{Stock_{Global}}{AnnualUse_{Global}(1-RecylingRate)}$

mate the cost of emissions, and the benchmark comparisons can be extended to monetary comparisons using appropriate scaling factors for a more conventional cost analysis.

Another application of these metrics is in defining "environmental design budgets" for engineered products and systems. Based on the impacts of a benchmark technology, or on the required impacts by a regulatory agency, an environmental design budget can be calculated which enforces a fixed maximum of environmental impacts a specific product or system can have. Intensity metrics can be used to define the budget, and this will drive the design and performance of the product or system under consideration. By integrating environmental design budgets into the product design process, engineers and designers can also define budgets and target environmental thresholds for sub-systems and components that make up the product being designed.

The role of metrics in engineering design and analysis cannot be overstated, Metrics serve as an "enabling technology" in the design process, especially from the vantage of achieving environmental sustainability through design. Effective and targeted metrics allow engineers and designers to focus on specific areas of interest during the design process. However, relying on "lumped" metrics, which aggregate multiple indicators, may be misleading as these metrics do not capture the competing drivers in the system. Ultimately, the quality and impact of engineering design and analysis is closely related to design of the metrics used in the analysis. Continued research is required on the characterization of sustainability metrics for manufacturing processes to achieve truly sustainable manufacturing technologies.

6 Acknowledgments

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