Perspective

The Quest for Sustainability: Challenges for Process Systems Engineering

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Introduction

Leaders in the global business community have begun to assign a new strategic significance to the term "sustainability." No longer confined to the economic realm, sustainability now embraces a broad spectrum of company characteristics related to social and environmental responsibility. This shift in thinking (dare we say enlightenment?) is due to growing recognition among business executives that profitability alone is inadequate as a measure of success, and that many of the nonfinancial concerns associated with sustainability are fundamental drivers of long-term shareholder value. Conversely, failure to recognize these strategic issues threatens the very survival of a business enterprise. For example, mounting concerns over the ability to curb industrial emissions of CO_2 and other global warming gases are only the tip of this proverbial iceberg.

The original concept of "sustainable development" (SD), defined over 15 years ago by a U.N. commission, suggested pursuing development in a way that respects both human needs and global ecosystems, assuring quality of life for future generations (WCED, 1987). It was clear even then that current trends in population growth and economic development were not sustainable. Without dramatic changes in the patterns of human activity, there will be severe challenges to the continued growth of global industries. Examples of these challenges include (World Bank, 2001):

- Adverse environmental impacts such as climate change; degradation of air, water, and land; depletion of natural resources, including fresh water and minerals; loss of agricultural land due to deforestation, soil erosion and urbanization; and threatened ecosystems.
- Adverse socio-economic impacts such as widespread poverty, lack of potable water, proliferation of infectious diseases, social disintegration resulting from displacement of traditional lifestyles, growing income gaps, and lack of primary education.

Rather than ignoring these ominous signals, a number of visionary business leaders have risen to the challenge and developed a new model of industrial progress that marries economic growth with social and environmental responsibility (Holliday et al, 2002). Many corporations are beginning to partner with governments and nongovernmental organizations to seek sustainable solutions that preserve their freedom to operate. Pragmatically speaking, such voluntary initiatives are certainly preferable to resistance or indifference, which would invite an increasingly onerous regulatory regime that limits industrial growth through economic or technological constraints.

Responding to the challenges of sustainability requires insight into the characteristics of a sustainable system, and a fundamental rethinking of how all industrial products and processes are designed, built, operated, and evaluated. Qualitative definitions of sustainability such as that given by the U.N. are not particularly helpful for engineering decision-making. The following definition is more useful: *A sustainable product or process is one that constrains resource consumption and waste generation to an acceptable level, makes a positive contribution to the satisfaction of human needs, and provides enduring economic value to the business enterprise.* The determination of an "acceptable level" represents a technical challenge, but it is common to assert that resource utilization should not deplete existing capital, that is, resources should not be used at a rate faster than the rate of replenishment, and that waste generation should not exceed the carrying capacity of the surrounding ecosystem (Robèrt, 1997).

Since sustainability is a property of the entire system, and not of an individual subsystem, incorporating sustainability into engineering requires the boundaries of "the process" to be greatly expanded—beyond the plant and even beyond the corporation. As shown in Figure 1, the analysis boundaries might extend to the economy and the ecosystem. Moreover, the scope of analysis needs to be expanded beyond cost and performance issues to include environmental integrity and socio-economic well being.

Life cycle assessment (LCA), now an ISO-standardized methodology, is an important example of the effort to expand the traditional process boundary. LCA considers both the upstream and downstream processes associated with a given product in terms of energy use, material use, waste generation, and business value creation (Consoli et al., 1993). The life cycle stages, shown in Figure 1, may include resource extraction, procurement, transportation, manufacturing, product use, service, and end-of-life disposition or recovery. The feedback loop indicates the importance of recycling, reuse, and reverse logistics. Careful consideration of life cycle implications can sometimes yield surprising results. For example, efforts to develop "green" plastics, such as polylactides, seem appealing because the feedstocks are renewable and the plastics are biodegradable. However, it turns out that the extraction and processing of the plastics is extremely energy intensive, and the biological breakdown of the plastics releases greenhouse gases (Gerngross and Slater, 2000). Similarly, hidden ecological burdens can be found in the semiconductor industry—the manufacture of a tiny microchip entails the consumption of large amounts of energy and materials (Williams et al., 2002). Only by expanding the system boundaries can such issues be fully understood.

