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Sustainability in Chemical Engineering Education: Identifying a Core Body of Knowledge

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Introduction

The quality of modern life depends on the availability of vast amounts of energy and an array of products provided by the chemical industry. Chemical processes provide products and materials used in health care, consumer products, transportation, agriculture, food processing, electronic materials, and construction. Highly energetic, globally transportable fuels are an essential element of global transportation and distribution systems. Yet, these same chemical processes and fuel systems that provide products essential for modern economies, like all engineered systems, consume resources and have environmental impacts. Growing demand for energy, food and materials have put increasing pressure on air and water, arable land, and raw materials. Concern over the ability of natural resources and environmental systems to support the needs and wants of global populations, now and in the future, is part of an emerging awareness of the concept of sustainability.

Sustainability is a powerful, yet abstract, concept. The most commonly employed definition of sustainability is that of the Brundtland Commission report—*development that meets the needs of this generation without compromising the ability of future generations to meet their needs*.[1] However, a search on the definition of sustainability will return many variations on this basic concept. For example, the 2006 National Research Council report on Sustainability in the Chemical Industry[2] defines sustainability as "*a path forward that allows humanity to meet current environmental and human health, economic, and societal needs without compromising the progress and success of future generations*". In engineering, incorporating a concern about sustainability into products, processes, technology systems, and services generally means integrating environmental, economic, and social factors in the evaluation of projects and designs. This can be referred to as "*sustainable engineering*", but other terms have also been used; green engineering, design for environment, pollution prevention, eco-efficiency and a variety of other terms.

To grasp the magnitude of the sustainability challenge, it is useful to invoke a conceptual equation that is generally attributed to Ehrlich and Holdren.[3] The equation relates impact (I), to population (P), affluence (A), and technology (T)

$$I = P * A * T$$

This conceptual relationship, commonly referred to as the IPAT equation, suggests that impacts, which could be energy use, materials use, or emissions, are the product of the population (number of people), the affluence of the population (generally expressed as gross domestic product of a nation or region, divided by the number of people in the nation or region), and the impacts associated with the technologies used in the delivery of the affluence (impact per unit of gross domestic product). For example, if the IPAT equation were used to describe energy use in the United States, then I would represent energy use per year, P would represent the population of the United States, A would represent the annual GDP per capita, and T would represent the energy use per dollar of GDP.

While the IPAT equation should not be viewed as a mathematical identity it can be used to assess the magnitude of the challenges that our societies face in material use, energy use and environmental impacts. By estimating growth in population and affluence, we can get an indication of the amount by which use of energy, use of materials, and emissions might increase over the next several decades, if our

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technologies were to remain static. Estimates from the United Nations[4] suggest that world population will increase at the rate of 1-2% per year until peaking at somewhere near 10 billion, over the next century. Affluence, as measured in economic output (e.g., gross domestic product) is growing in some regions of the world by 8–10% per year. On average, worldwide, affluence is growing by roughly 2–4% per year, depending on economic conditions. If these trends continue for several decades, then compounded growth would lead world economic output ($P * A$) to increase by 50% in 10 years, by 300% in 25 years, and by more than a factor of 10 in 50 years.

Invoking the IPAT equation, the implications of population and economic growth are that, if technology were to remain static, energy use, material use, and environmental impacts will grow 10-fold over the next 50 years. Reducing the impacts of technology (T in the IPAT equation) by an order of magnitude will be necessary if the world is to support 10 billion people, all aspiring to better living standards. Reducing energy use, material use and emissions will be a central challenge for engineers of the 21st century. Engineers will need to develop and master technical tools that will integrate the objectives of energy efficiency; materials efficiency and reduced environmental emissions into design decisions and engineers will be driven to create entirely new modes of production.

There is evidence that use of sustainability indicators is already increasing in engineering practice. Professional organizations, such as the American Institute of Chemical Engineers (AIChE), are developing indices to assess corporate performance in sustainability.[5] Programs such as LEED® building ratings,[6–8] and Energy Star,[9] and other product labeling programs are growing in prominence as differentiators in the marketplace. Some sustainability performance standards, such as those for renewable fuels,[10] are barriers to market entry.

