Sustainability Science and Engineering: The Emergence of a New Metadiscipline

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A case is made for growth of a new metadiscipline of sustainability science and engineering. This new field integrates industrial, social, and environmental processes in a global context. The skills required for this higher level discipline represent a metadisciplinary endeavor, combining information and insights across multiple disciplines and perspectives with the common goal of achieving a desired balance among economic, environmental, and societal objectives. Skills and capabilities that are required to support the new metadiscipline are summarized. Examples of integrative projects are discussed in the areas of sustainability metrics and integration of industrial, societal, and environmental impacts. It is clear that a focus on green engineering that employs pollution prevention and industrial ecology alone are not sufficient to achieve sustainability, because even systems with efficient material and energy use can overwhelm the carrying capacity of a region or lead to other socially unacceptable outcomes. To meet the educational and human resource needs required for this new discipline, the technological and environmental awareness of society must be elevated and a sufficient and diverse pool of human talent must be attracted to this discipline.

Introduction: Evolving Focus of Green Engineering and Environmental Science

At one time, single media environmental studies focused on water, air, or solid waste treatment with little consideration given to the other media where pollutants were transferred. Subsequently, the engineering field embraced a multimedia approach to treatment—and treatment was considered ineffective unless the pollutant was destroyed or rendered immobile. With respect to spatial focus, treatment issues were generally confined to a local or plant-level scale, and end-of-pipe treatment was considered the preferred solution for waste management.

Over time our knowledge of the temporal and spatial scales of environmental problems increased, as shown in Figure 1. Conventional pollutants were first studied and managed on a regional scale. The scale of issues in time and space increased further when bioaccumulative persistent toxic pollutants and global climate change chemicals of concern were considered. Many models and tools were developed for impact assessment that have been successful in predicting impacts for selected chemicals in selected environmental settings. These models have tied air and water quality to point and nonpoint sources and have been very useful for the development of emission control and compliance strategies. Unfortunately, these models were aimed primarily at evaluating the quantity of pollutants that could be discharged into the environment with acceptable impact. These efforts did not focus on pollution prevention nor, in many cases, develop mechanistic understandings of how pollutants are initially formed and released. Also, while individuals involved in this strategy of waste management were very adept at calculating the carrying capacity of the natural world, they assumed that pollutant generation and release were a normal part of commerce. In addition, the attractiveness of end-of-pipe approaches to waste management decreased, and strategies known as environmental conscious manufacturing, ecoefficient production, or pollution prevention gained prominence. These "green" approaches to the design and development of processes and products served as the basis for green chemistry and green engineering.

Figure 2 depicts the evolution of approaches to waste management. In the United States, the Pollution Prevention Act of 1990 developed a waste management hierarchy that placed pollution prevention and reduction as a more favorable management strategy than treatment or disposal, and the terms green chemistry and green engineering were commonly used during the two decades leading up to this century. The objective of these initial efforts was to work with existing industrial infrastructure and modify practice, programs, and processes such that pollution was reduced via greater recycling, inventory management, good housekeeping, and resource management. Once pollution prevention programs were implemented, many industries began to become more proactive in their environmental resource management efforts, with the implementation of life cycle assessment (LCA), full cost accounting, and company-wide environmental management plans. Some companies have now begun sustainable development initiatives by endorsing

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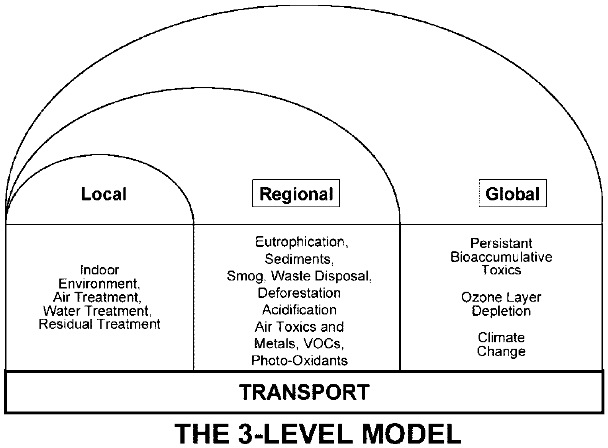

FIGURE 1. Models and impacts of environmental problems. The temporal and spatial scale of the problems increased as the problems that were studied moved from a local to global scale.

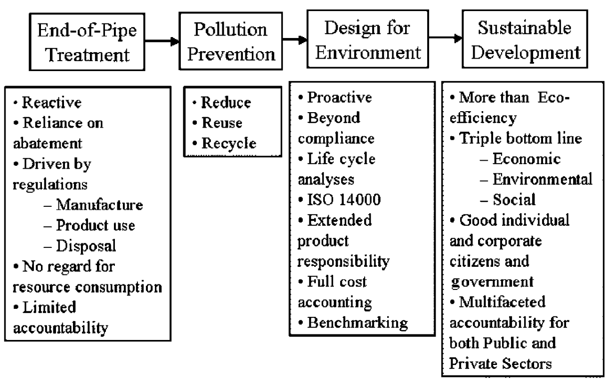

FIGURE 2. Evolution of environmental issues from a treatment perspective through green engineering to sustainable science and engineering (adapted from Jerry Rogers, General Motors).

the triple bottom line with responsible care initiatives serving as the basis for some of the progress (*1*). [Triple bottom line paradigm: The economic bottom line is congruent with improving social conditions and environmentally responsible manufacturing because (i) a motivated, healthy workforce living in a thriving community is more productive and (ii) using less resources, generating less waste, and improving quality reduces costs while increasing demand.]

Emergence of Sustainability Science and Engineering as a Metadiscipline

The United Nations (UN) Conference on the Human Environment (Stockholm, 1972) added the environment to the UN's list of global problems and resulted in the creation of UNEP. The 1972 report titled *The Limits of Growth* (*2*) warned that the earth's natural resources were being quickly depleted and that there might not be resources remaining to allow the developing world to industrialize. Spangenberg (*3*) pointed out that, at the time of its release, this report shaped debate in the United States to consider population growth as the main future environmental risk while in Europe the debate focused on patterns of individual and industrial consumption. However, the developing Southern Hemisphere saw this report as a method to deny the right to development.

