Benchmarking Sustainable Engineering Education: Final Report

EPA Grant Number:
X3-83235101-0

Project Title:
Benchmarking Sustainable Engineering Education

Investigators:
David Allen; Braden Allenby; Michael Bridges; John Crittenden; Cliff Davidson; Chris Hendrickson; Scott Matthews; Cynthia Murphy; David Pijawka

Institutions:
University of Texas at Austin, Carnegie Mellon University, Arizona State University

EPA Project Officer:
Cynthia Nolt-Helm

Project Period:
May 15, 2005 through December 31, 2008

Project Period Covered by this Report:
May 15, 2005 through December 31, 2008

Project Amount:
$350,000

RFA:
Benchmarking the Integration of Sustainability into Engineering Curricula at U.S. Institutions of Higher Education

This page intentionally left blank

Objectives:

The primary objectives of this project were to: (1) identify accredited engineering programs at US institutions that incorporate sustainability concepts into engineering curricula and within these programs characterize the design decision levels being employed and the degree to which information and concepts from non-engineering disciplines are being employed; (2) identify faculty who incorporate sustainability concepts into their research and other activities; (3) map results into a sustainability matrix that captures system complexity and size and the degree to which data and concepts from non-engineering disciplines are being employed; (4) identify best practices for sustainability engineering and leading contributors to sustainability engineering education; and (5) develop a preliminary roadmap with a protocol for a more formal roadmap that will define a path for achieving excellence in sustainability engineering education in the United States.

Key Findings

The administrative heads of 1368 engineering departments (or the equivalent) at 364 US universities and colleges were contacted and asked to complete a questionnaire about the extent to which sustainable engineering was being integrated into their departments. More than 20% of those contacted responded. Within that 20%, more than 80% reported teaching either sustainable engineering focused courses or integrating sustainable engineering material into existing courses. Roughly 70% reported some research activity in sustainable engineering. In a subsequent distribution, 327 additional individuals, identified as sustainable engineering champions, were contacted and asked to complete a second questionnaire for the purpose of capturing detailed information about courses taught and research activities in the area of sustainable engineering. A total of 137 valid responses were received, for a response rate of 43%. These high response rates indicate that engineering schools are actively engaged in incorporating sustainable engineering concepts into the curriculum.

Although there is significant diversity in the nature of the courses being taught and the research being conducted, the questionnaire responses reveal several common themes and elements. Within the curricula, courses concentrate primarily on smaller systems, particularly those limited to the firm (gate-to-gate or design for environment) or product (cradle to grave or environmental life cycle analysis). Less than half of the courses address larger systems that examine relationships between different firms or industrial sectors (industrial ecology) or between industrial and non-industrial sectors (cultural and social dimensions). Results also show that a substantive body of sponsored research is being conducted, with energy and power generation the dominant themes.

The engineering education community is now at a critical juncture. To date, there has been a significant level of “grass-roots” activities but little structure or organization. The next step will be for engineering accreditation bodies to think critically about what should or should not be included in a curriculum into which sustainable engineering has been incorporated. The path forward will require the evolution of a set of community standards. This document provides an inventory of what is currently available and can serve as a resource as professional organizations develop these standards.

This page intentionally left blank

Table of Contents

Executive Summary

Date of Final Report: December 31, 2008

EPA Agreement Number: X3-83235101-0

Title: Benchmarking Sustainable Engineering Education

Investigators: David Allen; Braden Allenby; Michael Bridges; John Crittenden; Cliff Davidson; Chris Hendrickson; Scott Matthews; Cynthia Murphy; David Pijawka

Institutions: University of Texas at Austin, Carnegie Mellon University, Arizona State University

Research Category: Sustainability

Project Period: May 15, 2005 through December 31, 2008

Description and Objective of Research

The primary objectives of this project were to: (1) identify accredited engineering programs at US institutions that incorporate sustainability concepts into engineering curricula and within these programs characterize the design decision levels being employed and the degree to which information and concepts from non-engineering disciplines are being employed; (2) identify faculty who incorporate sustainability concepts into their research and other activities; (3) map results into a sustainability matrix that captures system complexity and size and the degree to which data and concepts from non-engineering disciplines are being employed; (4) identify best practices for sustainability engineering and leading contributors to sustainability engineering education; and (5) develop a preliminary roadmap with a protocol for a more formal roadmap that will define a path for achieving excellence in sustainability engineering education in the United States.

The administrative heads of 1368 engineering departments (or the equivalent) at 364 US universities and colleges were contacted and asked to complete a questionnaire about the extent to which sustainable engineering was being integrated into their departments. More than 20% of those contacted responded. Within that 20%, more than 80% reported teaching either sustainable engineering focused courses or integrating sustainable engineering material into existing courses. Roughly 70% reported some research activity in sustainable engineering. In a subsequent distribution, 327 additional individuals, identified as sustainable engineering champions, were contacted and asked to complete a second questionnaire. A total of 137 valid responses were received, for a response rate of 43%. These respondents provided detailed information about courses and research programs.

Summary of Findings:

Courses

With the caveat that the results of these questionnaires represent a sample and not a full population, several trends do emerge as the result of this benchmarking. The first is that the trend to include sustainable engineering concepts into US engineering programs is becoming a widely accepted practice. The courses tend to emphasize the immediate environmental and social impacts of engineering designs, and consequently introduce students to the concepts of design for multiple objectives, especially when some of the objectives are difficult to monetize. In addition, a substantial number of the courses examine how engineering designs are influenced by larger product life cycles. This can be viewed as a return to systems approaches to engineering design and as a way of encouraging students to think about their designs at a larger scale. The courses being offered tend to be relatively mature and are offered to medium sized classes of predominantly upper division undergraduate and graduate students. While a stand-alone sustainable engineering course seems to be the most common approach, integrating sustainable engineering concepts into core engineering courses is also a widely used practice.

Research

Research funding in sustainable engineering is substantial. This work identified roughly a quarter of a billion dollars in funding. The dominant sponsor of this research is the National Science Foundation (NSF), and consequently, median project sizes (~$300,000) and durations (36 months) follow NSF norms. The funding is concentrated in top tier institutions; more than half of the research funding is found at top 40 PhD granting institutions. Student participation in these research programs is extensive. More than 500 graduate and roughly 400 undergraduate students are actively engaged in the projects.

Topical areas for research are heavily concentrated in energy and power systems; however, publication and other dissemination of results are not primarily directed toward energy conferences and journals; the two dominant journals that sustainable engineering researchers monitor and publish in are Environmental Science & Technology and the Journal of Industrial Ecology.

Program Structures

Three-fourths (73%) of engineering schools with PhD programs and that ranked in the top 100 had at least one department that participated in the questionnaire (Ranking numbers are from US News and World Report [USN&WR, 2008]). Since more than 80% of the respondents reported some level of course activity and 70% reported some research activity, it is clear that teaching and research in sustainable engineering are part of the activities of most of the top 100 engineering programs in the United States. The activity is most extensive at the largest institutions.

While most of the top 100 programs offer courses or conduct research, a much smaller percentage of programs offer degree programs. A total of 33 departments (12% of those responding) from 26 schools (14%) grant both Bachelors and Masters Degrees that are sustainable engineering related. An additional 17 departments from 17 institutions have Bachelors degree programs and 15 departments from 15 schools grant Masters only, for a total of 65 departments (23%) and 53 institutions (29%). A small number of interdisciplinary degree programs are emerging, but these programs are diverse and no systemic trends were identified.

Practices of Note

In addition to summarizing general patterns of research and education within the sustainable engineering community, specific programs and activities with features that are unusual were identified. The goal of identifying these programs and practices of note was to help identify potential pathways that the sustainable engineering education community may follow as it establishes common practices. The practices of note are organized into sections on undergraduate education, graduate education, research and institutional commitment. Within each of these major areas, programs or practices that are particularly comprehensive in breadth or depth, or that have unique features have been noted. The analysis does not identify all programs and practices that have these features, but rather provides exemplars of programs and practices.

Conclusions:

The engineering education community is now at a critical juncture. To date, there has been a significant level of “grass-roots” activities but little structure or organization. The next step will be for engineering accreditation bodies to think critically about what should or should not be included in a curriculum into which sustainable engineering has been incorporated. The path forward will require the evolution of a set of community standards. This document provides an inventory of what is currently available and can serve as a resource as professional organizations develop these standards.

Publications/Presentations:

Journal Publications

Allen, D.T., C.F. Murphy, B. Allenby, and C. Davidson, "Sustainable Engineering: A model for engineering education in the 21st century?" Clean Technologies and Environmental Policy, Vol. 8, pages 70-71, 2006.

Allen, D.T., C.F. Murphy, B. Allenby and C. Davidson, “Sustainability in Chemical Engineering Education, Chemical Engineering Progress, 2009 (in press)

Allenby, B.R., D.T. Allen, and C.I. Davidson, "Teaching Sustainable Engineering," Journal of Industrial Ecology, Vol. 11, pages 8-10, 2006.

Allenby, B.R., C.F. Murphy, D.T. Allen, and C.I. Davidson, “Sustainable Engineering Education in the United States,” Sustainability Science, Vol.4, No.1, 2009 (in press).

Davidson, C.I., H.S. Matthews, C.T. Hendrickson, M.W. Bridges, B.R. Allenby, J.C. Crittenden, Y. Chen, E. Williams, D.T. Allen, C.F. Murphy, and S. Austin, “Adding Sustainability to the Engineer's Toolbox: A Challenge for Engineering Educators, Environmental Science and Technology,” Vol. 41, pages 4847-4850, 2007.

Davidson, C.I., H.S. Matthews, and C.T. Hendrickson, Sustainability in Engineering: A New Sequence of Graduate Courses at Carnegie Mellon, International Journal of Engineering Education, Vol. 23, pages 287-293, 2007.

Allenby, B., D. Allen, and C. Davidson, Sustainable Engineering: From Myth to Mechanism, Environmental Quality Management, Vol. 17, pages 17-26, 2007.

<u>Book Chapters</u>

Allen, D.T., B.R. Allenby, and C.I. Davidson, Engineering Sustainable Technologies, in Designing in Engineering and Architecture: Towards an Integrated Philosophical Understanding, P. Kroes, A. Light, S.A. Moore, and P.E. Vermaas, editors, Kluwer Academic Publishers, Dordrecht, 2008 (in press).

<u>Published Conference Abstracts, Published Conference Proceedings, and Poster Presentations</u>

Davidson, C.I., C.T. Hendrickson, H.S. Matthews, D. Allen, C.F. Murphy, B. Allenby, and J. Crittenden, "Center for Sustainable Engineering: A National Dissemination Center supported by NSF and EPA," Poster presentation, National Conference, Engineers for a Sustainable World, Iowa City, IA, September 27-30, 2006. (Abstract only)

Davidson, C.I., C.T. Hendrickson, and H.S. Matthews, "A Graduate Course Sequence in Sustainable Engineering: The Carnegie Mellon Experience," Platform Presentation, Talking and Walking Sustainability: Second International Conference on Sustainability Engineering and Science, Auckland, New Zealand, February 20-23, 2007. (Paper written for Proceedings)

<u>Oral Presentations without Proceedings or Abstracts</u>

Allenby, B.R., “Teaching Sustainable Engineering,” IEEE International Symposium on Electronics and the Environment, San Francisco, CA, May 8-11, 2006.

Davidson, C.I., D. Allen, and B. Allenby, "The Center for Sustainable Engineering: Changing the Way Engineers are Taught," Platform Presentation, National Conference, American Association for the Advancement of Science, National Meeting, San Francisco, CA, February 15-19, 2007

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Center for Sustainable Engineering, US Business Council for Sustainable Development, July 10, 2005.

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Benchmarking Sustainable Engineering Education (BSEE) and Center for Sustainable Engineering (CSE), American Institute of Chemical Engineers (AIChE), Sustainable Engineering Forum, webinar, September 20, 2005.

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Benchmarking Sustainable Engineering Education (BSEE) and Center for Sustainable Engineering (CSE), Engineers for a Sustainable World Annual Meeting, Austin, Texas, October 8, 2005

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, "Sustainable Engineering: A Model for Engineering Education in the 21st Century," National Science Foundation, Environmentally Benign Design and Manufacturing, Sustainable Manufacturing V, Rochester Institute of Technology, Rochester, NY, September 18-22, 2007

Supplemental Keywords: green engineering, sustainability engineering, design for environment (DfE) , environmentally benign, environmentally conscious, life cycle assessment (LCA), curriculum development

Relevant Web Sites: Center for Sustainable Engineering (CSE) http://www.csengin.org/

This page intentionally left blank

Benchmarking Sustainable Engineering Education: Final Report

1.0 Introduction

Sustainability is a powerful, yet abstract concept. The most commonly employed definition of sustainability is that of the Brundtland Commission report: meeting the needs of the present generation without compromising the ability of future generations to meet their needs [World Commission on Environment and Development, 1987]; but if one does an internet search on the definition of sustainability, millions of variations on this basic concept will emerge.

The notion of sustainability is one of great breadth; it attempts to capture significant temporal and spatial scales and combines information and insights across multiple disciplines. While a specific and widely accepted definition of sustainability is still elusive, there is strong consensus that the goal of sustainability is to achieve a balance among economic, environmental, and societal objectives. In particular, there is growing recognition that natural and social science disciplines must be integrated into the design of engineered systems in order to adequately provide for stable and supportive natural and human systems. A conceptual model of the information flows that occur when sustainability is integrated into engineering design is shown in Figure 1.1 (adapted from [Mihelcic, J.R., et al, 2003]).

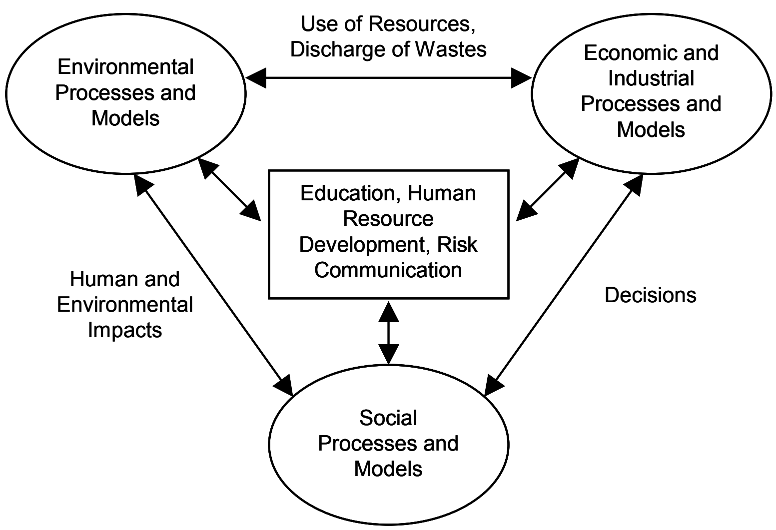


Figure 1.1. A conceptual model of information flows that occur when sustainability is integrated into engineering design is shown above (adapted from [Mihelcic, J.R., et al, 2003]).

Education across and within the disciplines represented in Figure 1.1 is needed to make informed decisions on current lifestyles that will not impair future generations, i.e., lifestyles that are sustainable. Engineers will need considerably more awareness of the nature of politics, social processes, and the influence of institutions on sustainability choices; the much larger community of non-engineers needs a stronger understanding of the impact of engineering decisions on societal structures. Sustainable engineering offers an intellectual “commons” where new knowledge can be shared, developed, and adjusted.

The broad range of concepts important to sustainability is just beginning to be incorporated into engineering education. Issues as basic as the definition of sustainability and the key educational elements are still in flux. As a consequence, there is great variety in how engineering educators are incorporating these issues into their teaching. While there is great variety in approaches to sustainability in engineering education, there are three broad categories of sustainability metrics applied to engineered systems that are generally agreed upon: economic, environmental, and societal. The analysis tools needed to evaluate economic metrics are generally covered in current engineering education programs. The tools needed to assess environmental metrics are covered in some engineering education programs, while the tools needed to evaluate social metrics are largely absent from engineering curricula. Some engineering education programs balance the absence of environmental and social metrics by offering joint degree programs with programs in public policy or environmental sciences. Other institutions fully integrate the concepts into undergraduate and graduate engineering education (e.g., the Department of Engineering and Public Policy at Carnegie Mellon University), and some universities simply do not cover these issues in their engineering curricula. The primary purpose of this project was to benchmark to what extent, and in what manner, engineering students are being trained to gather data and information necessary to evaluate the economic, environmental and social attributes of their designs.

Fully incorporating the economic, environmental and social concepts of sustainability into a curriculum requires a systems approach, with boundaries drawn at multiple levels within the design process. While many educational efforts (courses and programs) address sustainability, they often limit the analysis to a subset of these boundaries. Most commonly considered is design for environment (DFE), as one of the elements in a concurrent engineering “design for X” (DFX) approach. However, in order to capture the breadth of sustainability, the system boundaries need to extend far beyond what is perceived to be the traditional engineering sphere of influence.

It is useful to have a working organizational structure and a uniform set of terminology, a lexicon, to describe the elements of sustainability. This structure is presented in the context of design, using personal mobility as an example. In most of North America, personal mobility is achieved through the automobile. This choice necessitates other decisions involving land use, fuel infrastructures, industrial supply chains and societal investments in roadways. The levels of decision associated with providing mobility are shown conceptually in Figure 1.2.

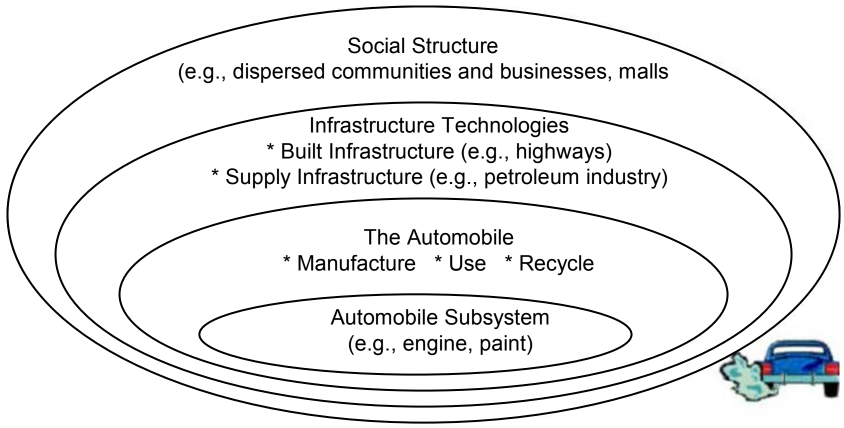


Figure 1.2. The technological-social system of the automobile exists in multiple layers; design decisions made in any of the layers shown influence decisions in all other layers (from [Graedel and Allenby, 1998]).

The engineering decisions that are made at each of these levels have the potential to affect economic and social as well as environmental sustainability, and the effects can be characterized via metrics based on information gathered using tools from the social and natural sciences. For the sake of simplicity, the following discussion will be limited to metrics based on information drawn from life sciences (human health), environmental science (ecosystem health), sociology and policy, economics, and the humanities (including aesthetics). Although it can be argued that one of the purposes of educating within the sustainability framework is to create awareness of the interdependencies between non-human and human health, a distinction will be made for the purposes of this study in order to recognize a division that commonly occurs in both education and in analytical tools. Table 1.1 presents a matrix that illustrates examples of the intersection between system boundaries (decision layers) and the disciplines (information) that inform these decisions. An example of one decision and a corresponding metric that might be considered in the design and provision of personal mobility at each layer is presented.

Table 1.1. Examples of the Intersection of Design Decision Layers and Tools.

		System Boundaries (Design Decision Layers)			
		Design for Environment (Gate to Gate)	Life Cycle Analysis (Cradle to Grave)	Industrial Ecology (Inter-Industry Interactions)	Cultural and Social (Extra-Industry Interactions)
		Example: Paint type	Example: Electric vs. gasoline	Example: Fuel or power infrastructures	Example: Highway system design
Tools from Various Disciplines	Life Sciences	Toxic releases from painting process	Exposure to toxic materials during automobile recycling	Land requirements for fuel types	Land-use patterns
	Environmental Sciences	Air pollutant dispersion	Ore and fuel extraction	Impacts of energy delivery systems	Impervious cover, water supply
	Sociology and Policy	Consumer preferences	Patterns of use by individual drivers	Energy independence	Access to services
	Economics	Manufacturing costs	Material and disposal costs	Capacities of energy delivery systems	Community business development
	Humanities and Aesthetics	Color and finish	Driving performance	Land use changes	Paved surface vs. green space

A first set of decisions, represented by the innermost layer of Figure 1.2, addresses the choices faced by a product or component design team. In selecting a paint type, for example, the engineer could select a water-based or solvent-based paint. The selection in turn may affect both human and ecosystem health around the factory through releases to air and water. The decision may have economic effects if the options affect affordability, and issues such as consumer response to the final product must be considered. Educational materials addressing these types of decisions will be referred to as Design for Environment (DFE) modules. The types of tools that can be used to address these issues and which could be included in a sustainable engineering program may be quite simple, such as lists of materials of concern, or more complex, such as full cost accounting. Specific examples of tools include the Restrictions on Hazardous Substances, or RoHS [European Union, 2003], full cost accounting [U.S. EPA, 1995; AIChE, 2000] and CARRI [Lashbrook, et al., 1997].

The next level of decisions, represented by the second layer from the center in Figure 1.2, considers supply chain impacts and the environmental impact of a product over its lifetime. An electrically powered automobile will produce different emissions during its use phase than a traditional gasoline powered car. The amount and type of materials extracted for fuel and batteries will also vary. Each has the potential to affect environmental metrics. The patterns of use by the individual are likely to vary (social metrics) and differing recycling options will affect the economics of vehicle end-of-life. Educational materials addressing these types of decisions will be referred to as Life Cycle Assessment (LCA) modules. A sustainable engineering approach might include LCA tools such as SimaPro, GaBi, or others (see links at the U.S. EPA LCAccess site, http://www.epa.gov/ORD/NRMRL/lcaccess/).

A third level of decisions and educational tools, represented by the third layer from the center in Figure 1.2, examines industrial and societal infrastructure issues. For mobility, as shown in Table 1.2, the materials invested in infrastructure are enormous, with 50,000-60,000 kg of materials per person just in roads [Graedel and Allenby, 1998]. These material flows, together with the fuel infrastructure, dwarf the materials used in the vehicle, highlighting the importance of infrastructures and systems. Educational materials addressing these types of systems analyses and decisions will be referred to as Industrial Ecology (IE) modules. Input/output analysis, such as EIO-LCA is an example of one of the better developed tools used at this decision level (http://www.eiolca.net/).

Table 1.2. Materials Invested in the World's Roadway Systems

Resource	Amount Embedded (Tg)	Embedded Amount per Capita (kg)
Asphalt Roadways		
Aggregate	280	50,000
Bitumen	4.5	810
Concrete Roadways		
Aggregate	19	3400
Sand	2.2	390
Cement	0.88	160
Reinforcing steel	0.0003	0.005

Finally, there are clearly societal and cultural implications of mobility. For example, an interesting feature of mobility is that throughout the world, the fraction of time spent and the fraction of income spent on mobility are relatively invariant [World Business Council on Sustainable Development, 2001]. This is shown in Figure 1.3. Note that the fraction of time dedicated to mobility is not only spatially invariant, it has remained relatively constant for centuries. In contrast, the distance traveled and the mode of travel varies significantly among the world's countries and has varied dramatically over time.

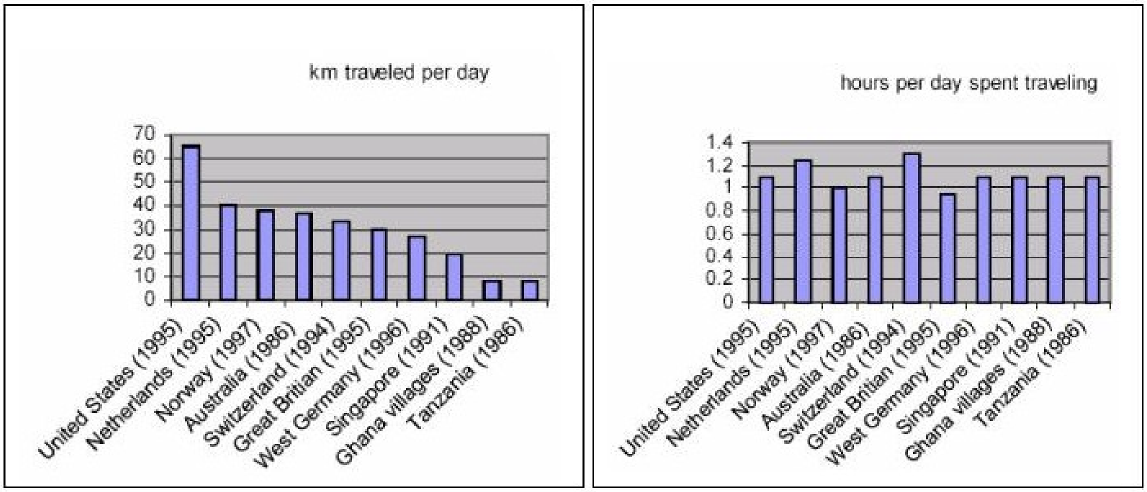


Figure 1.3. The faction of time spent on mobility is relatively invariant throughout the world. In contrast, the distance traveled, and the mode of travel varies significantly among the world's countries [World Business Council on Sustainable Development, 2001].

Searching for cultural and social invariants (such as fraction of time and income spent in travel) and contrasting these with uses of technology that vary (such as fraction of income spent on food or health care) require educational materials that transcend disciplines [Allenby, 1999]. Education materials that address these topics will be referred to as the Cultural and Social Dimensions (CSD) of Engineering Design. There are several tools available in this arena, such as agent-based modeling, a disaggregate approach which has the capability to capture values, knowledge, and incentives in individual object interactions [Axtell, et al. 2001].

Thus, our operating definition of sustainable engineering consists of the following design decision levels (or generalized system boundaries):

- Design for Environment
- Life Cycle Assessment
- Industrial Ecology
- Cultural and Social Dimensions

These systems are informed by data and information from the natural and social sciences. Through the use of appropriate design tools, analyses and results can be used to inform engineering, business, and policy decisions.

In engineering, incorporating sustainability into products, processes, technology systems, and services generally means including environmental and social performance in the evaluation of designs. While this may seem simple in the abstract, reducing this concept to the types of quantitative design tools and performance metrics that can be applied in engineering design is a challenge. Yet, it is a challenge that many engineering educators are embracing. This report presents the results of a benchmarking of educational practices employed in incorporating sustainability concepts into engineering education in the United States. The benchmarking was performed by a team from by the University of Texas at Austin, Arizona State University, and Carnegie Mellon University.

The primary focus of the benchmarking effort was the distribution and analysis of two questionnaires regarding sustainable engineering education. The first questionnaire focused on development of sustainable engineering at the program level. It was sent to the heads of all academic units within the US that included at least one ABET accredited engineering program. More than 1300 letters were sent out to department and program heads, and nearly 300 responses were received (a 21% response rate). Based on recommendations from department and program heads, as well as publication records and attendance at related workshops, a more detailed questionnaire was sent to 327 additional individuals identified as sustainable engineering champions. A total of 137 valid responses were received, for a response rate of 43%. These results provide representation by at least one individual from 97 (27%) of all 365 US institutions with engineering programs.

In interpreting the information below, the reader should bear in mind two caveats. First, while the questionnaire and process were designed to be inclusive, there is inevitably an element of self-selection involved in the responses, so the numbers provided below should be considered directional rather than definitive. Second, the questionnaire did not provide a comprehensive definition of either “sustainability” or “sustainable engineering,” which reflects the state of the art, but necessarily increases the subjectivity inherent in these results. In particular, the process of conducting the questionnaire highlighted the fact that several different approaches to sustainable engineering currently coexist, sometimes in the same institution: some courses and professors integrate sustainability into traditional course material, usually by selecting relevant case studies or exercises; others establish stand-alone “sustainable engineering” courses; still others use sustainable engineering modules within the framework of existing courses. Neither the data nor the analyses suggest that one approach is preferable to any other; they each have strengths and drawbacks. However, we believe a long-term goal of 21st century engineering education is to enable practicing engineers to incorporate tenets of sustainability into all phases of their practice, so that “sustainable engineering” eventually equates with “good engineering”.

2.0 Methodology

The key activities of this project were to generate, distribute, and analyze two questionnaires. The first questionnaire was directed at the heads of academic units and its purpose was to obtain a broad picture of the degree to which sustainable engineering is being integrated at the program level (or higher) in terms of curriculum development, program structure, and research. It was also used to help identify potential participants for the second questionnaire. The second questionnaire was directed at individuals who had been identified as leaders in the area of sustainable engineering. It was designed to be a much more in depth investigation of research activities and specific courses being taught. It also served as a vehicle for obtaining materials and resource information that could be used by others who wish to integrate concepts of sustainable engineering into their own programs.

Preliminary Analyses, Web Searches and Interviews

Three approaches were used to develop the content and form of the questionnaires. The following activities were completed roughly in parallel, with the results of each informing the others.

The first approach was to gather information and opinions directly from individuals and organizations known to be engaged in sustainable engineering research or activities; this involved representatives from both academia and industry. Presentations were made to the US Business Council for Sustainable Development, to the Sustainable Engineering Forum of the American Institute of Chemical Engineers (AIChE), at the IEEE International Symposium and the Environment (ISEE), at the annual conference of Engineers for a Sustainable World (ESW), and to participants in the NSF Center for Sustainable Engineering workshops. In each case feedback on potential scope of the questionnaires was solicited and recorded. In the case of the ISEE, ESW, and the NSF workshops, preliminary versions of the questionnaires were distributed in order to determine the effectiveness of the content and form.

The second activity was to review materials from academic colleagues known to be working in the area of sustainable engineering. This included publications, course syllabi, and professional activities. Web searches were conducted and provided limited additional information about general approaches but did provide specific information about individuals or programs.

Finally, several draft versions of the questionnaires were distributed to approximately 15 individuals well known to the investigative team. These individuals were subsequently interviewed by phone or email in order to determine what they felt was effective and on-target and what was not.

Administrative Head Questionnaire

Questionnaire Design

The purpose of the Administrative Head Questionnaire was to determine the extent to which sustainable engineering is being integrated into all engineering programs in the form of courses, degree programs, and research activities. In parallel, the level of coordination with non-engineering disciplines was also investigated, as this was thought to be a potential indicator of the tendency to introduce sustainable engineering content. No definition of sustainable engineering was provided to the participants, although prompts were provided in the form of a list of examples of sustainable engineering tools, concepts, and topics. These were:

Life Cycle Analysis (LCA)

Natural Resource Management

Climate Change

Design for Environment (DFE)

Policy and Regulations

Renewable Energy

Industrial Ecology

Economics (excluding short-term cost analysis)

Green Design

Material Flow Analysis (MFA)

Pollution Prevention

Reuse and/or Recovery of Products and Materials

The questionnaire first asked for the participant's contact information; this allowed the team to validate, correct, and update the contact database as appropriate. It also facilitated the elimination of duplicate entries and made it possible to send out a follow up reminder letter only to those who had not already responded.

The body of the questionnaire consisted of a total of 7 overarching questions that were intended to be quickly and easily answered. Five of the questions had either 5 or 6 sub-parts, for a total of 29 questions; the sub-parts were uniformly structured, thus simplifying the reading and answering of these questions. The primary objective was to determine the number of courses (past and present), degrees, research projects, and centers/institutes within the department that are sustainable engineering or interdisciplinary (with a non-engineering discipline) in nature. The answers were limited to "zero" (the default), "one", "two", and "three or more." This relatively simple set of answers was designed to capture general, rather than highly quantifiable data. Such an approach was taken because it was thought that any attempt to obtain exact values was likely to result in unreliable (or no) responses.

There was one question that asked for the number of students graduating per year, as a means of gauging department size. A final question asked for a description of any other sustainable engineering initiatives within the department. Except for this last question (which was a "fill-in-the-blank"), all of the answers were entered by clicking on radio buttons. After completion of the questionnaire, the respondents were asked to provide names of individuals who might be contacted for the follow-up sustainable engineering champion questionnaire.

Distribution of the Questionnaire

The scope of this effort is to evaluate engineering programs within US institutions of higher learning. In order to define the members of this population and limit the census composition in a formal manner, a list of the 1777 engineering programs that were accredited by ABET as of October 1, 2006 was downloaded from http://www.abet.org/schoolalleac.asp. This list was then used to identify academic units to be included in the census. Based on web searches on institution websites, the academic units within which these programs reside were identified along with the names and email addresses of the heads of these units. The academic units are primarily departments, but a small number of programs are administered through engineering schools. It is important to note that the intent was not to focus on ABET activities or to query only ABET programs, but simply to identify appropriate academic units. The actual questions were directed at the department level (or equivalent).

A letter requesting participation in the questionnaire was emailed to the 1368 identified administrative heads (typically department chairs). The letter contained a hyperlink to the on-line questionnaire and responses were input directly into an interactive Microsoft Access® database. In a few instances, participants requested paper copies; the responses for these were entered manually into the database by University of Texas personnel. Administrative heads were asked to complete the questionnaire themselves or to designate another individual who they deemed knowledgeable about these issues. The questionnaire was kept simple and short in order to ensure that difficulty and/or time demands were not a barrier to participation. A copy of the letter, along with the questionnaire, is presented in Appendix B. The first group of letters was sent in the spring of 2007. A follow-up letter was sent to those that had not yet participated the following fall.

Data Analysis

The tables within the Access® database that contained the responses were linked to form a flat file that could be exported to an Excel® spreadsheet. A small number of duplicates were identified and either eliminated or merged at the department level as appropriate. Although the questionnaire allowed the participant to answer at the department level and to indicate all the programs to which the answers applied, a few participants responded to the questionnaire multiple times and answered for each program individually. In all but two instances, the answers were identical and only a single set for the department was retained. In cases where the answers were different for different programs, the maximum values were retained.

In order to get the data density needed to perform any type of meaningful data analysis, departments were grouped into the following categories: Chemical, Bio-, and/or Materials Engineering; Civil, Architectural, and/or Environmental Engineering; Electrical and/or Computer Science and Engineering; Mechanical, Aero-, and/or Manufacturing Engineering; Industrial, Systems, and/or Sustainable Engineering; General Engineering; and "Other" Engineering (including Petroleum, Mining, and Nuclear Engineering). In the few instances where the department name did not fit neatly into one of these categories, the primary program name (e.g., Chemical, Civil, Mechanical, etc.) was used. For example, a Chemical and Environmental Engineering department would be grouped with Chemical, Bio-, and/or Materials.

Data from US News and World Report [USN&WR, 2008] was used to provide information about engineering school ranking, whether or not a PhD was offered, and institutional enrollment. In cases where this information was not provided (schools with ranks of 101 or more), searches on the institutions' websites were used to obtain these data.

Sustainable Engineering Champion Questionnaire

Questionnaire Design

The purpose of this questionnaire was to obtain detailed information about the activities of sustainable engineering champions within engineering programs at US colleges and universities with two main categories being of particular interest: courses and research. After completing a page of contact information, the respondents were given the opportunity to complete a course section and/or a research section. The participants were asked to use a separate questionnaire for each course described.

The research portion of the questionnaire contained 12 questions, most of which were fill-in the blank. Three main areas were addressed: sponsored research, dissemination and publication, and centers and institutes. No specific definition of sustainable engineering was given, but the respondents were prompted to consider research areas that involved topics such as life cycle assessment (LCA), design for environment (DFE) or green design, industrial ecology, policy and regulations, economics, material flow analysis (MFA), natural resource management, climate change, pollution prevention, and reuse and/or recovery of products and materials. The sponsored research sub-section was designed to gather information about sponsors, the length of the projects, and the level of funding provided. There was space to provide information for a maximum of three projects and there were no restrictions regarding the timeframe of the projects. In addition, the participants were asked to estimate the typical number of students (at any given time) involved in sustainable engineering research and working under the direction of the respondent. The questionnaire asked whether these were undergraduate or graduate students and whether they were fully-, partially-, or unsupported. Under the dissemination and publication section, participants were asked about the conferences they attend and journals they read in order to stay abreast of activities in sustainable engineering. They were also asked about the journals in which they personally had published or intended to publish sustainable engineering work. Finally, the respondents were asked to name and describe the focus of any center or institutes in which they are involved along with the number of full-time equivalent personnel, the approximate year in which the center was founded, and the respondent's role in the center or institute

The course portion of the questionnaire consisted of 20 overarching questions contained within 4 subsections. The purpose of the first subsection was to characterize the course with regard to the course type, the class size and make-up, the maturity of the course, and its structure. Participants were asked in the next subsection to name up to three textbooks, readings, websites, and software used within the course. This would not only permit commonly used resources to be identified, but also serve to populate a resource database that could be used by others. The third subsection addressed the degree to which and the manner in which sustainable engineering concepts were being incorporated into the course. The participants were asked to estimate the percentage of sustainable engineering material contained within the course. This was followed by a series of similarly structured questions that asked first for the percentage of course material that addressed four different system sizes and five non-engineering disciplines. One of the objectives in asking this set of questions was to map tendencies against the matrix presented in Table 1.1. For each of the system sizes (the columns of Table 1.1) and categories of non-engineering disciplines (the rows of Table 1.1) the respondents were asked to estimate the percentage of course material that addressed these different levels or incorporated tools of the various disciplines. These were "fill-in-the blank" questions, so participants could enter whatever amount (percent) they deemed appropriate to reflect the material. They were subsequently asked to check off topics that typically fall within these systems or disciplines if they were covered to any extent at all by the course. The final sub-section asked the respondent to rate his or her satisfaction with class size, attendance, the student's grasp of the material, and available teaching materials.