Engineers will be increasingly called upon to incorporate sustainability concepts into their designs, and in doing this, to invent the sustainable chemical and energy products of the future. However, if engineers are to design for sustainability what will their tools be? What is the body of knowledge for sustainable engineering? Design tools that allow engineers to improve energy efficiency, improve mass efficiency, and reduce emissions are certainly part of the tool set engineers will need. However, these are not entirely new tools for engineers. Energy and mass efficiency are objectives that have always been included in engineering design. What is new is the need to systematically and simultaneously incorporate economic, environmental and social objectives into engineering designs, at multiple scales. These tools and skills will be increasingly important, and challenging to apply, as chemical engineers operate in diverse global environments, with varying social perspectives and environmental priorities.

The remainder of this perspectives article will define a body of knowledge and a set of tools for sustainable engineering, and describe how this material could be incorporated into chemical engineering education, for both students and practicing engineers.

A Body of Knowledge and the Tools of Sustainable Engineering

Over the past decade, sustainability concepts and tools for sustainable engineering have begun appearing in engineering curricula. Murphy et al.[11] found that the overwhelming majority of engineering programs in the United States have some content related to sustainability and documented the body of knowledge covered in over 150 engineering courses on green engineering or sustainability.[11] Based on syllabi for the courses described in this inventory, as well as the material covered in the most commonly used texts identified in the inventory,[12–16] three major elements to the body of knowledge can be identified: Framing the challenge; assessment and design, and systems perspectives. These elements, along with possible methods for including these elements in chemical engineering curricula, are described in more detail following.

1. *Framing the challenge*: Few chemical engineers have been exposed, in a structured manner, to the basic concepts associated with sustainability. Coverage of these issues should include some or all of the following: Introduction to sustainable development concepts, trends, and industry perspectives, a characterization of the scale of sustainability challenges (e.g., using the IPAT equation described earlier in this *Perspectives* article), an introduction to national and global patterns of energy, water and material supplies and use, an introduction to emissions and their impacts, and some coverage of critical earth systems (global element cycles (C, N, etc.) and ecosystem function and pollutant assimilative capacity). Other topics to cover might include the network of regulations that place constraints on engineering designs.

This broad scope of introductory material should be structured around organizing principles. Two potential organizing principles are the risk based frameworks used in many environmental regulations and emerging life cycle (cradle to grave or raw material extraction to disposal) frameworks.

2. *Assessment and design*: Once the framework for defining sustainability challenges has been established, tools for assessing and improving the sustainability of engineering designs can be examined. For chemical engineers, these tools are applied at the molecular, unit operation and flow sheet level. Assessment tools most frequently quantify the energy use, water use, material use and emissions associated with designs, although some emerging frameworks also consider corporate and social performance metrics, as shown in Figure 1.[5,17–19] The assessments can include tools that partially monetize the sustainability measures.

Design toolkits take a variety of forms. One approach to developing a toolkit for engineers designing for sustainability has been to generate lists of guiding principles. For example, the "Hannover Principles" express the view that human systems must be designed to coexist with natural systems, renewable resources should be used, safe and long-lived products are desired, and elimination of waste is a priority.[20] The Augsburg materials declaration[21] identifies eight factors that must be considered to achieve sustainable production including: integration of environmentally benign design, materials and manufacturing over all stages of the life-cycle; optimization and exploitation of raw materials and natural resources; energy efficient production technologies and product distribution; regenerative energy sources; and durability, recyclability and closed loops. The "12 Principles of Green Engineering"[22] include inherently safe and benign, design for recycle or a commercial after life, energy and mass