Our Common Future was released in 1987 by a UN commission chaired by the Norwegian Prime Minister, Gro Harlem Brundtland, and the concept of "sustainable development" was adopted (*4*). The Brundtland Commission report provided the stimulus for holding the 1992 UN Conference on Environment and Development (i.e., the Earth Summit held in Rio de Janeiro). The Earth Summit was a landmark because it was the first global summit that addressed environmental problems. It also brought together two major issues for the first time, global environment issues and economic development. One outcome of the Earth Summit was the development of the nonbinding, 800-page Agenda 21 that set forth goals and recommendations related to environmental, economic, and social issues. The UN then created the Commission on Sustainable Development to oversee the implementation of Agenda 21.

The Brundtland Commission defined sustainable development as development "which meets the needs of the present without compromising the ability of the future to meet its needs" (*4*). However, it has been difficult for all groups and individuals interested in this topic to capture the meaning of sustainability. Part of the reason for this difficulty is the vagueness of the concept, and a diverse set of constituents have developed different visions of sustainability based on their different needs and aspirations. For example, Mebratu (*5*) defines the distinct drivers for institutional, ideological, and academic formulations of sustainability.

The great breadth contained in the definition of sustainability has thus made it difficult for many educators, researchers, and organizations to approach specific problems. However, individuals have begun to determine the need to integrate the physical and social science disciplines with engineering to address the ecological, economic, social, and political processes that determine the sustainability of natural and human life cycles and activities (*6*–*8*). Unfortunately, progress toward implementing sustainable development on a global scale has been slow, which served as the basis for the 2002 World Summit on Sustainable Development (Johannesburg, South Africa). Prior to Johannesburg, there were requests by the world community to not use this summit to develop additional philosophy and political debate but instead to begin to implement measurable actions and results.

Sustainability is defined here as the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment. These requirements reflect that social conditions, economic opportunity, and environmental quality are essential if we are to reconcile society's development goals with international environmental limitations. Accordingly, fundamental research, education, and knowledge transfer are needed to meet this vision (*6*, *9*, *10*).

While the work of the international community and individuals have helped to define the needs for a sustainability science effort that supports local, regional, and global decision-making, these efforts have had surprisingly little direct interface with new initiatives and research in industrial ecology, design for the environment, and pollution prevention. For example, a great deal of progress has been made in the development of methods for LCA to allow evaluations of environmental impacts across all stages of product production and use. As shown in Figure 3, these stages include the extraction of natural resources, manufacture, product use, and reuse, recycle or disposal. Figure 3 shows that product evolution through the life cycle (clockwise) involves material and energy use, releases to the environment, and associated costs (private and societal). In most cases, the inner loops of reuse and remanufacturing are preferred, requiring less raw materials, energy, time, and cost. These efforts to invoke LCA have been successful at reducing waste, pollutants, and energy use for a number of industries (e.g., refs *11* and *12*). The scale of LCA and pollution prevention has also increased as the analysis has expanded from the process and plant level to the firm and industry level.

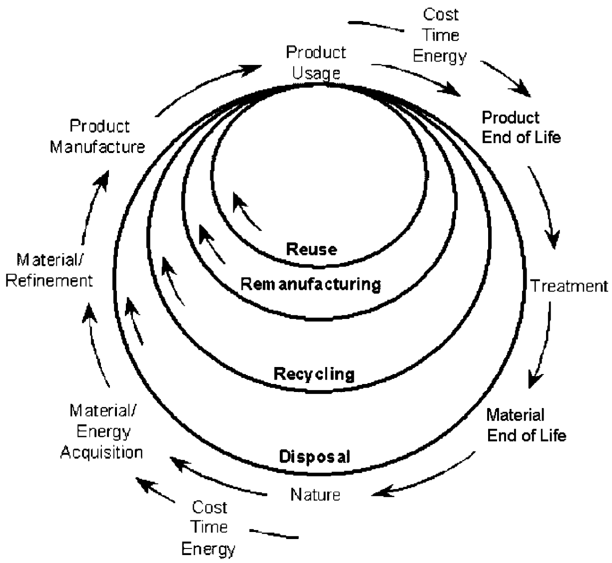

FIGURE 3. Life cycle stages of products. In most cases the inner loops of reuse and remanufacturing are preferred because they require less natural resources and energy.

The study of the flow of materials and energy through industry and implications for the overall production of products and waste is termed industrial ecology (*13*−*15*). Recently, the approach of industrial ecology has been expanded further to consider material and energy flows from multiple, often inter-related industries, and through local environments, regions, national economies, and global trade (*16*, *17*). This marriage of product and process design and systems analysis, employing LCA over a range of spatial, temporal, and organizational scales, has brought together environmental professionals and product and process designers to study and develop the interface between their fields.

The National Research Council's Board on Sustainable Development has stated in *Our Common Journey* that four components make up the research framework that will be required for work on sustainability issues. They are biological, geochemical, societal, and technological systems (*10*). Technological systems include the development of basic knowledge that can be used for the design and manufacturing of social goods. They have their engineering roots in treatment initiatives of the past century and green engineering approaches of the past two decades.

Role of Economic and Social Processes

While the union of industrial ecology and environmental impact and risk assessment has spawned new educational initiatives (*8*, *18*, *19*), there are further challenges to ensure that this approach has a broad and lasting impact. Indeed, we hesitate to call this sustainability science and engineering because it does not as yet consider broader impacts across the economic and social landscape, including implications for individual, household, corporate, and social decision-making, environmental justice, and the diffusion of knowledge through society. Consideration of such broader impacts is now feasible through new approaches such as economic input−output LCA (EIO-LCA), that considers resource utilization and waste generation and (potentially) the associated economic, human, and environmental impacts across the entire supply chain (*20*−*22*).