Another example of the effort to go beyond traditional economic boundaries is the rethinking of approaches to economic analysis of natural systems. Classical economics viewed natural resources as external to the market, and essentially free. Similarly, there was no economic penalty associated with industrial wastes, on the assumption that natural systems were resilient and would simply absorb them. In contrast, a new school of "ecological economics" has emerged in which ecological and social capitals are valued together with conventional capital as part of a larger "industrial ecosystem" (Fiksel, 2002). In this view, access to natural assets such as wind energy or intellectual assets such as human creative talent can be assigned a value along with traditional physical assets such as factories and equipment. Such studies indicate the high value of ecological goods and services (Costanza et al., 1997; Balmford et al., 2002). Economic policymakers and corporate strategists should seek to preserve and renew these nonfinancial assets to assure the well being of society and the enterprise, respectively.

Similarly, chemical engineering, along with other disciplines, needs to focus on the sustainability of its activities by considering factors beyond the traditional process, product, or enterprise. This represents a formidable technical challenge to the engineering community. Among all the specialties of chemical engineering, process systems engineering (PSE) is perhaps best positioned to address the challenges of sustainability. Unlike the reductionist approach of other specialties, PSE adopts a holistic or systems view, which is essential for understanding and modeling the complex interactions between industry, society and ecosystems. Such methods will become increasingly important for both new and existing technologies at all stages of their research, development, and use. This presents unprecedented challenges and exciting opportunities for PSE to play a crucial role in the quest for sustainability.

Previous related "Perspectives" articles have focused on PSE (Grossmann and Westerberg, 2000; Harold and Ogunnaike, 2000) and Green Engineering (Allen and Shonnard, 2001). The first two articles recognize the importance of including environmental considerations in PSE. Allen and Shonnard focus on the need for a new set of tools for Green Engineering and environmentally conscious design. However, the scope of sustainability is so broad that it requires integration of many disciplines including engineering, biology, medicine, economics, law, ethics, and social sciences. The purpose of this article is to summarize the business case for adopting sustainability, and to identify a number of key technical research challenges that need to be addressed in order to make progress toward sustainability. It complements the above articles, and specifically focuses on the important contributions that PSE can make for meeting these challenges.

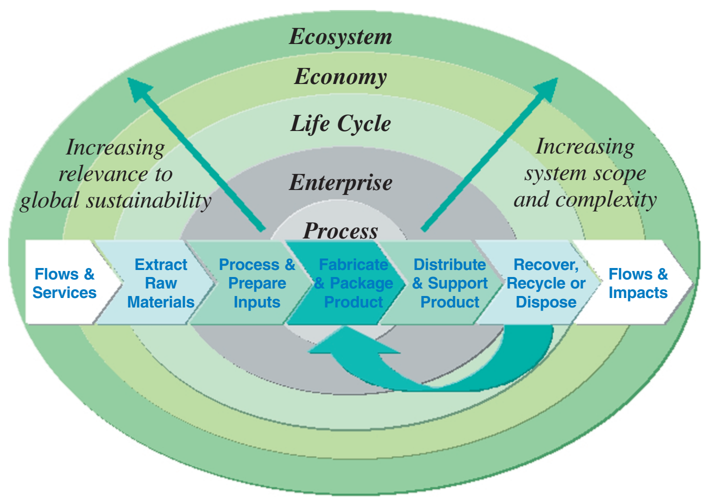

Figure 1. Hierarchy of sustainable process systems engineering. Each successive oval encompasses a broader set of life cycle steps. Gray areas represent existing PSE techniques. Green ovals represent new frontiers for PSE.

Understanding the Business Case

Corporations all over the world are realizing that sustainability makes good business sense and is essential for their survival and growth (Hoffman, 2001). Many CEOs have asserted a belief that sustainable business practices will improve both enterprise resource productivity and stakeholder confidence. At the same time, corporations are beginning to consider the interests of a broader range of stakeholders including not only customers and shareholders, but also employees, local communities, regulators, lenders, suppliers, and advocacy groups.

According to KPMG, 36% of the top 100 U.S. companies now publish annual Sustainability Reports (KPMG, 2002). A recent PriceWaterhouseCoopers (2002) survey of 140 U.S. companies, 101 of which are in the Fortune 1000, showed that 75% claim to have adopted sustainable business practices. The most common reasons cited were enhanced reputation, competitive advantage, and cost savings. Other factors that drive this trend include increasing emphasis on corporate ethics and accountability, including social responsibility and transparency; emerging regulatory initiatives aimed at climate stabilization and extended producer responsibility, and expansion of multinational companies into developing nations where they are increasingly concerned with poverty reduction and quality of life issues, including how to serve the vast, low-income markets at the "bottom of the pyramid" (Prahalad and Hart, 2002). The financial community has also begun to recognize that attention to sustainability is an indicator of overall superior management, as exemplified by the increasing interest in the Dow Jones Sustainability Index (DJSI, 2003).