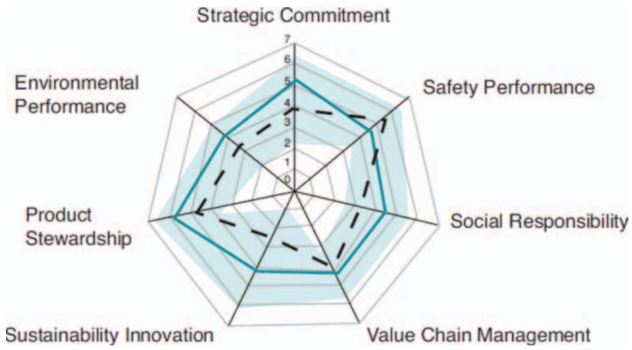

Figure 1. Sustainability performance indicators, developed as an index of performance of global chemical companies by the Institute for Sustainability of the American Institute of Chemical Engineers.[5]

efficiency, and integration with existing energy and material flows. The Sandestin Green Engineering Principles, developed as an outcome from a multidisciplinary engineering conference, emphasized the need for holistic thinking and the use of environmental impact and integrative analysis tools such as life cycle assessment.[23,24] The Sandestin Green Engineering Principles (also referred to as "Sustainable Engineering Principles"[25]) was developed based on a starting list of principles compiled from available sustainability or green engineering principles and declaratory statements including the Hanover Principles, CERES, Augsburg Materials Declaration, the Twelve Principles of Green Chemistry, Ahwahnee Principles, and Earth Charter Principles.

Examples illustrating the quantitative application of each of the guiding principles, applied to material properties, unit operations and flow sheets have been developed (e.g., the use of heat integration (pinch) technology applied to flow sheets to achieve energy efficient production). Examples are available in Allen and Shonnard[12] and at the US Environmental Protection Agency's green engineering website.[27]

These guiding principles can be a useful start, but eventually most chemical engineering designs will involve creating new materials or processes and quantitative analyses of material properties, unit operations and flow sheets. Computer-aided tools can help in these analyses when used in a coordinated and hierarchal fashion, as shown in Figure 2. These tools can aid in analyses over a range of scales, from molecular, to process level, to large-scale environmental systems.

3. *Systems perspectives*: Awareness that engineering designs are a system, embedded within systems, is a critical concept in sustainability education. Figure 3 illustrates the types of system scales that frequently impact, and are impacted by, engineering designs, using mobility systems as a case study. As shown in Figure 3, the personal device that is used to provide mobility in North America is the automobile. One method of incorporating sustainability into engineering design is to assess environmental and social impacts of decisions affecting the design of a new automobile (e.g., choice of paint type, or chassis and engine materials). At a larger scale, sustainability concepts can be incorporated into automotive design decisions involving the recyclability of the vehicle. At even larger scales, the impact of automobile design (e.g., gasoline or electric power) on fuel industries and road construction can be considered. Finally, the overall sustainability of mobility systems is also influenced by and influences the design of homes, communities and workplaces. These scales of design can be referred to as gate-to-gate, cradle to grave, interindustry interactions (e.g., interactions between fuel, automotive and roadway design) and extraindustry interactions (e.g., interactions between mobility and community design).

Providing a systems perspective, in the context of engineering for sustainability, means understanding that all of these scales impact engineering design decisions, often in