While these approaches have yielded positive developments in sustainability science and engineering, associated social processes (e.g., knowledge diffusion and understanding how belief systems impact consumption) have not been explicitly included in decision support tools. In addition, the

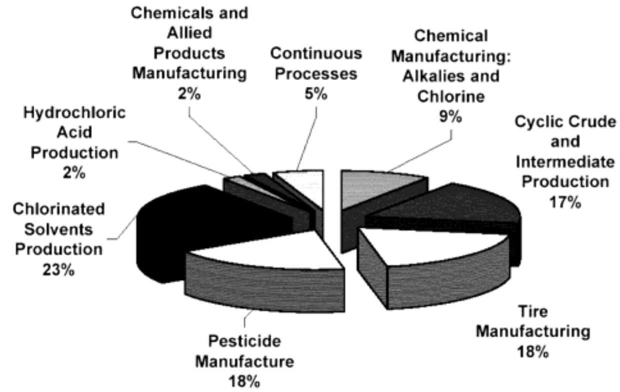

FIGURE 4. Sources of hexachlorobenzene in the United States (*27*).

degrees of freedom for an engineer, in terms of choices of product manufacturing, decrease as do the associated pollution prevention options as one moves closer to product manufacture. Accordingly, it is very important for engineers to understand individual and household belief systems to help motivate the selection and design of greener products. In this context, it is important to realize that the mechanistic understanding of how pollutants are generated includes not only the production process but also social, economic, and political choices (*23*) and the impact of consumption and population (*24*). For example, the "what would Jesus drive?" advertisement campaign of the past year in the United States was partially effective because it tapped into consumer beliefs rather than transient wants that are traditionally created by advertising. As an outcome of this initiative as well as other factors, there has been measurable movement in the past year by consumers to purchase smaller SUVs (*25*). Also, some Detroit automakers are now considering broader consumer concerns about SUVs and the cultural trends that influence the buying habits of the next generation of automobile buyers who many believe are shifting away from purchase of extremely low fuel economy vehicles (*26*).

As another example of how societal decisions could influence the environment, consider the release of hexachlorobenze. Hexachlorobenzene was widely used in the United States as a pesticide and fungicide until 1965. It was also used in several industrial applications. While intentional production of hexachlorobenzene has been eliminated in the United States, it is currently still produced as a byproduct of other chemical manufacturing processes. Figure 4 displays the documented sources of hexachlorobenzene in the United States. It indicates that over half of the hexachlorobenzene production could be reduced by several societal choices that include (i) designing clothing that does not require dry cleaning, (ii) using organic farming techniques to control agricultural pests, and (iii) reducing tire production by providing alternative transportation and more pedestrian-friendly neighborhoods and developing alternative methods for accessibility to products/information.

Moreover, a range of social processes that drive societal demands needs to be understood. Figure 5 offers a social network characterization of social diffusion processes. This model highlights four interlinked research needs for sounder decision-making: (i) model the diffusion of knowledge, belief change, and consensus development through stakeholder networks (center box); (ii) evaluate the implications of these findings for improving the social diffusion of knowledge based on content, form, and process, (iii) demonstrate the application of newly developed methods for identifying and simulating social networks, and (iv) predict how outcomes might change as a result of new information linkages and content (*28*−*32*). Agent-based modeling (*33*) could also be used for understanding values, knowledge, and incentives

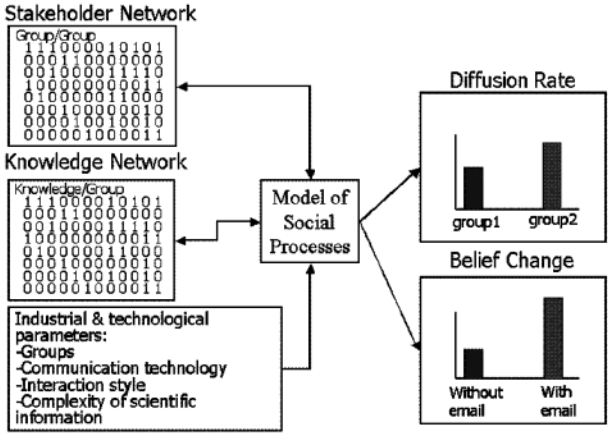

FIGURE 5. Key elements in a social network characterization of social diffusion. Interaction with stakeholder groups can be used to estimate the rate at which knowledge diffuses through society and also the rate which individuals or households may then change their beliefs and/or habits of consumption.

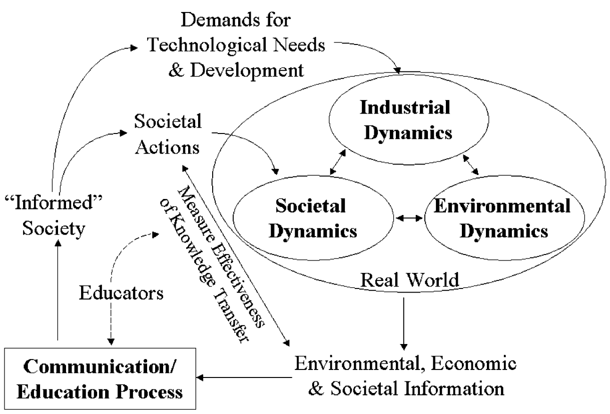

FIGURE 6. Role of education, knowledge transfer, and social processes in the creation of informed citizens and households.

faced by individual objects that are allowed to interact. The resulting evolution of the system can then be studied on an individual basis or from the perspective of the aggregate population.

Figure 6 displays the important role that education and knowledge transfer could play in this process. One outcome is to have an informed society that can make educated choices on sustainable options and decisions. Central to this change will be both theoretical understanding of the context for decision-making and active involvement of user groups and stakeholders in decision-making processes for sustainability (*34*). In addition, just as the engineering profession needs considerably more awareness of the nature of politics and of social processes and, especially, the influence of institutions on sustainability choices, the much larger community of nonengineers needs a stronger understanding of engineering.

Unfortunately, the public is largely unaware of what engineers do; and second, engineers have not done an effective job informing society of the long-term consequences of various alternative approaches to serve societal needs. Furthermore, many appointed and elected officials have the short-term view of annual budgeting, limited terms, and upcoming elections, and there is very little public pressure to encourage planners to adopt more sustainable approaches (*35*). Sustainability, however, offers an intellectual "commons" where new knowledge can be shared, developed, and adjusted. One burgeoning area of research, indicators of sustainability, offers an avenue to improved understanding. While none of the indicators are perfect, metrics that can be

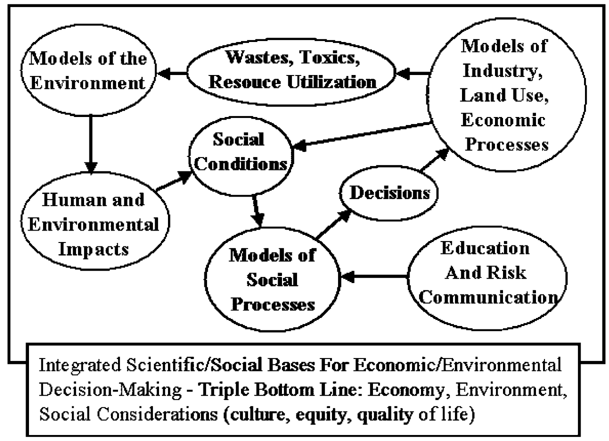

FIGURE 7. Discipline integration required for sustainability decision support.

used to discuss sustainability options are being developed at the local, regional, and global level (*10*, *36*, *37*).