<u>Distribution of the Questionnaire</u>

Individuals identified as sustainable engineering champions were targeted for this questionnaire. Participants in the Administrative Head Questionnaire were asked to provide the names of appropriate individuals within their department. To this list were added individuals identified based on 1) their participation in one of five workshops held by Center for Sustainable Engineering, 2) their participation in one of the National Science Foundation (NSF) sponsored workshops on Environmentally Benign Design and Manufacturing, or 3) at least one publication in select journals including the Journal of Industrial Ecology, the Journal of Cleaner Production, Clean Technologies and Environmental Policy, and Proceedings of the IEEE International Symposium on Electronics and the Environment. (Note that the latter is not specifically limited to the electronics industry). Selection criteria also required that they be a faculty member in one of the academic units that received the initial census questionnaire. On-line searches of institutional websites were used to verify that the individuals were faculty with appointments in the school of engineering.

A total of 327 letters were sent by email to individuals who were thus identified as champions of sustainable engineering. In the letter, these individuals were asked to respond to a questionnaire aimed at capturing detailed information about research and curriculum development activities in the area of sustainable engineering. The questionnaire was accessed through a link to a website and responses were input directly into an interactive Microsoft Access® database.

Data Analysis

Seven of the individuals were eliminated from the initial pool of potential respondents for several reasons including: they had left academia; they could not be reached by email; or, they de-selected themselves (i.e., they did not consider themselves to be active in sustainable engineering). Out of the 320 remaining potential respondents, 167 filled out the contact information (the first page of the questionnaire), but 30 did not answer any questions, leaving a total of 137 actual respondents (an overall response rate of 43%). These results provide representation by at least one individual from 97 (27%) of the 365 US institutions with engineering programs.

Departments were grouped together, as with the Administrative Head Questionnaire, into the following categories: Chemical, Bio-, and/or Materials Engineering; Civil, Architectural, and/or Environmental Engineering; Mechanical, Aero-, and/or Manufacturing Engineering; Industrial, Systems, and/or Sustainable Engineering; and "General and Other" Engineering. These are the same as for the first questionnaire except that, because of the low number of responses, Electrical and/or Computer Science and Engineering, General Engineering, and "Other" were grouped together into a single category. Data from US News and World Report [USN&WR, 2008] was used to provide information about engineering school ranking and institutional enrollment.

Synergistic Activities: Center for Sustainable Engineering Modules

The Center for Sustainable Engineering (CSE), funded by the National Science Foundation, was established in 2005 as a partnership among Carnegie Mellon University, The University of Texas at Austin, and Arizona State University to enhance education in sustainable engineering in both undergraduate and graduate programs around the country. To achieve this goal, the CSE has organized workshops to bring together faculty members from different schools who are developing courses or sections of courses on sustainable engineering. The workshops include sessions on concepts and tools of sustainable engineering, ways to incorporate sustainable engineering into courses, comparisons of programs at different schools, and methods of building a community of educators in sustainable engineering. Participants at the workshop also develop learning objectives for a new or revised course they will teach at their home institution, and are able to benefit from critical comments of other participants. This group provided valuable inputs and feedback in designing the questionnaires, particularly the one distributed to the sustainable engineering champions.

The CSE website (http://www.csengin.org/) will be used to host a number of materials related to sustainable engineering education including an electronic library of education modules. The modules consist of lecture notes, class handouts, homework problems, group projects, and other materials. The idea behind the modular approach is that there are a number of ways that sustainable engineering can be taught: as a stand-alone topic, as an augmentation of traditional (including environmental) engineering, as specific enabling technologies, or as an interdisciplinary course. In the case where sustainable engineering is presented as a stand-alone topic or as one or more enabling technology, comprehensive textbooks can and are being written. However, given the nascent nature of this field, the modular approach allows for information to be quickly introduced and modified as required. In the case where sustainable engineering concepts are being integrated into traditional materials, modules can be developed such that they complement standard textbooks and problem sets, in that they can be inserted as drop-in substitutes for or augment existing assignments and examples. Because of the variability inherent in any interdisciplinary approach a customized set of materials will almost certainly be required; this is also facilitated through use of a modular approach.

Participants who attend one of the CSE workshops are required to submit a module to the electronic library. All submissions are peer-reviewed, and hence the workshop attendees are also required to participate in the peer review process. The electronic library is still in its early stages of development, with a dozen modules received to date. Roughly 50-60 have been promised from past workshop participants and are arriving slowly. The current modules address the following topics:

- Sustainable Engineering Methods
  - Life Cycle Assessment
  - Ecological footprints
  - Introductory sustainable engineering
- Augmentation of Traditional Engineering
  - Green construction
  - Water and air quality (several modules)
- Enabling Technologies
  - Renewable energy
  - Metalworking fluids
- Interdisciplinary
  - Climate change
  - Public understanding of sustainable engineering

Modules expected to be completed in the near future cover a wide-range of topics, including nanomanufacturing, infrastructure development, waste minimization, green materials, and sustainable design. Two example modules are presented in Appendix F of this report. The first is entitled “Wind and Photovoltaic Solar Electricity Generation” by Daniel Giammar of Washington University. In addition to discussions of wind and solar power, the module includes information on conventional coal-fired power plants for comparison and presents a number of quantitative problems. The second module is "Terephthalic Acid Synthesis in High-Temperature Liquid Water" by Phillip Savage at the University of Michigan. Terephthalic acid (TPA) is used in making polyethylene terephthalate (PET) which is widely used in making water bottles and other beverage containers. The module discusses replacing acetic acid with high temperature water in TPA synthesis to reduce environmental hazards as well as other benefits. These modules provide complementary, and in some cases, more detailed information about content of courses than could be represented in benchmarking questionnaires.

3.0 Sustainable Engineering Courses: Findings

The sustainable engineering champions were asked to provide information about courses being taught at their institutions. The only limitations were that the course should contain four or more hours of lecture material (or the equivalent) focused on sustainable engineering and that it be offered by (or in cooperation with) an engineering department. Participants were able to enter information about as many courses as they liked, with a separate page used for each one. The respondents were also offered the opportunity to upload a syllabus or other class materials as well as provide the URL for any publicly available class websites. A copy of the questionnaire is provided in Appendix C.

The "Courses" section of the questionnaire was designed to determine a variety of characteristics about the nature of sustainable engineering coursework being offered. This includes the course type, the class size and make-up, the maturity of the course, and the amount of sustainable engineering material included. The participants were also asked to provide information about resources used to teach the course including textbooks, readings, websites, and software.

A total of 155 course names were described by the respondents. Detailed information was provided for about 80% of these. The courses come from a variety of disciplines as follows:

- Civil, Architectural, and/or Environmental Engineering, 64 courses
- Mechanical, Aero-, and/or Manufacturing, 32 courses
- General Engineering and Other (including Electrical and Nuclear), 28 courses
- Chemical, Bio-, and/or Materials Engineering, 18 courses
- Industrial, Systems, and/or Sustainable Engineering, 13 courses

The participants in the questionnaire come from a wide range of institutions, but smaller schools tend to be under-represented relative to larger schools. The middle range seems to be relatively evenly represented: one-third of the courses included in the responses are offered at institutions with a total enrollment of 10 to 20 thousand, which in turn constitute about one-fourth of colleges and universities with engineering programs. At either end of the spectrum, however, the proportions are more distorted. There are a total of 181 US institutions with engineering programs and student bodies of less than 10,000, and yet only 27 courses from those institutions are included here. On the other end, there are 13 engineering schools at universities with total enrollments in excess of 40,000, for which there are descriptions of 16 courses (Figure 3.1).

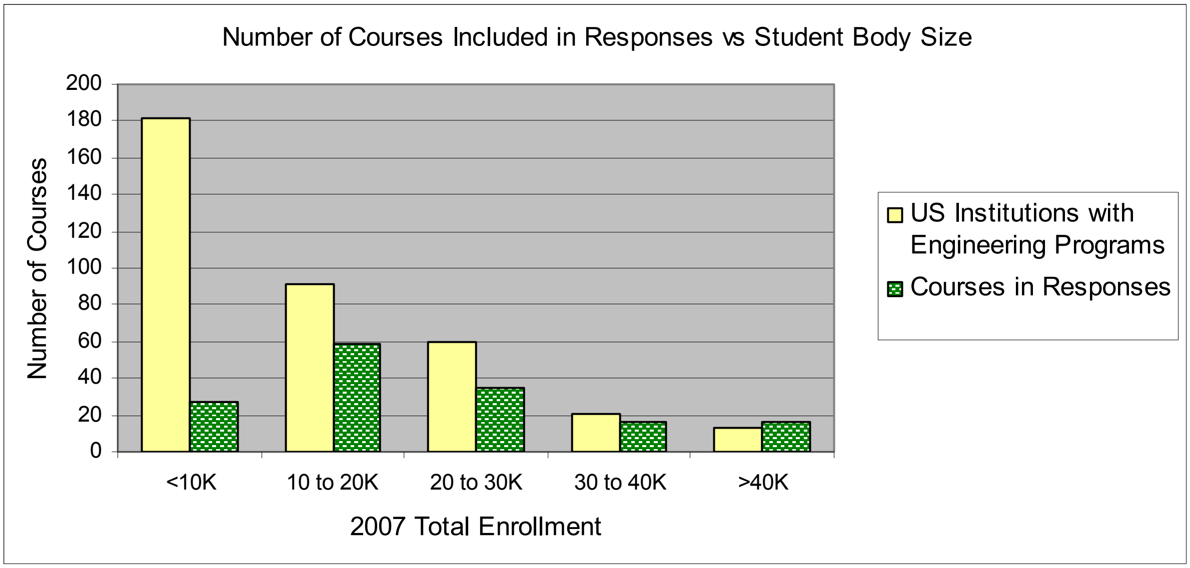


Figure 3.1. Courses taught at small institutions are under-represented relative to those taught at the largest universities. Within the middle range, however, the ratio of courses to school size appears to relatively uniform (enrollment data from [USN&WR, 2008]).

Based on data obtained from US News & World Report [USN&WR, 2008], 30 (24%) of the courses described by the questionnaire are offered at non PhD granting institutions and another fourth are taught at public PhD granting institutions that do not rank as a top 100 engineering school. As indicated by Figure 3.2, however, there is a tendency for the courses described in this report to reflect those taught at higher-ranking schools. For the courses described here, more than one-fifth (28 out of 125) of the courses are taught at PhD granting institutions and more than one-half of those taught at schools without a PhD program (18 out of 30) are offered at engineering schools that rank in the top 20 in that category of institution. It should be noted, however, that one fourth of the courses are taught at schools that are not in the top 100 (for those with PhD programs) and all of these are public institutions. In general, it would appear that the teaching of sustainable engineering concepts is not confined to upper echelon universities, but rather appears to be gaining broad acceptance.

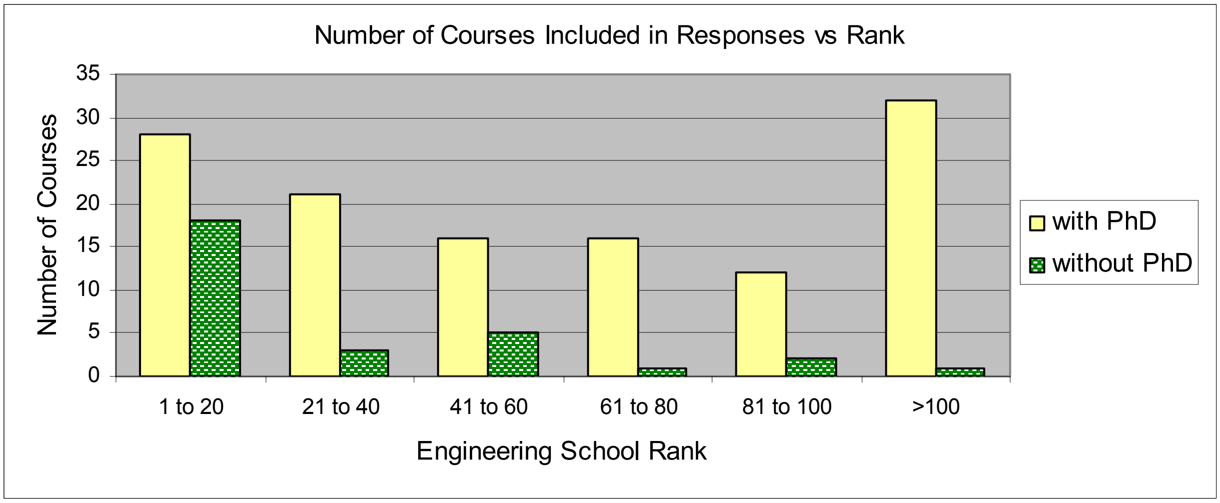


Figure 3.2. Of the courses included in the questionnaire responses, one fifth of those taught at institutions with a PhD program and roughly half of those taught at schools without a PhD program are ranked in the top 20; (ranking data from [USN&WR, 2008]).

Course Characteristics

Type (Category)

Based on the results of the questionnaires, and interviews with colleagues and workshops held in conjunction with the NSF Center for Sustainable Engineering, it appears that there are four primary means of incorporating sustainable engineering content and concepts into the curriculum. The first is to develop dedicated sustainable engineering courses; these tend to focus on the use of tools designed to address complex systems at relatively large scales (such as Life Cycle Analysis). Nearly half (48%) of the courses reported are described as having sustainable engineering as the dominant theme. Another approach is to integrate sustainable engineering concepts into traditional engineering courses with the goal of broadening students' awareness and skill set; approximately one-fourth (23%) of the courses fall into this category. A third type of course is that which focuses on the technologies predicted to be important in developing sustainable engineering solutions (such as carbon capture or solar power). A total of 21 (14%) of the courses described in this report fit this description. Finally, because most engineering faculty do not have the background to adequately address many of the multi-disciplinary aspects of sustainable engineering (e.g., economics, policy development, social psychology), the fourth approach is to work in conjunction with a non-engineering department and create a cross-listed or interdisciplinary course offering. The questionnaire includes 23 courses (15%) thus categorized by the participants.

The standing of each course within the overall curriculum is also of interest, as this is an indication of whether the teaching of sustainable engineering is the domain of a few dedicated individuals or rather a purposeful goal of the administration. To this end, the questionnaire asks whether the course is a stand-alone elective, part of an informal sequence, or a minor or major degree requirement. Those courses where sustainable engineering is the dominant theme are most often (67%) stand-alone courses (i.e., electives) (Figure 3.3). However, nearly one quarter (23%) are either a formal major (11%) or a minor (12%) degree requirement and 10% are part of an informal, multi-course sequence. Traditional engineering courses where concepts of sustainability are incorporated into the course design are typically either part of a formal major degree program (44%) or stand-alone courses (41%). Slightly more than one-half (52%) of courses that present technical material in support of sustainable engineering are stand-alone, one third are a major or minor degree requirement, and 14% are part of an informal, multi-course sequence. None of the cross-listed or interdisciplinary courses fall into this latter category and more than two-thirds are stand-alone courses.

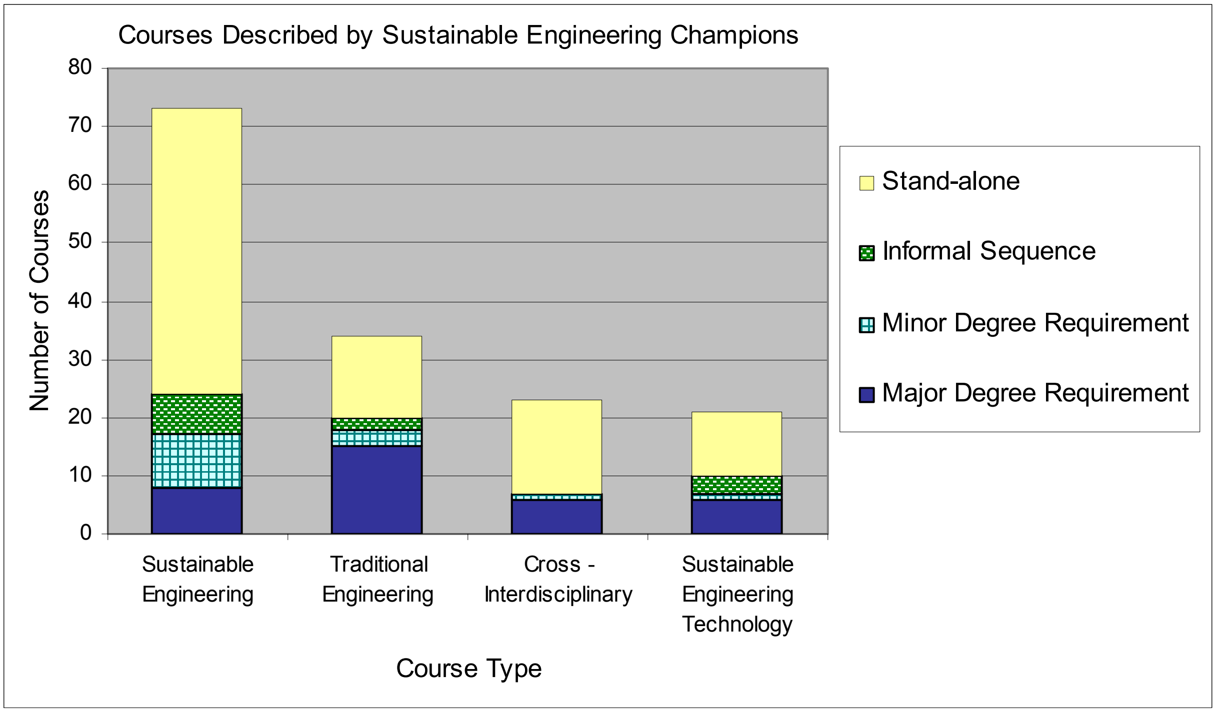


Figure 3.3. The majority of the courses described by the champion questionnaire respondents are stand-alone offerings. However, many are degree requirements, particularly those where sustainable engineering concepts are integrated into traditional engineering courses.

Class Size and Make-up

The participants were asked to estimate the percent of students enrolled in the class by level: lower division (freshman and/or sophomores), upper division (juniors and/or seniors), and graduate students. When these responses were compared to the course type, several patterns emerged. As can be seen in Figure 3.4, sustainable engineering courses are clearly targeted towards upper division and graduate students (91%), with nearly half a mix of the two. Traditional engineering courses with integrated sustainable engineering elements are dominated by undergraduates (65%), mostly upper division (44%). Sustainable engineering technology courses are offered primarily at the graduate level (38% graduate only, and 57% graduate and upper division). Cross- or interdisciplinary courses seem to lend themselves to all levels, but tend to be more restrictive in terms of mixing undergraduate and graduate students; 39% of these courses are undergraduate only and 30% are entirely graduate.

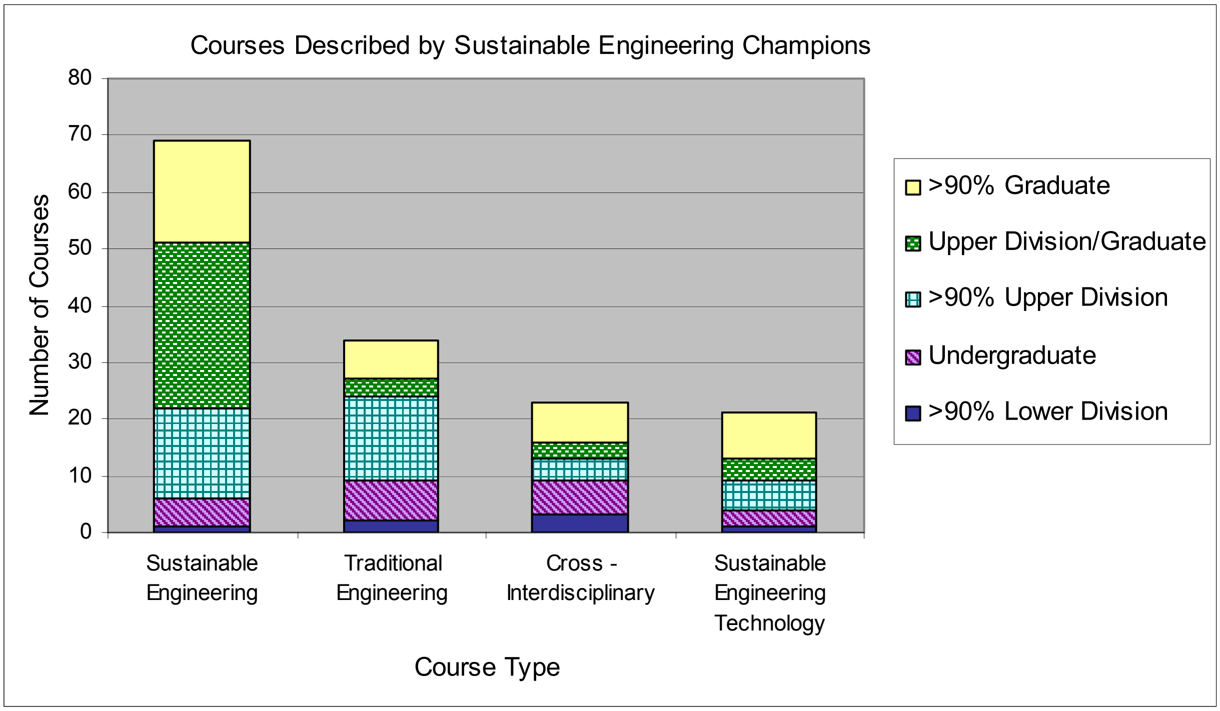


Figure 3.4. The majority of the students (91%) taking sustainable engineering courses are upper division and graduate students. Undergraduate students (65%) dominate the traditional engineering courses; most (44%) are upper division. Sustainable engineering technology courses are mostly aimed at the graduate and upper division levels (57%), but 38% of these courses have undergraduate students only.

One interesting aspect of these results is that cross- or interdisciplinary courses seem to be well suited for undergraduates, particularly lower division. This is more evident in Figure 3.5, where the percentage of course type is plotted as a function of the student level. Not surprisingly, graduate student-only classes lend themselves to presentation of sustainable engineering technology material. Only a small portion of classes geared to upper division undergraduates are cross- or interdisciplinary in nature.

In order to get a sense of how interdisciplinary the courses are in terms of students taking the class, the participants were asked to estimate the percentage of those enrolled by major, with the options being 1) the department through which the course is offered, 2) another engineering department, or 3) a non-engineering discipline. The results are presented in Figure 3.6. As might be expected, the courses with the largest percentage of non-engineering students are those that are cross-listed or interdisciplinary in nature, while those with the lowest percentage are technology-centric. The courses with the highest percentage of students from outside the home department are those designated as sustainable engineering focused.

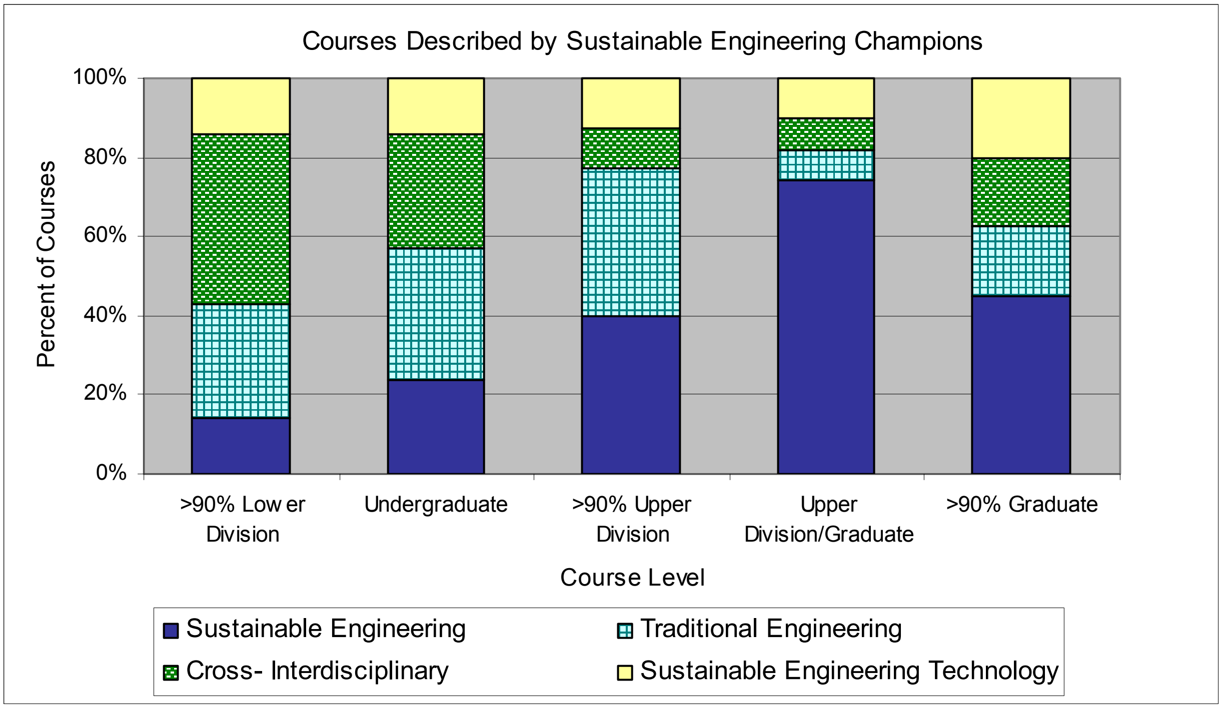


Figure 3.5. Lower division courses are most commonly cross-listed or interdisciplinary. Courses offered for both graduate and upper division undergraduate students are predominantly sustainable engineering focused.

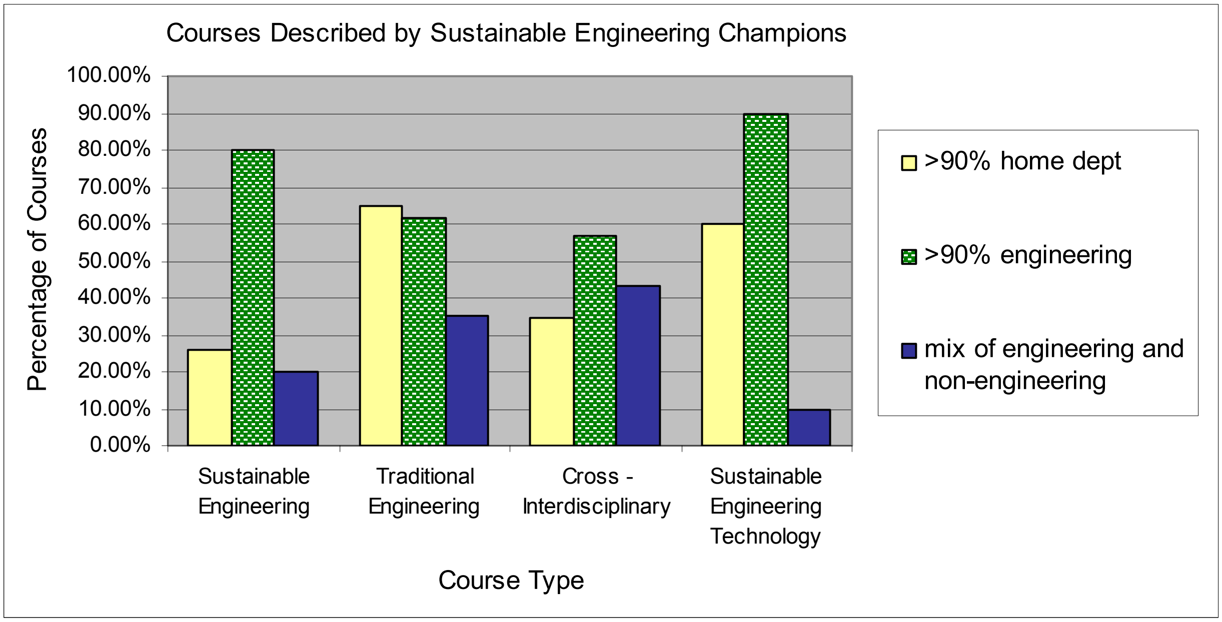


Figure 3.6. The courses with the largest percentage of non-engineering students are cross- or interdisciplinary in nature, while those with the lowest percentage are technology focused.

The distribution of class size is relatively insensitive to the type of course. The participants were asked to choose from one of the following selections: 1) less than 10, 2) 10 to 30, 3) 30 to 100, and 4) greater than 100. There were no classes with more than 100 students and fewer than 15% with less than 10; most are in the range of 10 to 30.

Course Maturity and Structure

Course maturity is estimated by three measures. The first is the age of the course (how many years ago was it first offered); the second is the number of times it has been taught; and the third is the number of student contact hours per offering. A total of 104 classes have been taught three or more times, 67 of them beginning in the 2002-2003 academic year or earlier. A total of 20 classes have been taught twice, 19 of them since 2005-2006. Only 22 classes have been taught just once. With the exception of 4, these 22 classes taught only one time were first taught during the 2007 – 2008 academic year. Only 5 classes appear not to be offered on at least an annual basis. The total number of weekly contact hours (lecture plus discussion plus lab/other) is very similar for all except the technology courses; the median number of hours for the latter is 4, compared to 3 for the other course types. For each of the four course types, there is only one course that is discussion only (i.e., no lectures). There are no lab-only courses. Discussion sessions are included for 35% of the cross- interdisciplinary courses, 20% of the sustainable engineering courses, 14% of the traditional engineering courses, and 5% of the technology courses.

Incorporation of Sustainable Engineering Concepts

Amount of Sustainable Engineering Material

One of the primary goals of the questionnaire was to determine the amount and nature of sustainable engineering content being introduced into the classroom, especially for those courses not self-described as being dominated by sustainable engineering material.

Participants were asked in question 17 of the questionnaire to estimate the portion of the course focused on sustainable engineering. The choices provided were 1) less than 10%, 2) 10 to 25%, 3) 25 to 50%, or 4) more than 50%. The intent of question 17 was to determine the amount of sustainable engineering material included in courses not categorized in question 1 as having sustainable engineering as the dominant theme; however a secondary benefit was that a comparison of the two questions served as a quality assurance check. It was expected that the fourth answer (i.e., more than 50% sustainable engineering content) would be selected for all of the courses categorized in question 1 as having sustainable engineering as the dominant theme. For 94%, this was in fact the case, indicating that the participants are relatively consistent in their assessments. There were 4 outlying courses where sustainable engineering was described as the dominant theme in question 1, but was said to contain less than 50% sustainable engineering material in question 17. Two of these are focused on alternative energy, and might have been better described as sustainable engineering technology courses in question 1. Based on the syllabus provided, the third of these 4 courses appears have almost exactly 50% sustainable engineering material and the answers to both questions 1 and 17 are likely accurate. The fourth course clearly contains more than 50% sustainable engineering material, which suggests that the respondent selected the wrong button when answering question 17.

In examining the three categories of courses that are not described as having sustainable engineering as the dominant theme, the responses suggest, not surprisingly, that the traditional engineering courses contain the least amount of sustainable engineering content (Figure 3.7). One third, however, contain more than 25%. Although the cross- or interdisciplinary courses contain slightly more than the technology courses; these two are relatively similar with at least 85% of the courses containing 10% or more sustainable engineering material and approximately half containing more than 25%.

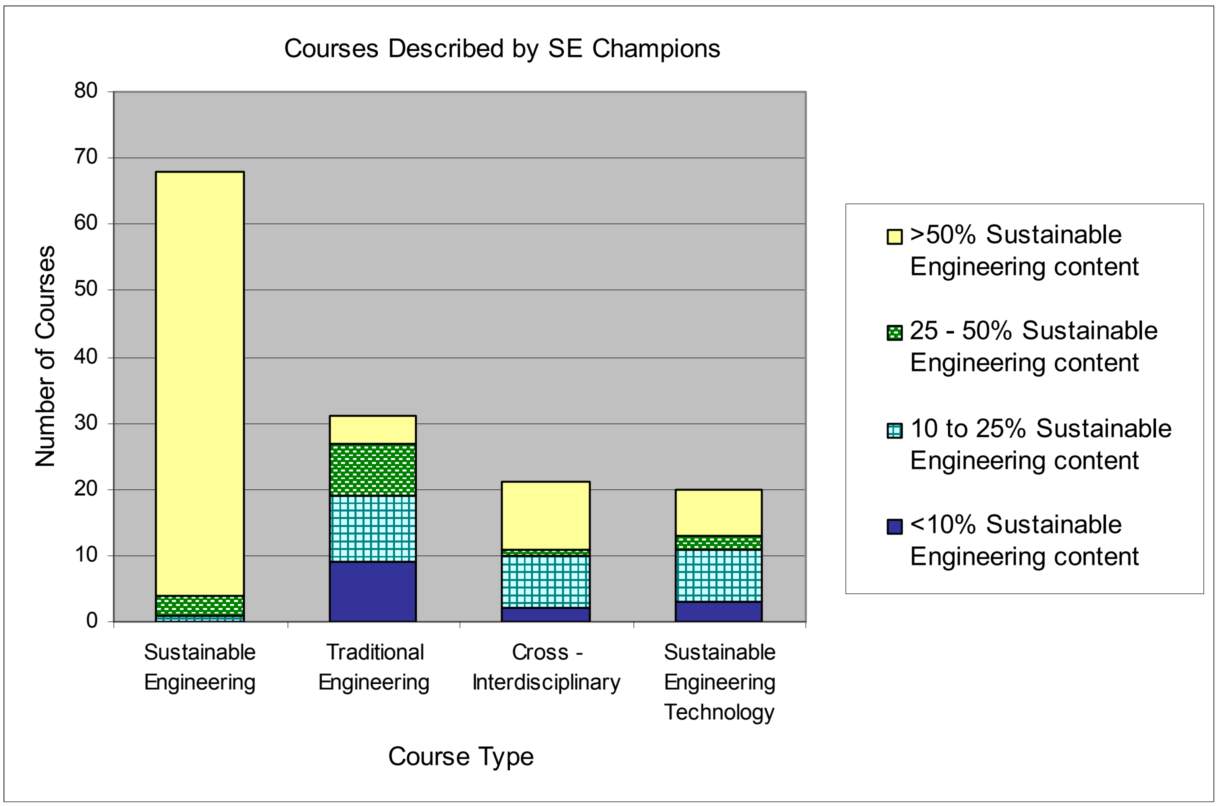


Figure 3.7. Nearly all (94%) of the courses categorized as dominated by sustainable engineering material were described as containing greater than 50% sustainable (SE) content; this indicates that the respondents are relatively consistent in their answers. More than two-thirds categorized as traditional engineering courses with sustainable engineering content are described as having a greater than 10% sustainable engineering focus; more than one-third have greater than 25%.

System Sizes and Non-engineering Disciplines Utilized

The working hypothesis in this investigation is that increased sustainable engineering content will be reflected in an increase in the system sizes considered, as well as an increased breadth of non-engineering disciplines employed in addressing problems. In order to capture this, participants were asked to consider four systems of increasing size and five different non-engineering discipline categories and to estimate the percentage of the course material that addressed these systems and disciplines (see Table 1.1). This was a fill-in-the-blank question, so participants could enter whatever amount (percent) they deemed appropriate to reflect the material. In analyzing the data, the entered percentages were binned into categories reflecting the relative amount of coverage given to these different system sizes in the teaching of the course. These bins were “none” (0%), “small” (1-10%), “moderate” (10-50%), or “significant” >50%.