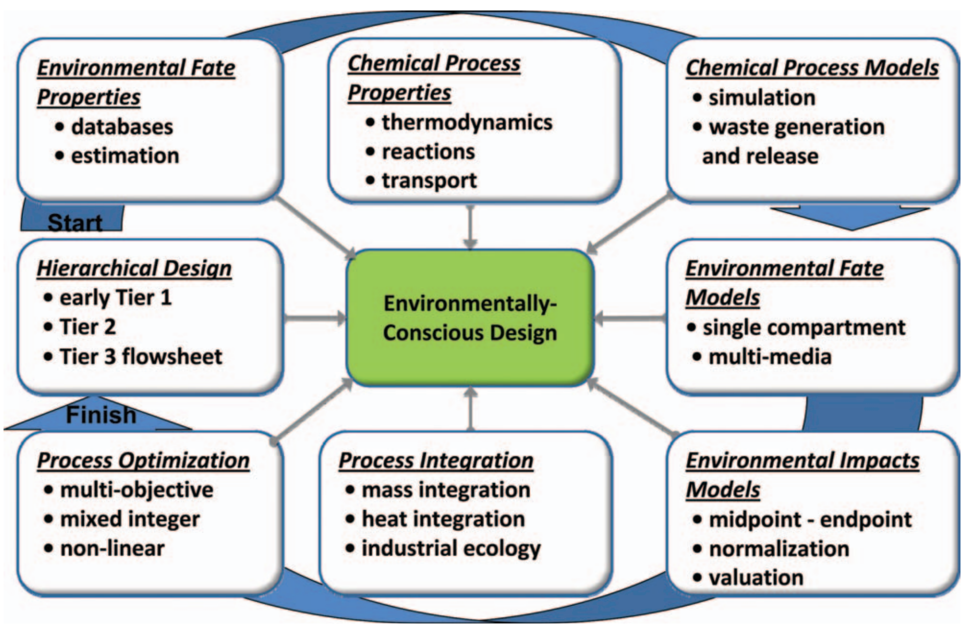

Figure 2. Computer-aided tools for environmentally-conscious design (E-CD) of chemical processes.[26]

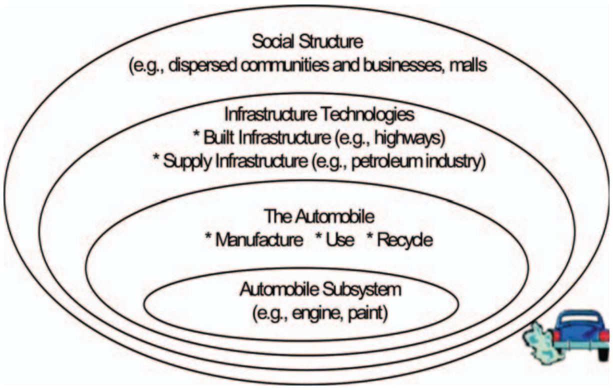

Figure 3. The technological-social system of the automobile exists in multiple layers; design decisions made in any of the layers shown influence decisions in all other layers.[28]

complex ways. For example, societal decisions requiring renewable fuels will influence the types of fuels that automobiles must be able to accept. Similarly, the range of travel between refueling stops that automobiles can provide will influence location and design of communities. In current engineering courses, the gate-to-gate and cradle-to-grave system scales are the primary focus.[11,29] Systems analysis tools such as life cycle assessments and material flow analyses are frequently covered. In contrast, interindustrial and extraindustrial topics are covered far less frequently in current curricula, yet an understanding of these larger scale phenomena can be very important in some applications.

As a contemporary case study of the potential importance of interindustrial and extraindustrial scales on engineered systems, consider issues associated with the use of hydraulic fracturing to produce natural gas, condensate, and in some cases, oil. Hydraulic fracturing of shale formations (shale gas) is projected by the Energy Information Administration to become the dominant source of domestic natural gas supply over the next several decades,[30] potentially transforming the nation's energy landscape. However, the environmental impacts associated with ''fracking'' for shale gas have made it controversial in some communities, and some communities are seeking to ban it.[31] Particularly controversial are the impacts of hydraulic fracturing on water use and water quality. The U.S. Environmental Protection Agency, at the direction of Congress, is examining the role of hydraulic fracturing on drinking water and groundwater.[32] Results from the first of these case studies are being released as this article is being written.[33] Air emissions associated with hydraulic fracturing are also a concern. Elevated concentrations of regional air pollutants in regions with active nonconventional oil and gas production have led to concerns about emissions of photochemical smog precursors and several studies are underway to investigate these phenomena.[34] Also controversial are the greenhouse gas emissions associated with the natural gas supply chain; some analyses suggest that these emissions could be significant enough to change the desirability, from a greenhouse gas emission perspective, of natural gas relative to coal, however, these analyses have been challenged and studies are underway to provide additional data to resolve the debate.[35,36]