Figure 7 displays the discipline integration of industrial, societal, and environmental systems that is required to develop decision support systems for sustainable decision-making. Not only are improved individual models required to evaluate environmental, societal, and economic systems but also these models must be integrated and in such a manner that they accept input from society. Obviously educators and universities have a role to establish appropriate educational materials/information for societal consumption and also judge the effectiveness of the knowledge transfer. However, the ethical implications of this knowledge transfer must be considered.

Figure 7 shows that what is required are models of social processes that predict decisions at various levels (e.g., institutions, governments, and households). These models could make predictions based on the knowledge of future sustainability metrics, human beliefs, and risk communication. Another need is to integrate human and industrial ecology models to economy-wide models. This connection can also be used to determine the wealth that is generated as a result of social decisions. For example, Templet (*38*) showed that firms that sought to increase their profitability created externalities that led to subsidies. Unfortunately, these subsidies were supported by the less wealthy, and the socioeconomic, energy, and environmental impacts on the public sector worsened as the externalities and subsidies increase. This effort must also include the entire supply chain because outsourcing on a regional and global level have complicated our ability to track environmental and social impacts of a manufacturing process. Once the quantity of wastes from the entire supply chain and human activity are known, models of the environment can be used to predict impacts on population growth and distribution, human health, species abundance, and diversity. Social conditions and valuations can then be related to these human, economic, and environmental impacts. Under the best scenario, the knowledge about "how sustainable the future is" would be effectively diffused throughout society, and a feedback mechanism would stimulate the evolution of sustainable decisions within a region. If such a network of models and metrics could be constructed, this set of integrated tools could form a basis for decision support.

The past discussion supports the emergence of sustainability science and engineering as a metadiscipline because it provides an over-arching framework for adopting and incorporating knowledge across many fields of study to inform human and environmental development and quality. Interdisciplinary approaches focus on activities at the

FIGURE 8. Some economic, environmental, and societal issues that could be included in selection of sustainability indicators.

interface between disciplines. Multidisciplinary approaches utilize knowledge from several disciplines to solve those problems. Like a meta-analysis in statistics (*39−41*), a metadisciplinary study can combine the information from multiple lines of inquiry to yield insights and perspectives not achievable with any one alone. The prefix meta refers to "after" and "beyond," thus, a metadiscipline is a higher level discipline. In the future, the metadisciplinary approach provides a systematic set of methods and procedures for bringing together the knowledge from the traditional, more-mature fields of the physical sciences, engineering, economics, and human behavioral studies to address the critical issues of sustainability.

Sustainability Indicators

Another important need is the definition of sustainability indicators that encompass key issues and are quantifiable (*10*, *36*, *37*, *42*). Unfortunately, less work has been performed on sustainability indicators than other indicators (*36*). Figure 8 illustrates that the selection of sustainability indicators should include considerations related to economics, society, and the environment. For example, the following indicators could be used: (i) the economic value of the goods and services produced; (ii) wastes that are generated, including solid waste, ozone-depleting chemicals, and chemicals that contribute to acid deposition and global warming; (iii) changes in terrestrial habitat that impact carbon sequestration and biodiversity; and (iv) social conditions such as environmental justice and equity, educational level, and wealth distribution. However, the process of selecting an appropriate set of indicators and the indicators themselves is ultimately dependent on whether the organization that develops the indicators are international or local, corporate, and government or nongovernmental.

Two very different cases (Great Lakes Basin and a village setting in northern Cambodia) can be used to demonstrate the current use of indicators for sustainability. The Great Lakes Basin has been called the ultimate test of the North American Region's capacity to adhere to the tenants of sustainable development (*43*). The challenges the basin faces are not only the large concentration of population and industrial activity in the area but also its large physical footprint (300 000 mi^2 of surface area) that holds one-quarter of the world's supply of freshwater. The development of a firm set of sustainability indicators that would allow policymakers to track changes over time as well as define research needs has been difficult and is controlled by what information is readily measurable. For example, the State of the Lakes Ecosystem Conference (SOLEC) has spent close to 10 yr defining indicators and has now developed 80 Great Lakes ecosystem health indices (*44*). The Lake Superior Binational Forum recently determined a smaller subset of socioeconomic sustainability indicators (less than 20) that were broken down into five areas: (i) reinvestment of natural capital (e.g., amount of sustainable forestry in the area), (ii) quality of human life, (iii) resource consumption, (iv) public awareness of the capacity of sustainability, and (v) economic vitality (*45*).

The International Institute for Sustainable Development (www.iisd.org) has been working on a set of indicators since 1995 to measure progress toward sustainable development. One example of the development and use of sustainability indicators applicable for the developing world is that undertaken by villagers living within the World Heritage Site of Angkor Wat in northern Cambodia. In this setting, villagers have spent the past 5 yr developing a local set of indicators to plan and evaluate a pilot community forestry project (*46*). The 27 indicators selected by the community address social, environmental, and economic sustainability concerns. What is interesting to note is the striking differences between the indicators that were selected for the two sites. While a few indicators are similar for the Great Lakes Basin and community forest project (e.g., environmental indicators that monitor land or water quality and timber coverage), most indicators are quite different because of the different scales of the project (local vs regional) as well as selection of indicators that are applicable for the developed and developing world. For example, economic indicators used for the community forestry project include widely accepted ones such as income generated from timber harvesting but also include items such as the transfer of knowledge and skills, benefits of community solidarity and morale, and increased technical skills. These effects are indicative of the type of broadly distributed knowledge generation and use envisioned by some (*7*, *47*).

Social indicators in the developing world setting may also include measuring the participation rate of under-represented socioeconomic groups and women. Graduate programs such as Michigan Tech's Master's International engineering program have provided students opportunities to perform their research in the developing world while serving 2 yr in the U.S. Peace Corps after taking associated coursework. This program educates students to understand the social, economic, and environmental limitations of implementing appropriate technology and sustainable engineering solutions to problems in the developing world (*48*). Students are also educated to understand that the challenges of sustainability in the developing world are different than in the industrialized world. For example, many problems in the developing world are not from manufacturing but are related to water, soil, agriculture, forestry, and fisheries (*49*). Interestingly, when combined with societal needs, appropriate technology may have been the precursor of sustainable development when in the mid-1960s the term was first promoted for developing countries.