Participants were also asked to indicate whether certain concepts and/or topics, typical of each system size were addressed. These were simple “yes/no” responses, indicated by checking a box, and the purpose was two-fold. One was simply to determine what topics are being taught. Secondly, however, it was also anticipated that these “laundry lists” might act as prompts that would assist the respondent in determining whether or not the particular system size or discipline under which they were listed was being addressed. The names of 155 unique courses were provided by those responding to the “champion” questionnaire; in the case of 30, no information regarding the system sizes addressed, the disciplines used, or topics covered was provided (i.e., questions 18 and 19 were left completely blank). Of the remaining 125, there were a number of courses for which topics were selected, but for which no estimation was made regarding the portion of the course considering that system size or utilizing specified non-engineering disciplines. In order to address this, a fifth bin termed “some” was created to reflect the fact that coverage within the given system size or discipline was clearly not zero.

System Size:

Table 3.1 lists the four system sizes and definitions for each that the participants were asked to assume; topics or concepts considered to fall within these system boundaries are also included. The results of the participants’ responses are presented in Table 3.2. Note that more than half of the courses (54%) have no course content (0%) that addresses systems larger than cradle-to-grave. Approximately two-thirds of the courses consider cradle-to-grave sized systems as a small or moderate portion of the total course material (10 to 50%).

Table 3.1. System Boundaries and Topics.

System Size	Description	Topics
Gate to Gate	Decisions made within a single facility or corporation by engineering and/or business units (i.e., site or industry sector specific activities).	Process design, including material and/or energy reduction
		Material or chemical selection
		Product design for a single phase of a product's life (e.g., design for recycling)
		Pollution prevention
		Media-based (i.e., air, water, solid waste) regulations
Cradle to Grave	Decisions made by different entities over the life of a product or sector activity. Activities are typically analyzed as sequential events (i.e., life cycle analysis).	Resource availability and economics
		Consumer behavior
		Product utility
		Reuse and recycling options
		Product based legislation (e.g., WEEE) and standards (e.g., ISO 14000)
		Life cycle inventory development
Inter-Industry (Industrial Symbiosis)	Decisions made by two or more entities (corporations or other stakeholders), often involving multiple sectors. The analysis typically captures spatial as well as temporal effects and scales, although temporal scales may be compressed such that activities are presumed to occur in parallel (i.e., industrial ecology)	Material flow analysis
		By-product synergy
		Eco-industrial development
		Multiple/nested LCA analysis
		Input-output analysis (either physical or economic)
Extra-Industry	Decisions made by multiple stakeholders, including industry, non-governmental organizations (NGOs), policy makers, consumers, etc.	Policy development (current and historical)
		Consumption patterns and preferences
		Eco-industrial development
		Multiple/nested LCA analysis
		Input-output analysis (either physical or economic)

Table 3.2. Extent to which Different Systems Sizes Are Addressed

Maximum values for each system size (within 2 percent points) are shaded to indicate tendencies.

System Size	Portion of Total Course Content				
	Some*	None	Small (1-10%)	Moderate (10-50%)	Significant >50%
Gate to Gate	27	19 (19%)	31 (32%)	38 (39%)	10 (10%)
Cradle to Grave	15	26 (24%)	35 (32%)	37 (34%)	12 (11%)
Inter-Industry Interactions (Industrial Symbiosis)	10	62 (54%)	25 (22%)	28 (24%)	0
Extra-Industry	11	62 (54%)	33 (29%)	19 (17%)	0

* Percentage of course content not specified by respondent, but topics within this system size selected

The various topics were graphed as a function of engineering discipline. Within gate-to-gate systems, 40 to 60% of the courses cover all five suggested topical areas (Figure 3.8). Nearly all those offered by Chemical, Bio-, and/or Materials Engineering departments address “pollution prevention”, compared to only 30% in Mechanical, Aero-, and/or Manufacturing Engineering courses. Civil, Architectural, and Environmental, as well as general engineering courses tend to be rather evenly focused in all areas. Courses offered through industrial, systems, and/or sustainable engineering place the most emphasis on “process design”. These results are not unexpected given the traditions of the engineering disciplines.

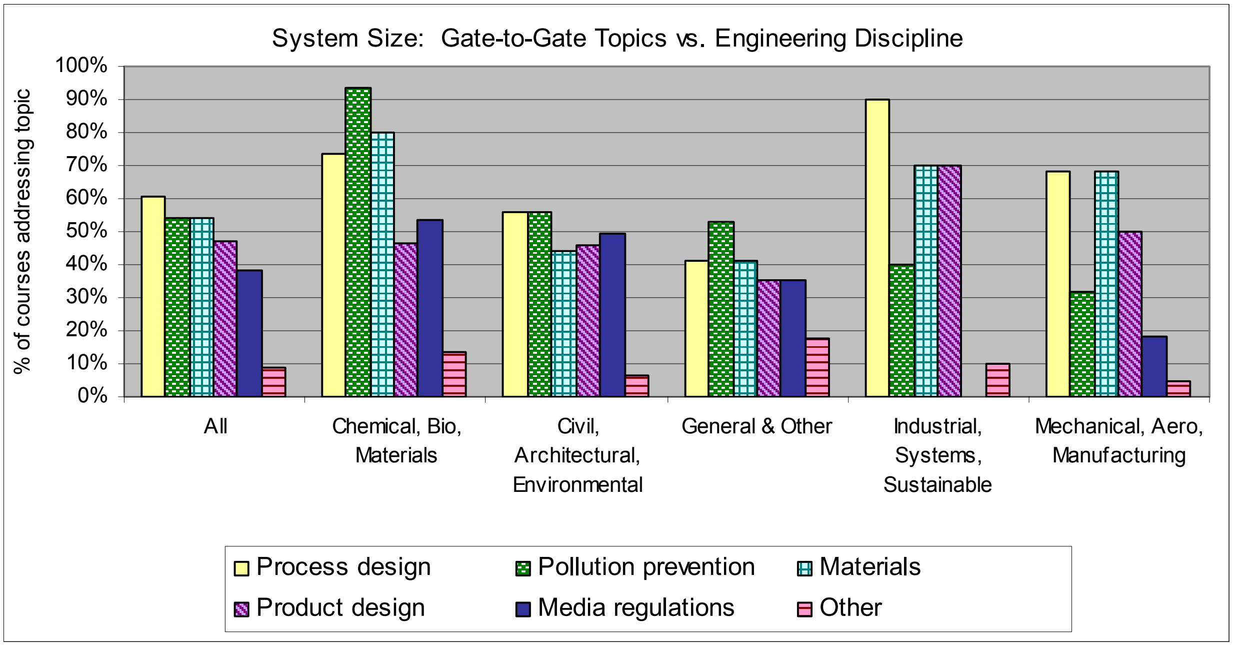


Figure 3.8. Differences in the amount of coverage of topics that tend to fall within gate-to-gate system sizes align along traditional engineering discipline bounds.

For cradle-to-grave type systems as well as with systems that consider inter-industry interactions (industrial symbiosis), the courses taught within industrial, systems, and/or sustainable engineering departments (Figures 3.9, 3.10) appear to cover the associated topics with the greatest frequency. The greatest variability in coverage of cradle to grave system topics occurs in the areas of “product utility” and “consumer behavior”; the greatest in inter-industry systems is with “by-product synergy”. With regard to industrial, systems, and/or sustainable engineering courses, 50 to 60% address these areas, while only 20% of those in Chemical, Bio-, and/or Materials Engineering do so; a similar disparity is observed for “consumer behavior”. Again, these patterns are consistent with traditional topics taught in these disciplines.

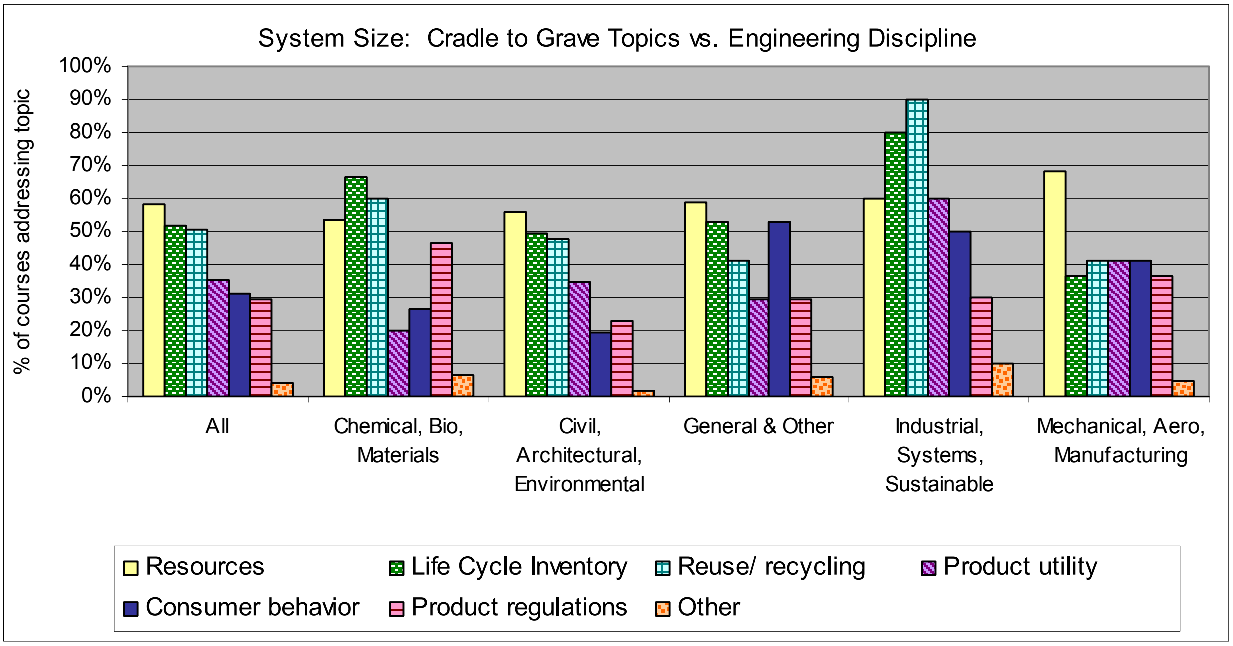


Figure 3.9. The most coverage of cradle-to-grave topics is offered by courses in industrial, systems, and/or sustainable engineering.

Topics in non-industry systems are given very little consideration by any of the courses, regardless of discipline, although nearly 50% of the industrial, systems, and/or sustainable engineering courses address them to some degree (Figure 3.11). Recall that the participants are not asked to what extent any of these topics are covered.

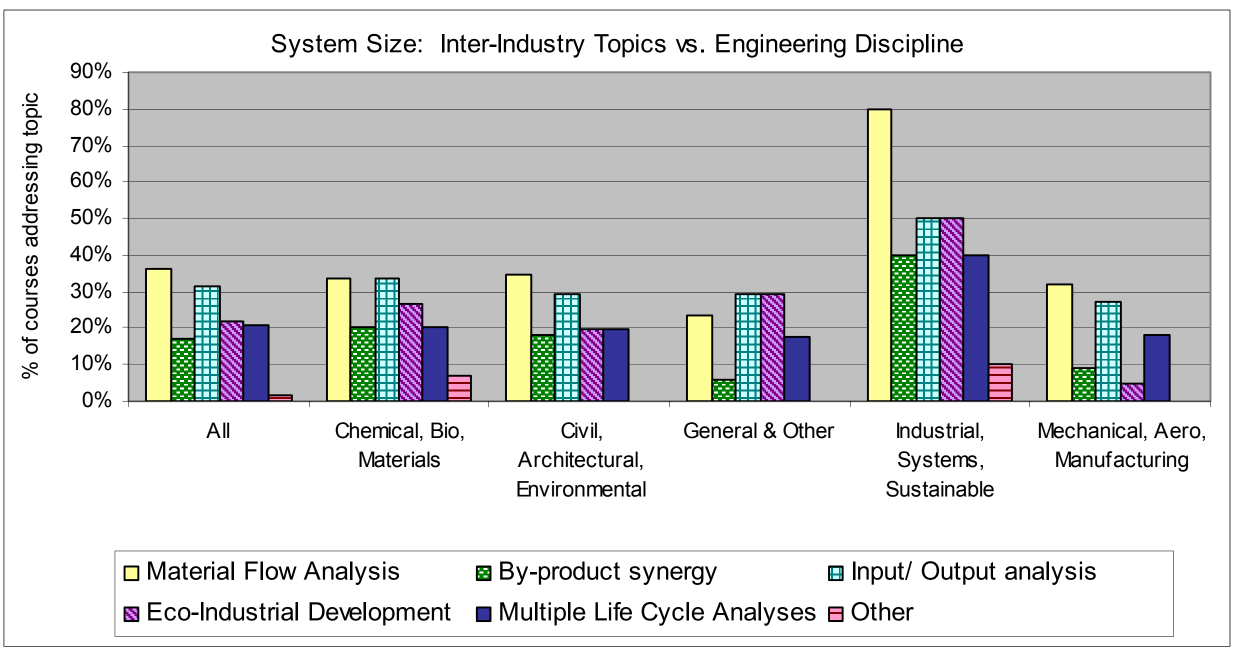


Figure 3.10. The most coverage of inter-industry topics is offered by courses in industrial, systems, and/or sustainable engineering.

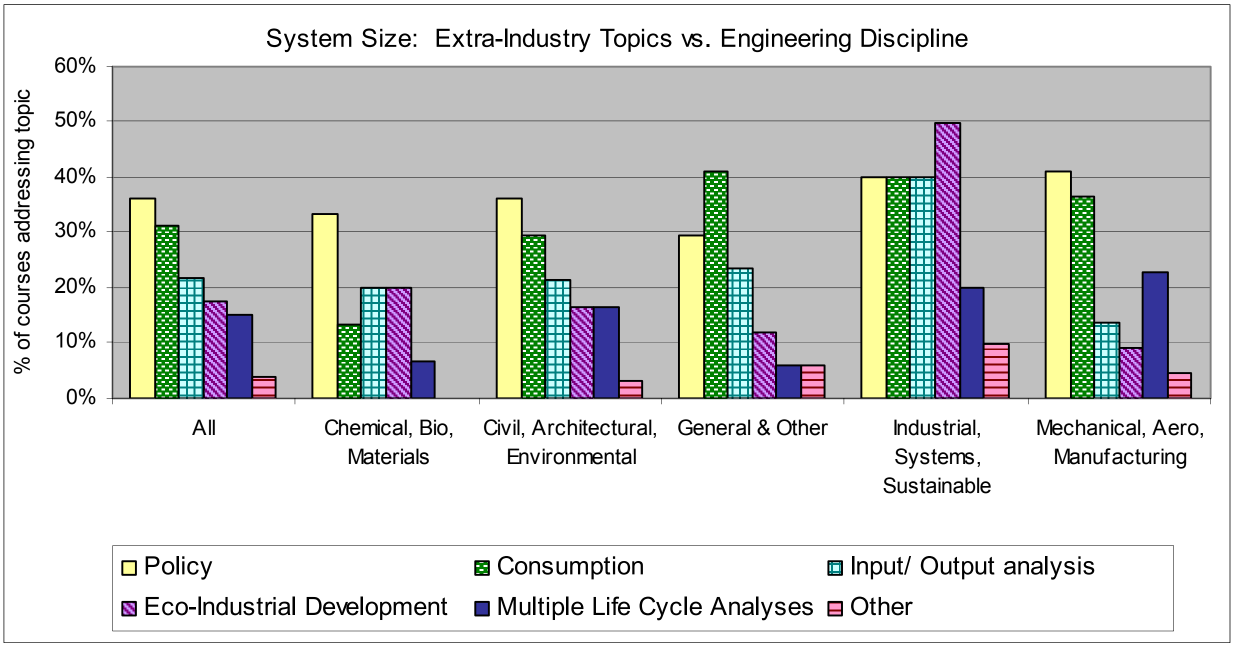


Figure 3.11. Topics in non-industry systems are given very little coverage by any of the disciplines, although nearly 50% of the industrial, systems, and/or sustainable engineering courses address them to some degree.

Non-engineering Disciplines

Participants were asked to consider five broadly defined non-engineering disciplines that might be employed in teaching sustainable engineering concepts and to estimate the portion of each utilized within the course. As with the system sizes the entered percentages were binned into "none" (0%), "small" (1-10%), "moderate" (10-50%), or "significant" >50% and a fifth bin termed "some" was created for courses where topics within the discipline were selected, but no percentage was entered. The five disciplines and corresponding definitions that the participants were asked to assume are presented, along with a list of topics or concepts that are typically considered to fall within these areas, in Table 3.3. The results of the participants' responses are presented in Table 3.4.

Table 3.3. Non-engineering Disciplines and Topics

Discipline	Description	Topics
Life Sciences	Human, animal, or plant health, where mortality and reproduction rates are the primary metrics.	Toxicology
		Biological ecosystems
		Nutrient availability
		Physical and Environmental Sciences
Physical and Environmental Sciences	Mechanical and chemical properties, activities, and interactions, where mass, energy, and time are the primary metrics.	Fate and transport
		Chemical reactions and behavior in the geo-biosphere
		Perturbations and flows within the geo-biosphere
		Physical input-output analysis
		Economics and Business
Economics and Business	Exchange of goods and services that accounts for natural and/or man-made capital at micro and/or macro levels, where currency is the primary metric.	Cost analysis
		Economic input-output analysis
		Life cycle cost analysis
		Sociology and Policy
Sociology and Policy	Control and analysis of human behavior, with values typically expressed as counts or fractions relative to a desired target.	Environmental regulations and legislation
		Consumer behavior
		Cultural and other value systems
		Humanities and Aesthetics
Humanities and Aesthetics	Consideration of elements that provide comfort and pleasure	Architecture
		Design
		Leisure

The only two disciplines that are noted as being significantly integrated into course materials are "physical and environmental sciences" and "economics and business". Table 3.4 shows that 9% of the courses are described as containing a significant portion of physical and environmental science material (>50% of course content) and one course is apparently dominated by business and economics. As might be expected, two-thirds of the courses do not cover any humanities. Perhaps more surprising is the fact that roughly half of the courses (56%) do not address life sciences. The trend highlighted by the shaded cells indicates that roughly two-thirds of the courses include at least a small portion of "economics and business and/or "sociology and policy" material. Thus, the 3 cornerstones of sustainability (environment, economics, and society) seem to have reasonable representation within the courses described by the questionnaire.

Table 3.4. Extent to which Different Non-engineering Disciplines Are Addressed
Maximum values for each system size (within 2 percent points) are shaded to indicate tendencies..

Discipline	Portion of Total Course Content				
	Some*	none	Small (1-10%)	Moderate (10-50%)	Significant >50%
Life Sciences	5	67 (56%)	40 (33%)	13 (11%)	0
Physical and Environmental Sciences	8	49 (42%)	31 (26%)	26 (22%)	11 (9%)
Economics and Business	12	44 (39%)	42 (37%)	26 (23%)	1 (1%)
Sociology and Policy	11	42 (37%)	53 (46%)	19 (17%)	0
Humanities and Aesthetics	5	81 (68%)	30 (25%)	9 (8%)	0

* Percentage of course content not specified by respondent, but topics within this discipline selected

The various topics were graphed as a function of non-engineering and engineering discipline (Figures 3.12-3.16). Observations are presented in the captions of each.

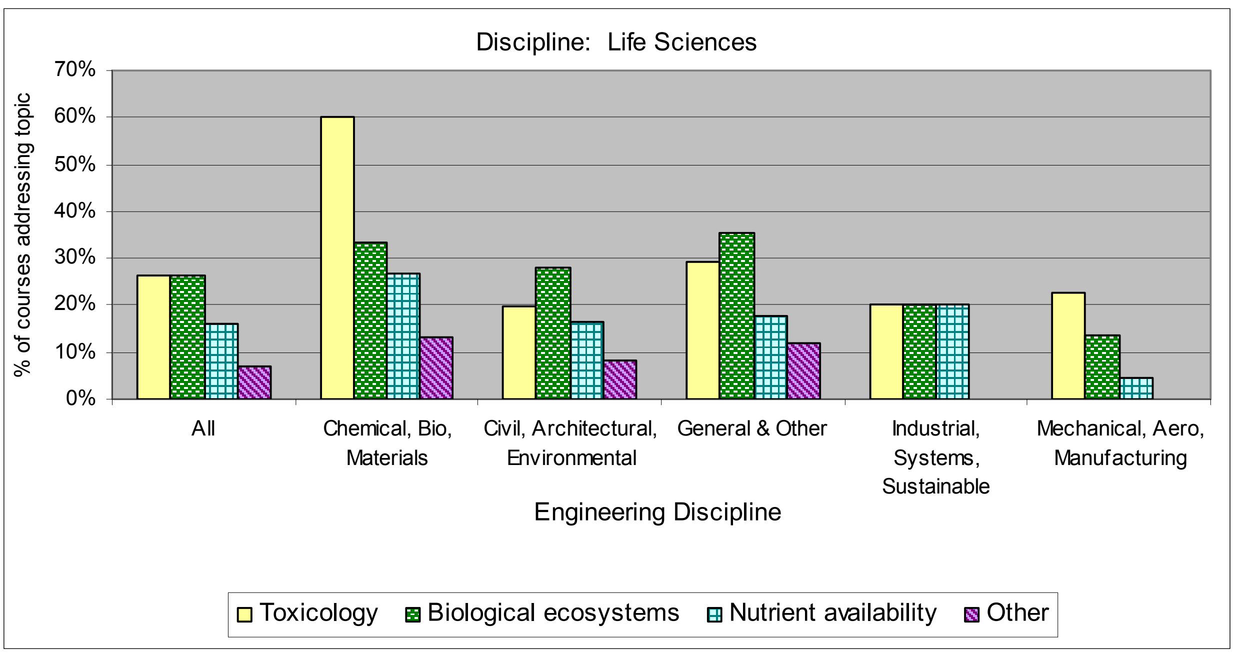


Figure 3.12. Life science topics, especially toxicology, are considered most frequently by Chemical, Bio-, and Materials Engineering courses; the least frequent coverage of these areas occurs in Mechanical, Aero-, and Manufacturing Engineering.

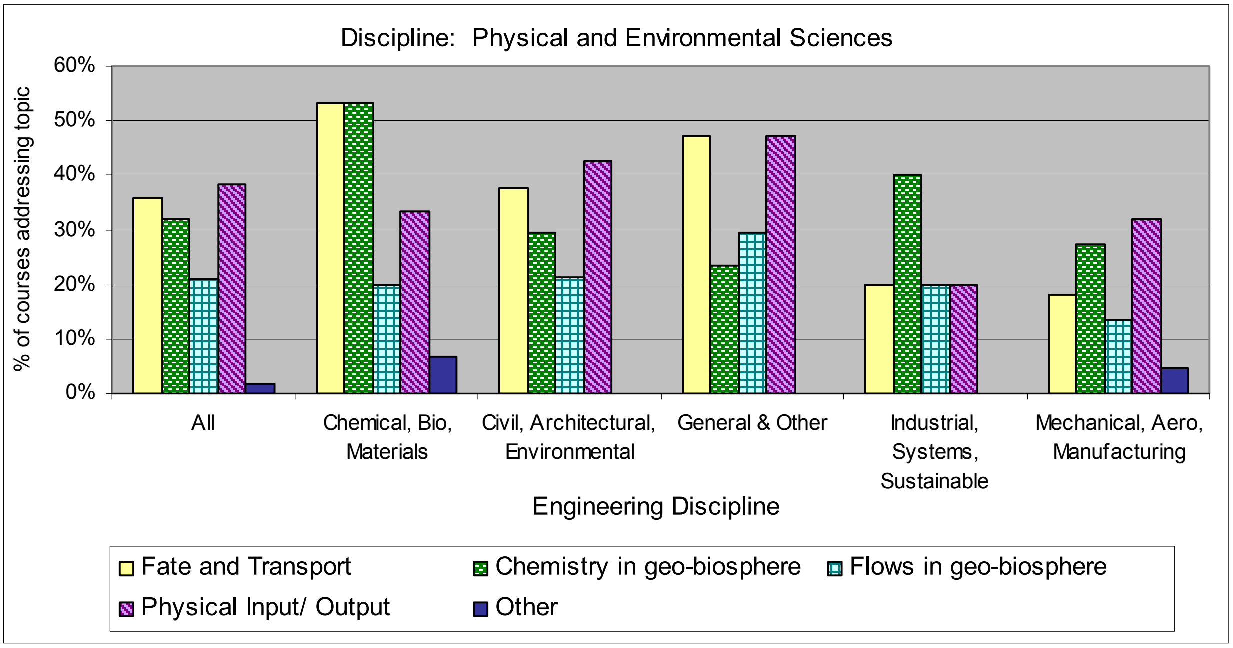


Figure 3.13. The most commonly considered topic in physical and environmental life sciences is fate and transport; the least amount of coverage is afforded flows in the geo-biosphere. The distribution is relatively insensitive to the particular engineering discipline.

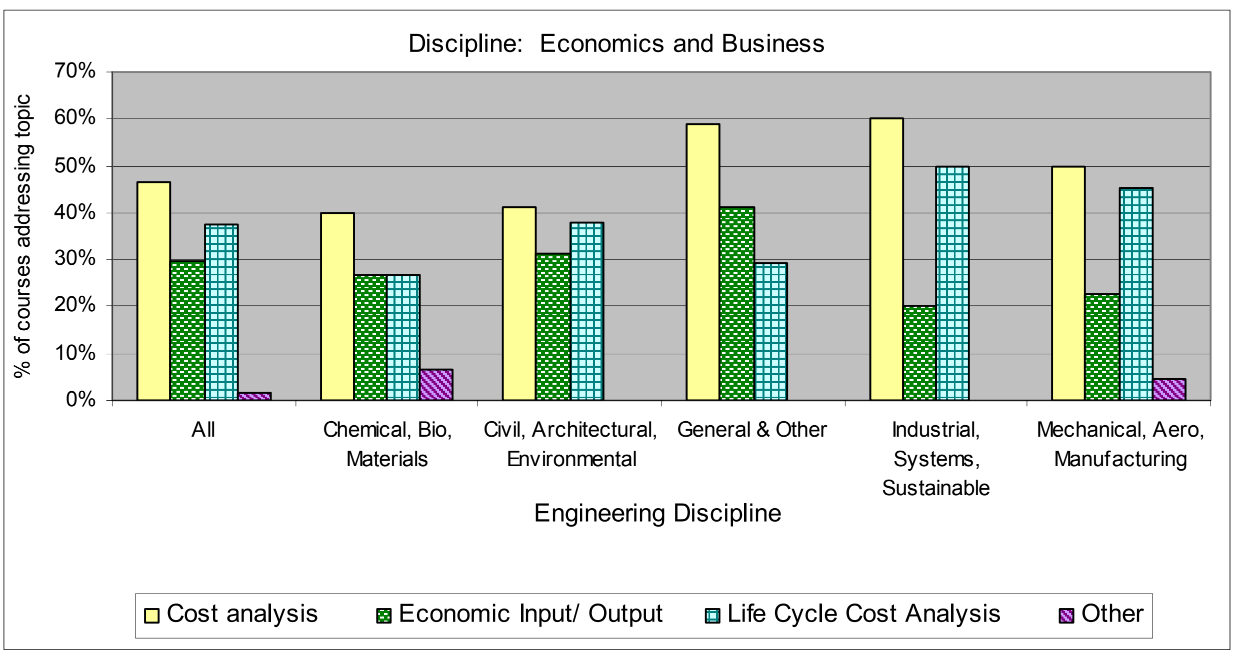


Figure 3.14. Cost analysis is the most commonly addressed topic in economics and business, particularly in industrial, systems, and sustainable engineering. Economic input/output analysis is utilized by the fewest number of courses.

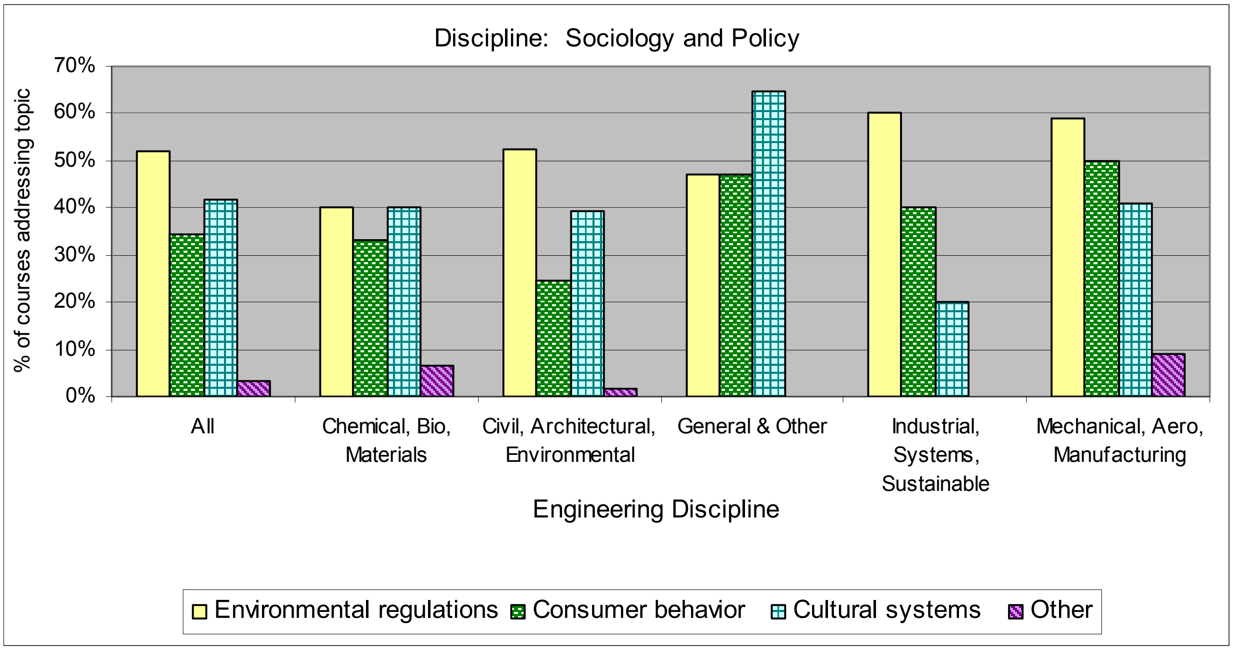


Figure 3.15. To the extent that they are included in the course material, topics in sociology are engaged rather evenly. Between one-third and one-half of all courses, regardless of engineering discipline, cover at least some aspect of these disciplines.

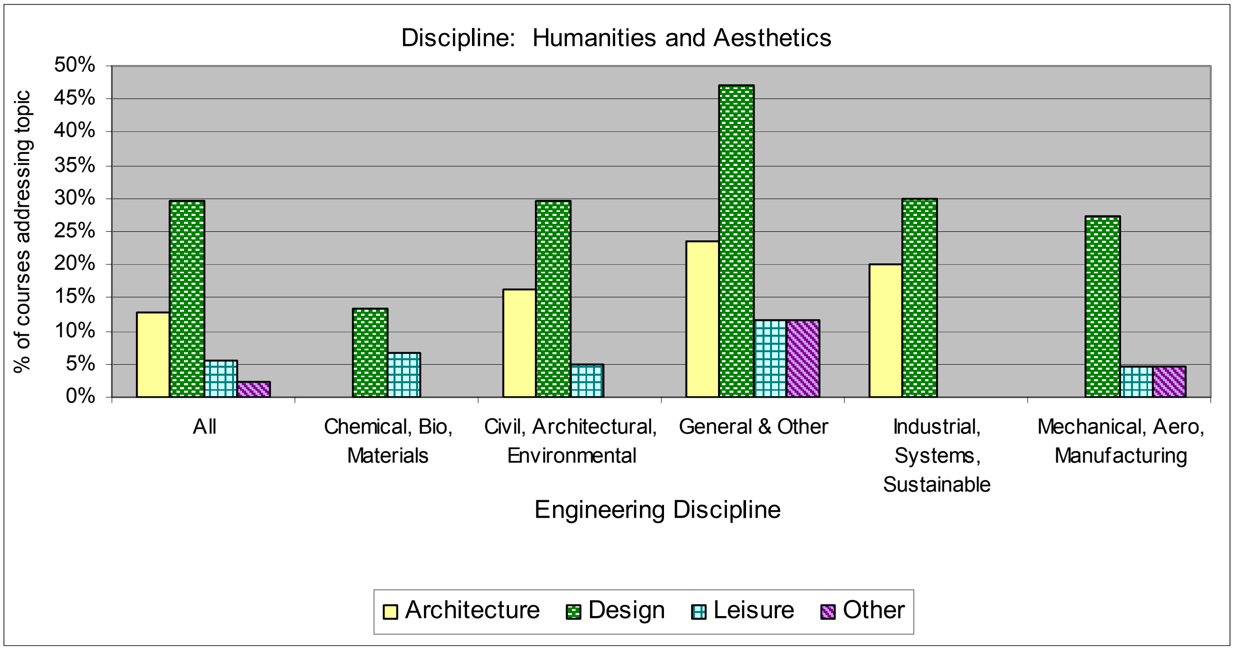


Figure 3.16. Humanities and aesthetics are covered in more than 10% of the courses, with design being the most common topic.

Resources Used:

Participants in the questionnaire were asked to provide information about the resources used in teaching each course. There were four categories

- Textbooks used, both traditional and sustainable engineering focus
- Readings in sustainable engineering concepts
- Websites containing sustainable engineering content
- Software for sustainable engineering related activities

The on-line questionnaire provided space for up to three resources in each category. However, many of the respondents referred to their website and/or syllabus as a substitute or as an augmentation to the information provided directly through the questionnaire. In order to achieve maximum consistency, the decision was made to merge and reconcile all three sources, direct responses to the questionnaire, website information, and syllabi. Another problem noted in going through the responses was the lack of consistency as to how the various resources were categorized: books were often listed as texts when only one or two chapters were assigned; reports, such as those generated by federal agencies were sometimes listed as textbooks; websites that simply posted informal material on html web pages (as opposed to acting as repositories for formal reports or other archival materials) were occasionally listed as readings. This was addressed by altering the assigned categories into "books", "readings" (all archival material without an ISBN number), "websites", and "software".

Categorization of Books and Readings

Each reading and text was examined by going through abstracts, subject headings and tables of contents. The latter were generally available either through previews at Google Book Search (http://books.google.com/), Amazon (www.amazon.com), or Barnes and Noble (www.barnesandnoble.com/); journal articles were accessed through the University of Texas online library. For the purpose of analysis, each was placed in one of eight categories. The results are shown in Tables 3.5 and 3.6.

Four engineering categories are used:

sustainable engineering

sustainable engineering technology (e.g., wind, solar, fuel cells, etc)

environmental engineering (excluding sustainable engineering)

traditional engineering (excluding environmental engineering).

Four non-engineering categories are also used:

social science/business/policy,

architecture/land use/human ecology,

natural/physical science

history/ethics/philosophy. .

Table 3.5. Number of Books within Each Category (by Discipline and Total)

Category	Chemical, Bio-, Materials	Civil, Architectural, Environmental	General & Other	Industrial, Systems, Sustainable	Mechanical, Aero-, Manufacturing	Total
Sustainable engineering	2	22	7	7	10	48
Sustainable engineering technology	2	3	1	1	8	15
Environmental engineering	0	23	0	0	0	23
Traditional engineering	5	17	2	1	24	49
Total Engineering	**9**	**65**	**10**	**9**	**42**	**135**
Natural and/or physical science	0	9	0	1	4	14
Social science, business and/or policy	1	32	7	11	13	64
History, ethics, and/or philosophy	0	5	2	2	9	18
Architecture, land use, and/or human ecology	0	17	0	0	1	18
Total Non-engineering	**1**	**63**	**9**	**14**	**27**	**114**
Total Books	**10**	**128**	**19**	**23**	**69**	**249**

Table 3.6. Number of Readings within Each Category (by Discipline and Total)

Category	Chemical, Bio-, Materials	Civil, Architectural, Environmental	General & Other	Industrial, Systems, Sustainable	Mechanical, Aero-, Manufacturing	Total
Sustainable engineering	3	11	20	37	33	104
Sustainable engineering technology	1	2	4	1	1	9
Environmental engineering	0	1	0	0	2	3
Traditional engineering	0	3	0	0	0	3
Total Engineering	**4**	**17**	**24**	**38**	**36**	**119**
Natural and/or physical science	1	2	0	5	1	9
Social science, business and/or policy	2	12	15	34	15	78
History, ethics, and/or philosophy	0	1	2	1	2	6
Architecture, land use, and/or human ecology	1	0	0	0	0	1
Total Non-engineering	**4**	**15**	**17**	**40**	**18**	**94**
Total Readings	**8**	**32**	**41**	**78**	**54**	**213**

A full list of all the resources has been entered into an Excel® spreadsheet that will be made available on the Center for Sustainable Engineering website (www.csengin.org). It is structured for easy import into a database software package such as Microsoft Access®, or may be used as is.