A significant factor in this newfound awareness was the creation of the World Business Council for Sustainable Development (WBCSD), a consortium of over 100 leading companies formed in 1990. WBCSD published *Changing Course*, an important manifesto describing both the challenges and the business opportunities associated with corporate sustainability (Schmidheiny, 1992). Subsequently, WBCSD has published a series of studies that demonstrate the business value of sustainable practices, and that present agendas for change in many industries. The goals of economic, ecological, and social well-being are often referred to as a "triple bottom line" that expands upon the financial bottom line (Elkington, 1997). This metaphor has been used as the basis for many sustainability assessment tools such as the Global Reporting Initiative (2002).

Recent studies suggest that there are three major pathways whereby sustainability contributes to shareholder value (Fiksel, 2003).

• Sustainable business practices can contribute directly to **tangible financial value** by enabling growth, reducing costs, conserving capital, and decreasing risks. For example, DuPont plans to expand into new markets by addressing unmet social needs. Baxter Healthcare reports the contribution of its environmental programs to reductions in capital and operating costs.

• Sustainability can directly improve **intangible assets** such as reputation, strategic relationships, human capital, and innovation. Examples include improved technology, as demonstrated by Xerox Corporation's pioneering efforts in reverse logistics and asset recovery for photocopiers; and improved customer relationships, as demonstrated by Ashland Chemical's alliances with customers to assure safe, economical, and productive use of chemical products.

• Sustainability can provide strategic advantage by creating **value for stakeholders**. For example, Procter & Gamble has focused its sustainability efforts on creating innovative products that address worldwide needs for water, health, and hygiene. Lafarge, the global cement producer, has partnered with environmental groups, governments, and local communities in advancing ecological stewardship, thus helping to improve its public image and assure its continued license to operate.

Pursuit of sustainability has resulted in the flourishing of a variety of innovative business practices. The following are examples of sustainable business practices that simultaneously benefit both an enterprise and its stakeholders.

• **Design for Sustainability** is defined as systematic consideration, during design and development, of sustainability over the full product and process life cycle. In the chemical industry, Design for Sustainability is manifested via development of "green" chemical routes, process intensification, and process redesign. For example, DuPont has developed a "Super Solids" ultralow emissions coating technology for use in automotive painting, reducing volatile organic compound (VOC) emissions by 25% in the final clear-coat step (Rittenhouse, 2003).

• **Eco-efficient Manufacturing**, popularized by WBCSD, focuses on reducing the "ecological footprint" of a company's operations, including the inputs of materials, natural resources, and energy required to manufacture and deliver a unit of output (Verfaillie and Bidwell, 2000). An eco-efficient process is generally less costly to operate, has higher yields, lower workplace hazards, and reduced waste streams. For example, BASF's eco-efficiency analysis for dyeing of blue denim revealed that electrochemical application of a vat solution was preferable to the use of powdered, granular, or biotechnologically-produced indigo (Saling et al., 2002).

• **Industrial Ecology** is more than a practice—it is a framework for shifting industrial systems from a linear model to a cyclical model that resembles the flows of natural ecosystems, which some have called "biomimicry" (Benyus, 1997). In this approach, all waste materials have potential value as nutrients, and industrial activities are approached with the goal of optimizing overall efficiency, and ultimately eliminating all waste. For example, the cement industry routinely uses discarded industrial wastes, such as used tires and fly ash from boilers, as substitutes for fuels and raw materials (WBCSD, 2002). However, the available tools for systematic design of industrial ecology networks are still in their infancy (Allen and Butner, 2002).

The above practices rely on a systems view and are logical outgrowths of earlier industry practices and PSE research, including environmental stewardship, pollution prevention, and waste minimization, which seek to replace "end-of-pipe" pollution control with more cost-effective process improvements. The differences are that sustainability is broader in its inclusion of environmental, social and economic impacts over the full product life cycle, and more strategic in its linkages to competitive advantage. Despite some notable successes in the above practices and the phenomenal growth of interest in sustainability, the field is still in its infancy, and has barely begun to consider the major challenges. Sustainability is largely unfamiliar to the mainstream worlds of business, finance, and engineering. One of the greatest barriers to broader adoption of sustainability is the lack of adequate insight, tools, and techniques to address the complexity of social, economic, and environmental issues at multiple levels from the process to the system life cycle to the biosphere levels. The rest of this article focuses on the implied challenges and opportunities for PSE.