There is also a plethora or work about the impact of the exponential growth of population on the natural resources stock. One of the factors that play a critical role in exacerbating the poverty of nations besides a lack of resources, limited educational opportunities and skill, and the general poor climate of economic, social, and political systems is rapid population growth. Figure 9 depicts the linkages between demographics and natural resources issues. Overall, the state of the natural resources is determined by a set of endogenous and exogenous factors. The figure describes what prevails in a typical developing country. Government policies help to determine the quality of development and thus how sustainable the management of natural resources is. The objective of sustainable development is therefore to help obtain desirable goals and to lower the chances of unexpected outcomes, and if the latter should occur, policies should be in place to remedy the condition.

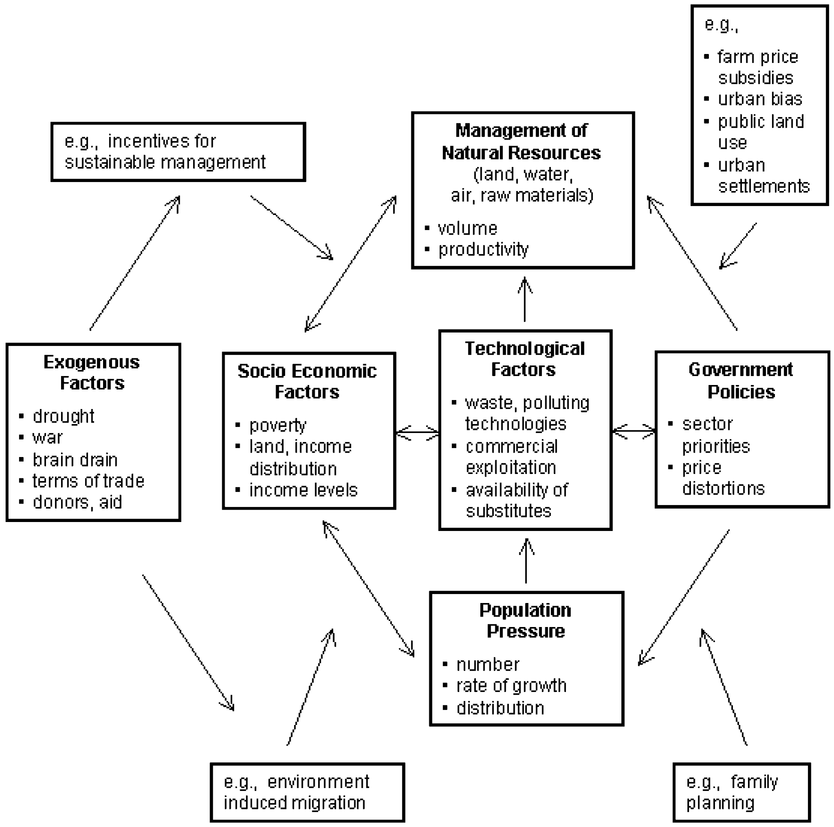

FIGURE 9. Connections between demographic and natural resource issues in the developing world.

Examples Illustrating the Evolution of Sustainability Science and Engineering

It is apparent that multiple skills and capabilities are required to support the new metadiscipline of sustainability science and engineering and that these skills go well beyond those required for the field of green engineering. These skills include (i) the fundamental physical sciences, social sciences, and mathematics needed for environmental assessment and engineering; (ii) basic economics including economic input–output analysis; (iii) industrial ecology and design at the process, plant, corporate, regional, national, and global scale; (iv) information technology for real-time monitoring of processes, remote sensing of the environment, and graphical information systems; (v) human and environmental impact modeling and risk assessment; (vi) social and behavioral research tools; (vii) understanding sustainable issues in a global context, with emphasis on the developing world; and (viii) professional and K-through-gray educational programs. This can be viewed as a natural continuation of the evolution of green engineering from subfields with a somewhat narrow focus (e.g., air treatment or LCA) to a metadisciplinary endeavor, combining information and insights across multiple disciplines and perspectives.

Sustainable solutions include these important elements/steps: (a) translating and understanding societal needs into engineering solutions such as infrastructures, products, practices, and processes; (b) explaining to society the long-term consequences of these engineering solutions; and (c) educating the next generation of scientists and engineers to acquire both the depth and breadth of skills necessary to address the important physical and behavioral science elements of environmental problems and to develop and use integrative analysis methods to identify and design sustainable products and systems (*9*).

The remainder of this section provides several examples of how sustainable science and engineering research is evolving to integrate industrial, environmental, and societal issues. Obviously these are not the only examples of progress in this area, and they also demonstrate the need for an integrative approach. Other tools that will be useful in future planning efforts include integrated assessment models, regional information systems, and long-range scenario development (*10*).

To accomplish the goals of environmentally conscious design, much progress has been made over the last 10–15 yr in linking industrial activities with associated environmental impacts in a systematic manner. LCA methods have been documented in ISO 14040–14043 standards, and these provide a sound basis for conducting and critically reviewing such studies. International consensus on classifying impacts has resulted in a core set of categories; however, much discussion still remains on issues related to complexity, sophistication, and accuracy of impact characterization approaches (e.g., midpoint vs end point, spatial and temporal dimensions, etc.) (*50*, *51*). National-level inventories have been compiled for energy consumption, for emission of criteria air pollutants, for global change compounds, for generation and management of toxic and hazardous wastes, for raw material utilization, and for other impact categories. These national inventories can be employed to normalize process or product impacts and to determine relevance and weighting factors for environmental impact categories. Societal- and science-based attempts to value environmental categories in a comparative manner have also been made (*52*). There appears to be, however, a wide range of strategies for applying the above methodologies in research and industrial practice.

Figure 10 shows the structure of four different molecules and their estimated aquatic toxicity and human carcinogenicity as determined by the Pollution Prevention Framework model (*53*). The undefined functional groups represent proprietary structures that are required for the molecule to

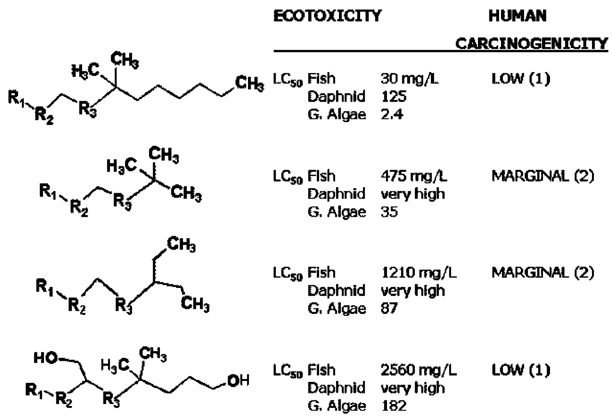

FIGURE 10. Example showing molecular modification and associated changes in aquatic and human toxicity.