All of these issues fit into the analysis frameworks currently presented in engineering curricula addressing sustainability. The well-to-burner (cradle-to-grave) economic, environmental and societal impacts of shale gas production can be examined and evaluated. Missing, however, from this type of analysis are the inter-industrial and extra-industrial considerations. Widespread availability of shale gas, and limited capacities for transporting shale gas to global markets, can drive down natural gas prices. This, in turn, can impact the use of natural gas in other industrial sectors. Lower prices for natural gas can lead to more use of natural gas in electricity generation. In some grid systems (e.g., Texas), switching to natural gas for electricity generation can reduce emissions of regional air pollutants and reduce water use.[37] Wider availability and potentially lower prices of condensate from gas production can change the use of feedstocks for commodity chemicals, changing emissions, water use and energy use in commodity chemical production in complex ways. So, what will be the overall economic, water use, water quality and air quality impacts of shale gas production? It will depend not only on the natural gas supply chain, but also the consequences of changes in the natural gas supply chain in other industrial sectors. Although there is a need to attribute material use, water use, energy use and emissions along the natural gas supply chain, there is also the need to examine the consequences of changes in this supply chain on other industrial sectors.

Recognition of the importance of this phenomenon of consequential impacts, in addition to impacts that can be attributed to a single supply chain, is recent.[38] However, these types of consequential impacts are not rare. For example, the widespread production and use of biofuels has the potential to impact food markets[39] by driving up prices and influencing global land use change. The water required for the production of biofuels can significantly impact water supplies, and, therefore, have consequences in almost every industrial sector.[40] Use of wind turbines to generate electricity requires generator magnets, which in turn require rare earth elements. Many of these same elements are required in advanced battery technologies used in products such as electric and hybrid vehicles, connecting the electricity generation and transportation sectors in new ways.[41] Developing the skills and tools required to identify and quantify the behavior of these inter-industrial systems will be an important addition to engineering education.

A summary of a body of knowledge on sustainability, for chemical engineers, is provided in Table 1. It is organized into three major elements: Framing the challenge; Assessment and design; and Systems perspectives. Key concepts and tools for each element are summarized.

Implications for Chemical Engineering Curricula

Table 1 provides a perspective on the knowledge base required for engineers working on issues related to sustainability. Three major elements are defined: Framing the challenge; assessment and design, and systems perspectives. In most engineering curricula this type of material is commonly covered in elective courses.[11] There are, however,

Table 1. Sustainability in Chemical Engineering Education: A body of Knowledge

Framing the challenge	Introduction to sustainable development, trends, and industry perspectives
	Introduction to the magnitude of sustainability challenges
	Overview of energy, water and material supplies and uses
	Overview of emissions and wastes of concern
	Legislation to protect human and ecosystem health
	Earth systems, global material cycles and ecosystem function
	Risk and life cycle frameworks for analyzing issues
Assessment and design	Sustainability metrics at multiple scales – molecular, process, product and systems scales
	General principles of designing for sustainability
	Applying general principles at unit operation scales – tools and case studies
	Applying general principles at flowsheet scale – tools and case studies
	Applying general principles for products and materials – tools and case studies
	Monetizing sustainability metrics
System Perspectives	Life cycle assessments along single supply chains – tools and case studies
	Consequential life cycle assessments (inter-industry and extra-industrial scales) – tools and case studies
	Global material flow analyses – tools and case studies
	Consequential material flow analyses (inter-industry and extra-industrial scales) – tools and case studies

opportunities for incorporating these concepts into required courses, even in a crowded curriculum.

Freshman Engineering. Required freshman engineering courses are beginning to emerge in engineering curricula. The most common educational goals in freshman engineering courses are to expose students to the nature of the design process, the creativity inherent in design, the tradeoffs associated with meeting design objectives, and the iterative nature of the engineering design process. Because these courses frequently seek to expose students to the contributions that engineers can make in solving the grand challenges facing human societies, design problems that incorporate environmental constraints and objectives are attractive choices. For example, at Villanova, freshman engineering students design a process to make biodiesel from waste oils.[42] As an alternative to a design project, commonly taught principles of green or sustainable engineering could be included in freshman courses.[13] Since most engineering designs involve the specification of materials, students can be introduced to the energy and environmental footprints of commodity materials as they select materials for their designs. The introduction of material footprints would also introduce students to supply chain (life cycle) implications of their material choices and would introduce students to engineering tradeoffs, as they seek to simultaneously minimize energy use, materials use and emissions. All of these principles can be applied at multiple scales, ranging from the molecular (e.g., design of molecules that could serve as replacements for gasoline) to the product or process level (e.g., design of a process to grow algae to make diesel fuel) to the design of infrastructures (storage and delivery systems for biofuels).