Challenges and Opportunities for PSE

PSE has played an important role in developing and improving "decision-making processes for the creation and operation of the chemical supply chain" from the molecular to the enterprise level (Grossmann and Westerberg, 2000). PSE has developed many useful concepts, tools, and techniques for improving the viability of chemical processes, and for making the results of chemical engineering science industrially feasible. Responding to business drivers, PSE has gradually shifted from a traditional focus on the chemical process and its economic aspects to a broader focus on the chemical supply chain with the inclusion of safety and environmental factors, as well as economics. This successful evolution of PSE has frequently been enabled by integration across disciplinary boundaries, such as the use of optimization and artificial intelligence methods in process design, and of statistical signal processing techniques in process operation.

With the emergence of sustainability as a new business driver, PSE has the opportunity to play a critical role, both in modifying the design and operation of existing processes to make them more sustainable, and in developing new products and technologies that are inherently designed for sustainability. Examples of some promising developments include results of green chemistry and process intensification such as (Stankiewicz and Moulijn, 2002),

• Reduction in inventory by 99% and in impurities by 93% by using spinning disk reactors, as demonstrated by GlaxoSmithKline.

• Byproduct reductions of 75% by use of heat exchanger reactors, as demonstrated by ICI.

PSE needs to continue such innovation guided by the drive towards sustainability.

Furthermore, PSE needs to expand beyond the traditional temporal, spatial and organizational scales, implying a broadening of the "chemical supply chain" to the "chemical value chain". Managing this dynamic web of supplier and customer relationships has emerged as a strategic capability that can increase profits and create competitive advantages. Due to both regulatory pressures and stakeholder expectations, sustainability issues are becoming a key factor in driving improved business performance through value chain excellence. However, these improvements have been lacking in scientific rigor, and there are no systematic, comprehensive methods for analyzing process improvement opportunities for the chemical value chain from the perspective of sustainability.

Over the past half a century, process engineering has evolved from an *ad hoc* activity that relied entirely on experience, to a heuristics-based approach, to one that supplements experience and heuristics by sophisticated modeling and simulation. Sustainable PSE is at a stage reminiscent of the early period of process engineering. Like mainstream PSE, it needs to evolve by developing the relevant experience, heuristics, and models for all process engineering tasks. Sustainable PSE faces some of the same challenges as traditional PSE, albeit with a higher degree of difficulty. It requires a synthesis of existing PSE techniques including optimization, uncertainty analysis, planning and scheduling, supply chain management, modeling of nonlinear dynamic systems, and molecular modeling. However, formidable new challenges arise due to expanding the analysis boundary to include socio-economic-ecological aspects. An overview of some of the key challenges for PSE is provided in the rest of this section. The relationship between current business practices, associated challenges, and existing concepts and methods is summarized in Figure 2.

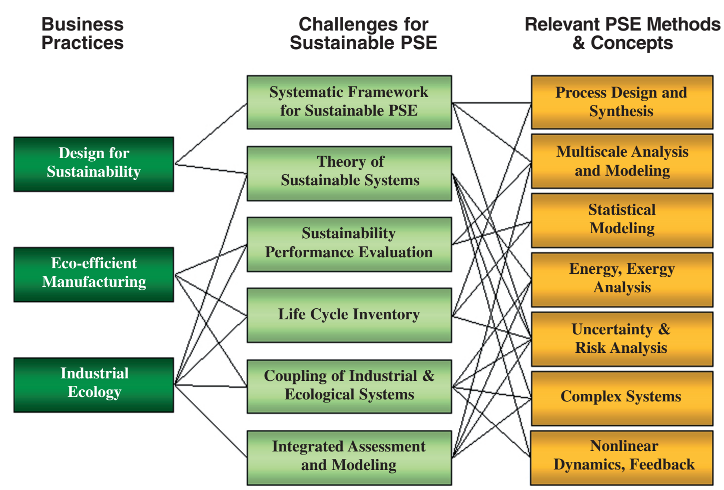

Figure 2. Relationships among Business Practices, Challenges for Sustainable PSE, and Existing PSE Methods and Concepts.

Systematic Framework for Sustainable PSE

A systematic framework is essential for developing and applying scientifically rigorous tools and techniques for sustainable PSE. Given the complex, multiscale and multidisciplinary nature of this task, hierarchical methods are appealing due to their ability to handle such systems in a systematic manner. Hierarchical methods are already popular for many tasks, including product and process design, process operation, materials design, optimization, and signal processing. For example, Douglas' (1988) hierarchical approach develops a conceptual design via multiple levels with increasing detail. At each level, the economic potential is evaluated and a list of alternatives is generated. Since the levels interact with each other, approaches which incorporate optimization and search strategies have also been developed (Daichendt and Grossmann, 1998). Such methods are widely used for process design and retrofit.