Books

A total of 249 unique book titles (with multiple editions counted as a single title) were taken from the inputs provided. With the exception of 5 books, very few publications were listed more than once or twice; the 5 books that account for 51 (20%) of the listings are:

- *Industrial Ecology*, Graedel and Allenby (12 mentions),
- *Green Engineering: Environmentally Conscious Design of Chemical Processes*, Allen and Shonnard (12 mentions),
- *Pollution Prevention: Fundamentals and Practice*, Bishop (11 mentions),
- *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*, Hendrickson, Lave, and Matthews (6 mentions), and
- *Cradle to Cradle: Remaking the Way We Make Things*, McDonough and Braungart (10 mentions).

Complete information regarding each of these books and others is available in Appendix E.

Readings (Articles, Papers, and Reports)

Readings assigned from journal papers or magazine articles as well as published reports constituted a total of 213 titles. There were a number of these that were used in 2 or 3 different courses, but only one appeared to be a "standard": Garrett Hardin's classic 1968 publication in Science, "The Tragedy of the Commons" [Hardin, 1968], which was assigned in 6 different courses. A more useful set of statistics, perhaps, is a list of the dominant publications from which readings are drawn.

- *Journal of Industrial Ecology* (19 papers)
- *Environmental Science and Technology* (13 papers)
- *Scientific American* (8 papers)
- *International Journal of Life Cycle Assessment* (7 papers)
- *IEEE International Symposium on Electronics and the Environment* (7 papers)
- US DOE (6 reports)
- US EPA (6 reports)

Full citations of readings listed by the respondents are provided in Appendix E.

Websites

Roughly 130 individual websites are listed by the respondents. However, since many are related, it is difficult to provide a precise count. In order to assess the most commonly utilized websites, only the primary URL was considered, rather than subsequent links. In doing so, 72 unique website hosts are given. The US Environmental Protection (US EPA) website was the most commonly listed resource, with mentions for 12 (8%) of the courses described. A total of 22 subordinate websites within EPA were listed; the most frequently mentioned were the Toxic Release Inventory pages (http://www.epa.gov/tri) including the TRI Explorer, (http://www.epa.gov/triexplorer/); these were used by 5 different courses. If references to National Labs are included, the US Department of Energy is the second most commonly used (mentioned in 11 different courses), often with 2 to 3 different DOE sites per course. The DOE sites listed with the greatest frequency are

NREL (National Renewable Energy Lab), http://www.nrel.gov, 4 mentions,

EERE (Energy Efficiency and Renewable Energy), http://www.eere.energy.gov, 4 mentions, and

EIA (Energy Information Administration), http://www.eia.doe.gov, 3 mentions

Three other popular websites at 4 mentions each are Redefining Progress (http://www.rprogress.org/index.htm) with its Ecological Footprint Calculator (http://www.myfootprint.org/en/), PRé Consultants (http://www.pre.nl/), the makers of SimaPro software, and who also provide general LCA information on their website, and the U.S. Green Building Council (http://www.usgbc.org). A complete list of website hosts is provided in Appendix E.

Software

Software reported by participants was divided into one of four categories:

Life Cycle Assessment (LCA),

Environmental

Design and General Engineering

Building Related

Although there are only 5 different LCA software packages reported, there are 27 different courses that make use of one of the five. The second most common type of package is that for design and general engineering; these are used most commonly by courses offered through Chemical, Bio-, and/or Materials Engineering departments and Mechanical, Aero-, and/or Manufacturing Engineering departments (12 out of 17 instances). Environmental software is used predominantly by Chemical, Bio-, and/or Materials Engineering and Civil, Architectural, and/or Environmental Engineering courses (10 out of 11 instances). Building related software is the exclusive domain of Civil, Architectural, and/or Environmental engineering (8 out of 8 instances).

A summary of the LCA software is presented in Table 3.7. Complete information is available in Appendix E.

Table 3.7. LCA Software Packages Used by Number of Courses

Software	Distributed By	Chemical, Bio-, Materials	Civil, Architectural, Environmental	General & Other	Industrial, Systems, Sustainable	Mechanical, Aero-, Manufacturing	TOTAL
EIO-LCA	CMU, Green Design Institute		7	1	2	5	15
SimaPro	PRé Consultants		2		4	3	9
GaBi	PE International					1	1
Umberto	ifu, Hamburg, GmbH					1	1
GREET	US DOE, Argonne National Laboratory	1					1
	LCA TOTAL	1	9	1	6	10	27

Topics as Suggested by Books and Readings

During the process of categorizing the books and readings, it became apparent that these resources could be further characterized by a number of themes. In this assessment, a single dominant theme was recognized for each book or paper, but all themes addressed at roughly 10% were accounted for. While the category expresses the discipline or perspective used to present the material (the "how"), the theme is intended to capture the subject or subjects (the "what"). Thus a paper using life cycle analysis to compare natural gas to coal-fired power generation would be categorized as "sustainable engineering" with "energy" as the dominant theme; LCA would be listed as a subordinate theme.

A total of 22 themes emerged during this process. These are given in Table 3.8 along with the frequencies at which they were observed. It can be seen from Table 3.8 that certain topics are repeatedly addressed even when they are not the dominant theme, such as "policy", "agriculture and land use", and "natural resources". Conversely, several themes that may not be discussed with great frequency may still be dominant when addressed (that is they tend to be stand-alone topics); transportation, building and construction, urban systems, and material flow analysis fall into this category.

When normalized by discipline (i.e., the number of instances within a disciplinary offering divided by the number of courses in that discipline), the themes of interest shift slightly from that suggested by Table 3.8. "Energy," "LCA," and "Systems, Metrics, & Information Management" are the three most common dominant themes, while "Building & Construction", "MFA," and "Human Health" are the least likely to be covered, regardless of discipline. Three topics that are important within a particular set of disciplines are "End of Life" and "Waste Management" in general and other engineering, "Industrial Processes" in Chemical, Bio-, and/or Materials engineering, and "Water" in Civil, Architectural, and/or Environmental Engineering.

Table 3.8. Themes Observed in Books and Readings

Shaded cells indicate top 10 in each category

Theme	# Times Dominant Theme of Reading or Book	# Times Addressed to a Notable Degree	If Addressed, % Time it was Dominant Theme
Energy & Power Generation	84	203	41%
LCA (Life Cycle Assessment)	67	148	45%
Business & Economics	39	182	21%
Industrial Ecology	38	65	58%
Systems, Metrics, & Information Management	38	139	27%
Water	36	71	51%
Industrial Processes	33	123	27%
Humanities (philosophy, ethics, history)	31	109	28%
End of Life and Waste Management	26	98	27%
Design	22	127	17%
Pollution Prevention, Fate & Transport	22	80	28%
Transportation	20	58	34%
Policy	18	157	11%
Biogeochemical Systems (incl. Ecology)	16	77	21%
Materials	16	69	23%
Building & Construction	15	45	33%
Urbanism and Urban Systems	14	36	39%
Climate Change	13	62	21%
Agriculture and Land Use	12	81	15%
Natural Resources	10	97	10%
Material Flow Analysis	6	16	38%
Human Health	2	49	4%

Conclusions

With the caveat that the results of this questionnaire represent a sample and not a full population, several trends do emerge as the result of this study. The first is that while the trend to include sustainable engineering concepts into US engineering programs may be slightly dominated by larger, higher ranked schools, it is clear that this is a becoming a widely accepted practice. The courses being offered tend to be relatively mature and are offered to medium sized classes of predominantly upper division undergraduate and graduate students. While a stand-alone sustainable engineering course seems to be the most common approach, the other three categories of incorporating this material are also widely used.

4.0 Sustainable Engineering Research: Findings

Introduction:

The participants in the champion questionnaire were asked to answer a set of questions regarding sustainable engineering research in which they are or have been involved. No specific definition of sustainable engineering was given, but the respondents were prompted to consider research areas that involved topics such as life cycle assessment (LCA), design for environment (DFE) or green design, industrial ecology, policy and regulations, economics, material flow analysis (MFA), natural resource management, climate change, pollution prevention, and reuse and/or recovery of products and materials. The purpose of this section was to gather information about 1) sponsored research, 2) dissemination and publications, and 3) centers and institutes. A copy of the questionnaire is provided in Appendix C.

Sponsored Research

Questionnaire respondents were invited to provide information for up to 3 sponsored research projects that they felt lay in the area of sustainable engineering. In addition to the title of the project they were asked for the name of the sponsor, the duration of the project and the total amount of sponsorship. Respondents from 81 different universities self-identified a total of 238 unique projects. Three projects were noted as un-sponsored; these are included in the thematic analysis but not the funding analysis below. Two of the named projects have duplicate records as the result of having co-PIs at different institutions; only the prime is used in the analysis presented here. It should be noted that neither the project that is the focus of this report (i.e., Benchmarking Sustainable Engineering Education) nor its companion effort, the NSF Center for Sustainable Engineering are included.

Funding

The total funding for the projects described is nearly one-quarter of a billion dollars ($223 million). Some of the projects are of very short duration (3 months), while 5 are funded for 10 years or more. The mean project length is 32 months, the median is 24 months, and the average funding rate is just over $255,000 per year. Sponsors were grouped into one of 10 categories (Table 4.1 and Figure 4.1). The National Science Foundation has provided the greatest amount of total funding (45%) as well as having an annual funding rate of just over $100,000 per year. The second largest source of funds is the US Department of Defense (DOD); however, most of the funding ($45 million) comes from a single Army Corp of Engineers project to support development of sustainable fisheries in the Pacific Northwest. While this single award tends to distort the mean (indeed DOD would rank second to last without this project) the median award from DOD, at $580,000, is the largest of any category suggesting a tendency towards bigger projects relative to other sources.

Table 4.2 breaks out the funding by the home department of the respondent (usually the principal investigator). Due to incomplete data, the total number of projects (221) accounted for in these analyses is slightly lower than the total number of projects listed (238).

Table 4.1 Funding Characteristics by Sponsor Type

Sponsor Category	Count	Annual Funding Rate	Total Funding	% of Total Funding	Median Funding per Project	Median Duration (months)
National Science Foundation (NSF)	63	$18,381,592	$100,355,993	45%	$325,000	36
US Department of Defense (DOD)	9	$11,830,000	$48,180,000	20%	$580,000	36
Industry	22	$4,779,060	$20,081,428	8%	$226,000	24
State and Local	30	$4,601,464	$9,058,014	4%	$97,856	24
US Department of Energy (DOE)	21	$3,085,024	$11,837,000	5%	$200,000	36
US Federal, other	13	$2,501,559	$8,077,670	3%	$100,000	24
Foreign	4	$1,492,500	$15,510,000	7%	$530,000	48
US Environmental Protection Agency (EPA)	24	$1,365,035	$4,982,745	2%	$85,000	22
Institutional	21	$1,250,617	$2,918,100	1%	$20,000	24
Other	14	$889,772	$1,760,007	1%	$55,000	24
TOTAL	221	$50,176,623	$222,760,957			

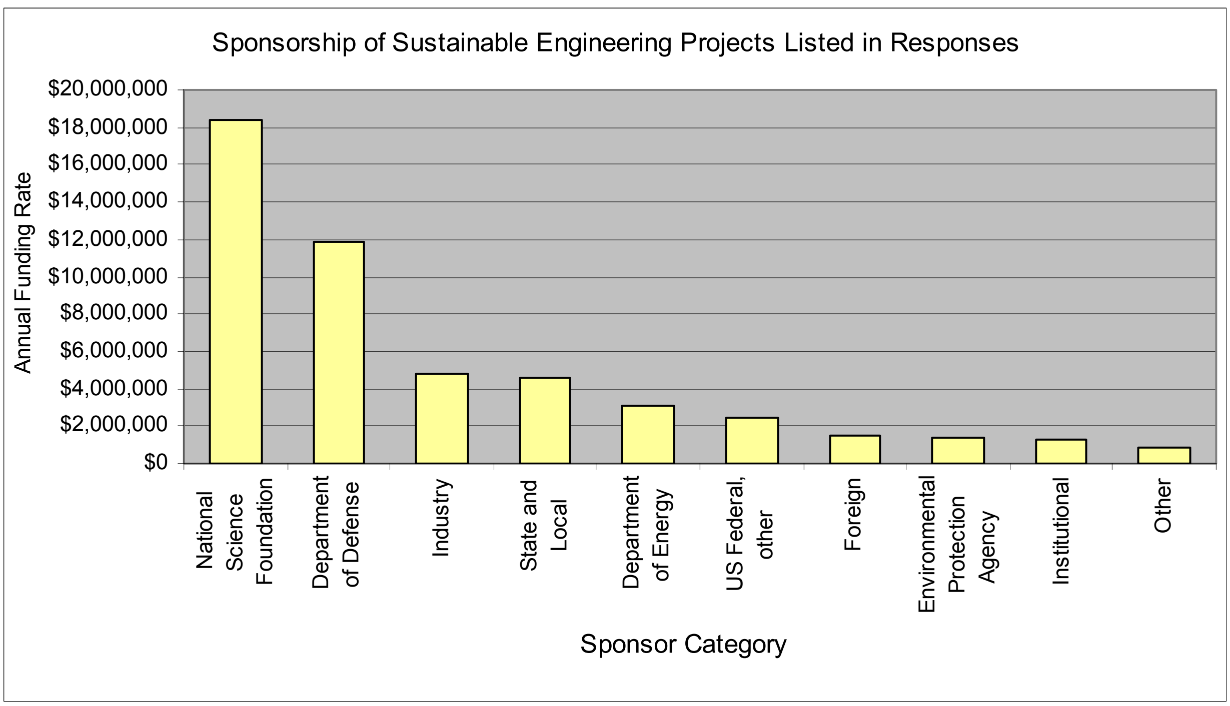


Figure 4.1. The National Science Foundation (NSF) and the US Department of Defense (DOD) are the largest current sponsors of sustainable engineering research, based on questionnaire responses.

Table 4.2 Funding Characteristics by Discipline

Discipline	# of Projects	Total Funding	Mean Award	Median Award
Mechanical, Aero-, Manufacturing	63	$89,777,904	$1,425,046	$250,000
Civil, Architectural, Environmental	65	$77,953,333	$1,199,282	$200,000
Chemical, Bio-, Materials	28	$25,435,552	$908,413	$200,000
Industrial, Systems, Sustainable	23	$6,036,566	$262,459	$120,000
General & Other	20	$23,557,602	$1,177,880	$100,000

Themes

The same categories used to characterize the readings assigned in courses were used to assess the dominant and prevailing themes of the sponsored research reported on through the questionnaire (Table 4.3). Only the project titles were used to make this determination, since, unlike the readings, there is often limited public information available about the project and the participants were not asked for details.

“Energy and Power Generation” top the list of themes for both research projects and course readings. Also high on both lists are “Water,” “Industrial Processes,” and “End of Life and Waste Management.” Note that in the case of the latter, two dominant sub-themes are electronics (not specifically accounted for) and water for both class readings and research. “LCA” as well as “Business and Economics” are often the main theme of course materials, but are more commonly subordinate themes in research projects.

Two-thirds (42 out of 61) of the energy related sponsored research projects are in the area of renewable fuels, with just under half of these (19) addressing biofuels in some manner. The remaining projects are split roughly between wind-power and solar. All of the projects where “Humanities” is the dominant theme are focused on education, including sustainable engineering curriculum development.

The largest projects, as measured by funding, exhibit a relatively even distribution between the various themes, although it could be argued that three of the mega-projects (those with more than $10M in funding) which are counted as being focused on “Industrial Processes” and “Materials” also fall within the energy domain and overlap with one another. The mega-project on disassembly factories addresses end-of-life vehicles and could also be argued as being in the area of “Industrial Processes.”

Table 4.3. Sponsored Research Themes, Ranked by Number of Projects
Shaded cells indicate top 8 in each category

Theme	# of Projects with Theme Dominant	# of Projects where Theme is Significant	Total Funding (Dominant)	Projects >$10M	Rank of Theme in Course Readings
Energy & Power Generation	61 [1]	77	$22,654,000		1
Industrial Processes	25	42	$24,867,799	catalysis systems, $15M	7
Materials	22	32	$25,672,989	nanomanufacturing, $12M; crop oil feedstock, $10M	15
End of Life and Waste Management	20	26	$22,083,405	disassembly factories, $14M	9
Building & Construction	16	20	$4,086,861		16
Water	14	22	$42,004,313	water purification, $39M	6
Transportation	13	20	$1,819,800		12
Humanities (including education)	10 [2]	15	$1,562,300		8
Climate Change	9	9	$10,494,606		18
Human Health	9	15	$3,222,803		22
Pollution Prevention, Fate & Transport	9	19	$3,550,295		11
Systems, Metrics, & Information Management	9	24	$5,213,828		5
Biogeochemical Systems (including ecology)	4	9	$45,426,000	sustainable fisheries, $45M	14
Industrial Ecology	3	5	$29,102		4
Agriculture and Land Use	2	5	$200,000		19
Business & Economics	2	13	$185,000		3
Design	2	8	$1,800,000		10
LCA (Life Cycle Assessment)	2	19	$0		2
Material Flow Analysis	2	2	$3,400,000		21
Urbanism and Urban Systems	2	4	$4,360,000		17
Policy	1	10	$97,856		13
Natural Resources	0	0	$0		20

[1] 42 of the Energy projects are focused on biofuels, solar, or wind
[2] All 10 of the Humanities projects are in education

Distribution of Funding

Nearly all ($219M or 98.9%) of the sponsored research funding identified through the questionnaire is going to engineering schools that have doctoral programs; more than two-thirds is being received by engineering schools ranked in the top 20 (Table 4.4). For schools without PhD programs, more than half of the funding is directed at those ranked in the top 20. If the actual number of projects is considered, the distribution is slightly more uniform (Figure 4.2). One-fourth of all projects, representing $28.8M worth of support, are being conducted at public institutions that do not rank in the top 100.

Table 4.4 Sponsored Research Funding by Engineering School Rank
(ranking data from [USN&WR, 2008])

	w/ PhD		w/o PhD	
Engineering School Rank	**Total $**	**# projects**	**Total $**	**# projects**
1 to 20	$80,715,500	11	$1,487,513	5
21 to 40	$48,706,089	9	$655,500	3
41 to 60	$32,435,692	9	$276,000	3
61 to 80	$23,636,084	8	$78,100	1
81 to 100	$4,951,313	5	$0	0
>100	$28,799,166	18	$0	0
TOTAL	$219,243,844	60	$2,497,113	12

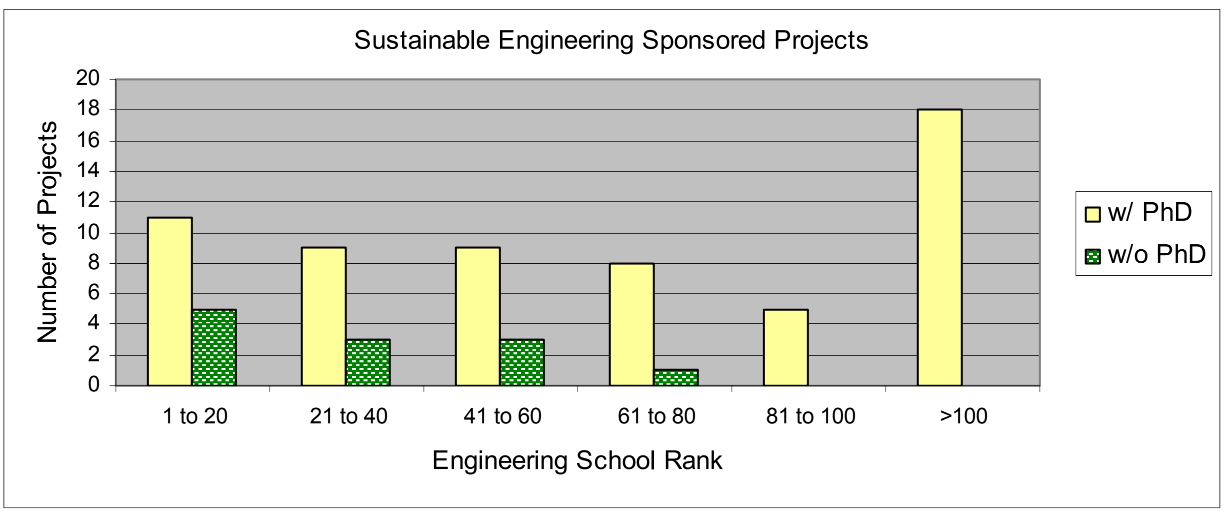


Figure 4.2. More than 80% of the sponsored projects are being conducted by PhD granting engineering schools; nearly one-third are at schools that do not rank in the top 100 (ranking data from [USN&WR, 2008]).

Student Support

The questionnaire participants were asked for the typical number of students (working under their direction) involved in sustainable engineering at any given time. The responses indicate that this number is in excess of 1000 (Table 4.5). Of these, 544 are graduate students, with 392 (72%) being fully supported, and the rest partially or not supported (15% and 13%, respectively). Over 500 undergraduates are also involved, with 97 fully supported (18%) and the rest either partially (37%) or not at all supported (44%).

Table 4.5. Sustainable Engineering Student Support by Respondents

	Undergraduate students	**Graduate students**
fully supported	97	392
partially supported	196	82
Unsupported	231	70
Total	524	544

Dissemination and Publications

As there are currently no formal professional societies dedicated exclusively to the discipline of sustainable engineering, the dissemination of research results in this area typically occurs in peripherally aligned organizations and publications. The participants were asked to name up to three conferences in which they are involved and/or attend in the area of sustainable engineering. In addition, they were asked which publications they read in order to remain abreast of progress in the area as well as the names of journals in which they have or intend to publish the results of their own research in sustainable engineering.

Conferences

A total of 87 respondents listed one or more conferences in which they were involved in the area of sustainable engineering. The largest single event attended by the questionnaire participants, a total of 16 (or 18%), is the IEEE International Symposium on Electronics and the Environment (ISEE). This conference has been renamed the International Symposium on Sustainable Systems and Technology, reflecting in part the need to extend from environmental to sustainability issues. The second most commonly attended function is the International Society for Industrial Ecology, attended by 9 (10%) of the respondents. A significant number are also involved in various meetings sponsored by professional societies, particularly the American Institute of Chemical Engineers (AIChE) and the American Society of Mechanical Engineers (ASME). Of the 9 respondents listing meetings of the American Chemical Society, 4 specified the Green Chemistry and Engineering conference. With the exception of IEEE, where 16 out of 17 noted participation in the ISEE conference, either no specific conference of these professional societies was mentioned or many different meetings were listed. A summary is presented in Table 4.6; only those with 4 or more respondents reporting participation are listed.

Table 4.6. Conferences Attended
Only those with 4 or more respondents reporting participation are listed

Various Meetings by Sponsoring Organization	# Attending
American Chemical Society (ACS) - including Green Chemistry and Engineering	9
American Institute of Chemical Engineers (AIChE)	13
American Society for Engineering Education (ASEE)	10
American Society of Civil Engineers (ASCE)	4
American Society of Mechanical Engineers (ASME)	19
Association of Environmental Engineering and Science Professors (AEESP)	5
Institute of Electrical and Electronics Engineers (IEEE) - including ISEE	17
Specific Meetings	**# Attending**
ACS Green Chemistry and Engineering	4
American Solar Energy Society (ASES) National Solar Conference	4
CIRP International Conference on Life Cycle Engineering	7
Global Conference on Sustainable Manufacturing and Life Cycle Engineering	4
IEEE International Symposium on Electronics and the Environment (ISEE)	16
International Society for Industrial Ecology (ISIE)	9

<u>Publications</u>

A total of 92 different journals were listed as being read in order to keep abreast of sustainable engineering activities; 112 journals were named as those in which they have published sustainable engineering results. The two that stand out both as being the most commonly read as well as the place to publish are *Environmental Science & Technology* and the *Journal of Industrial Ecology*. These publications were also noted as the most likely sources of readings in the classroom (Chapter 3 of this report).

A total of 31 (35%) of the 88 respondents participating in this portion of the questionnaire, reported reading *Environmental Science & Technology* for sustainable engineering content and 26 (30%) named the *Journal of Industrial Ecology*. The third most widely read publication is the *Journal of Cleaner Production* at 13 (15%). A list of those journals reported as being read by 4 or more respondents is provided in Table 4.7.

Almost one-fourth (20 or 23%) of the respondents have published sustainable engineering material in *Environmental Science & Technology*, while 15 (17%) intend to submit one or more papers. Slightly less, 12 (14%), have published in the *Journal of Industrial Ecology* with 13 planning to submit a paper in the future. The *Journal of Cleaner Production* is the third most commonly mentioned publication with respect to papers published in the past, but the newly formed *International Journal of Sustainable Manufacturing* (only one issue to date), is third in terms of where the respondents anticipate publishing in the future. A list of journals in which 4 or more participants have published or hope to publish is provided in Table 4.7.

Table 4.7. Publications Noted for Sustainable Engineering Content

Only those with 4 or more respondents reporting are listed

Journal Title	Read for Sustainable Engineering Content	Have Published in	Considering Submission to
Environmental Science & Technology	31	20	15
Journal of Industrial Ecology	26	12	13
Journal of Cleaner Production	13	8	4
Science	7	2	4
International Journal of Life Cycle Assessment	6	3	3
Resources, Conservation, and Recycling	4	5	3
International Journal of Sustainable Manufacturing	3	3	6
CIRP Annals - Manufacturing Technology	4	2	2
Biomass & Bioenergy	2	0	4
Journal of Engineering Education	2	0	4
Journal of Global Environment Engineering	0	0	4

Centers and Institutes

The questionnaire asked respondents to name one center or institute in which they are involved. They were not asked to limit these organizations to those involved in sustainable engineering. A total of 58 different centers, including the NSF Center for Sustainable Engineering, were listed. Fourteen of these were not obviously sustainable engineering focused centers, but the remaining 44 were. The subsequent analysis addresses only the sustainable engineering focused centers or institutes.

Table 4.8 lists the number of centers and/or institutes that have a focus or which address to a significant degree one of the 22 themes identified in Tables 3.8 (readings) and 4.3 (research topics). Note that the prevailing theme is “energy and power generation.” “Industrial processes are also high on all three lists. Policy, while not the dominant theme of any center or institute, is a significant aspect of 9 or more than 20% of all the organizations. The term “systems” is used to describe “umbrella” organizations that act to integrate a number of research groups (typically

5 or more) and which do not appear to fall under one of the other themes; actual systems engineering is a significant aspect of only one center.

Table 4.8. Centers and Institutes with Sustainable Engineering Focus
Shaded cells indicate top 7 or 8 in each category

Theme	Primary Focus of Center or Institute	Significant Aspect of Center or Institute	% Primary Focus
Energy & Power Generation	7	15	16%
Systems*	7	8	16%
Industrial Processes	4	12	9%
Building & Construction	3	4	7%
Design	3	6	7%
End of Life and Waste Management	3	8	7%
Pollution Prevention, Fate & Transport	3	5	7%
Human Health	2	5	5%
LCA (Life Cycle Assessment)	2	5	5%
Transportation	2	3	5%
Urbanism and Urban Systems	2	7	5%
Water	2	9	5%
Biogeochemical Systems (incl. Ecology)	1	6	2%
Climate Change	1	4	2%
Industrial Ecology	1	2	2%
Natural Resources	1	2	2%
Agriculture and Land Use	0	5	0%
Business & Economics	0	5	0%
Humanities (philosophy, ethics, history)	0	3	0%
Material Flow Analysis	0	7	0%
Materials	0	1	0%
Policy	0	9	0%
Total	44		

* all centers and institutes, where "systems" is listed as the primary focus, are umbrella organizations

Nearly half of the sustainable engineering research centers and institutes (19) are more than 5 years old and three-quarters (35) are more than 2 years old. Only 9 have been formed as recently as 2007. The majority (23) have more than 10 full-time equivalent researchers, faculty and staff and 10 (23) have 30 or more.

Conclusions

Research funding in sustainable engineering is substantial. This work identified roughly a quarter of a billion dollars in current funding. The dominant sponsor of this research is the National Science Foundation (NSF), and consequently, median project sizes (~$300,000) and durations (36 months) follow NSF norms. The funding is concentrated in top tier institutions; More than half of the research funding is found at top 40 PhD granting institutions. Student participation in these research programs is extensive. More than 500 graduate and roughly 400 undergraduate students are actively engaged in the projects.

Topical areas for research are heavily concentrated in energy and power systems; however, publication and other dissemination of results are not primarily directed toward energy conferences and journals; the two dominant journals that sustainable engineering researchers monitor and publish in are *Environmental Science & Technology* and the *Journal of Industrial Ecology*.

5.0 Program Structures: Findings

The administrative heads of 1368 academic units from 364 different US institutions were asked to provide general information about courses, research projects, centers or institutes, and degree-granting programs related to sustainable engineering. Responses were provided by 270 individuals representing 286 different academic units (21% of those contacted) at 180 universities and colleges (49% of those contacted). A copy of the letter sent to potential questionnaire participants, along with the questionnaire, is presented in Appendix B. Most of the academic units represented are departments, but a few programs are organized at the level of school or college of engineering. In order to avoid awkward wording, the discussion that follows will use the word "department" to refer to all academic units.

Characteristics of Respondents

Departments were grouped into six general categories with the total number responding as follows:

- Chemical, Bio-, and/or Materials 82 departments
- Civil, Architectural, and/or Environmental 59 departments
- Mechanical, Aero-, and/or Manufacturing 52 departments
- Electrical and/or Computer 41 departments
- Industrial, Systems, and/or Sustainable Engineering 18 departments
- General 18 departments
- Other (including Petroleum, Mining, and Nuclear) 16 departments

The participants in the questionnaire come from a wide range of institutions. Most (almost 90%) have total enrollments of 30,000 or less and nearly 40% (71) have fewer than 10,000 students (Figure 5.1). The size of the departments themselves, however, tend to be large, with one-third graduating 95 or more students per year; a secondary mode occurs at about 30 departmental graduates per year (Figure 5.2).

The results are somewhat biased towards higher ranking, PhD granting institutions. Three-fourths (73%) of engineering schools with PhD programs and that ranked in the top 100 had at least one department that participated in the questionnaire. (Ranking numbers are from US News and World Report [USN&WR, 2008]). About half the schools (48%) ranked in the top 100 and that do not grant PhDs are represented by at least one department. Only 32% of schools not ranked in the top 100 (with or without PhD programs) had one or more department that responded (Figure 5.3). It is not known whether these schools did not respond because they do not have any activities in sustainable engineering or whether they simply did not wish to participate.

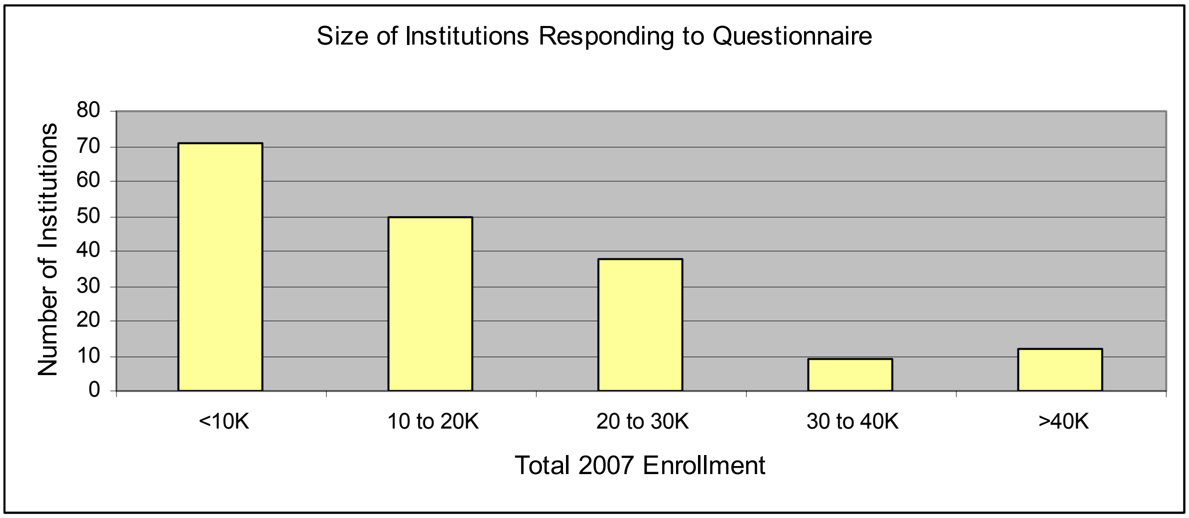


Figure 5.1. Nearly 40% of the institutions represented by the respondents have total enrollments of less than 10,000 students.

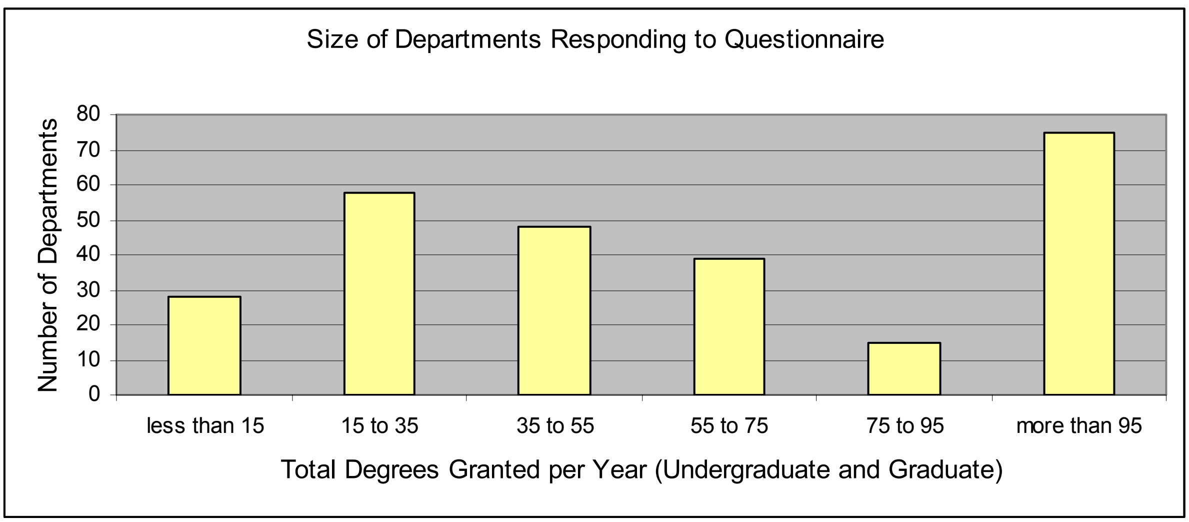


Figure 5.2. One-third of the departments represented by the respondents graduate more than 95 students per year.

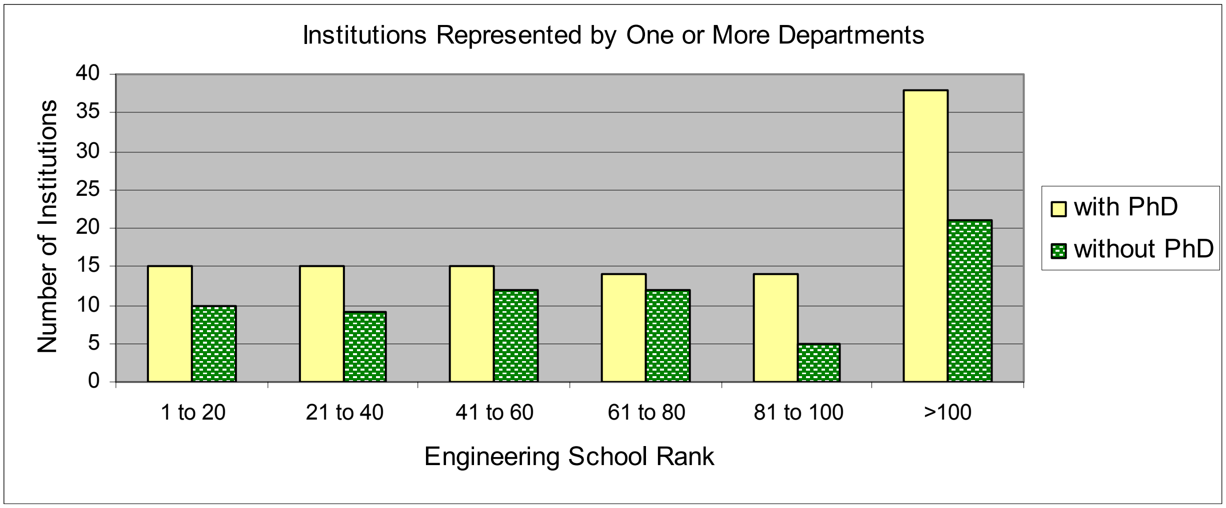


Figure 5.3. Three-quarters of engineering schools ranked in the top 100 and that grant PhDs are represented by at least one department in the responses. Approximately half of non-PhD granting institutions ranked in the top100 responded.