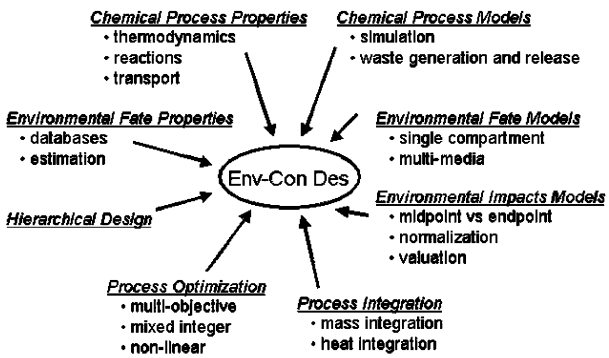

FIGURE 11. Integrated methods and capabilities for environmentally conscious design and assessment.

function properly. To reduce toxicity, changes in the aliphatic branching were considered, and it appears that the addition of an OH group (as shown in the bottom molecule) reduces aquatic and human toxicity. Zhang et al. (*54*) expanded this relatively simple example by developing a methodology that integrates plant level knowledge of reaction pathways with output from a multimedia fate and exposure model to develop risk indices for human health and aquatic life. They used this methodology to compare four reaction pathways that could produce glycerine. Their example demonstrated that the selection of the most sustainable reaction pathway depends on the specific environmental index that is examined (i.e., end point of fish or human health). More importantly, that study illustrated that the integration of toxicity and chemical fate is very important in evaluating the potential risk from production changes at a manufacturing facility.

Chemical processes are often created by employing a hierarchical approach that provides opportunities for incorporating environmental assessments at several stages in the design process. Accordingly, computer-aided analysis tools providing the integrated capabilities indicated in Figure 11 will therefore be necessary to efficiently link chemical process/product design with critical environmental processes in a larger systems analysis. At the earliest stage of design, choices are made among competing alternatives for reaction pathways, raw materials, solvents, and energy sources. Next, technological choices are made regarding equipment for carrying out these reaction and separation steps. A flowsheet containing connections between these unit operations is then generated, and the material and energy requirements are predicted using commercial process simulation software. Opportunities for energy and mass integration are then evaluated in attempts to reduce energy consumption and waste generation. In a final process design step, the flowsheet

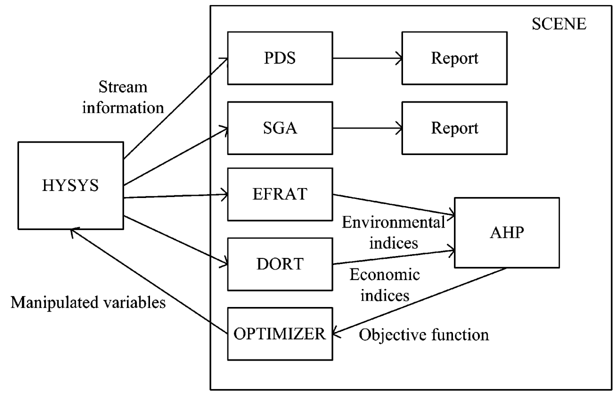

FIGURE 12. Integrated software (SCENE) developed at Michigan Technological University for predicting environmental and economic impacts of chemical process designs. HYSYS, a commercial chemical process simulator software; EFRAT, a software for calculating environmental impacts; DORT, a software to estimate equipment costs and operating costs; AHP (analytic hierarchy process), multi-objective decision analysis; PDS, process diagnostic summary tables; SGA, scaled gradient analysis.

TABLE 1. Comparison of Benzene to *n*-Butane Routes for Maleic Anhydride (MA) Production[a]

environmental index	benzene	*n*-butane
I_{FT}	6.83×10^{-6}	3.03×10^{-6}
I_{ING}	3.32×10^{-3}	3.11×10^{-3}
I_{INH}	4.57×10^{-2}	3.78×10^{-2}
I_{CING}	1.43×10^{-4}	0.00
I_{OD}	1.43×10^{-4}	0.00
I_{GW}	0.00	0.00
I_{SF}	2.04×10^{-1}	1.20×10^{-1}
I_{AR}	2.51×10^{-5}	4.37×10^{-6}
	0.00	0.00

[a] Risk indices are further defined in ref *59*, and all units are in kg/mol of MA. I_{FT}, fish toxicity index (ecotoxicity indicator); I_{ING}, human ingestion noncarcinogenic index; I_{INH}, human inhalation noncarcinogenic index; I_{CING}, human ingestion carcinogenic index; I_{OD}, stratospheric ozone depletion index; I_{GW}, global warming index; I_{SF}, smog formation index; I_{AR}, acidification indicator.

is optimized in order to identify process operating parameters that maximize profit and minimize environmental impacts.

As an example, the integrated software depicted in Figure 12 was employed to design, assess, and improve alternative routes for the production of maleic anhydride, starting from benzene or from *n*-butane (*55*). At early design stages, a comparison between the benzene and *n*-butane routes was made based on raw material costs and nine environmental impact indicators. A table comparing these routes was generated using literature reaction yields and selectivities (*56*), downstream separation specifications, pollutant emission estimation software (*57*), and pollution control efficiency. Table 1 shows this comparison and provides a definition of the environmental impact indicators (*58*). The *n*-butane route is superior in each category of impact, and the cost per mole of MA produced is significantly lower for the *n*-butane processes ($0.0203/mol of MA) as compared to benzene ($0.0312/mol of MA).

Using the hierarchical process design and improvement approaches, these alternative processes for MA production were developed, improved, and finally optimized using an aggregate objective function that combines economic and environmental impacts using the AHP tool shown in Figure 12. The *n*-butane process exhibited a higher profitability (net present value (NPV) of $5.0 MM) as compared to the benzene process (NPV of $3.5 MM) for a production rate of 50×10^6 lb of MA/yr. In terms of environmental impacts, the *n*-butane

TABLE 2. Predicted Peak Methylene Chloride Levels (ppm) (Short-Term Exposure) for Six Paint-Stripper Product Labels under Four Reading Scenarios (*62*)

product label	label reading scenario: 1 (first five directions)	2 (bold directions only)	3 (all directions)	4 (entire label)
A	1860	1600	1600	270
B	710	1600	1400	710
C	1860	1860	1860	1860
D	1600	1600	1600	710
E	1860	1600	1860	710
F	1600	1600	1600	1600

process was marked with a much lower process composite index (I_{PC}), which is an aggregate index combining the nine listed in Table 1 (*58*). This aggregation is accomplished using a normalization step and national-level impacts for each category in Table 1 (*59*) and a valuation step using a distance-to-target approach (*52*). I_{PC} for the optimum *n*-butane process was a factor of 174 lower than for the optimum benzene process. The main differentiating factor in the environmental impact assessment is the emission of a carcinogenic compound (benzene) from the benzene process.