A hierarchy that may be used for sustainable process engineering is shown in Figure 1. It gradually expands the spatial boundary to incorporate environmental and sustainability considerations in a systematic manner. The levels in this hierarchy include: selected *process*, product or activity; *enterprise* or direct suppliers and users; process *life cycle* or important value chain participants; *economy*; and *ecosystems*. Just as the economic potential usually decreases in Douglas' conceptual design hierarchy, the environmental "footprint" in the proposed hierarchy will tend to grow as the spatial scale increases, and as more industrial processes are considered. However, the economic potential may not be affected. The process life cycle level has already received some attention in PSE (Pistikopoulos, 1999; Burgess and Brennan, 2001). The next level considers interactions between economic sectors, and can use methods such as economic input-output analysis. Finally, the ecosystem level considers the flow of ecological goods and services, which fall outside traditional economic analyses. Techniques from ecological economics or exergy analysis may be useful for this level.

Such a systematic framework should be used at all stages of the chemical value chain, and for every process engineering task. It presents innumerable opportunities for PSE such as:

- Evaluating the sustainability of existing processes and products to identify retrofit opportunities, and for quick screening of alternatives;
- Operating existing processes and their value chains in a sustainable manner;
- Guiding the development and evaluating the sustainability of new technologies such as, nano- and biotechnology, process intensification, and green chemistry.
- Designing and evaluating novel unit operations, processes, and networks of industrial ecosystems.

Applying this hierarchy requires relevant data at each scale, and there are numerous ongoing efforts to compile such data in commercial or public databases. Examples include economic input-output data, life cycle inventory databases, materials and substance flow data, and toxic release inventory (Adriaanse et al., 1997; Ukidwe and Bakshi, 2003). Unfortunately, many of these data are of limited use due to their unknown quality and proprietary derivation. PSE can play an important role in assessing and improving data quality by reconciling disparate data sources to satisfy basic thermodynamic laws. Furthermore, process engineering knowledge about various unit operations can be used to develop realistic modules that contain life cycle information including economics, emissions and inputs from the ecosystem. Such modules for "gate-to-gate" LCA are being developed for specific processes and unit operations (Jimenez-Gonzalez et al., 2000). Opportunities exist for enhancing existing process simulation tools or developing new ones to permit realistic evaluation of industrial processes at all scales of the sustainability hierarchy.

Sustainability Theory and Performance Evaluation

Given our incomplete understanding of natural, economic, and social systems, a theory of sustainable systems presents an important and exciting multidisciplinary challenge. PSE may be able to contribute to such a theory by combining its expertise in large nonlinear dynamic and complex systems (Ottino, 2003) with insight into ecosystems. The potential benefits of combining information theory with ecological modeling are illustrated by Cabezas and Fath (2002). A theory of sustainable systems may even provide a formal definition of sustainability.

Despite the lack of a rigorous theory or definition, many sustainability measurement tools are being developed and used in a variety of industries. Ideally, sustainability metrics should be easy to calculate with available data, useful for decision-making, reproducible, scientifically rigorous, useable at multiple scales of analysis, and extendable with improved understanding (Schwarz et al., 2002). This subsection discusses typical metrics that are relevant to chemical processes, and challenges that PSE can potentially address.

Efforts to evaluate each dimension of the "triple bottom line" of sustainability have progressed independently, and over vastly different time frames (Fiksel, 2000). *Economic performance* measures include a variety of managerial accounting practices to support internal decisions, and highly standardized methods for external financial accounting. Over the past 20 years, new accounting methods, such as activity-based accounting and economic value added (EVA) accounting, have helped to reveal the underlying drivers of economic performance and shareholder value (Blumberg et al., 1997). Current challenges include quantification of hidden costs associated with the utilization of material, energy, capital, and human resources; estimation of uncertain future costs associated with external impacts of industrial activity, understanding the full costs and benefits incurred by various stakeholders across the life cycle of a product or process; and valuing impacts upon natural and social capital. Valuation techniques that convert all costs and impacts to monetary terms are attractive, but are highly subjective and may lack a sound biological or physical basis.

Environmental performance indicators typically presented in conventional environmental reports include wastes and emissions, employee lost-time injuries, notices of violation, etc. More recently, many companies have adopted sustainability-oriented indicators that measure resource intensity, stewardship, and eco-efficiency. The process of environmental performance evaluation has become standardized as part of the ISO 14000 series. However, there are significant challenges remaining—environmental indicators generally measure flows of materials and energy rather than the ultimate impacts of these flows upon human and ecological health. More formal impact assessment techniques such as eco-indicator99 (Goedkoop and Spriensma, 2000), aggregate and weight the impact categories to obtain a single score or "end point". However, lack of adequate models of human and ecosystem impact for different emissions and of human valuation limit the use of these techniques.