A total of 47 states, plus Puerto Rico, the District of Columbia, and one overseas American school are represented in the results; only Vermont, Maine, and Wyoming had no institutions that responded to the questionnaire. Roughly half the responses are from 10 states, either based on the number of institutions participating (93 out of 180) or the number of departments (146 out of 286). New York, California, Pennsylvania, and Ohio had the greatest number of both institutions and departments responding at 17 (27), 13 (20), 12 (23), and 9 (14) respectively. Indiana, Missouri, and Virginia had a large number of departments that responded from a relatively small number of schools with 5 (11), 5 (10), and 4 (14), respectively (Figure 5.4).

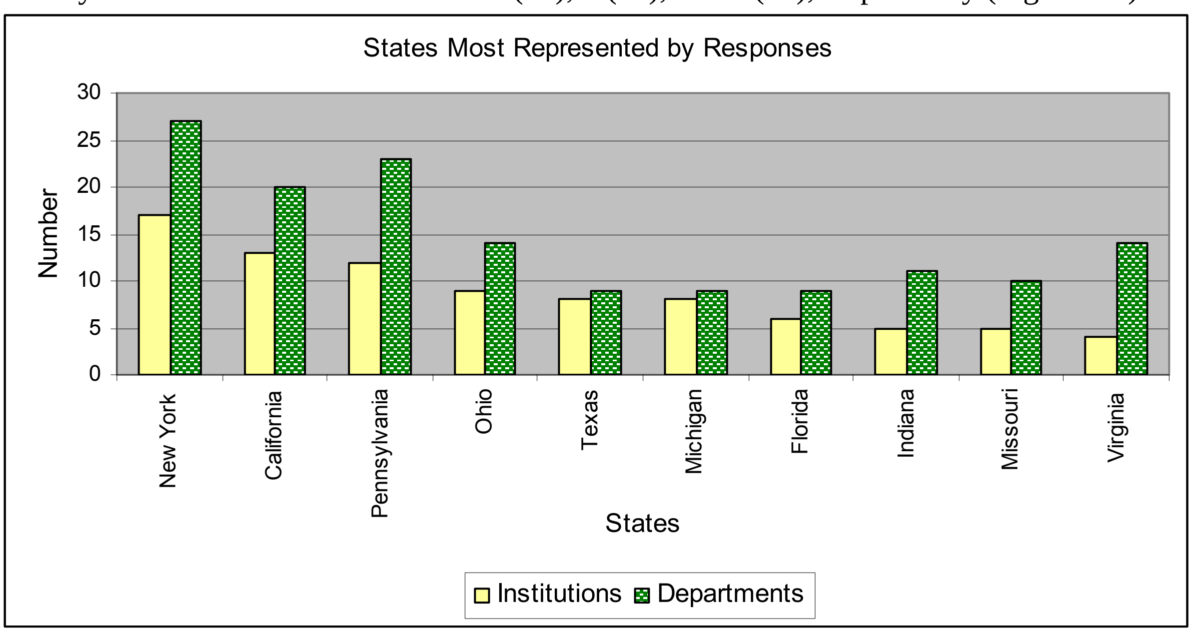


Figure 5.4. Roughly half the responses, whether by number of institutions or number of departments participating, are represented by 10 states.

If states are grouped by regions, the mid-Atlantic and Great Lakes regions have the most representation in the questionnaire responses (Figure 5.5).

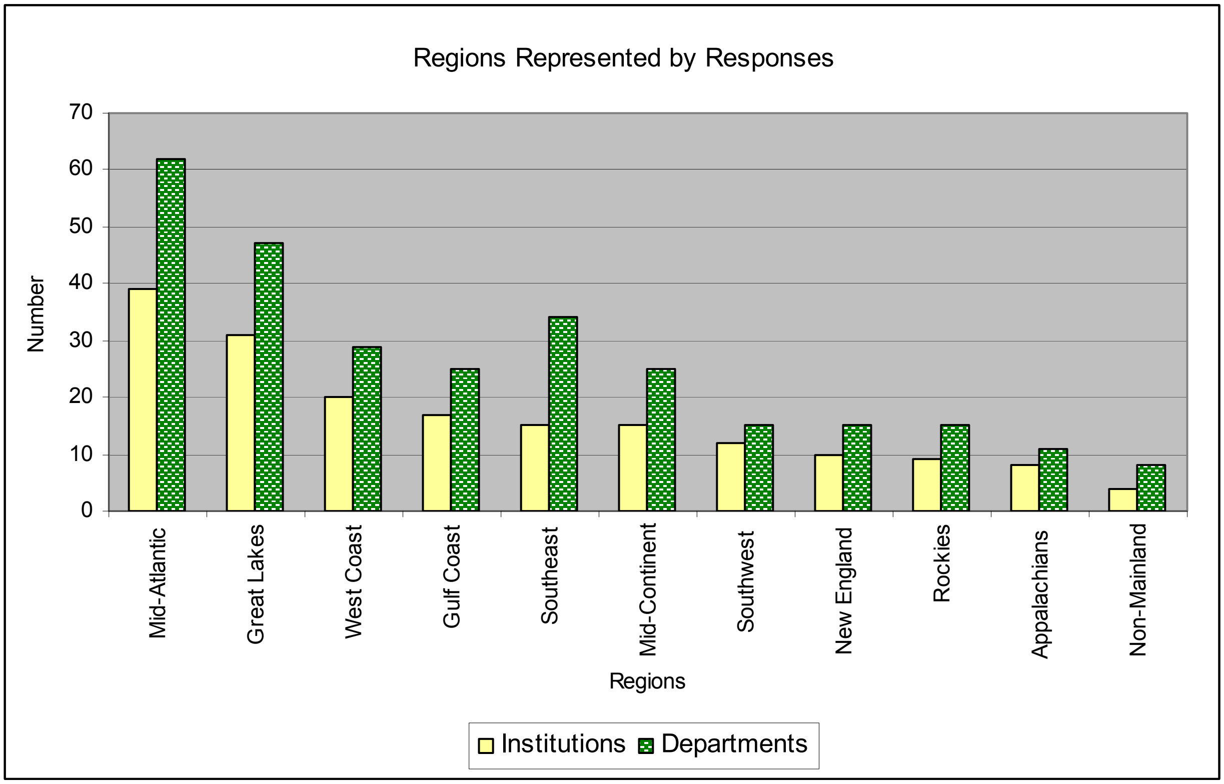


Figure 5.5. States from the mid-Atlantic and Great Lakes regions represent about one-third of all the responses

Mid-Atlantic (New York, New Jersey, Pennsylvania, Delaware, District of Columbia, Maryland)
Great Lakes (Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio)
West Coast (California, Oregon, Washington)
Gulf Coast (Alabama, Mississippi, Louisiana, Texas)
Southeast (Virginia, North Carolina, South Carolina, Georgia, Florida)
Mid-Continent (Missouri, Oklahoma, Arkansas, North Dakota, South Dakota, Nebraska, Iowa, Kansas)
New England (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut)
Rockies (Idaho, Montana, Wyoming, Colorado)
Southwest (Arizona, New Mexico, Utah, Nevada)
Appalachians (West Virginia, Tennessee, Kentucky)
Non-Mainland (Alaska, Hawaii, Puerto Rico, International)

Courses

Of the 286 departments represented by this questionnaire, 229 (80%) are **not** represented in the results of the course portion champion questionnaire, discussed in Chapter 3 of this report. Conversely 41% (64 out of 155) of the courses described in Chapter 3 are not represented by a departmental response in this section. In part, this is likely a reflection of the difficulties of conducting a true census; it may also be indicative of the need to improve coordination and communication between systemic activities at the department level and individuals working to promote sustainable engineering within the department. The third possibility is that although more than 80% of the responding departments report offering sustainable engineering focused material in their curricula and/or courses into which sustainable engineering content has been integrated, 35% of these report offering only integrated courses and no sustainable engineering focused courses (Table 5.1). These departments, therefore, may not have an obvious sustainable engineering champion who would have been contacted through the champion questionnaire.

Table 5.1. Types of Courses Reported

Engineering Discipline	No Sustainable Engineering Focused or Integrated Courses		Sustainable Engineering Focused but No Integrated Courses		Integrated Courses but No Sustainable Engineering Focused		Both Sustainable Engineering Focused and Integrated Courses	
	#	%	#	%	#	%	#	%
Chemical, Bio-, Materials	7	11.0%	3	6.1%	21	40.2%	28	42.7%
Civil, Architectural, Environmental	9	11.9%	5	5.1%	33	35.6%	35	47.5%
Electrical, Computer	16	39.0%	1	2.4%	14	34.1%	10	24.4%
General	1	5.6%	1	5.6%	8	44.4%	8	44.4%
Industrial, Systems, Sustainable	3	16.7%	0	0.0%	6	33.3%	9	50.0%
Mechanical, Aero-, Manufacturing	10	19.2%	4	7.7%	15	28.8%	23	44.2%
Other	4	25.0%	2	12.5%	5	31.3%	5	31.3%
Total	50	17.5%	16	5.6%	102	35.7%	118	41.3%

Respondents to the administrative head questionnaire were asked about both past courses (those offered between fall 2003 and spring 2007) and current courses (those slated for the 2007-2008 academic year). There was virtually no difference in the numbers, so the discussion that follows will address both collectively and will be described as courses offered within the past 5 years.

Sustainable Engineering Content

The first type of course addressed in the questionnaire is that where sustainable engineering is the focus. Almost half of all departments (47%) report having offered at least one course in this area within the last 5 years. Roughly one-sixth (16%) have offered 3 or more such courses (Figure 5.6). The engineering discipline where lack of these courses is most prevalent is electrical and/or computer engineering with 73% having no courses. Departments categorized as "Other" have the greatest percentage (25%) of departments offering 3 or more sustainable engineering focused courses. There are very few departments in any discipline with 2 courses in this area.

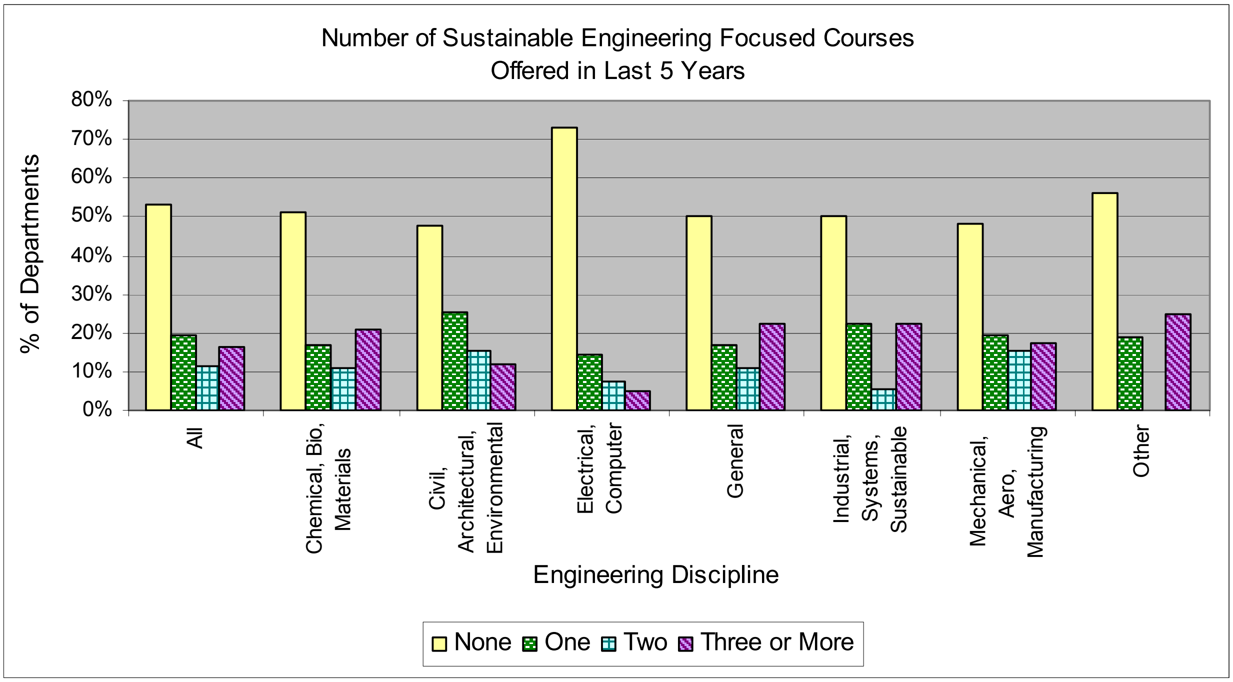


Figure 5.6. Approximately half of all departments (47%) report offering at least one course focused on sustainable engineering within the last 5 years. One in six departments (16%) has offered 3 or more courses. The discipline where lack of these courses is most prevalent is electrical and/or computer engineering with 73% having no courses. Departments categorized as "Other" have the greatest percentage (25%) of departments offering 3 or more courses.

The second type of course about which the respondents were queried is that where concepts of sustainable engineering are integrated into traditional engineering courses. Approximately three-quarters (77%) of the responding departments report having offered at least one such course. More than 40% of electrical and/or computer engineering departments offer no such courses, while nearly 60% of Civil, Architectural, and/or Environmental Engineering departments have offered three or more (Figure 5.7).

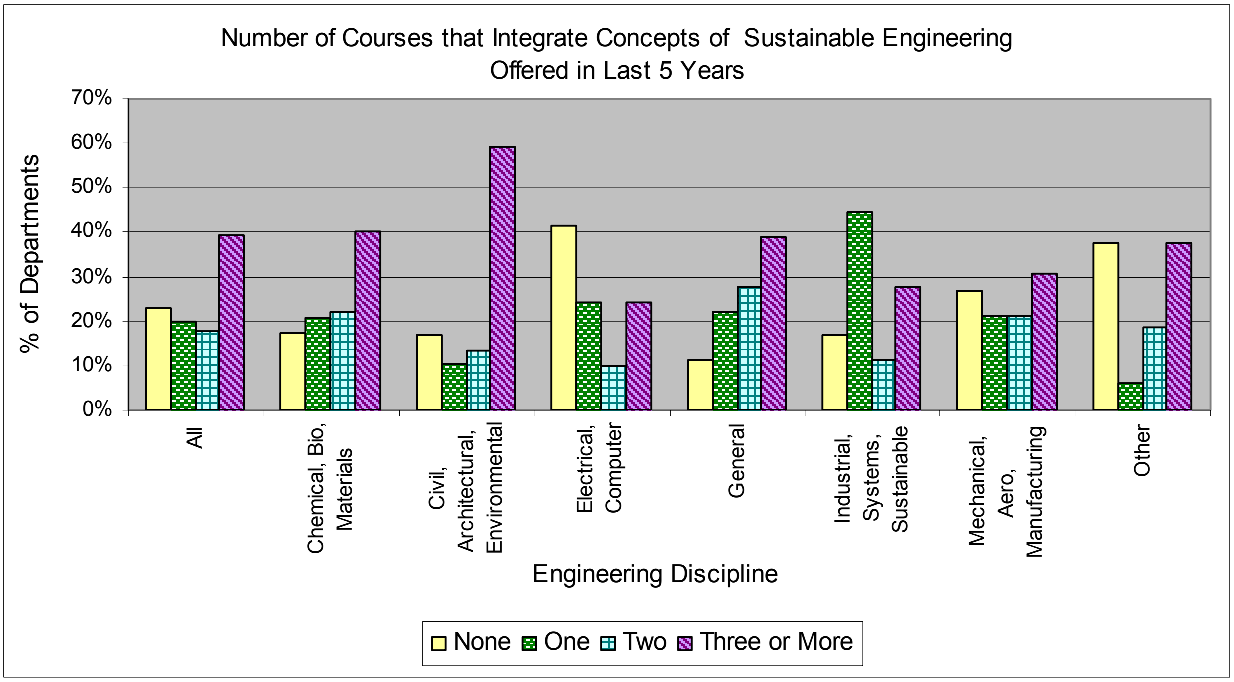


Figure 5.7. More than three-quarters (77%) of the responding departments have offered at least one course into which concepts of sustainable engineering have been integrated. More than 40% of Electrical and/or Computer Engineering departments offer no such courses, while nearly 60% of Civil, Architectural, and/or Environmental Engineering departments offer three or more.

If these two types of courses are considered together (i.e., those that focus on sustainable engineering plus those into which sustainable engineering concepts have been integrated), several observations can be made (Figure 5.8). First, Electrical and/or Computer Science and Engineering departments have the fewest number of courses addressing sustainable engineering concepts, whether as stand-alone courses or as integrated material. More than one-third (39%) of the responding departments offer no courses of either type and only 5% report offering 3 or more of each type (i.e. a total of 6 or more sustainable engineering courses). On the other end of the spectrum, 94% of General Engineering Departments offer at least one course of one type or the other. Although only 11% of these departments offer 6 or more courses, this may be a reflection of the fact that General Engineering departments (or equivalent academic units) tend to be located at schools with smaller enrollments (two-thirds of the general engineering departments at participating institutions have less than 10,000 students) and therefore have a smaller number of total course offerings.

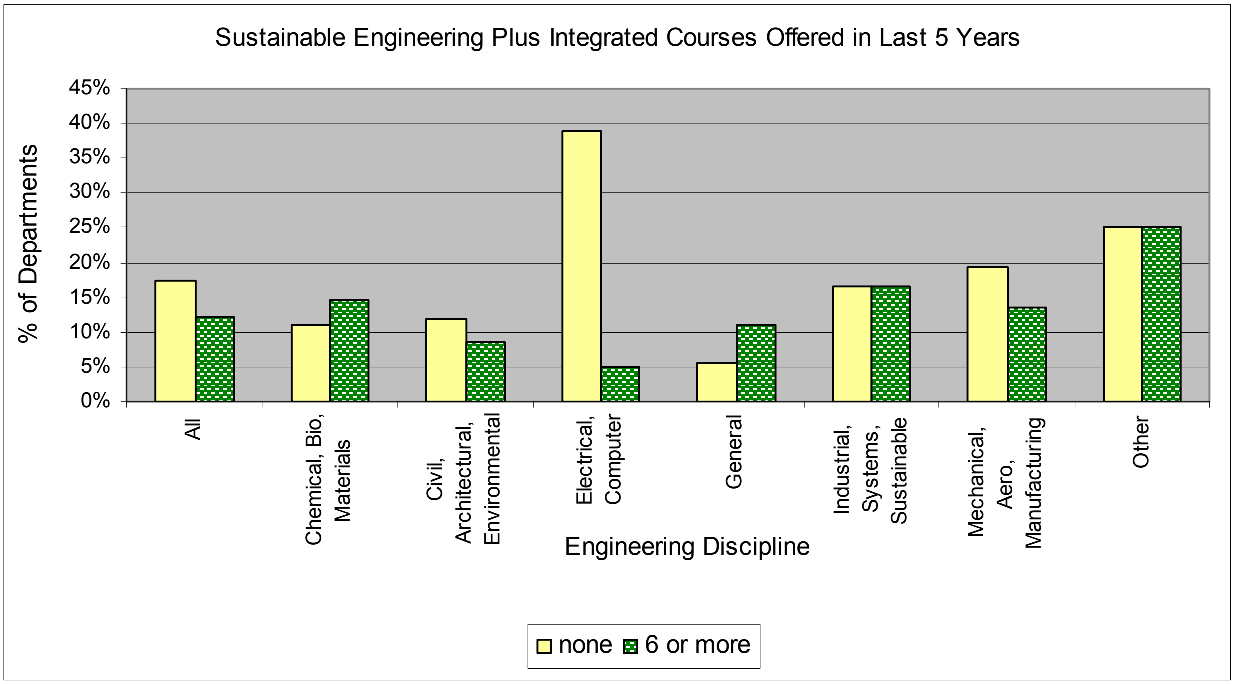


Figure 5.8. Electrical and/or Computer Science and Engineering departments have greatest percentage of departments with no sustainable engineering or integrated courses. General Engineering has lowest percentage of departments with no courses, but does not have a particularly high percentage with 6 or more. The "Other" department category has the second highest percentage of "no courses", but the highest with 6 or more.

Departments that are grouped together as "Other" and which include such fields as mining, petroleum, and nuclear engineering have the highest percentage of sustainable engineering content courses. One-fourth (25%) offer 3 or more sustainable engineering focused courses as well as 3 or more courses into which sustainable engineering concepts have been integrated (i.e., a total of 6 or more). The discipline grouping with next highest percentage of departments offering 6 or more sustainable engineering courses is Industrial, Systems, and/or Sustainable Engineering with one-sixth (17%) of departments reporting 3 or more courses of both types. These two discipline groupings also have the second and fourth highest percentage, respectively, of departments that offer no courses with sustainable engineering content, suggesting that there is a tendency for a department in these categories to either embrace sustainable engineering as an area of focus or to de-emphasize this area. It is observed that 75% of all Chemical, Bio-, and/or Materials Engineering departments and 80% of all Civil, Architectural, and Environmental Engineering departments offer between 1 and 5 SE content courses and therefore do not appear to be firmly at either extreme.

Sustainable engineering content is most commonly offered in the form of a mixture of course types (both sustainable engineering focused courses and integrated course material), with 41% of responding departments indicating this approach (Table 5.1 and Figure 5.9). Nearly as many departments (36%), however, offer only integrated courses. It should be noted that no guidance was offered in the questionnaire as to how much sustainable engineering material needed to be integrated in order for it to qualify as an integrated course, nor was any definition of sustainable engineering provided. Therefore, this is unlikely to be a very precise number and likely to be an overestimate. The discipline grouping "Other" has the highest percentage of departments that offer sustainable engineering focused courses but no integrated courses. This may reflect that as highly specialized departments themselves, there may be a "cultural bias" towards specialized courses.

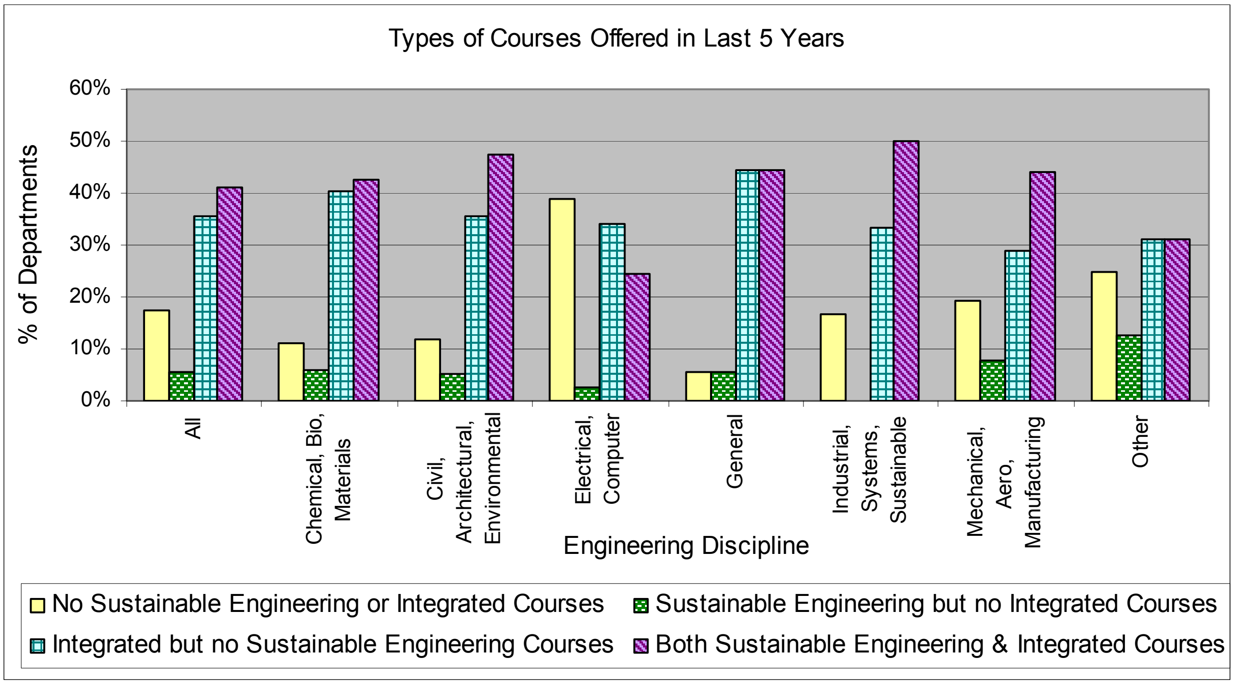


Figure 5.9. Most departments (41%) offer integrated courses in combination with sustainable engineering focused courses. Departments grouped as "Other" have the highest percentage of sustainable engineering focused courses only.

Department Size

The size of a department was thought to be a potential factor in influencing the assimilation of sustainable engineering into the curriculum. A small department might not have the critical mass of students or faculty needed to add non-traditional material; on the other hand a smaller department might also have greater flexibility in determining curriculum content. The participants were asked to estimate the number of degrees granted per year by their department. This is assumed to be an acceptable estimate of the department size. Because the answers were limited to discrete multiples of ten, a three-point running average was used as a data-smoothing device. The relationship between the department size and whether 1) any sustainable engineering courses were being taught and 2) whether a significant number (i.e., 3 or more) of courses were being taught was then investigated graphically. In both cases, it appears that the barriers to making such course offerings increases gradually until the department grants approximately 70 degrees or more per year, at which point, there is both a distinct drop in number of departments offering no sustainable engineering courses as well as a marked increase in the number of departments offering 3 or more such courses (Figures 5.10 and 5.11).

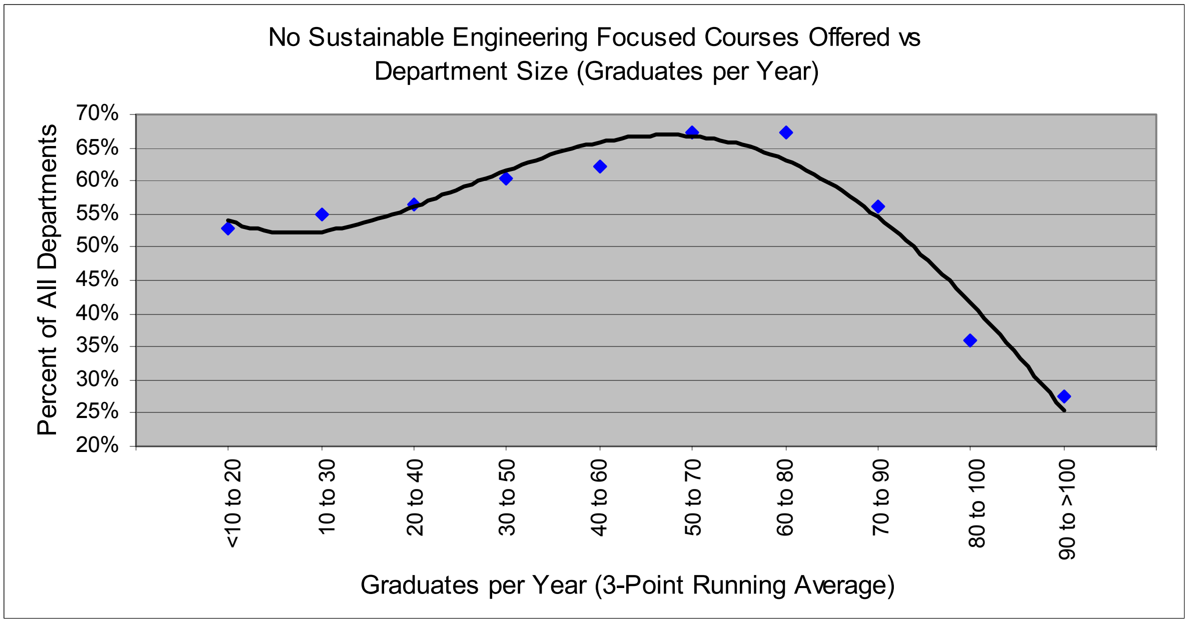


Figure 5.10. There is a slight increase in the percentage of departments offering no sustainable engineering focused courses up to about 70 graduates per year, at which point there is a significant decrease as department size increases to 100 or more graduates per year.

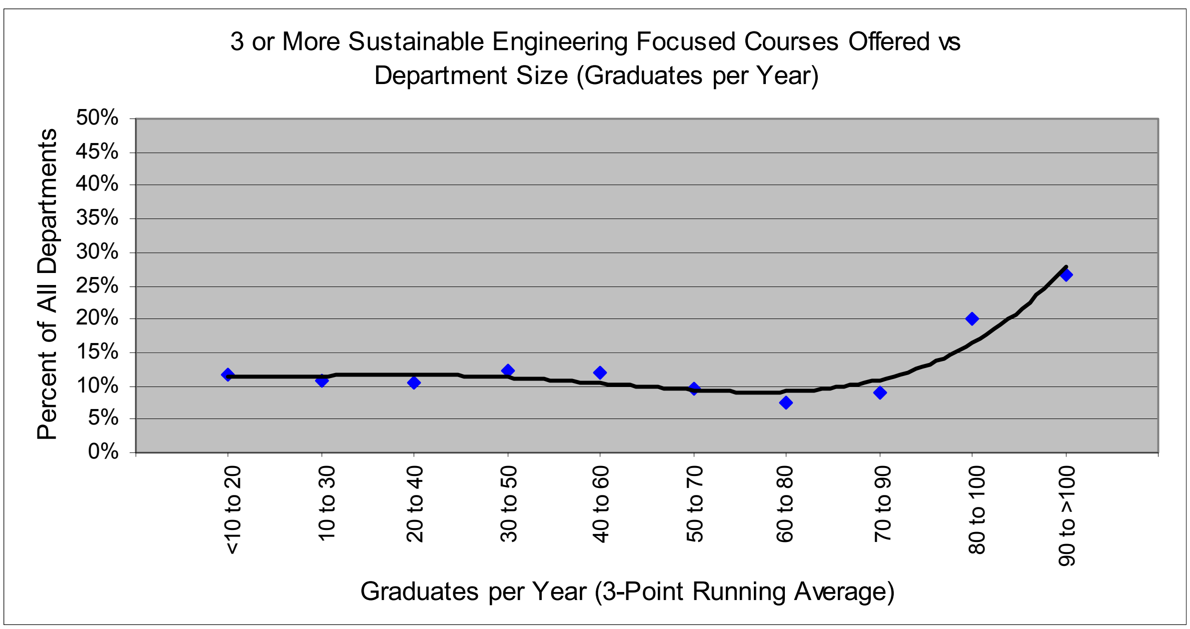


Figure 5.11. There is a slight decrease in the percentage of departments offering three or more sustainable engineering focused courses up to about 70 graduates per year, at which point there is a significant increase as department size increases to 100 or more graduates per year.

A similar pattern is seen when the number of integrated courses is compared to department size, except that there is a secondary inflection point at about 20 graduates per year. This suggests that very small departments may encounter less resistance to curriculum changes (Figures 5.12 and 5.13).

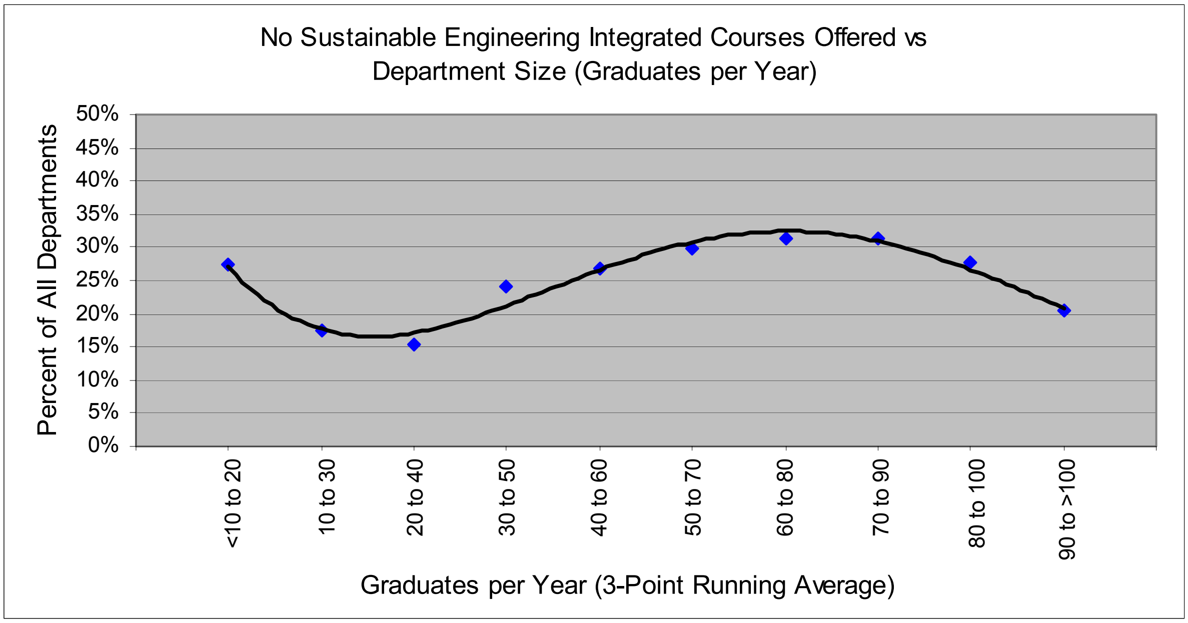


Figure 5.12. The highest percentages of departments offering no integrated courses are those with fewer than 20 graduates per year and those with approximately 70 graduates per year.

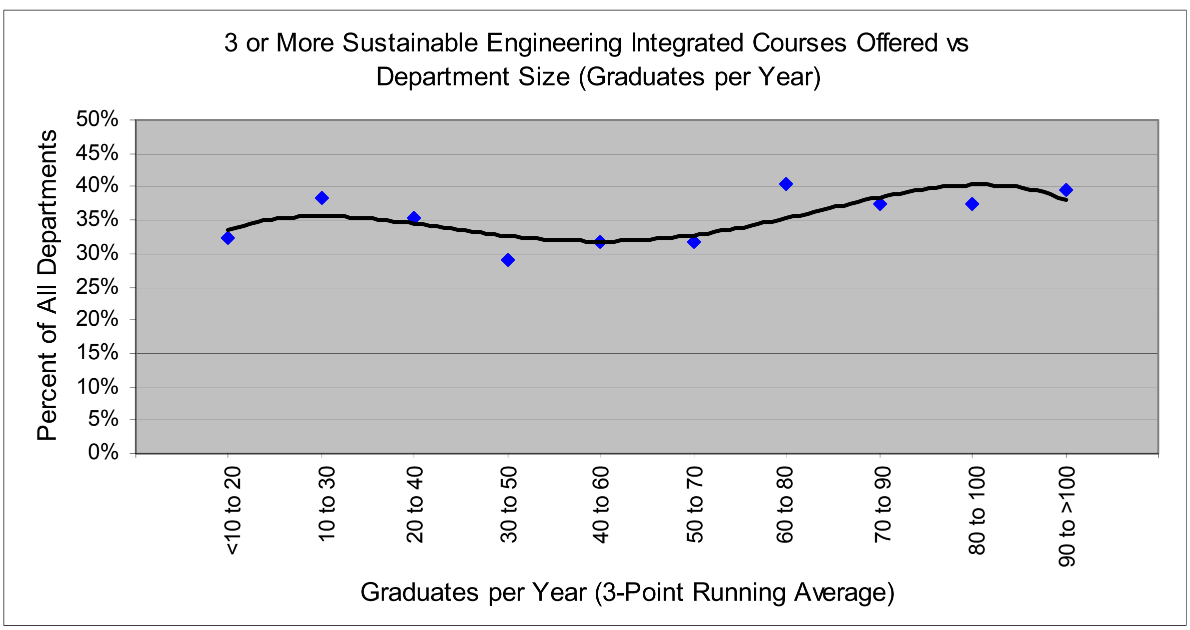


Figure 5.13. The highest percentages of departments offering 3 or more integrated courses tend to be small (with approximately 20 graduates per year) or large (approximately 100 graduates per year) but trends are not dramatic.