Sophomore through Junior Level Courses. Required chemical engineering courses offer multiple opportunities for covering the guiding principles of sustainable engineering, examining tools and case studies. For example, many chemical engineering curricula have materials courses, which could include modules on the impact of material selections on global material flows and environmental impacts.[13] At the University of Texas, the materials course taken by chemical engineers contains a module on critical materials, such as rare earth elements, and the geopolitical implications of their availability. At Michigan Technological University, the mass transport course includes a module on the environmental fate of pollutants. Courses on material and energy balances frequently include case studies on life cycle assessment. These case studies can give students insights into concepts that are difficult to teach. For example, the concept of a purge in a recycle stream is often difficult for students to understand, but the need to remove contaminants from plastic grocery sacks that are being recycled can help students grasp this concept.[43] Other examples include courses on separation processes and reaction engineering that could include modules and case studies that illustrate sustainability concepts,[11] such as energy efficiency, earth systems literacy, atom economy, and others.

Senior Design Capstone design courses are ubiquitous in engineering curricula. As capstone courses, they seek to synthesize knowledge students have been exposed to throughout their curriculum through a design challenge. The educational goals parallel freshman design courses. The goals are to expose students to the nature of the design process, the creativity inherent in design, the tradeoffs associated with meeting design objectives, and the iterative nature of the engineering design process. Just as in freshman courses, the design problems frequently incorporate environmental constraints and objectives. So for senior design courses, like freshman design courses, the commonly taught principles of green or sustainable engineering that could be incorporated are life cycle assessments, environmental cost accounting, and energy and material use profiling of designs. For example, Michigan Technological University has students evaluate environmental releases and societal impacts associated with proposed process designs and determine the regulatory approvals that would be required (for methods, see Ref. [12]). Other institutions have students perform designs that are motivated by sustainability goals, such as the design of biofuel production and refining operations.

Implications for Engineering Practice

Because the incorporation of sustainability issues into engineering curricula is a relatively new phenomenon, most practicing engineers did not encounter sustainability concepts in their formal education. Therefore, a variety of certification and training programs are beginning to emerge for practicing engineers, and the knowledge required for these certifications will impact expectations for undergraduate education. A certification program emerging from the Institute for Sustainability of the America Institute of Chemical Engineers articulates a Body of Knowledge similar in concept to the Body of Knowledge for university engineering students, identified in Table 1. The main differences are an expansion of the topics covered to include corporate and institutional sustainability metrics and leadership.

Conclusions

The current state of development of engineering for sustainability can be compared to the evolution of chemical engineering education. Chemical engineering emerged late in the 19th century as a field of applied or industrial chemistry.[44] Chemical engineers at the beginning of the 20th century studied individual industrial technologies. They learned almost exclusively through case studies. By the 1920s, however, it became apparent that most chemical processes had common unit operations. Chemical engineers began to study the design of reactors, distillation columns and other unit operations, rather than specific processes. In the last 50 years sophisticated mathematical tools for modeling chemical reactions, transport phenomena, and thermodynamics have been developed, and these sophisticated design tools have been applied at spatial scales from molecular (e.g., modeling the properties of nanomaterials) to the scale of unit operations and chemical processes, to global scales (e.g., modeling atmospheric chemistry at global scales). These sophisticated analytical tools also span a wide range of temporal scales, from nanoseconds to decades.