Researchers have also begun to apply past research on the interaction between individual risk perception, behavior, and pollutant exposure and risk for environmental health problems that are based on consumer decision-making. Examples have included the use of household chemicals (*60*–*62*) and the dry cleaning of garments (*63*). Table 2 summarizes results for the predicted reduction in the peak methylene chloride exposure concentration experienced by a home furniture stripper following the use and safety directions presented on six labels for available methylene chloride-based furniture stripping products. In addition to the predicted high variation in exposures resulting from the different labels and associated reading and product-use behaviors, the study raises critical questions about the overall roles of consumer knowledge and communication-based strategies for risk management for products of this type. A comprehensive study of this type of problem must clearly consider the chemistry and efficacy of alternative product formulations, the physical chemistry of product volatilization and other routes of exposure, and the factors affecting the behavior of consumers in choosing and using products.

An integrative method to evaluate the environmental impact associated with regional economic activity can be performed by combining output from a chemical fate and transport model that has been developed for large regional scales (*64*) with emissions obtained from the EIO-LCA model (*21*, *22*) (see www.eiolca.net). This approach (*65*) has been applied to investigate sustainability issues associated with the production of motor vehicles and passenger car bodies.

The EIO-LCA relates economic activity to specific environmental impacts associated with a product's complete supply chain and considers the life of a product through the manufacturing stage. The EIO-LCA not only provides information on what the resulting economic activity is in a particular economic sector associated with the principal economic activity (in this case, manufacture of car bodies) but also provides the environmental impact associated with these economic sectors that are related to the principal product's supply chain. Examples of environmental impacts that are quantified by the EIO-LCA include toxics release and transfer, hazardous waste generation, release of conventional air pollutants, and resource utilization (i.e., water, ore, fuel, and electricity usage).

Table 3 summaries the economic activity, resources utilized, and wastes that are generated from production of one million dollars worth of automobile bodies. The table includes the economic activity and environmental impact for the five highest sectors based on economic activity. One outcome of this approach is being aware that the environmental impact associated with release and transfer of toxic chemicals from the manufacture of car bodies is associated with many economic sectors, and the five listed in Table 3 account for only 60% of the total toxics releases/transfers; thus, a greater portion of the supply chain needs to be accounted if toxic releases/transfers are of concern. However, when evaluating the industrial sectors associated with the environmental impact from release of a conventional air pollutant such as NO_2, the industrial sector that results in the greatest source of NO_2 during manufacture of automobile bodies is electric services and utilities, followed by the industrial sectors of trucking and courier services, carbon black, and primary aluminum. These sectors are not listed in Table 3 because they did not contribute to the top five industrial sectors based on economic activity; thus, in this case an individual must look farther down the supply chain to identify a sector that results in a greater environmental impact.

Figure 13a displays the fraction of the toxic release inventory (TRI) releases associated with the top 10 supply chain sectors for automobiles. Figure 13b displays the fraction

TABLE 3. Resources Utilized and Wastes Produced for Manufacture of 1 Million Dollars Worth of Automobiles Using an Economic Input–Output Life Cycle Analysis[a]

item	overall activity	motor vehicles and passenger car bodies	motor vehicle parts and accessories	wholesale trade	automotive stampings	automotive repair shops and services
overall economic activity ($million)	2.81	1.01	0.31	0.17	0.09	0.07
electricity (kW-h)	738,490	113,877	100,280	71,900	57,785	29,762
fuels (TJ)	11.81	3.49	1.71	0.98	0.61	0.55
ores–at least (t)	326.11	137.59	96.01	32.49	25.28	20.88
water (million gal)	6.31	3.48	1.18	0.28	0.22	0.17
conventional pollutants (t)						
SO_2	3.21	1.85	0.31	0.18	0.15	0.08
CO	4.82	1.31	0.84	0.58	0.48	0.29
NO_2	2.57	0.84	0.36	0.26	0.18	0.12
VOC	1.18	0.32	0.16	0.06	0.06	0.06
lead	3.05×10^{-3}	2.54×10^{-3}	1.94×10^{-4}	7.9×10^{-5}	5.6×10^{-5}	4.5×10^{-5}
PM_{10}	0.35	0.099	0.045	0.038	0.021	0.016
hazardous waste (t)	47.44	27.30	5.58	2.33	2.10	2.09
toxics release and transfer (t)	2.02	0.33	0.29	0.25	0.24	0.11

[a] The results that are shown are from the overall economic activity of 485 sectors associated with the manufacture of automobiles (referred to as overall activity) and the top five sectors based on economic activity (*65*).

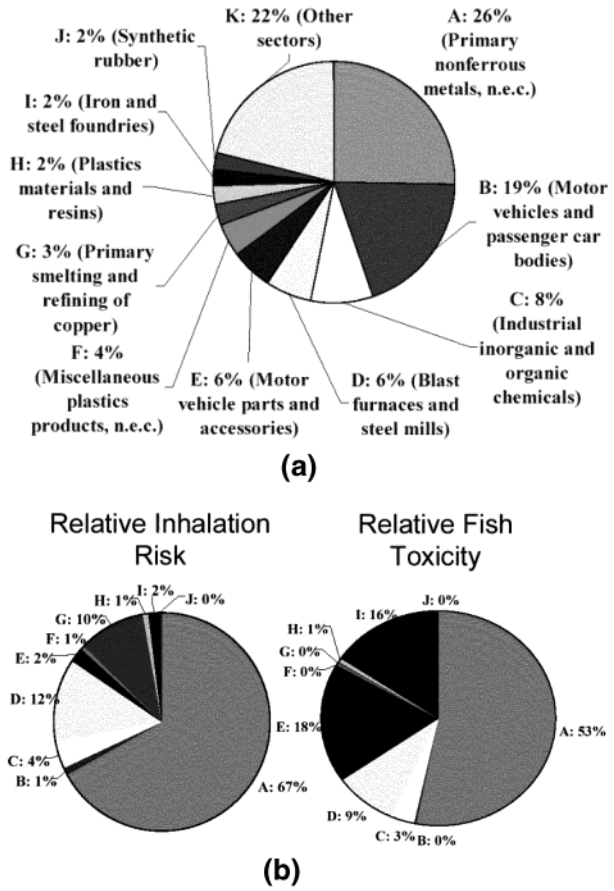

FIGURE 13. (a) Percent of total toxic releases (does not include transfer of toxics) for the top 10 industrial sectors associated with manufacturing automobiles (letters A−J). The letter K corresponds to "other" sectors in the supply chain that includes the remaining 475 industrial sectors. (b) Percentage risk for human inhalation and fish toxicity for the top 10 industrial sectors associated with manufacturing of automobiles. Letters A−J correspond to the sectors listed in panel a.