When the number of sustainable engineering focused courses are considered together with integrated courses and compared to department size, major inflection points are observed at 60 to 70 graduates per year, after which the percentage of departments having 3 or more of each type of sustainable engineering increases sharply, and the percentage having none decreases in a corresponding manner. Twenty-five percent of all departments with 100 graduates per year offer 3 or more sustainable engineering courses of each type (i.e., 6 or more courses total) and only 8% offer none. In contrast, only 5% of departments with 60 graduates per year offer 3 or more courses of each type and 28% have no sustainable engineering courses. There are also minor inflections at 20 graduates per year for the percentage of departments having at least one sustainable engineering course (of either type) and at 40 graduates per year for having 3 or more courses of each type (Figure 5.14).

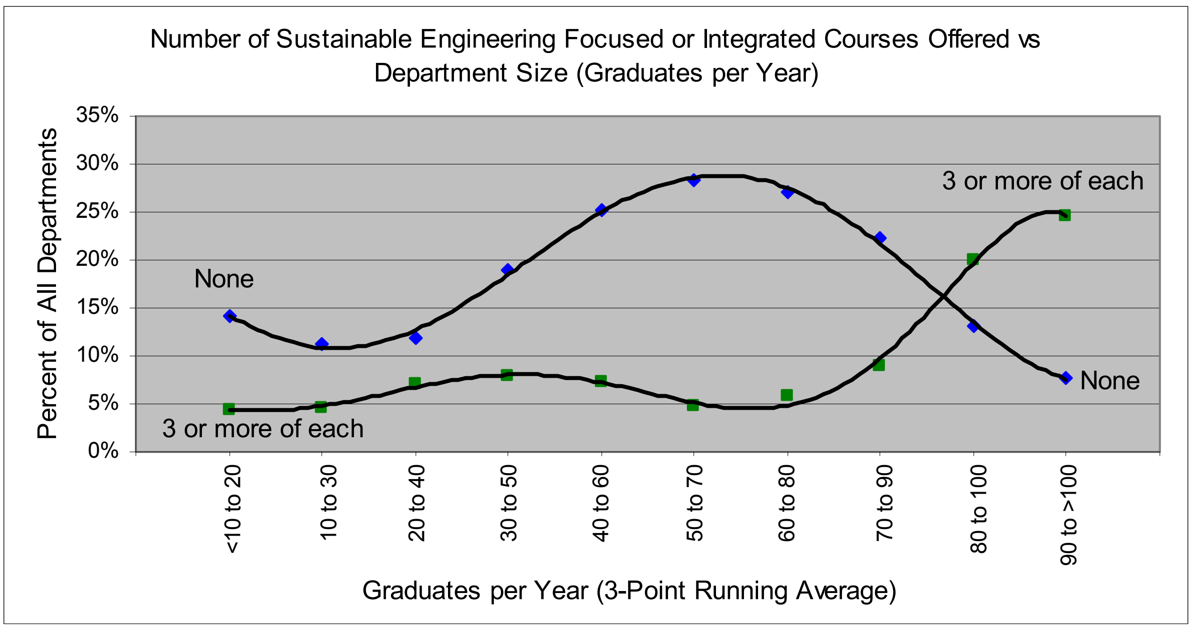


Figure 5.14. The percentage of departments offering no sustainable engineering courses decreases significantly when the number of students graduating per year is greater than 60. There is a corresponding increase in the percentage of departments offering 3 or more courses of each type when the number of graduates per year exceeds 70.

Interdisciplinary Courses

Questionnaire participants were asked about interdisciplinary courses offered, in addition to sustainable engineering courses. While interdisciplinary courses by themselves are not inferred to constitute sustainable engineering, it is thought that interdisciplinary thinking and teaching is a means to facilitate inclusion of sustainable engineering content into the curriculum. Based on the results of the questionnaire, however, there is no obvious correlation between the number of interdisciplinary courses and the number of sustainable engineering courses taught. A graphical depiction of the number of interdisciplinary courses by engineering discipline is presented in Figure 5.15. Mechanical, Aero-, and/or Manufacturing Departments are the most likely to offer no inter-disciplinary courses and the least likely to offer 3 or more. General Engineering has opposite trend, as might be expected given that they tend to be associated with smaller institutions and represent a less specialized discipline. The non-engineering discipline with which an inter-disciplinary course offering is made is most commonly in the Natural Sciences; the least likely area is in the Humanities (Figure 5.16).

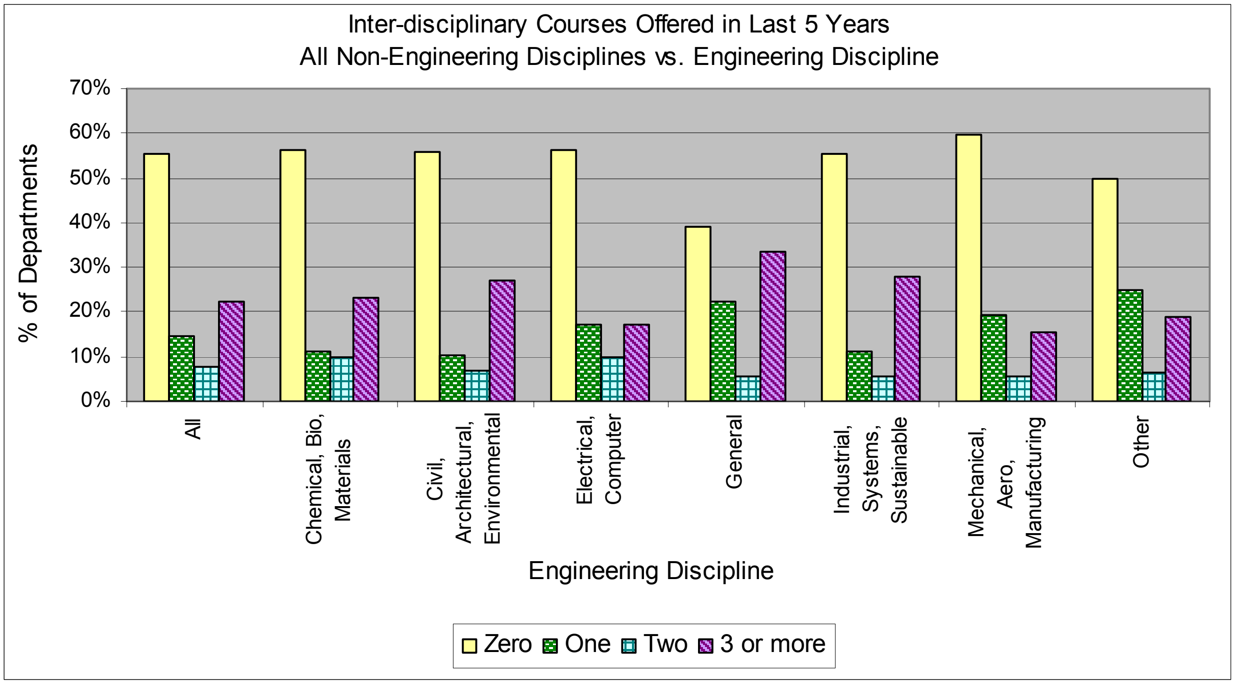


Figure 5.15. Mechanical, Aero-, and/or Manufacturing Departments are the most likely to offer no inter-disciplinary courses and the least likely to offer 3 or more. General Engineering has opposite trend, as might be expected.

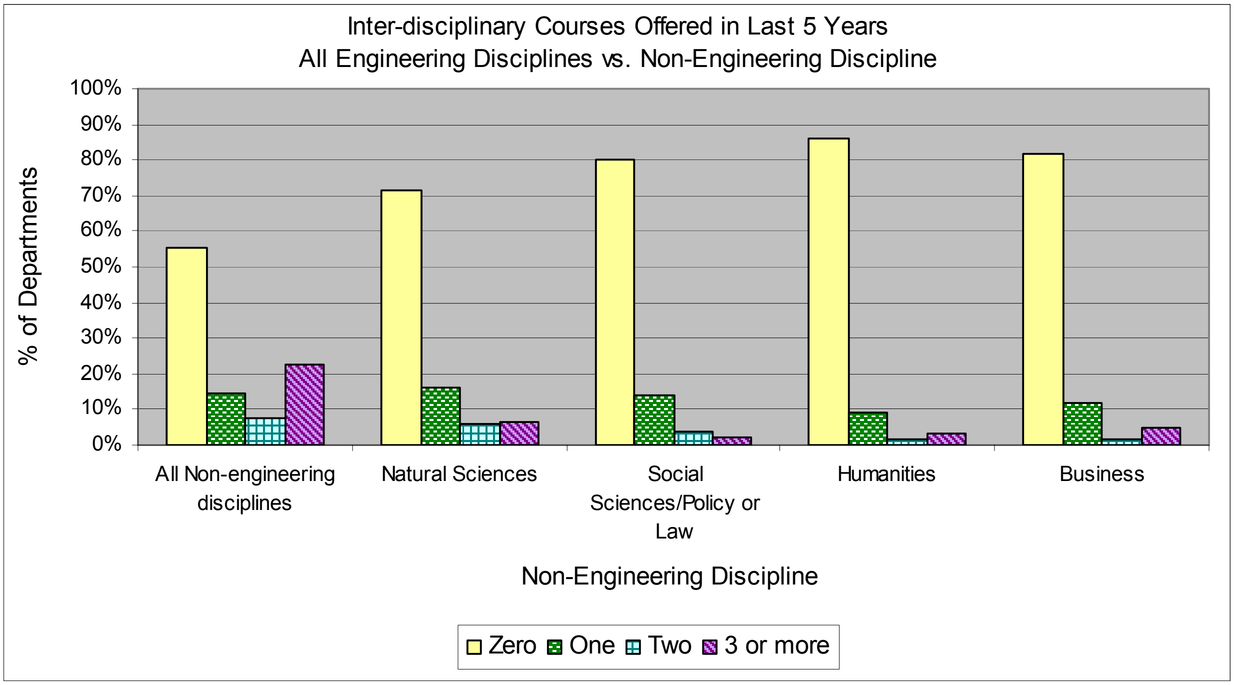


Figure 5.16. Just under half of the departments have at least one inter-disciplinary course with a non-eng department. Humanities is least likely area and Natural Science is the most likely.

Degrees

A total of 33 departments (12% of those responding) from 26 schools (14%) grant both Bachelors and Masters Degrees that are sustainable engineering related. An additional 17 departments from 17 institutions have Bachelors degree programs and 15 departments from 15 schools grant Masters only, for a total of 65 departments (23%) and 53 institutions (29%). None of the departments responding to the questionnaire grant sustainable engineering related doctoral degrees.

One-third of all General engineering departments offer Bachelors and/or Masters degrees in a sustainable engineering related area (Table 5.2). Those departments classified as “Other” along with Chemical, Bio-, and/or Materials Engineering departments offer nearly the same percentage (31%), with a total of 5 and 18 departments, respectively. There are 19 (23%) Civil, Architectural, and/or Environmental departments and 10 (19%) Mechanical, Aero-, and/or Manufacturing departments that offer degrees. Electrical and/or Computer Science and Industrial, Systems, and/or Sustainable engineering offer the lowest percentages at 4 (10%) and 2 (11%) respectively.

Table 5.2. Sustainable Engineering Related Degrees by Discipline

Engineering Discipline	Departments responding	Bachelors only		Masters only		Bachelors and Masters		Total Departments with One or More Degree Programs	
	#	#	%	#	%	#	%	#	%
Chemical, Bio-, Materials	59	4	6.8%	3	5.1%	11	18.6%	18	30.5%
Civil, Architectural, Environmental	82	2	2.4%	6	7.3%	11	13.4%	19	23.2%
Electrical, Computer	41	0	0.0%	1	2.4%	3	7.3%	4	9.8%
General	18	4	22.2%	0	0.0%	2	11.1%	6	33.3%
Industrial, Systems, Sustainable	18	0	0.0%	1	5.6%	1	5.6%	2	11.1%
Mechanical, Aero-, Manufacturing	52	4	7.7%	3	5.8%	3	5.8%	10	19.2%
Other	16	2	12.5%	1	6.3%	2	12.5%	5	31.3%
Total	286	17	5.9%	15	5.2%	33	11.5%	65	22.7%

Participants were also asked about interdisciplinary degree offerings between their department and other non-engineering departments. It was hypothesized that departments that offered interdisciplinary degrees would tend to be more flexible and therefore be more likely to offer a sustainable engineering related degree as well. The total number of sustainability degrees offered per department was summed and compared against the sum of interdisciplinary degrees in each non-engineering discipline category. There was a positive correlation between sustainable engineering and interdisciplinary degrees in natural sciences, social sciences, and humanities; however, the correlation between sustainable engineering and engineering/business interdisciplinary degrees was weakly negative. The correlation coefficients are low, but given that the range of values is only zero to three or zero to two in the number of interdisciplinary and sustainable engineering degrees, respectively, this is not unexpected. The correlation between the number of sustainable engineering degrees and engineering/natural science interdisciplinary degrees is the strongest, followed by interdisciplinary degrees with social sciences. If the number of natural and social science interdisciplinary degrees per department is summed, thus effectively doubling the range, the correlation coefficient improves. The general relationship is that there is likely to be one sustainable engineering degree for every three interdisciplinary degrees (Figure 5.17). Data were too sparse to evaluate these trends by specific engineering discipline.

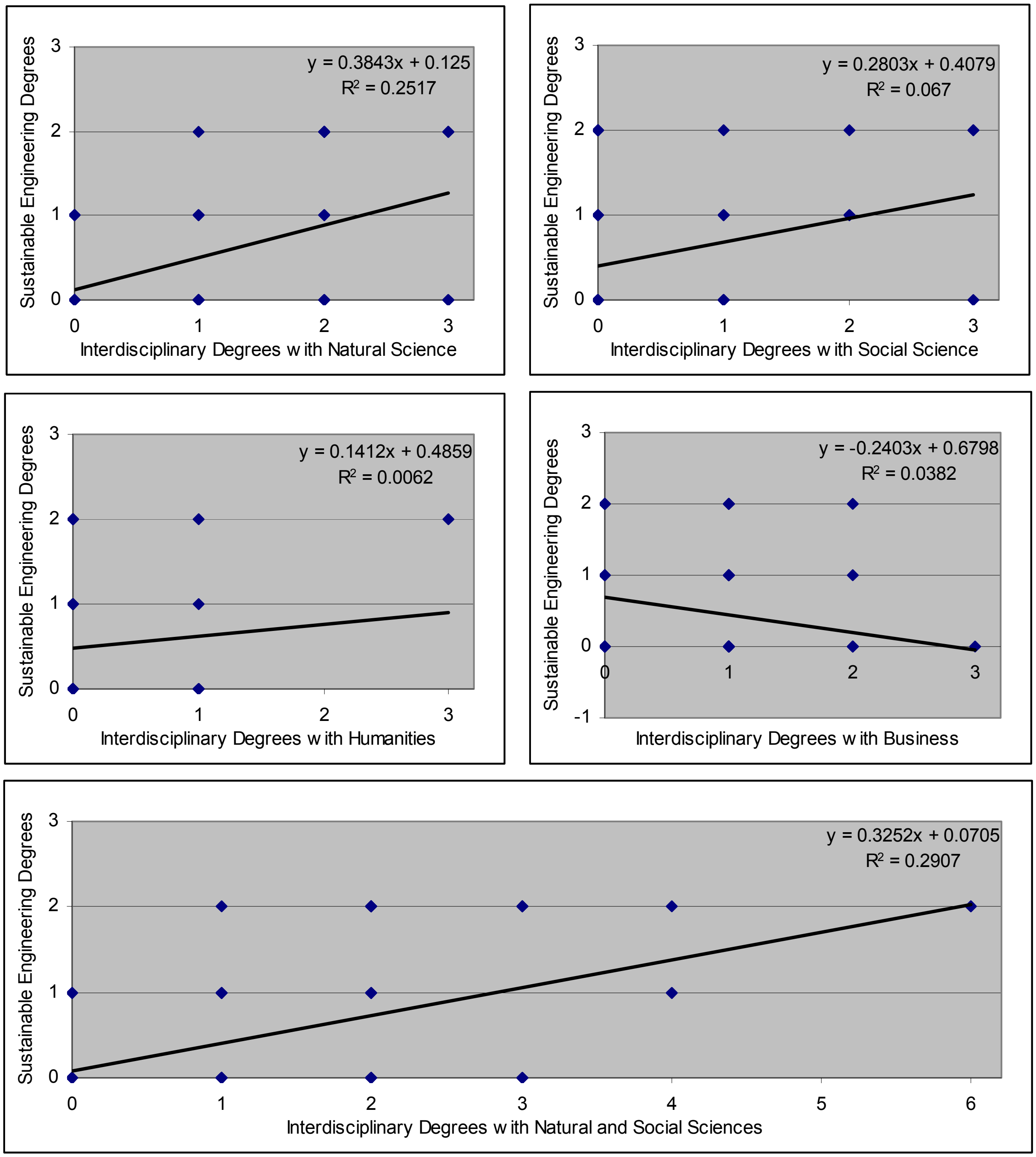


Figure 5.17. With the exception of engineering/business interdisciplinary degrees, there is a positive correlation between the number of interdisciplinary degrees offered by a department and the number of sustainable engineering degrees.

Research

The questionnaire asked about the number of research projects as well as centers and institutes in which the departments were involved. A total of 87 departments (30%) report that since July 2003, that their program has had no research projects that focused primarily on concepts, and/or topics of sustainable engineering and no projects that were coordinated with a non-engineering program. Although these schools tend to be slightly smaller, slightly lower ranked, and to not have a PhD program, these differences are only marginal. For example, 36% of the departments that have no such research projects do not offer PhDs, compared to 26% of those that do.

The number of sustainable engineering research projects is substantially greater than the number of interdisciplinary projects with non-engineering disciplines. More than half of all departments report at least one sustainable engineering project (Figure 5.18) and more than one-third have three or more. Approximately one-third of the departments have or have had at least one project that was coordinated with natural sciences.

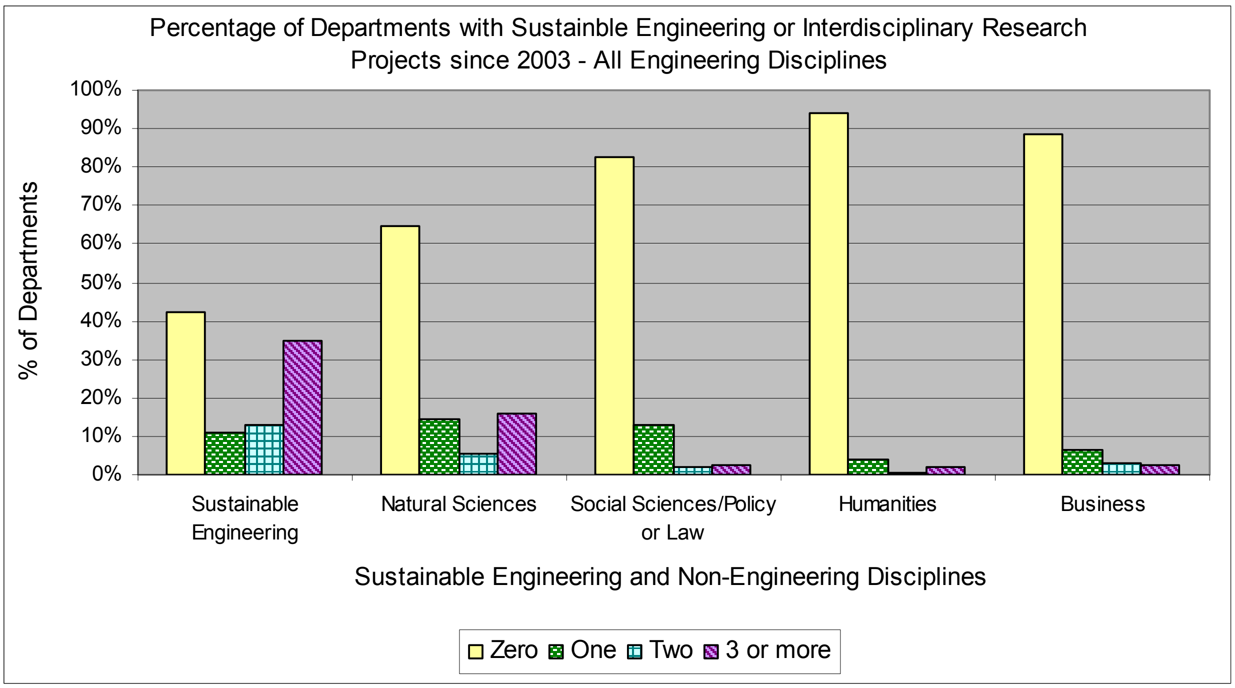


Figure 5.18. The number of sustainable engineering research projects is substantially greater than the number of interdisciplinary projects with non-engineering disciplines. More than half of all departments report at least one sustainable engineering project.

If sustainable engineering projects are examined by engineering discipline, it can be seen that Chemical, Bio-, and Materials Engineering and Civil, Architectural, and Environmental Engineering departments have the highest percentage of department reporting any (69%) as well as the highest percentage with 3 or more (45% and 48% respectively).

More than half of the departments (57%) report hosting one or more centers that are focused on sustainable engineering or that are interdisciplinary with a non-engineering department; 42% are sustainable engineering focused and 6% have 3 or more either sustainable engineering focused centers or interdisciplinary centers with the natural sciences.

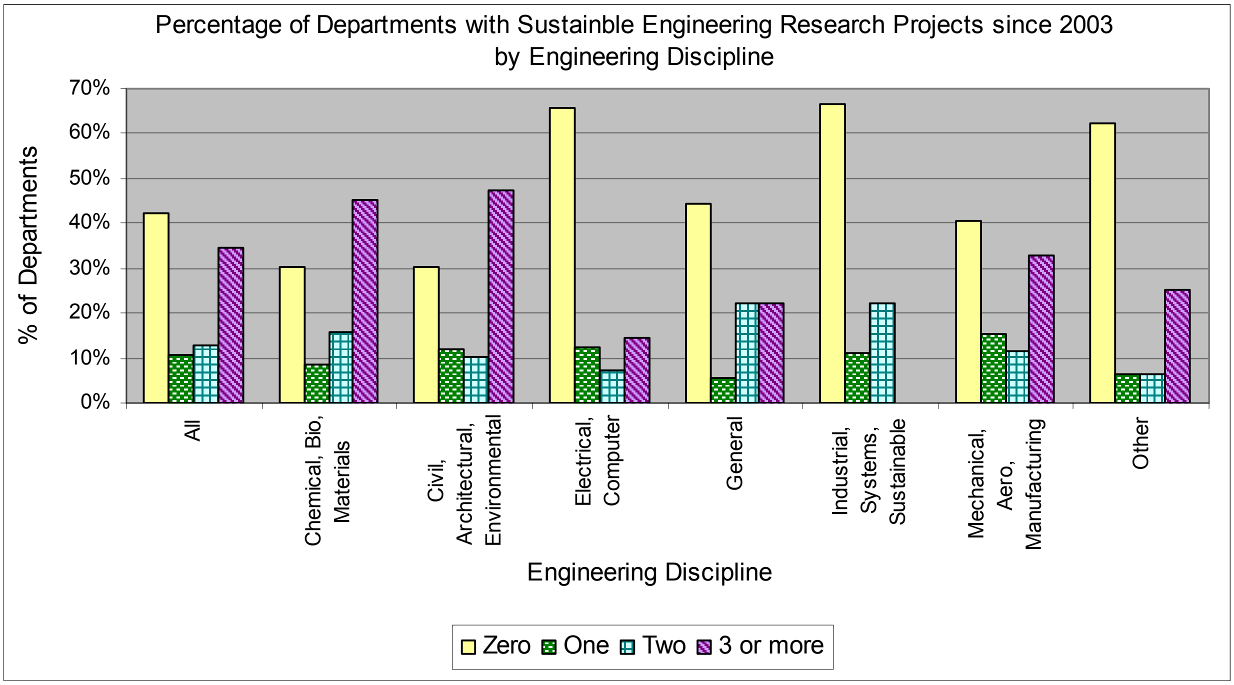


Figure 5.19. Chemical, Bio-, and Materials Engineering and Civil, Architectural, and Environmental Engineering departments have the highest percentage of departments with sustainable engineering research projects.

Conclusions

Three-fourths (73%) of engineering schools with PhD programs and that ranked in the top 100 had at least one department that participated in the questionnaire (Ranking numbers are from US News and World Report [USN&WR, 2008]). Since more than 80% of the respondents reported some level of course activity and 70% reported some research activity, it is clear that sustainable engineering concepts are part of the activities of most of the top 100 engineering programs in the United States. The activity is most extensive at the largest institutions.

While most of the top 100 programs offer courses or conduct research, a much smaller percentage of programs offer degree programs. A total of 33 departments (12% of those responding) from 26 schools (14%) grant both Bachelors and Masters Degrees that are sustainable engineering related. An additional 17 departments from 17 institutions have Bachelors degree programs and 15 departments from 15 schools grant Masters only, for a total of 65 departments (23%) and 53 institutions (29%). A small number of interdisciplinary degree programs are emerging. but these programs are diverse and no systemic trends have been identified.

6.0 Practices of Note

The sustainable engineering education community is now at a critical juncture. To date, there has been a significant level of "grass-roots" activities but little structure or organization. This has led to a proliferation of diverse activities. The path forward will require the evolution of a set of community standards. While developing and encouraging the adoption of standards is the province of engineering accreditation bodies, this benchmarking activity provides an inventory of current practices and can serve as a resource as professional organizations develop these standards.

Previous sections of this report have summarized the general patterns of research and education within the sustainable engineering community. In this section, specific programs and activities with features that are unusual are described. The goal of identifying these programs and practices of note is to help identify potential pathways that the sustainable engineering education community may follow as it establishes common practices.

The information will be organized into four major sections:

- Undergraduate education
- Graduate education
- Research
- Institutional commitment

Within each of these major areas, programs or practices that are unusually comprehensive in breadth or depth, or that have unique features will be noted. The analysis will not identify all programs and practices that have these features, but rather will provide exemplars of programs and practices of note.

Undergraduate Education

An exemplar of an institution with an unusually comprehensive approach to undergraduate education in sustainable engineering is Virginia Tech. At Virginia Tech, students from any undergraduate engineering program can choose a concentration related to sustainable (green) engineering. The students take a total of 18 semester credit hours of courses with sustainable engineering content: six hours within their major, 6 hours of interdisciplinary electives and 6 credit hours that are core to the option. The two core courses provide a general background in environmental science and an introduction to life cycle approaches to engineering problem solving. The consistent approach across all engineering departments and the common core courses, taken by engineers from all departments, make this program noteworthy.

An exemplar of a unique practice in undergraduate education can be found at the University of Texas. At the University of Texas, engineering faculty have developed and taught university courses with no pre-requisites that are offered as part of a reform of the undergraduate core curriculum. The curriculum reform requires that all university students take "Signature Courses" that teach multi-disciplinary approaches to addressing complex and pervasive societal problems. A course titled "Sustaining a Planet" describes material and energy cycles in the natural world (e.g., the carbon cycle), how natural systems interact with and are modified by engineered systems (e.g., how carbon emissions from engineered systems perturb global carbon cycles), and how their lives fit into these systems. Signature courses have also been developed on more focused topics in sustainable engineering (e.g., energy systems). These courses provide insight into how sustainable engineering topics can be delivered to broad audiences at the undergraduate level.

Graduate Education

The University of Pittsburgh offers a Sustainable Engineering Fellowship program funded through the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) Program. The focus of the program is on construction and water use, and includes topics such as new materials, reducing energy use and life cycle design and planning. The program partners with the University's Center for Latin American Studies and the University of Campinas in Sao Paulo, Brazil, to host an 8-month international experience in green construction and sustainable water use for the graduate students participating in the program. Students take a course sequence that includes an Introduction to Sustainable Engineering, technical electives, a two semester capstone design sequence, and language instruction. This program is an example of multi-institutional partnering to deliver sustainable engineering education opportunities.

The Colleges of Engineering at the University of Michigan and Yale have partnered with their highly rated Schools of Natural Resources and Environment (Michigan) and Forestry and Environmental Studies (Yale) to develop joint Masters degree programs. Both of these programs are new, launched in 2007. The Michigan program offers three tracks: Sustainable Energy Systems, Sustainable Design and Manufacturing and Sustainable Water Resources. The 30 credit engineering masters program is integrated with the 42 credit natural resources program to yield a 54 credit dual degree program, with a final master's report required. The Yale program also involves core courses from both the School of Engineering (water resources, industrial ecology and sustainable design) and the School of Forestry and Environmental Studies (environmental science, social ecology, economics, and policy and law) and is projected to take students 2.5 years to complete. These programs are exemplars of Colleges of Engineering partnering with other colleges to deliver sustainable engineering education opportunities.

Much more long-standing programs are offered through the Department of Engineering and Public Policy at Carnegie Mellon University. For more than 30 years, this program has offered BS and PhD programs to students interested in both technical and policy dimensions of topics such as energy and environment. The undergraduate program is available only as a double major with any of the traditional engineering departments or with Computer Science. The core of the program consists of selected courses in decision analysis, economics, statistics, and technical topics plus two project courses where students work in teams on a current unstructured problem for an outside client. Graduate student requirements include courses in policy analysis, economics, and probability and estimation methods for engineering systems. Graduate students can pursue a single major in EPP or a double major. This program can be contrasted with the programs at Yale and Michigan, in that it combines engineering, environment and policy into programs that reside within the College of Engineering; most faculty in the Department of

Engineering and Public Policy (EPP) have dual appointments in EPP and one of the traditional engineering departments or Computer Science.

Research

The approach that different institutions take in conducting sustainable engineering research can be categorized in the same manner as teaching in this area. The following models are considered in discussing the exemplary programs currently underway at US universities:

- Integration of sustainable engineering concepts in order to evaluate or improve an existing infrastructure or industry sector
- Development of technologies that will facilitate sustainable behavior and systems
- Interdisciplinary efforts to address complex systems
- Sustainable engineering tool development and optimization

Integration of sustainable engineering concepts in order to evaluate or improve an existing infrastructure or industry sector is the most common approach taken in sponsored research. Institutions that have made large scale commitments to these types of efforts tend to be those with geographic and/or industry ties. The University of California-Berkeley has worked closely with the semiconductor industry, particularly with equipment suppliers, to address full life-cycle impacts of the industry. Similarly, the auto industry and in particular its suppliers, have significantly influenced the work at the University of Michigan. In a third notable example, Arizona State University is able to leverage its location within a rapidly expanding, environmentally challenged urban environment to address issues related to urbanization and development.

The second most common approach to conducting sustainable engineering research is to develop technologies that will result in reduced environmental, economic, and social burdens. Current funding in this area is nearly all energy related. Notable examples include efforts at the University of Texas to address carbon capture and sequestration through a small number of well funded projects. Another model is to coordinate a large number of smaller, but related efforts. Through its Global Sustainable Industrial Systems (GSIS), Purdue is addressing sustainable manufacturing by addressing the improvement of materials and manufacturing processes (https://engineering.purdue.edu/Engr/Research/Initiatives/GSIS).

One of the most effect ways to address complex systems and influence public policy is to create large interdisciplinary umbrella research organizations. The Brook Byers Institute for Sustainable Systems at Georgia Tech (http://sustainability.gatech.edu/research_centers/) is an exemplar of this approach. It brings together 24 different research centers within the university covering a wide range of topics and objectives including water and air quality, urban systems, energy policy and management, sustainable design and manufacturing, and technology development. Another large coordinated effort is The Cornell Center for a Sustainable Future (http://www.sustainablefuture.cornell.edu/index.php); here the university is able to leverage its long history in the areas of food production and social issues in order to address sustainable engineering topics that, in particular, affect the developing world.

Sustainable engineering as a separate discipline, where the development and use of sustainable engineering tools are the focus, is notable effort at Carnegie Mellon University (CMU), Yale, and Ohio State University (OSU). Researchers at CMU are recognized for developing the EIO-LCA tool and for continuing to look at complex industrial sectors through the use of this and related tools. At Yale, the Stocks and Flows Project is a very long term and well funded effort to use and develop Material Flow Analysis (MFA) methodologies. Finally, OSU, through its Center for Resilience and other individual efforts, has focused on Design for Environment (DfE) and thermodynamic methods for measuring the sustainability of systems and projects.

Institutional Commitment

At a number of Universities, institutional commitment to sustainability is evidenced by the formation of Institutes or Schools. Examples include Arizona State University, the University of Michigan, and Rochester Institute of Technology. The most extensive commitment has been made by Arizona State University (ASU), which in 2007 established the world's first School of Sustainability (SOS). The SOS is the educational arm of the ASU Global Institute of Sustainability (GIOS), responsible for integrating sustainability initiatives and associated research initiatives across the University as a whole. The SOS/GIOS mission is to bring together multiple disciplines and leaders to create and share knowledge, train a new generation of scholars and practitioners, and develop practical solutions to some of the most pressing environmental, economic, and social challenges of sustainability, especially as they relate to urban areas. Currently, SOS offers both masters and Ph.D. level degrees in sustainability, and has just begun to offer an undergraduate program.

ASU's approach is noteworthy because it has involved the creation of a school dedicated to sustainability and, unlike many sustainability initiatives at other universities, it has from the beginning emphasized the importance of engineering and technology for sustainability. Accordingly, there has been a close and active relationship between SOS/GIOS and the Ira A. Fulton School of Engineering at ASU. Among other things, this has enabled joint research on challenges such as the theory and practice of sustainable urban infrastructure, water system design and management in desert environments, and life cycle evaluation of complex technology systems such as nanotechnology, and information and communications technology. It has also facilitated development of courses and programs across the two schools, perhaps best illustrated by the recent renaming of the Department of Civil and Environmental Engineering, which is now the Department of Civil, Environmental, and Sustainable Engineering (CESE). CESE remains entirely within the Fulton School of Engineering, but also includes within its curriculum courses on industrial ecology (IE), design for sustainability, and earth systems engineering and management (ESEM) that are cross-listed between the two schools, and designed to be beneficial to students from either school (primarily but not necessarily at the graduate school level). Students in CESE are able to specialize in the traditional tracks of civil and environmental engineering, or in a new track designated "sustainable engineering" which emphasizes IE and ESEM.

References

[USN&WR,2008] US News & World Report (2008). Best Colleges 2009: Premium Online Edition, Undergraduate Engineering Programs, accessed September, 2008 (available for a fee at http://colleges.usnews.rankingsandreviews.com/college/engineering).

[Graedel and Allenby, 1998] Graedel, T.E. and Allenby, B.R., *Industrial Ecology and the Automobile*, Prentice Hall, Upper Saddle River, NJ, 1998

[Hardin, 1968], Hardin , G. (1968). "The Tragedy of the Commons," Science, 162: 1243-1248.

[Mihelcic, J.R., et al, 2003] Mihelcic, J.R., et al., "Sustainability Science and Engineering: The Emergence of a New Metadiscipline," *Environ. Sci. Technol*, 2003 (37), 5314-5324

[U.S. EPA, 1995] United States Environmental Protection Agency (US EPA), "An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms" EPA 742-R-95-001, June, 1995

[AIChE, 2000] American Institute of Chemical Engineers Center for Waste Reduction Technologies (AIChE CWRT), "Total Cost Assessment Methodology", AIChE, New York (ISBN 0-8169-0807-9), 2000.

[Lashbrook, et al., 1997]. Lashbrook, W., et al., "Design for Environment Tools for Management Decision Making in a Selected Case Study," *Proc, IEEE ISEE*, May1997.

[World Business Council on Sustainable Development, 2001] World Business Council for Sustainable Development, "Mobility 2001 - World Mobility at the End of the Twentieth Century and Its Sustainability," August 2001.

[Allenby, 1999]. Allenby, B.R., Industrial Ecology: Policy Framework and Implementation, Prentice Hall, Upper Saddle River, NJ, 1999.