Engineering tools for improving sustainability are at a mixture of these three stages. Although the field is no longer restricted to just examining case studies, case studies are still revealing new insights. Through the examination of many case studies, common principles have begun to emerge. Risk analysis frameworks and tools, life cycle frameworks and analysis tools, methods for selecting sustainable materials, and a collection of other increasingly sophisticated analytical tools, have gained general acceptance. A distinctive feature of sustainability education for chemical engineering is the recognition that knowledge outside of our discipline, and also working with outside experts, will be necessary to achieve sustainable chemical engineering designs. The field is at a point where a systemic approach to incorporating sustainability into chemical engineering is appropriate.

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Literature Cited

1. *World Commission on Environment and Development. Our common future*. Oxford, UK: Oxford University Press; 1987.
2. *National Research Council. Sustainability in the chemical industry*. Washington, DC: National Academy Press; 2006.
3. Ehrlich P, and Holdren J. 1971. Impact of population growth. *Science*. 1971;171:1212–1217.
4. United Nations World Population Prospects: The 2006 Revision, United Nations, 2007 accessed at United Nations Population Information Network. http://www.un.org/popin/data.html. Accessed February 27, 2012.
5. Cobb C, Schuster D, Beloff B, Tanzil D. The AIChE sustainability index: The factors in detail. *Chem Eng Prog*. 2009;105(1):60–63.
6. LEED®, Leadership in Energy and Environmental Design. U.S. Green Building Council. http://www.usgbc.org/LEED/Project/CertifiedProjectList.aspx. Accessed February 27, 2012.
7. US Green Building Council (USGBC), 2011. http://www.usgbc.org. Accessed February 27, 2012.
8. Foley HC. Challenges and opportunities in engineered retrofits of buildings for improved energy efficiency and habitability. *AIChE J*. 2012;58:658–667. doi:10.1002/aic.13748.
9. US Environmental Protection Agency (2012b). Energy star. http://www.energystar.gov. Accessed February 27, 2012.
10. US Environmental Protection Agency. Renewable fuel standard. http://www.epa.gov/otaq/fuels/renewablefuels. Accessed February 27, 2012.
11. Murphy C, Allen DT, Allenby B, Crittenden J, Davidson C, Hendrickson C, Matthews S. Sustainability in engineering education and research at U.S. universities. *Environ Sci Technol*. 2009;43:5558–5564.
12. Allen DT, Shonnard DR. *Green Engineering: Environmentally Conscious Design of Chemical Processes and Products*. Englewood Cliffs, NJ: Prentice Hall; 2001.
13. Allen DT, Shonnard DR. *Sustainable Engineering: Concepts, Design and Case Studies*. Englewood Cliffs, NJ: Prentice Hall; 2012.
14. Graedel TE, Allenby BR. *Industrial Ecology*. Englewood Cliffs, NJ: Prentice Hall, NJ; 1995.
15. Graedel TE, Allenby BR. *Industrial Ecology*. 2nd ed. Englewood Cliffs, NJ: Prentice Hall; 2002.
16. Graedel TE, Allenby BR. *Industrial Ecology and Sustainable Engineering*. Englewood Cliffs, NJ: Prentice Hall; 2009.
17. Sikdar S. Sustainable development and sustainability metrics. *AIChE J*. 2003;49:1928–1932.
18. Sugiyama H, Fischer U, Hungerbuhler K, Hirao M. Decision framework for chemical process design including different stages of environmental, health, and safety assessment. *AIChE J*. 2008;54:1037–1053.
19. Tugnoli A, Santarelli F, Cozzani V. Implementation of sustainability drivers in the design of industrial chemical processes. *AIChE J*. 2011;57:3063–3084.
20. McDonough W.Braungart M. Hannover principles. http://www.mindfully.org/Sustainability/Hannover-Principles.htm. 1992. Accessed February 27, 2012.
21. Augsberg Materials Declaration. Materials Research Society, September 2002. http://idw-online.de/pages/de/newsimage5429.jpg. Accessed February 27, 2012.
22. Anastas PT, Zimmerman JB. Design through the 12 principles of green engineering. *Environ Sci Technol*. 2003;37(5):94A–l01A.
23. Abraham MA, Nguyen N. Green engineering: Defining the principles - Results from the Sandestin conference. *Environ Prog*. 2003;22(4):233–236.