Social performance metrics flourished briefly, but were abandoned in the 1980s (Epstein, 1996). Currently, however, corporate social responsibility has become a very active field, thanks in part to recent accounting scandals and concerns over business ethics. Some of the issues addressed by social indicators include tolerance, diversity, worker well being, and social equity. In general, the social dimension of the triple bottom line remains the least explored, the most difficult to quantify, and the most lacking in an underlying theoretical framework. Moreover, the linkages between PSE and social performance are elusive, although one can argue that process characteristics influence social parameters such as skill requirements, exposure to hazards, and community satisfaction. Especially in developing nations, patterns of industrial growth will have a significant impact upon livability, mobility, and availability of goods and services in both urban and rural settings.

Despite the proliferation of sustainability metrics and indicators, and the widespread adoption of integrated approaches such as the Balanced Scorecard (Kaplan and Norton, 1996), there is still a need to address a number of challenges. The concept of sustainability often requires macroscale consideration of the ecosystem and economy, yet actual decisions are made at finer scales. Therefore, methods are needed for translating the effects of decisions at finer scales upon global sustainability, and, conversely, for interpreting global sustainability goals and indicators to guide detailed decision-making. Practically speaking, metrics need to be hierarchical or nested to permit communication between different levels of an organization. Aggregated metrics may be useful for management decision-making, but detailed underlying information may be necessary for identifying opportunities for operational improvements. There is also a need for improved methods of handling both uncertainties in metrics and the potential interactions and redundancy between multiple metrics representing different goals and interests. Multivariate statistical methods like those used in process monitoring may be helpful. As researchers develop new measurement techniques and means of aggregating across the multiple dimensions of sustainability, companies that are true "learning organizations" will adapt and refine these methods as part of their quest for sustainability.

Coupling of Industrial and Ecological Systems

One root cause of the lack of sustainability in current human activities is the tendency to take the contribution of ecological goods and services for granted. Many recent efforts including LCA and ecological footprint assessment attempt to jointly analyze industrial and environmental systems. However, most of these methods focus on the impact of emissions, while ignoring the contribution of ecosystems (Bakshi, 2002). Furthermore, assessing the impact of emissions is fraught with large uncertainties. PSE can play an important role because of the potential for thermodynamics to provide a scientifically rigorous approach to the joint analysis of industrial and ecological systems and the design of sustainable industrial-ecological networks.

Methods such as pinch, exergy, and cumulative exergy analysis have been popular for improving process efficiency (Szargut et al., 1988; Seider et al., 1999). Exergy or available energy is the fraction of energy that can do useful work. It represents the distance or distinguishability from the surroundings, and captures all types of abilities to do work including physical, thermal, chemical, potential, and kinetic. Cumulative exergy analysis expands exergy analysis to consider the life cycle scale. These methods are appealing due to their scientific rigor and ability to represent all energy and material streams in consistent thermodynamic units. However, they ignore the contribution of ecosystems, and impact of emissions.

Thermodynamic methods have also been popular for analyzing ecosystems. Systems ecologists commonly represent ecosystems as networks of energy flow, with solar, tidal and geothermal being the major independent sources of energy that drive all ecological processes (Odum, 1996; Jorgensen, 1997). The network of ecological processes transforms energy from the primary sources to produce ecological goods such as wood, coal, and water, and services such as carbon sequestration, rain, and wind. As energy flows to higher trophic levels in the food chain, a smaller fraction is available to do useful work, and the overall efficiency decreases, while the ability of these higher organisms and processes to influence their environment increases. The efficiencies of many ecological products and processes have been studied and compiled by systems ecologists (Odum, 1996). Treating ecosystems as networks of energy flow has proven to be a powerful approach for their analysis, modeling, and assessment (Odum, 1996; Ulanowicz, 1997; Jorgensen, 1997). Such methods were also explored for the analysis of social systems in the 1970s (Rappaport, 1975).

The popularity of many thermodynamic methods has waned since the 1980s, partly due to lack of adequate data and analysis techniques. Moreover, the extremely broad claims about the ability of these concepts to explain the behavior of *all* systems encountered much skepticism, and in most cases, have not been backed up by empirical evidence. However, the methods developed then are extremely relevant for evaluating life cycle aspects and sustainability, particularly since they can facilitate the linkage of concepts and models across multiple disciplines. The availability of life cycle inventory data, and other recent methodological advances can also overcome many previous shortcomings of these techniques. PSE can play an important role in these developments.