[Axtell, et al. 2001] Axtell, R. L., et al., "Agent-Based Modeling and Industrial Ecology," *Journal of Industrial Ecology*, 2001 (5), 10-13

[World Commission on Environment and Development, 1987] World Commission on Environment and Development, *Our Common Future*, Oxford University Press, 1987

Appendix A. Publications and Presentations

List of Publications Citing EPA Grant

<u>Journal Publications</u>

Allen, D.T., C.F. Murphy, B. Allenby, and C. Davidson, "Sustainable Engineering: A model for engineering education in the 21st century?" Clean Technologies and Environmental Policy, Vol. 8, pages 70-71, 2006.

Allen, D.T., C.F. Murphy, B. Allenby and C. Davidson, "Sustainability in Chemical Engineering Education, Chemical Engineering Progress, 2009 (in press)

Allenby, B.R., D.T. Allen, and C.I. Davidson, "Teaching Sustainable Engineering," Journal of Industrial Ecology, Vol. 11, pages 8-10, 2006.

Allenby, B.R., C.F. Murphy, D.T. Allen, and C.I. Davidson, "Sustainable Engineering Education in the United States," Sustainability Science, Vol.4, No.1, 2009 (in press).

Davidson, C.I., H.S. Matthews, C.T. Hendrickson, M.W. Bridges, B.R. Allenby, J.C. Crittenden, Y. Chen, E. Williams, D.T. Allen, C.F. Murphy, and S. Austin, "Adding Sustainability to the Engineer's Toolbox: A Challenge for Engineering Educators, Environmental Science and Technology," Vol. 41, pages 4847-4850, 2007.

Davidson, C.I., H.S. Matthews, and C.T. Hendrickson, Sustainability in Engineering: A New Sequence of Graduate Courses at Carnegie Mellon, International Journal of Engineering Education, Vol. 23, pages 287-293, 2007.

Allenby, B., D. Allen, and C. Davidson, Sustainable Engineering: From Myth to Mechanism, Environmental Quality Management, Vol. 17, pages 17-26, 2007.

<u>Book Chapters</u>

Allen, D.T., B.R. Allenby, and C.I. Davidson, Engineering Sustainable Technologies, in Designing in Engineering and Architecture: Towards an Integrated Philosophical Understanding, P. Kroes, A. Light, S.A. Moore, and P.E. Vermaas, editors, Kluwer Academic Publishers, Dordrecht, 2008 (in press).

<u>Published Conference Abstracts, Published Conference Proceedings, and Poster Presentations</u>

Davidson, C.I., C.T. Hendrickson, H.S. Matthews, D. Allen, C.F. Murphy, B. Allenby, and J. Crittenden, "Center for Sustainable Engineering: A National Dissemination Center supported by NSF and EPA," Poster presentation, National Conference, Engineers for a Sustainable World, Iowa City, IA, September 27-30, 2006. (Abstract only)

Davidson, C.I., C.T. Hendrickson, and H.S. Matthews, "A Graduate Course Sequence in Sustainable Engineering: The Carnegie Mellon Experience," Platform Presentation, Talking and Walking Sustainability: Second International Conference on Sustainability Engineering and Science, Auckland, New Zealand, February 20-23, 2007. (Paper written for Proceedings)

Oral Presentations without Proceedings or Abstracts

Allenby, B.R., "Teaching Sustainable Engineering," IEEE International Symposium on Electronics and the Environment, San Francisco, CA, May 8-11, 2006.

Davidson, C.I., D. Allen, and B. Allenby, "The Center for Sustainable Engineering: Changing the Way Engineers are Taught," Platform Presentation, National Conference, American Association for the Advancement of Science, National Meeting, San Francisco, CA, February 15-19, 2007

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Center for Sustainable Engineering, US Business Council for Sustainable Development, July 10, 2005.

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Benchmarking Sustainable Engineering Education (BSEE) and Center for Sustainable Engineering (CSE), American Institute of Chemical Engineers (AIChE), Sustainable Engineering Forum, webinar, September 20, 2005.

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, Benchmarking Sustainable Engineering Education (BSEE) and Center for Sustainable Engineering (CSE), Engineers for a Sustainable World Annual Meeting, Austin, Texas, October 8, 2005

Murphy, C.F., D.T. Allen, C.I. Davidson, and B.R. Allenby, "Sustainable Engineering: A Model for Engineering Education in the 21st Century," National Science Foundation, Environmentally Benign Design and Manufacturing, Sustainable Manufacturing V, Rochester Institute of Technology, Rochester, NY, September 18-22, 2007.

Appendix B. Administrative Head Questionnaire

The following letter was sent to the heads of all academic units in which one or more ABET engineering program was housed. This was typically a department head or chair, but in some cases the person was a program chair or dean. The letters were personalized and, based on responses, it appears to have been an effective approach. Email addresses were found through website searches. The letters were first sent out in the spring of 2007. A second round was sent a few months later to those that had not yet participated.

Dear Dr. <Last Name>:

The University of Texas, Carnegie Mellon University, and Arizona State University, with funding from the National Science Foundation and the US Environmental Protection Agency, have formed the Center for Sustainable Engineering (CSE). The purpose of the CSE is to promote, expand, and facilitate the inclusion and integration of concepts of sustainability into engineering programs at US colleges and universities. Issues of sustainability, including the environment, economics, and social concerns, have been recognized as part of the engineering problem set and engineers of the future must not only be aware of the nature and magnitude of the problems, but must also have the skills, knowledge, and tools necessary to deal with them.

In order to characterize the current status of this increasingly important field, we are conducting a study to benchmark the extent to which concepts of sustainability are being incorporated into engineering education at both the undergraduate and graduate levels. We are requesting the assistance of you or your colleagues in collecting information by asking that you complete a questionnaire, available at http://web.austin.utexas.edu/bsee/. This is a census questionnaire that is being distributed to engineering departments across the country; consequently, the more responses we receive, the more accurate our evaluation. As administrative head of <Program Name(s)> at <Institute>, we would appreciate it if you could provide input regarding this (these) particular program(s) as well as any other programs for which you are responsible. The questionnaire should take only 10 minutes to complete and the answers may be supplied by either you or someone designated by yourself as being the most knowledgeable about these issues. In addition, if there are individual champions within your program(s) who are involved in sustainable engineering curriculum development and/or research, it would greatly facilitate our effort if you could supply us with their contact information on the last page of the questionnaire. A separate set of questions will be distributed to these persons in order to characterize specific activities.

A summary report of the study findings will be forwarded to all those who complete the questionnaire. In addition to the report being of general interest, it is hoped that you will find the results valuable in considering how your department might incorporate societal issues into engineering curricula, such as to meet ABET requirements. Results of the questionnaires also will be used to help guide the development of a roadmap and education materials to be made publicly available through the Center for Sustainable Engineering.

Thank you very much for your time and consideration. If you have any questions, please feel free to contact any of us.

Regards,

Cindy Murphy, University of Texas, 512-475-6259, cfmurphy@che.utexas.edu
Dave Allen, University of Texas, 512-475-7842, allen@che.utexas.edu
Cliff Davidson, Carnegie Mellon University, 412-268-2951, cliff@andrew.cmu.edu
Brad Allenby, Arizona State University, 480-727-8594, Braden.Allenby@asu.edu

Upon going to the website the participants were asked to provide contact information. The actual questionnaire follows.

If you are responding to this questionnaire for more than one program, you may group programs together as desired. It is recommended that you glance through the questions first and then decide how to group your programs. If you wish to answer separately for one or more program separately, please complete an additional questionnaire for each set of answers. A prompt will be provided at the end to allow you to repeat the process.

The following answers relate to the following **program(s)**. Please select all that apply:
(Hold the ctrl button down and left click when making multiple selections.)

Select Program Below:

- Aerospace Engineering
- Architectural Engineering
- Chemical Engineering
- Civil Engineering
- Computer Engineering Option in Electrical Engineering
- Electrical Engineering
- Environmental and Water Resource Engineeirng
- Geosystems Engineering and Hydrology
- Mechanical Engineering
- Petroleum Engineering
- Other

Are there any other degree programs not listed to which the answers to the questionnaire should apply? If so, please list them in the space below:

For reference, examples of sustainable engineering tools, concepts, and topics are listed below

Life Cycle Analysis (LCA)	Natural Resource Management	Climate Change
Design for Environment (DFE)	Policy and Regulations	Renewable Energy
Industrial Ecology	Economics (excluding short-term cost analysis)	Green Design
Material Flow Analysis (MFA)	Pollution Prevention	Reuse and/or Recovery of Products and Materials

For questions regarding interdisciplinary activities, biology, geology, human health, economics, sociology, and policy are of the greatest interest.

START QUESTIONNAIRE

1) In 2006 approximately how many total students (graduate and undergraduate) received degrees in these program(s).

<10
10
20
30
40
50
60
70
80
90
100
>100

2) Between Fall 2003 and Spring 2007, how many unique courses were offered within your program that...

	None	1	2	3 or more
a. focused primarily on tools, concepts, and/or topics of Sustainable Engineering?	●	○	○	○
b. integrated concepts of Sustainable Engineering, but which did not have a Sustainable Engineering focus?	●	○	○	○
c. were coordinated with a non-engineering program in Natural Sciences?	●	○	○	○
d. were coordinated with a non-engineering program in Social Sciences/Policy or Law?	●	○	○	○
e. were coordinated with a non-engineering program in Humanities?	●	○	○	○
f. were coordinated with a non-engineering program in Business?	●	○	○	○

3) For the 2007-2008 academic year, how many courses in your program are planned that...

	None	1	2	3 or more
a. will focus primarily on tools, concepts, and/or topics of Sustainable Engineering?	●	○	○	○
b. will integrated concepts of Sustainable Engineering, but which did not have a Sustainable Engineering focus?	●	○	○	○
c. will be coordinated with a non-engineering program in Natural Sciences?	●	○	○	○
d. will be coordinated with a non-engineering program in Social Sciences/Policy or Law?	●	○	○	○
e. will be coordinated with a non-engineering program in Humanities?	●	○	○	○
f. will be coordinated with a non-engineering program in Business?	●	○	○	○

4) Since July 2003, how many significant research projects, including those with other institutions, have been funded within your program that...

	None	1	2	3 or more
a. focus primarily on topics, concepts, and/or topics of Sustainable Engineering?	●	○	○	○
b. were coordinated with a non-engineering program in Natural Sciences?	●	○	○	○
c. were coordinated with a non-engineering program in Social Sciences/Policy or Law?	●	○	○	○
d. were coordinated with a non-engineering program in Humanities?	●	○	○	○
e. were coordinated with a non-engineering program in Business?	●	○	○	○

5) In how many Centers or Institutes involving 3 or more professionals does your program currently participate that...

	None	1	2	3 or more
a. focus on Sustainable Engineering?	●	○	○	○
b. run in cooperation with in Natural Sciences?	●	○	○	○
c. run in cooperation with Social Sciences/Policy or Law?	●	○	○	○
d. run in cooperation with Humanities?	●	○	○	○
e. run in cooperation with Business?	●	○	○	○

6) Is your program involved in the granting of any degrees that...(choose all that apply)

	None	BS	MS	Doctorate
a. are Sustainable Engineering related?	●	○	○	○
b. are coordinated with a non-engineering program in Natural Sciences?	●	○	○	○
c. are coordinated with a non-engineering program in Social Sciences/Policy or Law?	●	○	○	○
d. are coordinated with a non-engineering program in Humanities?	●	○	○	○
e. are coordinated with a non-engineering program in Business?	●	○	○	○

7) Is your program involved in other Sustainable Engineering initiatives? If so please describe:

Appendix C. Sustainable Engineering Champion Questionnaire

Administrative heads from 366 engineering colleges in the United States were asked, as part of the Department Questionnaire (Appendix B) to identify faculty who were active in incorporating sustainability into their teaching and research. Additional individuals, identified through their publications or participation in educational workshops related to sustainability, were added to the list provided by department chairs and program heads. A total of 327 engineering faculty were sent requests to complete detailed questionnaires describing their activities related to sustainability. The following letter was sent to these individuals on xxx, 2008.

Dear Dr. <Last Name>

The University of Texas, Carnegie Mellon University, and Arizona State University, with funding from the National Science Foundation and the US Environmental Protection Agency, have formed the Center for Sustainable Engineering (CSE). The purpose of the CSE is to promote, expand, and facilitate the inclusion and integration of concepts of sustainability into engineering programs at US colleges and universities.

You have been recognized as being a leader in Sustainable Engineering and we would appreciate knowing more about both your research and teaching experiences in this area. To that end, we are requesting that you complete a questionnaire, available at http://web.austin.utexas.edu/bsee/champstart.cfm.

The first section of the questionnaire asks about Sustainable Engineering research activities; the second asks about courses taught. The course part may be repeated as many times as desired and we request that a separate form be used for each individual course. There are only four required fields in the entire questionnaire: your state, your institution name, your last name and your email address, so you may participate at any level you feel comfortable. You are also invited to upload any course documents (such as a syllabus) at the end of the questionnaire.

If you wish to leave the questionnaire at any time and return, you need only click the "SUBMIT" button at the bottom of the page to save your changes to date. Upon returning, you will need to enter your email address to recall previous entries. You may continue to add or edit information through Friday April 4th.

A summary report of the study findings will be forwarded to all those who complete the questionnaire. Thank you very much for your time and consideration. If you have any questions, please feel free to contact any of us.

Regards,

Cindy Murphy, University of Texas, 512-475-6259, cfmurphy@che.utexas.edu
Dave Allen, University of Texas, 512-475-7842, allen@che.utexas.edu
Cliff Davidson, Carnegie Mellon University, 412-268-2951, cliff@andrew.cmu.edu
Brad Allenby, Arizona State University, 480-727-8594, braden.allenby@asu.edu

Upon going to the website the participants were asked to provide contact information. The actual questionnaire, in two parts, follows.

.

WHAT STARTS HERE CHANGES THE WORLD
THE UNIVERSITY OF TEXAS AT AUSTIN

ARIZONA STATE UNIVERSITY

Carnegie Mellon

CSE

National Science Foundation
WHERE DISCOVERIES BEGIN

For reference, examples of sustainable engineering tools, concepts, and topics are listed below

Life Cycle Analysis (LCA)	Natural Resource Management	Climate Change
Design for Environment (DFE)	Policy and Regulations	Renewable Energy
Industrial Ecology	Economics (excluding short-term cost analysis)	Green Design
Material Flow Analysis (MFA)	Pollution Prevention	Reuse and/or Recovery of Products and Materials

RESEARCH

If you wish to skip this section and go directly to the "COURSE" section of the questionnaire click **HERE**:

Sponsored Research Information

1) Please describe up to 3 sustainable engineering research projects in which you have been involved

Project 1

Project Title ______________________________

URL (if available) ______________________________

Your Role ○ PI ○ co-PI ○ Researcher ○ Other

Name of Sponsor ______________________________

Length of Project (months) ______________________________

Total Sponsorship ($) ______________________________

Project 2

Project Title ______________________________

URL (if available) ______________________________

Your Role ○ PI ○ co-PI ○ Researcher ○ Other

Name of Sponsor ______________________________

Length of Project (months) ______________________________

Total Sponsorship ($) ______________________________

Project 3

Project Title ____________________

URL (if available) ____________________

Your Role ○ PI ○ co-PI ○ Researcher ○ Other

Name of Sponsor ____________________

Length of Project (months) ____________________

Total Sponsorship ($) ____________________

2) What is the typical number of students (working under your direction) involved in sustainable engineering research at any given time?

Undergraduate

Fully Supported ________

Partially Supported ________

Unsupported ________

Graduate

Fully Supported ________

Partially Supported ________

Unsupported ________

<u>Dissemination and Publications</u>

3) Name up to 3 conferences in which you are involved in the area of sustainable engineering:

________________, ________________, ________________,

4) What journals do you read to keep abreast of sustainable engineering activities?

________________, ________________, ________________,

5) In what journals have you published sustainable engineering work?

________________, ________________, ________________,

6) In what journals are you considering publishing current work in sustainable engineering?

________________, ________________, ________________,

<u>Centers and Institutes</u>

Please provide information for centers and/or institutes in which you are personally involved.

7) Center or Institute Name ____________________

8) URL Address ____

9) When was this center or institute established?

- ○ 2007 – 2008
- ○ 2005 – 2006
- ○ 2003 – 2004
- ○ 2002 or earlier

10) What is the number of full-time equivalent researchers, faculty and staff?

- ○ Less than 10
- ○ 10 to 30
- ○ 30 to 100
- ○ More than 100

11) In a few words, please describe the focus of this center/institute including particular industries, resources, products, or substances addressed

____

12) What is your role in the center/institute?

____

.

COURSES

Please fill out a separate questionnaire for each course. We are particularly interested in courses that include 4 or more hours of lecture material (or the equivalent) focused on sustainable engineering. Complete only for those courses that are offered by (or in cooperation with) engineering departments. At the end of the questionnaire you will be given the opportunity to upload a syllabus for each course, if desired.

Name of Course ____

Course URL (if publicly available) ____

Primary Department through which it is offered ____

Name of the professor(s) or instructor(s) ____

Prerequisites or expected background ____

1) What best characterizes the course:

○ Sustainable engineering is dominant theme
○ Sustainable engineering concepts are integrated into the course rather than being the dominant theme
○ Technical material that supports sustainable engineering (e.g., alternative fuels, emerging materials, design
○ Cross- or interdisciplinary

2) Is this course (check one):

○ A self-standing course
○ Part of an informal, multi-course sequence
○ A formal minor degree requirement
○ A formal degree requirement

3) If this course is not a self-standing course, how many other courses (expressed as one-term equivalents) are included in the sequence:

- ○ One
- ○ 2-5
- ○ >5
- ○ not applicable

4) If this course is not a stand-alone course, please provide the names of other instructors involved in teaching the sequence.

5) Through what other departments schools (if any) is this course offered or cross-listed?

6) When was the course first offered:

- ○ 2007 – 2008 academic year
- ○ 2005 – 2006 or 2006 – 2007
- ○ 2003 – 2004 or 2004 – 2005
- ○ 2002 – 2003 or earlier

7) How many times has this course been offered?

- ○ Once
- ○ Twice
- ○ Three or more
- ○ Not sure

8) What is the typical number of students per class?

- ○ Less than 10
- ○ 10 to 30
- ○ 30 to 100
- ○ More than 100

9) What is the number of weekly contact hours?

Lectures	___
Discussion	___
Lab	___
Other	___

10) Estimate percentages of those enrolled in class by level:

Freshman and/or Sophomores	___
Juniors and/or Seniors	___
Graduate Students	___
Total	100%

11) Estimate the percentage of those enrolled in class by major

Department through which course is offered	___
Other engineering department	___
Non-engineering	___
Total	100%

Questions 12 through 15 are an attempt to identify the most useful resources (books, papers, websites, and software tools) available rather than a full cataloguing of all materials; therefore, please focus on those that you would particularly recommend to others or that are central to teaching the course.

12) Textbooks used, both traditional and sustainable engineering focus (max 3)

Title	______________________	Author	______________________
Title	______________________	Author	______________________
Title	______________________	Author	______________________

13) Readings in sustainable engineering concepts (max 3)

Title	______________________	Author	______________________
Title	______________________	Author	______________________
Title	______________________	Author	______________________

14) Web Sites containing sustainable engineering content (max 3)

Title	______________________	URL	______________________
Title	______________________	URL	______________________
Title	______________________	URL	______________________

15) Software for sustainable engineering related activities

Title ______________________________ URL (if applicable ______________________

Title ______________________________ URL (if applicable ______________________

Title ______________________________ URL (if applicable ______________________

16) Projects, homework sets, or other non-classroom activities focused on sustainable engineering

Title ______________________________ URL (if applicable ______________________

Title ______________________________ URL (if applicable ______________________

Title ______________________________ URL (if applicable ______________________

17) What portion of this course would you describe as being focused on sustainable engineering?

○ less than 10%
○ 10 to 25%
○ 25 to 50%
○ More than 50%

18) What portion of this course considered the following system boundaries? In addition, check all of the concepts that were addressed in the class

Gate to Gate % of total course content ________

Definition: Decisions are made within a single facility or corporation by engineering and/or business units.

Check all that were covered by the course.

☐ process design, including material and/or energy reduction
☐ material or chemical selection
☐ product design for a single phase of a product's life (e.g., design for recycling)
☐ pollution prevention
☐ media-based (i.e., air, water, solid waste) regulations
☐ other (specify) ____________________

Cradle to Grave % of total course content ________

Definition: Decisions are made by different entities over the life of a product or sector activity. Activities are typically analyzed as sequential events.

Check all that were covered by the course.

☐ resource availability and economics
☐ consumer behavior
☐ product utility
☐ reuse and recycling options
☐ product based legislation (e.g., WEEE) and standards (e.g., ISO 14000)
☐ life cycle inventory development
☐ other (specify) ____________________

Inter-industry or stakeholder interactions % of total course content ___________

Definition: Decisions are made by two or more entities (corporations or other stakeholders), often involving multiple sectors. Typically captures spatial as well as temporal effects and scales, although temporal scales may be compressed such that activities are presumed to occur in parallel.

Check all that were covered by the course.

- ☐ material flows analysis
- ☐ by-product synergy
- ☐ eco-industrial development
- ☐ multiple/nested LCA analysis
- ☐ input-output analysis (either physical or economic)
- ☐ other (specify) water management

Extra-industry % of total course content ___________

Definition: Decisions are made by multiple stakeholders, including industry, non-governmental organizations (NGOs), policy makers, consumers, etc.

Check all that were covered by the course.

- ☐ policy development (current and historical)
- ☐ consumption patterns and preferences
- ☐ eco-industrial development
- ☐ multiple/nested LCA analysis
- ☐ input-output analysis (either physical or economic)
- ☐ other (specify) water management

19) Assuming that sustainable engineering is multi-disciplinary, please indicate the relative coverage given to each of the following 5 general non-engineering disciplines within this course. In addition, check all of the concepts that were addressed in the class and indicate specific analysis tools or software that were applied.

Life Sciences % of total course content ___________

Definition: Human, animal, or plant health. Mortality and reproduction rates are primary metrics.

Check all that were covered by the course.

- ☐ toxicology
- ☐ biological ecosystems
- ☐ nutrient availability
- ☐ other (specify) ___________________________

Analytical tools used (including databases, software and web sites):.

____

Physical and Environmental Sciences % of total course content ___________

Definition: Mechanical and chemical properties, activities, and interactions. Mass, energy, and time are primary metrics.

Check all that were covered by the course.

- ☐ fate and transport
- ☐ chemical reactions and behavior in the geo-biosphere
- ☐ perturbations and flows within the geo-biosphere
- ☐ physical input-output analysis
- ☐ other (specify) ___________________________

Analytical tools used (including databases, software and web sites):.

____

Economics and Business % of total course content ___________

Definition: Exchange of goods and services. Accounts for natural and/or man-made capital at micro and/or macro levels. Currency is primary metric.

Check all that were covered by the course.

- ☐ cost analysis
- ☐ economic input-output analysis
- ☐ life cycle cost analysis
- ☐ other (specify) ___________________________

Analytical tools used (including databases, software and web sites):.

____

Sociology and Policy % of total course content ___________

Definition Control and analysis of human behavior. Values typically expressed as counts or fractions relative to a desired target.

Check all that were covered by the course.

- ☐ environmental regulations and legislation
- ☐ consumer behavior
- ☐ cultural and other value systems
- ☐ other (specify) ___________________________

Analytical tools used (including databases, software and web sites):.

____

Humanities and Aesthetics % of total course content ___________

Definition: Elements that provide comfort and pleasure.

Check all that were covered by the course.

- ☐ architecture
- ☐ design
- ☐ leisure
- ☐ other (specify) ___________________________

Analytical tools used (including databases, software and web sites):.

____

20) If you are teaching or taught the class how satisfied were you with the following?

Student Involvement

Class size	○ about right	○ too small	○ too large
Attendance	○ good	○ adequate	○ poor
Students' grasp of material	○ excellent	○ adequate	○ poor

Available Teaching Materials

Textbooks	○ good	○ adequate	○ poor
Readings	○ good	○ adequate	○ poor
Software	○ good	○ adequate	○ poor
Websites	○ good	○ adequate	○ poor

Additional Comments:

____

Appendix D. Course Syllabi

Copies of the course syllabi are available online at the CSE website (http://www.csengin.org/)

This page intentionally left blank

Appendix E. Resources

Books and Readings

Architecture, land use, and/or human ecology

<u>Agriculture and Land Use</u>

Jackson, J.B., 1986, Discovering the Vernacular Landscape, Yale University Press

Lampkin, N.H. and Padel, S. (eds), 1994, The Economics of Organic Farming: An International Perspective, CAB International

McHarg, I. L., 1992, Design with Nature, John Wiley & Sons

Ndubisi, F., 2002, Ecological Planning: A Historical and Comparative Synthesis, Johns Hopkins University Press

Spirn, A.W., 1998, Language of Landscape, Yale University Press

Building & Construction

Haselbach, L., 2008, The Engineering Guide to LEED-New Construction, McGraw-Hill

Kibert, C.J., 1999, Reshaping the Built Environment: Ecology, Ethics, and Economics, Island Press

Kibert, C.J., 2008, Sustainable Construction: Green Building Design and Delivery, 2nd ed, John Wiley & Sons

Kreider, J.F., Rabl, A., and Curtiss, P., 1994, Heating and Cooling of Buildings: Design for Efficiency, McGraw-Hill

Mendler, S.F., Odell, W. and Lazarus, M.A., 2006, The HOK Guidebook to Sustainable Design, 2nd ed, John Wiley & Sons

Schaeffer, J., 2005, Real Goods Solar Living Sourcebook: Your Complete Guide to Renewable Energy Technologies and Sustainable Living, 12th ed, Gaiam Energy Tech, Inc

USGBC, 2005, LEED® for New Construction & Major Renovations, Version 2.2, US Green Building Council, October 2005

<u>Design</u>

Johnson, B.R. and Hill, K., 2002, Ecology and Design: Frameworks for Learning, Island Press

McLennan, J.F., 2004, The Philosophy of Sustainable Design, Ecotone Publishing Company

Spirn, A.W., 1984, The Granite Garden: Urban Nature and Human Design, Basic Books

Steiner, F.R., 2002, Human Ecology: Following Nature's Lead, Island Press

Van der Ryn, S. and Cowan, S., 1996, Ecological Design, Island Press

<u>Transportation</u>

Forman, R.T.T, Sperling, D., Bissonette, J.A., and Heanue, K., 2003, Road Ecology: Science And Solutions, Island Press

<u>Urbanism and Urban Systems</u>

Barlett, P.F. (ed), 2005, Urban Place : Reconnecting With the Natural World, MIT Press

Environmental engineering

<u>Biogeochemical Systems (incl. Ecology)</u>

Davis, M.L. and Masten, S.J., 2004, Principles of Environmental Engineering and Science, McGraw-Hill

<u>End of Life and Waste Management</u>

Amezquita, H.A., Hammond, R.C., Salazar, M., and Bras, B.A., 1995, Characterizing the remanufacturability of engineering systems, P. ASME Advances in Design Automation Conference, Boston, Massachusetts, September 17-20, 1995, DE-Vol. 82, 271-278,

Amezquita, T., and Bras, B.A., 1996, Lean remanufacture of an automobile clutch, P. 1st International Workshop on Reuse, (S.D. Flapper and A.J. de Ron eds.), Eindhoven, The Netherlands, November 11-13, 1996, 35-52

Tchobanoglous, G. and Kreith, F., 2002, Handbook of Solid Waste Management, McGraw-Hill

Pollution Prevention, Fate & Transport

Allen, D.T. and Rosselot, K.S., 1997, Pollution Prevention for Chemical Processes, John Wiley & Sons

American Institute for Pollution Prevention (AIPP) and Aldrich, J.R., 1993, A Primer for Financial Analysis of Pollution Prevention Projects, US EPA, ORD, EPA/600/R-93/059, April 1993

Bishop, P.L., 2000, Pollution Prevention: Fundamentals and Practice, McGraw-Hill

Masters, G.M. and Ela, W.P., 2008, Introduction to Environmental Engineering and Science, 3rd ed, Prentice Hall

Masters, G.M., 1997, Introduction to Environmental Engineering and Science, 2nd ed, Prentice Hall

Water

Bitton, G., 1999, Wastewater Microbiology, 2nd ed, Wiley-Liss

Cheryan, M., 1998, Ultrafiltration and Microfiltration Handbook, 2nd ed, CRC Press

Crites, R.W. and Tchobanoglous, G., 1998, Small and Decentralized Wastewater Management Systems, McGraw-Hill

Crittenden, J (ed.), 2005, Water treatment : principles and design / MWH , 2nd ed, John Wiley & Sons

Davis, M.L. and Cornwell, D.A., 2006, Introduction to Environmental Engineering, 4th ed, McGraw-Hill

Degrémont Technologies, 1991, Water Treatment Handbook, 6th ed, Lavoisier Publishing

Faust, S.D. and Aly, O.M., 1998, Chemistry of Water Treatment, 2nd ed., Lewis Publishers

Hillis, P., ed, 2000, Membrane Technology in Water and Wastewater Treatment, Royal Society of Chemistry

Mays, L.W., 2005, Water Resources Engineering, John Wiley & Sons

Omelchenko, A., Pivovarov, A.A., and Swindall, W.J. (eds), 2005, Modern Tools and Methods of Water Treatment for Improving Living Standards, Springer

Reynolds, T.D. and Richards, P.A., 1996, Unit Operations and Processes in Environmental Engineering, 2nd ed., PWS Publishers

Rittman, B. and McCarty, P.L., 2001, Environmental Biotechnology: Principles and Applications, McGraw-Hill

Schafer, A., 2001, Natural Organics Removal Using Membranes: Principles, Performance, and Cost, Technomic Pub

Spellman, F.R. and Drinan, J., 2000, The Drinking Water Handbook, CRC Press

Tchobanoglous, G., Burton, F.L. and Stensel, H.D., 2003, Wastewater Engineering: Treatment and Reuse / Metcalf and Eddy, Inc., McGraw-Hill

Viessman, W., and Hammer, M.J., 2005, Water Supply and Pollution Control, 7th ed, Pearson Prentice Hall

Xie, Y., 2002, Disinfection Byproducts in Drinking Water: Formation, Analysis, and Control, CRC Press, Taylor & Francis Group
History, ethics, and/or philosophy

Energy & Power Generation

Fouquet, R. and Pearson P.J.G., 1998, "A Thousand Years of Energy Use in the United Kingdom", The Energy Journal, 19: (4) 1-41
Freese, B., 2003, Coal: A Human History, Perseus Publishing
Rose, M.H. and Clark, J.G., 1979, Light, Heat, and Power: Energy Choices in Kansas City, Wichita, and Denver, 1900-1935, J. Urban History, 5 (3): 340-364
Smil, V., 1994, Energy in World History, Westview Press, Chapter 5, pp. 157-222
Tarr, J.A. and DuPuy, G. (eds), 1988, Technology and the Rise of the Networked City in Europe and America, Temple University Press, 246-281

Humanities (philosophy, ethics, history)

Bernstein, P.L., 1996, Against the Gods: The Remarkable Story of Risk, John Wiley & Sons
Diamond, J., 1995, “Easter Island’s End”, Discover Magazine, August 1995
Florman, S. C., 1996, The Existential Pleasures of Engineering, 2nd ed, St. Martin’s Griffin
Garreau, J., 2005, Radical Evolution: The Promise and Peril of Enhancing Our Minds, Our Bodies -- and What It Means to Be Human, Doubleday
Gorman, M.E., Mehalik, M.M., and Werhane, P.H., 2000, Ethical and Environmental Challenges to Engineering, Prentice Hall
Lima, M. and Oakes, W.C., 2006, Service Learning: Engineering in Your Community, Great Lakes Press
Nye, D.E., 1999, Consuming Power: A Social History of American Energies, MIT Press
Pursell, C.W. (ed), 1990, Technology in America, 2nd ed, MIT Press
Rome, A., 2001, The Bulldozer in the Countryside: Suburban Sprawl and the Rise of American Environmentalism, Cambridge University Press
Shearman, R., 1990, The meaning and ethics of sustainability, Environmental Management, 14 (1):1-8
Vallero D.A. and Vesilind, P.A., 2006, Socially Responsible Engineering: Justice in Risk Management, John Wiley
Wilson, E.O., 2002, The Future of Life, Alfred A. Knopf
Woodruff, P.H., 2006, Educating Engineers to Create a Sustainable Future, J. Environmental Engineering, 132 (4) 434-444

Industrial Ecology

Frosch, R.A., 1992, "Industrial Ecology: A Philosophical Introduction", P. National Academy of Sciences, 89 (3:) 800-803

Transportation

Jackson, K.T., 1985, Crabgrass Frontier: The Suburbanization of the United States, Oxford University Press

Urbanism and Urban Systems

Jacobs, J., 1992, The Death and Life of Great American Cities, Vintage Books
Klinenberg, E., 2002, Heat Wave: A Social Autopsy of Disaster in Chicago, University of Chicago Press
Melosi, M.V., 2000, The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present, Johns Hopkins University Press

Vale, L.J. and Campanella, T.J., 2005, The Resilient City: How Modern Cities Recover from Disaster, Oxford University Press

Natural and/or Physical Science

Biogeochemical Systems (incl. Ecology)

Erickson, P.A, 1994, A Practical Guide to Environmental Impact Assessment, Academic Press
Gould, J.L. and Keeton, W.T., 1996, Biological Science, 6th ed, W.W. Norton & Co
Kormondy, E.J., 1996, Concepts of Ecology, 4th ed, Prentice Hall
Leopold, A., 1968, Sand County Almanac, Oxford University Press
Lovelock, J.E., 1979, Gaia: A New Look at Life on Earth, Oxford University Press
Lovelock, J.E., 1990, Hands up for the Gaia hypothesis, Nature, 08 March 1990, 344 (6262): 100-102
Madigan, M., Martinko, J., and Parker, J., 2006, Brock Biology of Microorganisms, 10th ed., Pearson Prentice Hall
Odum, E.P., 1993, Ecology and Our Endangered Life-support Systems, Sinauer Associates
Paillard, D., 2006, “What Drives the Ice Age Cycle?”, Science, 313 (5786) 455-456
Smil, V., 1997, Cycles of Life: Civilization and the Biosphere, Scientific American Library

Climate Change

Collins, W., Colman, R., Haywood, J., Manning, M.R., and Mote, P., 2007, "The Physical Science Behind Climate Change", Scientific American, August 2007, pp. 64-73
IPPC, 2007, Climate Change 2007: Synthesis Report: "Summary for Policymakers", IPCC Fourth Assessment Report (AR4)

Energy & Power Generation

Albrecht, G.J., 2005, Energy: Physical, Environmental, and Social Impact, 3rd ed, Pearson Prentice Hall
Hinrichs, R.A. and Kleinbach, M.H. , 2006, Energy: Its Use and the Environment, 4th ed, Thomson, Brooks/Cole
MacKay, D.J.C, 2008, Sustainable Energy - Without the Hot Air, on-line publication
Smil, V., 2006, Energy: A Beginner's Guide, Oneworld Publications

Human Health

Rapport, D.J., 2002, The Health of Ecology and the Ecology of Health, Human and Ecological Risk Assessment, 8 (1): 205-213

Natural Resources

Kerr, R.A., 1998, The Next Oil Crisis Looms Large--and Perhaps Close, Science, 281 (5380): 1128-1131
Pimm, S.L., 2001, The World According to Pimm: A Scientist Audits the Earth, McGraw-Hill

Systems, Metrics, & Information Management

Benyus, J. M., 1997, Biomimicry: Innovation Inspired by Nature, William Morrow
Holling, C.S., 2001, "Understanding the Complexity of Economic, Ecological, and Social Systems", Ecosystems, 4 (5): 390-405
Rosen, R., 2005, Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life, Columbia University Press. pp 20-22, 64-66, 245-247

Water

Smith, E.T. and Zhang, H.X., 2004, How Do We Know It's Sustainable?: Measuring Water Sustainability Effectively Is Challenging, Water Environment and Technology, June 2004. p.37-41

Social science, business and/or policy

Agriculture and Land Use

Pretty, J.N., 2002, Agri-Culture: Reconnecting People, Land, and Nature, Earthscan

Röling, N.G. and Wagemakers, M.A.E., 1998, Facilitating Sustainable Agriculture: Participatory Learning and Adaptive Management in Time of Environmental Uncertainty, Cambridge University Press

Vorley, W. and Keeney, D. (eds), 1998, Bugs in the System: Redesigning the Pesticide Industry for Sustainable Agriculture, Earthscan Publications