24. Shonnard DR, Lidner A, Nguyen N, Ramachandran PA, Fichana D, Hesketh R, Slater CS, Engler R.*Green Engineering - Integration of Green Chemistry, Pollution Prevention, and Risk-Based Considerations*. In: *Kent and Reiger's Handbook of Industrial Chemistry and Biotechnology*. 11th ed. New York: Springer Science; 2007;1.
25. Abraham MA, ed. *Sustainability Science and Engineering: Defining Principles*. Amsterdam and Boston: Elsevier Science; 2006.
26. Anastas P, Wood-Black F, Masciangiola T., McGowan E.Ruth L, eds. *Exploring Opportunities in Green Chemistry and Engineering Education: A Workshop Summary to the Chemical Sciences Roundtable*. *National Research Council*. Washington, DC: National Academy Press; 2007.
27. US Environmental Protection Agency (2012c). Green engineering. http://www.epa.gov/oppt/greenengineering. Accessed February 27, 2012.
28. Graedel TE, Allenby BR. *Industrial Ecology and the Automobile*. Englewood Cliffs, NJ: Prentice Hall; 1997.
29. Allen DT, Murphy CF, Allenby B, Davidson C. Incorporating sustainability in chemical engineering education. *Chem Eng Prog*. 2009;105(1):47–53.
30. Energy Information Administration. Shale gas. http://www.eia.gov/energy_in_brief/about_shale_gas.cfm. Accessed February 27, 2012.
31. Reuters. New York Judge upholds fracking ban in towns (February 12, 2012). http://www.reuters.com/article/2012/02/22/us-newyork-fracking-idUSTRE81L05820120222. Accessed February 27, 2012.
32. US Environmental Protection Agency (2012d). EPA's study of hydraulic fracturing and its potential impact on drinking water resources. http://www.epa.gov/hfstudy. Accessed February 27, 2012.
33. US Environmental Protection Agency (2012e). Groundwater investigation, Pavillion. http://www.epa.gov/region8/superfund/wy/pavillion/index.html. Accessed February 27, 2012.
34. National Oceanic and Atmospheric Administration. NOAA study targets high ozone pollution events in western oil and gas fields. http://researchmatters.noaa.gov/news/Pages/utah.aspx. Accessed February 27, 2012.
35. Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change*. 2011;106:679–690.
36. Cathles LM III, Brown L, Taam M, Hunter A, eds. A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by Howarth RW, Santoro R, Ingraffea A. *Climatic Change*. 2011. doi:10.1007/s10584-011-0333-0.
37. Alhajeri NS, Donohoo P, Stillwell AS, King CW, Webster MD, Webber ME, Allen DT. Using market-based dispatching with environmental price signals to reduce emissions and water use at power plants in the Texas grid. *Environ Res Lett*. 2011;6:044018 doi.org/10.1088/1748–9326/6/4/044018.
38. National Research Council. Hidden costs of energy: *Unpriced consequences of energy production and use*. Washington, DC: National Academy of Sciences Press; 2009.
39. US Environmental Protection Agency (2012f). Renewable fuels: Regulations and standards (including summary of life cycle assessment docket). http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm. Accessed February 27, 2012.
40. King CW, Webber ME. Water intensity of transportation. *Environ Sci Technol*. 2008;42:7866–7872.
41. US Dept of Energy. Critical materials strategy (December 2010). http://energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf. Accessed February 27, 2012.
42. Satrio JA, Chin LA. Introducing Freshmen Students to the Multi-Faceted World of Engineering and Sustainability through Biofuels Synthesis from Waste Cooking Oil. *AIChE Annual Meeting*; November 2012.
43. Allen DT, Bakshani, N, Rosselot, KS. *Pollution Prevention: Homework and Design Problems for Engineering Curricula*. New York: AIChE; 1992.
44. Peppas NA. *One Hundred Years of Chemical Engineering*. Amsterdam: Kluwer; 1989.