For example, a recent study of the thermodynamic methods used in systems ecology and engineering reveals their close conceptual link and identifies conditions for equivalence (Hau and Bakshi, 2003). A simplified illustration demonstrates the potential benefits of this insight and the use of thermodynamics for joint analysis of ecological and industrial systems. Figure 3 shows the exergy flow in selected processes in the life cycle for making electricity from coal and from sunlight. Traditional cumulative exergy consumption (CEC) analysis used in engineering ignores the contribution of ecological services, and finds that coal-based electricity is twice as efficient as solar thermal electricity. This result matches the current economic reality that coal-based electricity is cheaper than solar electricity. However, an ecological cumulative exergy consumption (ECEC) analysis that also accounts for ecological services leads to the opposite conclusion. Making coal accessible to humans relies on the sedimentary cycle, and is estimated to require 40,000 times the exergy required for the same exergetic content in sunlight. This lower ecological efficiency of coal as compared to sunlight may indicate its high energy intensity and scarcity (Odum, 1996). This is the "free" service that nature provides, which is not valued in current market prices. Consequently, the efficiency of coal-based electricity based on the joint ecological-industrial processes is five orders of magnitude *less* than that of solar-thermal electricity (Hau and Bakshi, 2003). This example is purely illustrative, and does not consider crucial issues such as land use, equipment, and impact of emissions.

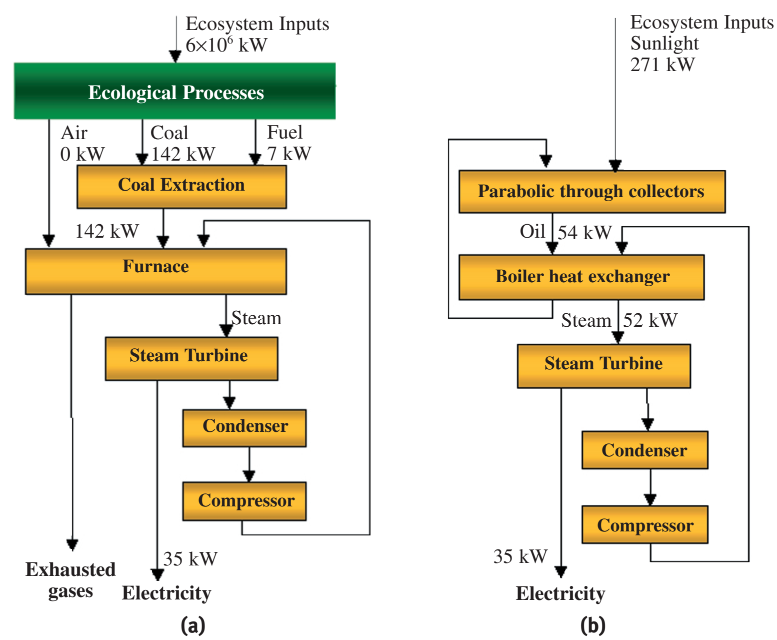

Figure 3. Exergy flow through industrial and ecological systems for life cycle of (a) coal-based electricity, and (b) solar thermal electricity. Coal and fuel require ecosystem services for making them available near the earth's crust. In contrast, sunlight does not need any ecosystem services (Hau and Bakshi, 2003).

Nevertheless, this example hints at the potential benefits of using thermodynamics for life cycle and sustainability analysis. Thermodynamic information about nature's contribution can provide a rigorous biophysical basis for human valuation of these services, which can then be used in techniques like AIChE's Total Cost Assessment. Furthermore, such methods can analyze material and energy streams in consistent units, and provide metrics for evaluating the potential impact or sustainability of industrial systems. As in ecosystems, it is likely that the lower the efficiency of joint ecological-industrial systems, the greater the impact of the product or process on its surroundings. According to the second law, decreasing the entropy of a system causes a larger increase in entropy of the surroundings. Consequently, making a lower entropy (more ordered) product creates more entropy (more disorder) in the surroundings. Thus, *lower entropy products may have a larger life cycle impact on their surroundings*, as demonstrated recently for a microchip (Williams et al., 2002). In the coal vs. solar electricity example, the higher efficiency of solar electricity is consistent with its potential for being more sustainable than coal-based electricity. However, efficiency or entropy changes alone are not enough to characterize sustainability, since it depends on how the generated entropy cascades through other industrial and ecological processes, and whether the resources are renewable. Close interaction with systems ecology can lead to novel insights and thermodynamic metrics for evaluating the sustainability of industrial systems and technologies (Bakshi, 2002).