of the risk for human inhalation associated with these 10 sectors and the fraction of the risk for aquatic toxicity associated with these releases for the various sectors after the integrative approach mentioned earlier was performed. Note that the sector of primary nonferrous metal accounts for over half of the human inhalation risk (67%) and risk to fish (53%) while the motor vehicle parts and accessory sector has a much larger impact on the total risk to fish (18%) than that to humans (2%). The results that are shown in Figure 13b are deceptively simple in appearance but are the result of considering the fate, transport, and exposure of 300 chemicals using a comprehensive multimedia model (*64*, *65*). Of course, a full evaluation of environmental effects from the automobile must consider subsequent use and recycle/disposal impacts (*66*). Nonetheless, this study demonstrates how the areas of industrial ecology, chemical fate, environmental assessment modeling, and risk assessment can be integrated in order to provide insights on issues related to sustainability.

There are numerous research and educational challenges/opportunities in the new metadiscipline of sustainable science and engineering. Many of these research opportunities are discussed elsewhere (e.g., ref *10*). It is clear that pollution prevention and industrial ecology alone are not sufficient to achieve sustainability, because even systems with efficient material and energy use can overwhelm the carrying capacity of a region or lead to other socially unacceptable outcomes.

Perhaps the most critical endeavors that must be undertaken in ensuring the viability of the sustainability metadiscipline are in the area of education and human resource development. Educational activities must occur on two levels. On the first level, the technological and environmental awareness of the entire citizenry must be elevated. On the second level, we must begin attracting a sufficient and diverse pool of human talent to solve the problems in sustainability. Early intervention will be a key at both levels.

In 1996, through a project sponsored in part by NSF and NASA, the International Technology Education Association (ITEA) published its report *Technology for All Americans: A Rationale and Structure for the Study of Technology* (*67*). This report set a goal of technological literacy for all citizens defined as the ability to "use, manage, and understand technology" (*68*). A citizenry that adequately understands technology will make better decisions about technological devices and information systems. In a democracy, where citizens routinely make decisions related to sustainability, it is important that all citizens be technologically literate to some degree.

In today's society, technological literacy is confined mostly to those people who are directly working in technological fields such as engineering, manufacturing, science, or mathematics. Environmental literacy is often defined to those in biological, chemical, social, or environmental science and engineering. The vast majority of U.S. citizens have little or no comprehension of basic concepts upon which technology is based nor do they fully understand the environmental issues that are a part of the daily news (*69*). Although students take courses in math, science, social science, and English, they rarely, if ever, take courses where they integrate these topics and skills, are exposed to the design process, make ethical choices in the use and development of technology, or learn about how engineers and technologists use mathematical and scientific principles in the solution of society's problems (*70*, *71*). A lack of instruction and understanding of technological and environmental issues will seriously hamper the ability of future citizens to keep pace with the ever-expanding role of technology in all facets of their lives (*72*). Many believe that the study of problems with an environmental focus could help attract students to scientific and technological careers in general and that when the environment is used as an integrating concept in K−12 education, improvements in student interest, attitude, achievement, and attendance are realized (*73*).

In an effort to combat technological illiteracy, the ITEA, along with other organizations, recently published Standards for Technology Education for the K−12 curriculum (April 2000). Of the 20 standards for technological literacy, nearly one-third are devoted to issues closely related to the sustainability metadiscipline. Specifically, these related standards are as follows:

Students will develop an understanding of the relationships among technologies and the connections between technology and other fields of study.

Students will develop an understanding of the cultural, social, economic, and political effects of technology.

Students will develop an understanding of the effects of technology on the environment.

Students will develop an understanding of the role of society in the development and use of technology.

Students will develop an understanding of the influence of technology on history.

Students will develop the abilities to assess the impact of products and systems.

It is clear that K−12 sustainbility education endeavors could play a key role in improving technological literacy for all students through the implementation of these standards.

This will in turn lead to a citizenry that has a better understanding of sustainability issues.

On another front, our nation is facing a severe crisis that could have a far-reaching impact into the future. Simply stated, the engineering and scientific professions are not attracting an adequate proportion of the best and the brightest in the human talent pool. To quote William A. Wulf, president of the National Academy of Engineering (*74*), "We need to understand why in a society so dependent on technology, a society that benefits so richly from the results of engineering, a society that rewards engineers so well, engineering isn't perceived as a desirable profession .... Our profession is diminished and impoverished by a lack of diversity."

There is evidence to suggest that groups that are currently underrepresented in engineering, particularly women, are attracted to careers where they feel that they can have a positive impact on society. For example, the number one reason on the list of why women do not go into engineering has been stated to be "Lack of connection between engineering and the problems of our society. Lack of understanding what engineers do" (*75*). In a recent *Chronicle of Higher Education* article (*76*), responding to a query about how engineering can attract more women, Domenico Grasso, director of engineering at Smith College, is quoted as saying "The challenge for engineering programs is not to show that math and science are fun, but that these disciplines have social value and relevance". In addition, recent articles have highlighted the fields of civil and environmental engineering as a means to have a positive impact on society (*77*, *78*).

Educational experiences in the new sustainability metadiscipline, with its focus on societal impact and interconnectedness, should have a broad appeal, especially to young women. National trends in environmental engineering education show that nearly 50% of the students who enroll in this discipline are women (*79*). Working toward solving environmental and societal problems resonates with women; young girls will be motivated to study science and engineering if they understand that careers in these fields will enable them to positively impact society. Hopefully this message will also resonate with other under-represented groups.

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