Thermodynamic methods may also be useful for identifying symbiosis opportunities in industrial ecosystems, and for approximating the impact of emissions. Since exergy of emissions is the work done on the environment as the emissions reach the ambient state, it may provide a proxy for environmental impact (Ayres et al., 1998). This approach has met with some success (Seager and Theis, 2002), but more work is needed. Such an approach is attractive since it does not require detailed impact information about each emission, and can be used for estimating the combined effect of multiple emissions. Such methods should be useful for preliminary evaluation of emissions where detailed toxicity studies are not readily available, as is common in nanotechnology and biotechnology.

Integrated Multidisciplinary Modeling

The reductionist practice of scientific research tends to focus on the details of a system, while paying little attention to the broader implications of the work. This narrow view is further exacerbated by the difficulty in crossing disciplinary boundaries. Since environmental issues affect so many disciplines, cross-disciplinary interaction is essential for developing robust environmental policies. The ten-year outlook for the National Science Foundation on complex environmental systems (Pfister and AC-ERE, 2003) identifies the long-term need to "develop environmental synthesis to frame integrated interdisciplinary research questions and activities and to merge data, approaches and ideas across spatial, temporal and societal scales". Failure to account for these interactions has often just shifted undesired impacts from one domain to another, and resulted in unexpected surprises from well-intentioned actions. For example, replacing lead-based solder with bismuth-based solder seems to make sense since it would reduce the availability of a known toxic substance. However, the life cycle of bismuth indicates that encouraging its use may not reduce the availability of lead since lead is a byproduct of bismuth mining (Allenby, 1999). Another example is the "rebound effect" of improving energy efficiency. Improvements in automobile efficiency may not result in a proportional decrease in fuel consumption, if the lower fuel cost encourages people to drive more. Anxiety over such unexpected side effects is hampering the development and application of many new technologies, such as genetic engineering and nanotechnology.

Within chemical engineering, PSE is in the best position to take up this challenge. Economic methods, such as input-output, and general equilibrium modeling, are commonly used for considering the complex interaction between economic sectors. Such models may be coupled with LCA to evaluate the broader impact of engineering decisions and industrial activity. Thus, LCA can provide information about material and energy use and emissions throughout the life cycle, while economic models can use this information to estimate their effect on the economy. Of course, the effect of societal and consumer behavior and values should also be included—a nontrivial exercise. Evaluating the impact of emissions can rely on environmental fate and transport models tailored for a geographic location. The contribution of ecosystems can be included via techniques from environmental economics. Thermodynamic methods can provide a rigorous biophysical basis for valuation exercises, and common currency for many models.

Such integrated or coupled socio-economic-technical-environmental models can provide unprecedented insight into the effect of engineering decisions, government regulations, and policies. This insight can be used for formulating innovative policies for sustainable development. Existing applications of integrated assessment models for studying the effects of climate change (IPCC, 2001; Rotmans and deVries, 1997), and large-scale energy-economy models (Wene, 1996) may provide a good starting point for meeting this important challenge. Experience with large-scale and multiscale modeling, optimization, hierarchical methods, uncertainty and risk analysis, stochastic methods, agent-based modeling, and complex systems should facilitate this endeavor.

Conclusions

Sustainable development is among the most pressing and urgent challenges facing humanity today. The need for research and education to meet this challenge has been identified in virtually every recent study on engineering research needs (Pfister and AC-ERE, 2003; NRC-BCST, 2003). Fortunately, many corporations are realizing that sustainability is essential for their long-term prosperity and survival and makes good business sense. However, achieving sustainability is a formidable challenge since it cuts across all disciplinary boundaries and requires a broad, systems view that integrates social, environmental and economic aspects of technology and human activity. It requires fundamental rethinking or "creative destruction" (Hart and Milstein, 1999) of long accepted ways of doing business and human activity, along with technological breakthroughs, methods for holistic analysis, and transformation from a reliance on growth of physical capital to a growth of just intellectual capital. Among chemical engineering specialties, PSE is best positioned to address these challenges due to its broad systems view and multidisciplinary nature.

Achieving sustainability requires a new generation of engineers that are trained to adopt a holistic view of processes as embedded in larger systems. Engineering can no longer be performed in isolation, and must consider interactions among industrial processes and human and ecological systems. Therefore, the quest for sustainability requires research and educational innovation and advances not just in engineering, but also in many other disciplines, including management, economics, and sociology. Ultimately, this may be the most effective way of initiating the necessary long-term social, political, economic and technological changes for assuring human prosperity and ecological integrity throughout the world.

Acknowledgments

Partial financial support from the National Science Foundation (BES-9985554 and DMI-0225933) and insightful comments from Scott Butner, David Allen, Julio Ottino, and anonymous reviewers are gratefully acknowledged.

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