Biogeochemical Systems (incl. Ecology)

Broswimmer, F., 2002, Ecocide, A Short History of the Mass Extinction of Species, Pluto Press

Business & Economics

Anderson, D.R., 2005, Corporate Survival: The Critical Importance of Sustainability Risk Management, iUniverse

Anderson, R.C., 1999, Mid-Course Correction: Toward a Sustainable Enterprise: The Interface Model, Chelsea Green Publishing

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Maeler, K-G., Schneider, S., Starrett D., and Walker, B., 2004, Are we consuming too much?, J. Economic Perspectives, Summer 2004, 18 (3): 147–172

Cleveland, C.J., Kaufmann, R.K., and Stern, D.I., 2000, Aggregation and the role of energy in the economy, Ecological Economics, 32 (2):301–317

Daly, H. and Cobb , J.B., 1994, For the Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future, Beacon Press

DeSimone, L.D. and Popoff, F., 1997, Eco-Efficiency: The Business Link to Sustainable Development, MIT Press

Devarajan, S., and Fischer, A., 1981, "Hotelling's 'Economics of Exhaustible Resources': Fifty Years Later" , J. Economic Literature 19 (1): 65-73

Dolan, P. and Elkjer , T., 2003, True to Our Roots: Fermenting a Business Revolution, Bloomberg Press

Dresner, S., 2002, The Principles of Sustainability, Earthscan

Duchin, F., 1992, Industrial input-output analysis: Implications for industrial ecology, P. National Academy of Sciences, 89 (3) 851-855

Esty, D.C. and Winston, A.S., 2006, Green to Gold: How Smart Companies Use Environmental Strategy to Innovate, Create Value, and Build Competitive Advantage, Yale University Press

Farley, J. and Daly, H.E., 2003, Ecological Economics: Principles and Applications, Island Press

Fichter, K., 2002, E-commerce: Sorting out the environmental consequences, J. Industrial Ecology, 6 (2): 25-41

Forum for the Future, 2001, “Sustainability of the Chemical Industry”, UK Dept. of Trade and Industry, Chemicals Innovation and Growth Team (CIGT)

Lambkin, M. and Day, G.S., 1989, Evolutionary Processes in Competitive Markets: Beyond the Product Life Cycle, J. Marketing, 53 (3): 4-20

Leontief, W., 1986, Input-Output Economics, 2nd ed, Oxford University Press pp. 19-24

Lomborg, B., 2001, The Skeptical Environmentalist: Measuring the Real State of the World, Cambridge University Press

McDonough, W. and Braungart, M., 1999, The NEXT Industrial Revolution, Atlantic Monthly, October 1999

Odum, H.T. and Odum, E.C., 2006, “The Prosperous Way Down”, Energy, 31 (1): 21-32

Pearce, D.W., Atkinson, G.D. and Dubourg, W.R., 1994, "The Economics of Sustainable Development", Annu Rev Energy Environ, 19: 457-74

Pernick, R. and Wilder, C., 2007, The Clean Tech Revolution: The Next Big Growth and Investment Opportunity, Collins

Pezzey, J.C.V. and Toman, M.A., 2002, "The Economics of Sustainability: A Review of Journal Articles", Resources for the Future, Discussion Paper 02-03, January 2002

Porter, M.E. and Kramer, M.R., 2006, Strategy and Society: The Link Between Competitive Advantage and Corporate Social Responsibility, Harvard Business Review, 84 (12): 78-92

Saranow, J., 2006, The Greening of Luxury Cars, Wall Street Journal, Thursday 13 April 2006, p. D1 & D6

Schmidheiny, S., 1992, Changing Course: A Global Business Perspective on Development and the Environment, MIT Press

Scientific American, 2005, Crossroads for Planet Earth, Scientific American, Special Issue, September 2005, 293 (3)

Seager, T.P., in press, The Science of Sustainability, Business Strategy and the Environment, accepted for publication

Solow, R.M., 1974, "The Economics of Resource or the Resources of Economics", The American Economic Review, May 1974, 64 (2): 1-14

Szekely, F., 2005, Responsible Leadership and Corporate Social Responsibility: Metrics for Sustainable Performance, European Management Journal, 23 (6): 628-647

US EPA, 1995, An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms, US EPA, Office of Pollution Prevention and Toxics, EPA 742-R-95-001, June 1995

Climate Change

Hawkins, D.G., Lashof, D.A., and Williams, R.H., 2006, “What to Do about Coal”, Scientific American, 295 (3): 68-75

Janssen, M. and Rotmans, J., 1995, Allocation of fossil CO2 emission rights quantifying cultural perspectives, Ecological Economics, 13 (1): 65-79

US DOE, 2006, Strategic Plan, US DOE, U.S. Climate Change Technology Program, DOE/PI-0005, September, 2006, pp. 1-56

Design

Jobs, S., 2007, "A Greener Apple", Editorial, Apple Company, 2 May 2007

US Congress, 1992, Green Products by Design: Choices for a Cleaner Environment, Office of Technology Assessment, OTA-E-541, US Government Printing Office, October 1992

End of Life and Waste Management

Carroll, C., 2008, "High-Tech Trash: Will your discarded TV end up in a ditch in Ghana?", National Geographic Magazine, January 2008, 65-87

DeWinter, K.C., 2001, From here to eternity: Recycling hi-tech junk, Waste Age, March 2001, 186-190

Ekvall, T., 2000, "A Market-based Approach to Allocation at Open-loop Recycling", Resources, Conservation and Recycling, 29 (1,2): 91-109

European Union, 2000, "Directive 2000/53/EC of the European Parliament and of the Council of September 18 2000 on End-Of Life Vehicles", Official Journal of the European Communities, 21.10.2000, L 269/34-42.

European Union, 2003, "Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment", Official Journal of the European Communities, 13.2.2003, L 37/24-38.

Hindo, B., 2006, "Everything Old is New Again - Caterpillar", Business Week, September 25, 2006, 64-70

Porter, R.C., 2002, The Economics of Waste, RFF Press

Saphores, J.-D.M, Nixon, H., Ogunseitan, O.A. and Shapiro, A.A., 2006, Household Willingness to Recycle Electronic Waste: An Application to California, Environment and Behavior, 38 (2): 183-208

Weinberg, A.S., Pellow, D.N., and Schnaiberg, A., 2000, Urban Recycling and the Search for Sustainable Community Development, Princeton University Press

<u>Energy & Power Generation</u>

Campbell, C.J. and Laherrere, J.H., 1998, The end of cheap oil, Scientific American, March 1998, 278 (3): 78-83

Dahmus, J.B. and Gutowski, T.G., 2005, “Efficiency and Production: Historical Trends for Seven Industrial Sectors", Working Paper, presented at the 3rd Biennial Conference of the US Society for Ecological Economics, Tacoma, Washington, USA, July 20-23, 2005

Fanchi, J.R., 2005, Energy In The 21st Century, World Scientific Publishing Company

Flavin, C. and Lenssen, N., 1994, Power Surge: Guide to the Coming Energy Revolution, W.W. Norton & Company

Herring, H., 1999, Does energy efficiency save energy? The debate and its consequences, Applied Energy, 63 (3): 209-226

Johansson, T.B. and Goldemberg, J. (eds), 2002, "Energy for Sustainable Development: A Policy Agenda", United Nations Development Programme (UNDP)

Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H. (eds) , 1993, Renewable Energy, Island Press

Lovins, A.B., 1976, "Energy Strategy: The Road Not Taken?", Foreign Affairs, October 1976, 65-96

National Commission on Energy Policy, 2004, Ending the Energy Stalemate: A Bipartisan Strategy to Meet America’s Energy Challenges, National Commission on Energy Policy, December 2004

National Commission on Energy Policy, 2006, Siting Critical Energy Infrastructure: An Overview of Needs and Challenges, National Commission on Energy Policy, June 2006, pp. 4-21

Nersesian, R.L., 2006, Energy for the 21st Century: A Comprehensive Guide to Conventional and Alternative Sources, M.E. Sharpe

Scheer, H., 2007, Energy Autonomy: The Economic, Social and Technological Case for Renewable Energy, Earthscan

Sovacool B.K. and Brown M.A. (eds.), 2007, Energy and American Society – Thirteen Myths, Springer

State of Georgia, Governor's Energy Policy Council, 2006, State Energy Strategy for Georgia, Division of Energy Resources of the Georgia Environmental Facilities Authority (GEFA), December 14, 2006

Vaitheeswaran, V.V., 2003, Power to the People – How the Coming Energy Revolution Will Transform Industry, Change Our Lives, and Maybe Even Save the Planet, Farrar, Straus and Giroux

Yergin, D. and Stoppard, M., 2003, "The Next Prize" , Foreign Affairs, 82 (6), July/August 2003, 103-114

<u>Human Health</u>

Blacksmith Institute, 2007, The World's Worst Polluted Places: The Top Ten (of the Dirty Thirty), Blacksmith Institute, September 2007

Allenby, B., 2000, Earth systems engineering and management, IEEE, Technology and Society Magazine, Winter 2000-2001, 19 (4): 10-24

Allenby, B., 2005, Reconstructing Earth: Technology and Environment in the Age of Humans, Island Press

Cairns, J.J., 2003, A preliminary declaration of sustainability ethics: Making peace with the executioner, Ethics in Science and Environmental Politics, 26: 43-48

Callenbach, E., 1981, Ecotopia Emerging, Banyan Tree Books

Costanza, R., 2001, Visions, values, valuation and the need for an ecological economics, Bioscience, 51 (6): 459-468

Dubos, R. J., 1980, The Wooing of Earth, Scribner Book Company

Kelly, P., 2006, Becoming a Sustainability Professional, Futures, 696-707

Orr, D.W., 1992, Ecological Literacy: Education and the Transition to a Postmodern World, State University of New York Press

Orr, D.W., 2002, The Nature of Design: Ecology, Culture, and Human Intention, Oxford University Press

Prugh T. and Assadourian, E., 2003, What is Sustainability, Anyway?, Worldwatch Live Online Discussion, September 5, 2003

Scientific American, 2005, Crossroads for Planet Earth, Scientific American, Special Issue, September 2005, 293 (3)

Thompson, M., 2000, "Understanding Environmental Values: A Cultural Theory Approach.", Summary of presentation to Carnegie Council for Ethics in International Affairs, New York, October 2, 2000

<u>Industrial Ecology</u>

Ehrenfeld, J.R., 2000, "Industrial Ecology: Paradigm Shift or Normal Science?", American Behavioral Scientist, 44 (2): 229-244

Ehrenfeld, J.R., 2002, "Industrial Ecology: Coming of Age", Environ. Sci. Technol., 36 (13): 280A-285A

Gertler, N. and Ehrenfeld, J., 1997, Industrial ecology in practice: The evolution of interdependence at Kalundborg, J. Industrial Ecology, 1 (1): 67-79

McDonough, W. and Braungart, M., 2002, Cradle to Cradle, North Point Press

Smelser, N.J. and Baltes, P.B. (eds), 2001, International Encyclopedia of the Social & Behavioral Sciences, Elsevier

<u>Industrial Processes</u>

Sarkis, J., 2001, Greener Manufacturing and Operations: From Design to Delivery and Back, Greenleaf Publishing

Thorpe, B., 1999, Citizen's Guide to Clean Production, Clean Production Network, August 1999

Materials

European Union, 2003, "Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment", Official Journal of the European Communities, 13.2.2003, L 37/19-23.

Geiser, K., 2001, Materials Matter: Toward a Sustainable Materials Policy, MIT Press

Phillips, W.G.B. and Edwards, D.P., 1976, “Metal Price as a Function of Ore Grade”, Resources Policy, 2 (3): 167-178

Young, J.E., Sachs A., and Ayres, E. (eds)., 1994, The Next Efficiency Revolution: Creating a Sustainable Materials Economy, Worldwatch Institute, Paper 121

Natural Resources

Hotelling, H., 1931, "Economics of Exhaustible Resources", J. Political Economy 39 (2), April 1931, 137-175; reprinted in Bulletin of Mathematical Biology (1991) 53 (1,2): 281-312

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W., 1972, The Limits to growth: A report for the Club of Rome's Project on the Predicament of Mankind, Universe Books

Mikesell, R.F., 1995, "The Limits to Growth: A Reappraisal.", Resources Policy, 21 (2): 127-131

Neumayer, E., 2003, Weak Versus Strong Sustainability: Exploring The Limits Of Two Opposing Paradigms, 2nd ed, Edward Elgar Publishing

Simon, J.L., 1996, The Ultimate Resource 2, Princeton University Press

Tilton, J., 1996, "Exhaustible Resources and Sustainable Development: Two Paradigms.", Resources Policy, 22 (1,2): 91-97

Policy

Bernards, N. (ed), 1991, The Environmental Crisis: Opposing Viewpoints, Greenhaven Press

Brown, L.R., 2006, Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble, Earth Policy Institute, W.W. Norton & Co

Brown, M.A. and Chandler, S., in press, Governing confusion: How statutes, fiscal policy, and regulations impede clean energy technologies, Stanford Law and Policy Review

Colby, M.E., 1990, Environmental management in development: The evolution of paradigms, World Bank Discussion Paper No 80. Washington, DC: The World Bank

Keil, R., Bell, D.V.J., Penz, P., and Fawcett, L. (eds), 1998, Political Ecology: Global and Local, Routledge

Sachs, J.D., 2005, Investing in Development: A Practical Plan to Achieve the Millennium Development Goals, United Nations Millennium Project, Earthscan

Schoenung, J.M., Ogunseitan, O.A., Saphores, J.-D.M. and Shapiro, A.A., 2004, “Adopting Lead-Free Electronics: Policy Differences and Knowledge Gaps”, J. Industrial Ecology, 8 (4): 59-85

Schoenung, J.M., Ogunseitan, O.A., Saphores, J.-D.M. and Shapiro, A.A., 2004, “Green Electronics: A U.S. Perspective on Policy, Risk, and Product Design", Electronics Goes Green 2004+, H. Reichl, H. Griese, and H. Poetter (Editors), Fraunhofer IRB Verlag, pp. 83-88.

Taylor, J., 2002, "Sustainable Development: A Dubious Solution in Search of a Problem.", Policy Analysis 449 (August 26, 2002). Cato Institute

Taylor-Gooby, P. and Zinn, J.O. (eds), 2006, Risk in Social Science, Oxford University Press

US DOE, 2002, Energy and Water for Sustainable Living : A Compendium of Energy and Water Success Stories, US DOE, Argonne National Laboratory, DOE/PI-0001, July 2002

World Commission on Environment and Development, Our Common Future, Oxford University Press, Oxford, England, 1987, 1987, Our Common Future, UN World Commission on Environment and Development [Also known as the "Brundtland Report"]., Oxford University Press

Systems, Metrics, & Information Management

Berreby, D., 1990, The numbers game, Discover Magazine, April 1990, 11: 42-47

Glaser, B., 2002, Efficiency Versus Sustainability in Dynamic Decision Making: Advances in Intertemporal Compromising, Springer-Verlag

Hallsmith, G., 2003, The Key to Sustainable Cities: Meeting Human Needs, Transforming Community Systems , New Society Publishers

Hardin, G., 1968, The Tragedy of the Commons, Science, 162: 1243-1248

Herath, G. and Prato, T., 2006, Using Multi-Criteria Decision Analysis in Natural Resource Management, Ashgate Publishing

Hobbs, B.F. and Meier, P., 2000, Energy Decisions and the Environment - A Guide to the Use of Multicriteria Methods, Kluwer Academic Publishers

Kang, H.-Y., Ogunseitan, O., Shapiro, A.A. and Schoenung, J.M., 2007, "A Comparative Hierarchical Decision Framework on Toxics Use Reduction Effectiveness for Electronic and Electrical Industries", Environ. Sci. Technol., 41 (2): 373-379

Kiker, G.A., Bridges, T.S., Varghese, A, Seager, T.P. and Linkovjj, I., 2005, Application of Multicriteria Decision Analysis in Environmental Decision Making, Integrated Environmental Assessment and Management, 1 (2): 95-108

Kolsch et al., in press, "Socio-Eco-Efficiency Analysis: The Method", Int J Sustainable Development

Krimsky, S. and Golding, D. (eds), 1992, Social Theories of Risk, Praeger

Marshall, J.D. and Toffel, M.W., 2005, Framing the Elusive Concept of Sustainability: A Sustainability Hierarchy, Environ. Sci. Technol., 39 (3): 673-682

National Research Council; Stern, P.C and Fineberg, H.V. (eds.), 1996, Understanding Risk: Informing Decisions in a Democratic Society , National Academy Press

Odum, H.T. and Odum, E.C., 1976, Energy: Basis for Man and Nature, McGraw-Hill

Seager, T.P., Satterstrom, F.K., Linkov, I., Tuler, S.P., and Kay, R., 2007, Typological Review of Environmental Performance Metrics (with Illustrative Examples for Oil Spill Response), Integrated Environmental Assessment and Management, 3 (3): 310–321

Vanclay F. and Bronstein D.A. (eds), 1995, Environmental and Social Impact Assessment, John Wiley & Sons

Venetoulis, J. and Cobb, C., 2004, The Genuine Progress Indicator: 1950-2002 (2004 Update), Redefining Progress

Wackernagel, M. and Rees, W.E., 1996, Our Ecological Footprint: Reducing Human Impact on the Earth, New Society Publishers

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C,. Lohl, J., Myers, N., Norgaard, R., and Randers, J., 2002, Tracking the

ecological overshoot of the human economy, P. National Academy of Sciences, 99 (14): 9266-9271
York, Rosa, Dietz, 2005, The Ecological Footprint Intensity of National Economies, J. Industrial Ecology, 8 (4): 139-154

Transportation

Åkerman, J. and Höjer, M., 2006, “How Much Transport Can the Climate Stand?: Sweden on a Sustainable Path in 2050,”, Energy Policy, 34 (14): 1944-1957
Holden, E., 2007, Achieving Sustainable Mobility: Everyday and Leisure-time Travel in the EU, Ashgate Publishing

Urbanism and Urban Systems

Beatley, T. and Manning, K., 1997, The Ecology of Place: Planning for Environment, Economy and Community, Island Press
Beatley, T., 1999, Green Urbanism: Learning from European Cities, Island Press
Beriatos, E. et al (eds), 2003, Sustainable Planning and Development / Vol 6. The Sustainable World, WIT Press
Gottdiener, M., and Hutchison, R., 1999, The New Urban Sociology, 2nd ed, McGraw-Hill
Judd, D.R. and Fainstein, S.S., 1999, The Tourist City, Yale University Press
Rees, W.E., 1992, “Ecological Footprints and Appropriate Carrying Capacity: What Urban Economics Leaves Out”, Environment and Urbanization, 4 (2): 121-130
Register, R., 2002, Ecocities: Building Cities in Balance With Nature, Berkeley Hills Books
Shore, W.B., 2006, Land use, Transportation and Sustainability, Technology in Society, 28 (1-2): 27-43

Water

Erie, S.P., 2006, Beyond Chinatown: The Metropolitan Water District, Growth, and the Environment in Southern California, Stanford University Press
European Union, 2000, Towards a Sustainable/Strategic Management of Water Resources: Evaluation of Present Policies and Orientations for the Future, Luxembourg: Office for Official Publications of the European Communities; Lanham, Md.: Bernan Associates (distributor). Part of the series “Regional development studies (Brussels, Belgium)”; v. 31.
Gleick, P.H., 1998, "Water in Crisis: Paths to Sustainable Water Use", Ecological Applications, 8 (3): 571-579
Gleick, P.H., 2001, "Safeguarding Our Water", Scientific American, 284 (2): 38-55
Gleick, P.H., ed., 1993, Water in Crisis: A Guide to the World's Fresh Water Resources, Oxford University Press
Gleick, P.H., Loh, P., Gomez, S., and Morrison, J., 1995, “California Water 2020: A Sustainable Vision”, Pacific Institute Report, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, U.S.A.,
Kenney, D.S. (ed), 2005, In Search of Sustainable Water Management: International Lessons for the American West and Beyond, Edward Elgar Publishing
MacDonnell, L.J., 1999, From Reclamation to Sustainability: Water, Agriculture, and the Environment in the American West, University Press of Colorado
Owens-Viani, L., Wong, A.K., Gleick, P.H., 1999, Sustainable Use of Water: California Success Stories, Pacific Institute for Studies in Development, Environment, and Security

Sustainable engineering

Agriculture and Land Use

Borlaug, N., 1997, Feeding a world of 10 billion people: the miracle ahead. , Plant Tissue Culture and Biotechnology, 3: 119-127

Lyle, J.T., 1999, Design for Human Ecosystems: Landscape, Land Use, and Natural Resources, Island Press

Prince George's County, MD, 1999, Low-Impact Development Design Strategies: An Integrated Design Approach, Prince George's County, Maryland, Department of Environmental Resources Programs and Planning Division, June 1999

VanLoon, G.W., Patil, S.G. and Hugar, L.B., 2005, Agricultural Sustainability: Strategies for Assessment, Sage Publications

Biogeochemical Systems (incl. Ecology)

Kennedy, D (ed), 2006, Science Magazine's State of the Planet 2006-2007, Island Press

Building & Construction

Brown, D.E., Fox, M., Pelletier, M.R., and Hoffman, L., 2000, Sustainable Architecture White Papers, Earth Pledge Foundation

Business & Economics

Ayres, R.U., 1997, The Kuznets curve and the life cycle analogy, Structural Change and Economic Dynamics, 8 (4): 413-426

Ayres, R.U., 1998, Ecothermodynamics: Economics and the second law, Ecological Economics, 26 (2): 189-209

Ayres, R.U., 2004, On the life cycle metaphor: Where ecology and economics diverge, Ecological Economics, 48 (4): 425-438

Ayres, R.U., van den Berrgh, J., and Gowdy, J., 2001, Strong versus weak sustainability: Economics, natural sciences, and consilience, Environmental Ethics, 23 (2): 155-168

Nixon, H., Saphores, J.-D.M., Ogunseitan, O.A., Lincoln, J.D, and Shapiro, A.A., 2006, Californian Households~ Willingness to Pay for Green PCs, P. IEEE International Symposium on Electronics and the Environment, 8-11 May 2006, 150-155

Climate Change

Cruzen, P.j., 2006, “Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?”, Climatic Change, 77 (3,4): 211-217

Houghton, J.T., et al (eds), 2001, Climate Change 2001: The Scientific Basis / Intergovernmental Panel on Climate Change. Working Group I, Cambridge University Press

IPPC, 2007, "Mitigation Options for Residential and Commercial Buildings", Chapter 6 in Climate Change 2007: Working Group III Report "Mitigation of Climate Change", IPCC Fourth Assessment Report (AR4)

Pacala, S. and Socolow, R., 2004, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies", Science, 305 (5686) 968-972

Socolow, R.H. and Pacala, S.W. , 2006, “A Plan to keep Carbon in Check”, Scientific American, 295 (3): 50-57

Socolow, R.H., 2005, Can We Bury Global Warming?, Scientific American, 293 (1): 49-55

Design

Bras, B., 1997, Incorporating environmental issues in product realization, Industry and Environment, United Nations UNEP/IE, Vol. 20, No. 1-2 (double issue), pp. 7-13, 1997.

Coulter, S.L., and Bras, B.A., 1997, "Reducing Environmental Impact Through Systematic Product Evolution", Int J Environmentally Conscious Design and Manufacturing, 6 (2): 1-10

Fiksel, J. (ed), 1996, Design for Environment, McGraw-Hill

Graedel, T.E. and Allenby, B.R., 1996, Design for Environment, Prentice Hall

Kutz, M. (ed), 2007, Environmentally Conscious Mechanical Design, John Wiley & Sons

Lewis, H. and Gertsakis, J., 2001, Design + Environment: A Global Guide to Designing Greener Goods, Greenleaf Publishing

<u>End of Life and Waste Management</u>

Baumgartner, S. and de Swaan Arons, J., 2003, Necessity and inefficiency in the generation of waste - A thermodynamic analysis, J. Industrial Ecology, 7 (2): 113-123

Bhuie, A. K., Ogunseitan, O.A., Saphores, J-D.M. and Shapiro, A.A., 2004, Environmental and economic trade-offs in consumer electronic products recycling: A case study of cell phones and computers, P. IEEE International Symposium on Electronics and the Environment, 10-13 May 2004, 74-79

Coulter, S.L., Bras, B.A., Winslow, G., and Yester, S., 1996, "Designing for Material Separation: Lessons from Automotive Recycling", P. ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, August 22-24, 1996. Paper no. 96-DETC/DFM-1270

Craighill, A.L. and Powell, J.C., 1996, Lifecycle assessment and economic evaluation of recycling: A case study, Resources, Conservation and Recycling, 17 (22): 75-96

Dahmus, J.B. and Gutowski, T.G., 2006, Material Recycling at Product End-of-Life, P. IEEE International Symposium on Electronics and the Environment, 8-11 May 2006, 206-211

Emblemsvag, J. and Bras, B.A., 1995, "The Use of Activity-Based Costing, Uncertainty and Disassembly Action Charts in Demanufacture Cost Assessments", P. ASME Advances in Design Automation Conference, Boston, Massachusetts, DE-Vol. 82, September 17-20, 1995, pp. 285-292

Hammond, R., Amezquita, T., and Bras, B.A., 1998, "Issues in the Automotive Parts Remanufacturing Industry: Discussion of Results from Surveys Performed among Remanufacturers", Int J Engineering Design and Automation - Special Issue on Environmentally Conscious Design and Manufacturing, 4 (1): 27-46

Hammond, R., and Bras, B.A., 1996, "Design for Remanufacturing Metrics", P. 1st International Workshop on Reuse, (S.D. Flapper and A.J. de Ron eds.), Eindhoven, The Netherlands, pp. 5-22, November 11-13, 1996.

Hendrix, J. Massey, K.A., Whitham, E., Russell, M., and Bras, B.A., 1997, "Technologies for the Identification, Separation, and Recycling of Automotive Plastics", Int J Environmentally Conscious Design and Manufacturing, 6 (2): 37-50

Isaacs, J. A. and Gupta, S.M., 1997, Economic Consequences of Increasing Polymer Content on the US Automobile Recycling Infrastructure, J. Industrial Ecology, 1 (4): 19-33

Ishii, K., 1999, Incorporating End-of-Life Strategy in Product Definition, P. IEEE International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign '99), 1-3 Feb 1999, Los Alamitos, CA, 364 - 369

Lincoln, J.D., Ogunseitan, O.A., and Shapiro, A.A., 2006, Meta-analysis of Hazard Criteria Designation for Electronic Waste, P. IEEE International Symposium on Electronics and the Environment, 8-11 May 2006, 89-94.

Lincoln, J.D., Ogunseitan, O.A., Shapiro, A.A., and Saphores, J.-D.M., 2007, Leaching Assessments of Hazardous Materials in Cellular Telephones, Environ. Sci. Technol., 41 (7): 2572 -2578

Thomas, V.M., 2003, “Demand and dematerialization impacts of second hand markets”, J. Industrial Ecology, 7 (2) 65-76

Energy & Power Generation

Andrews, J. and Jelley, N., 2007, Energy Science: Principles, Technologies, and Impacts, Oxford University Press

Bernesson, S., Nilsson, D., Hansson, P-A., 2004, A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions, Biomass and Bioenergy, 26 (6): 545-559

Brown M.A. and Sovacool, B.K., 2006, Developing an “Energy Sustainability Index” to evaluate U.S. energy policy, Georgia Institute of Technology School of Public Policy Working Paper, December 2006

Dewulf, J., and Van Langenhove, H. (eds), 2006, Renewables-Based Technology: Sustainability Assessment, John Wiley & Sons

Hafemeister, D.W., 2007, Physics of Societal Issues: Calculations on National Security, Environment, and Energy, Springer

Kruger, P., 2006, Alternative Energy Resources: The Quest for Sustainable Energy, John Wiley & Sons

Malkina-Pykh, I.G. and Pykh, Y.A., 2002, Sustainable Energy : Resources, Technology and Planning, WIT Press

MIT, 2007, The Future of Coal: Options for a Carbon-Constrained World, MIT

Natural Resources Canada, 2005, Clean Energy Project Analysis: RETScreen Engineering & Cases Textbook, Minister of Natural Resources Canada

Ramage, J., 1997, Energy: A Guidebook, 2nd ed, Oxford University Press

Ristinen, R.A. and Kraushaar, J.J., 1999, Energy and the Environment, John Wiley & Sons

Ristinen, R.A. and Kraushaar, J.J., 2006, Energy and the Environment, 2nd ed, John Wiley & Sons

Humanities (philosophy, ethics, history)

Ellis, M.D., 1994, The Role of Engineering in Sustainable Development: Selected Readings and References for the Profession, Amer Assn of Engineering Societies

Reichart, I. and Hischier, R., 2003, The Environmental Impact of Getting the News, J. Industrial Ecology, 6 (3-4): 185-200

Industrial Ecology

Ausubel, J. and Sladovich, H.E. (eds), 1989, Technology and Environment, National Academy Press, 23-49.

Ayres, R.U. and Ayres, L., 2002, A Handbook of Industrial Ecology, Edward Elgar Publishing

Bellandi, R. (ed), 2004, Strategic Environmental Management for Engineers / O'Brien & Gere Engineers, John Wiley & Sons, pp 17-70

Chertow, M., 2000, Industrial symbiosis: Literature and taxonomy, Annu Rev Energy Environ, 25: 313-337

Graedel, T.E. and Allenby, B.R., 2003, Industrial Ecology, 2nd ed, Prentice Hall

Korhonen, J., 2001, Four ecosystem principles for an industrial ecosystem, J. Cleaner Production, 9 (3): 253-259

Levine, S., 2003, Comparing products and production in ecological and industrial systems, J. Industrial Ecology, 7 (2): 33-42

Seager, T.P. and Theis, T.L., 2002, A uniform definition and quantitative basis for industrial ecology, J. Cleaner Production, 10 (3): 225-235

Socolow, R.H., 1996, Industrial Ecology and Global Change, Cambridge University Press, pp. 3-16

Thomas, V., Theis, T., Lifset, R., D. Grasso, D., Kim, B. Koshland, C., and Pfah, R., 2003, Industrial Ecology: Policy Potential and Research Needs, Environmental Engineering Science, 20 (1) 1-9

Industrial Processes

Allen, D.T. and Shonnard, D.A., 2001, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall

Billatos, S.B. and Basaly, N.A., 1997, Green Technology and Design for the Environment, Taylor & Francis

Coulter, S., Bras, B.A., and Foley, C., 1995, "A Lexicon of Green Engineering Terms", P. 10th International Conference of Engineering Design (ICED 95), Zurich, Switzerland, August 22-24, 1995, 1033-1039

Gutowski, T.G., Dahmus, J., Thiriez, A., Branham, M., Jones, A., 2007, “A Thermodynamic Characterization of Manufacturing Processes”, P. IEEE International Symposium on Electronics and the Environment, 7-10 May 2007, Orlando, FL, 137-142

Gutowski, T.G., Murphy, C.F., Allen, D.T., Bauer, D.J., Bras, B., Sheng, P.S., Sutherland, J.W., Thurston, D.L., Wolff, E.E., 2001, Environmentally Benign Manufacturing, WTEC Panel Report, Baltimore, MD: International Technology Research Institute, April 2001

Hill, M., Saviello T., and Groves, S., 2002, "The Greening of a Pulp and Paper Mill", J. Industrial Ecology, 6 (1): 107-120

National Research Council, 2005, Sustainability in the Chemical Industry: Grand Challenges and Research Needs - A Workshop Report, National Academy Press

Thiriez, A. and Gutowski, T. , 2006, "An Environmental Analysis of Injection Molding", P. IEEE International Symposium on Electronics and the Environment, 8-11 May 2006, 195-200

Williams, E.D., Ayres, R.U., and Heller, M., 2002, “The 1.7 Kilogram Microchip”, Environ. Sci. Technol., 36 (24): 5504-5510

LCA (Life Cycle Assessment)

Bare J., Gloria, T., and Norris, G., 2006, Development of the method and U.S. normalization database for life cycle impact assessment and sustainability metrics, Environ. Sci. Technol., 40 (16): 5108 -5115

Bare J.C. and Gloria, T.P., 2006, Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches, Environ. Sci. Technol., 40 (4): 1104-1113

Bare J.C., 2002, Developing a consistent decision-making framework by using the U.S. EPA's TRACI, Presentation, American Institute of Chemical Engineers (AIChE) Annual Meeting, Indianapolis, IN, November 3–8

Bare, J.C., Norris, G.A., Pennington, D.W., and McKone, T., 2002, TRACI: The tool for the reduction and assessment of chemical and other environmental impacts, J. Industrial Ecology, 6 (3/4): 49-78

Bauman, H. and Tillman, A.-M., 2004, Hitch Hiker's Guide To LCA: An Orientation in Life Cycle Assessment Methodology and Application, Studentlitteratur AB

Bengtsson, M. and Steen, B., 2000, Weighting in LCA – Approaches and applications, Environmental Progress, 19 (2): 101- 109

Ciambrone, D.F., 1997, Environmental Life Cycle Analysis, Lewis Publishers

Clarke, R., Heijungs, R., Huppes, G., Dutilh, C.E., Udo de Haes H.A., and Van de Berg, N.W., 1996, Life Cycle Assessment: What is it and How to do it, United Nations Environment Program. , United Nations Publications

Curran M.A., 2007, Co-product and input allocation approaches for creating life cycle inventory data: A literature review, Int J LCA, 12 (2): 65-78

Ekvall, T. and Finnveden, G., 2001, Allocation in ISO 14041— a critical review, J. Cleaner Production, 9 (3): 197-208

Emblemsvag, J. and Bras, B.A., 1997, "An Activity-Based Life-Cycle Assessment Method", P. ASME Design for Manufacturing Symposium, Proceedings 1997 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Sacramento, California, September 14-17, 1997, Paper no. 97DETC/DFM-4376,

Emblemsvag, J. and Bras, B.A., 1999, "LCA Comparability and the Waste Index", Int J LCA, 4 (5): 282-290

Finnveden, G., 1999, "Methodological Aspects of Life Cycle Assessment of Integrated Solid Waste Management Systems", Resources, Conservation and Recycling, 26 (3-4:) 173-187

Giudice, F., La Rosa G., and Risitano, A., 2006, Product Design for the Environment: A Life Cycle Approach, CRC Press, Taylor & Francis Group

Graedel, T.E., 1998, Streamlined Life-Cycle Assessment, Prentice Hall

Grote, K.-H. and Antonsson, E.K. (eds), 2008, Springer Handbook of Mechanical Engineering, Spring-Verlag (in press)

Guinée, J.B., et al, 2002, Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards, Kluwer Academic PublisherS

Heijungs, R. and Kleijn, R., 2001, "Numerical Approaches Towards Life Cycle Interpretation", Int J LCA, 6 (3): 141-148

Heijungs, R. and Suh, S., 2002, Computational Structure of LCA, Kluwer Academic Publishers

Heijungs, R., 2007, Bias in normalization: Causes, consequences, detection and remedies, Int J LCA, 12 (4): 211-216

Hendrickson, C., Lave, L. and Matthews, H.S., 2006, Environmental Life Cycle Assessment of Goods and Services, an Input-Output Approach, RFF Press

Hertwich, E.G. and Hammitt, J.K., 2000, A theoretical foundation for life-cycle assessment: Recognizing the role of values in environmental decision making, J. Industrial Ecology, 4 (1): 13-28

ISO, 2000, Sections 5-9 in Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment, ISO 14042, International Organization for Standardization, ISO 14042

ISO, 2006, Environmental Management - Life Cycle Assessment - Principles and Framework, ISO 14040, 2nd ed, International Organization for Standardization, ISO 14040:2006(E)

Jolliet O, Margni M, et al., 2003, IMPACT 2002+: A new life cycle impact assessment methodology, Int J LCA, 8 (6): 324-330

Joshi, S., 2000, Product environmental life cycle assessment using input-output techniques, J. Industrial Ecology, 3 (2,3): 95-120

Keoleian, G.A. and Menerey, D., 1993, Life Cycle Design Guidance Manual: Environmental Requirements and the Product System, US EPA, ORD, EPA 600/R-92/226, January 1993

Kim, S. and Overcash, M.R., 2000, Allocation Procedure in Multi-Output Process: An Illustration of ISO 14041, Int J LCA, 5 (4): 221-228

Landis, A.E. and Theis T.L., in press, "Comparison of Impact Assessment Tools: TRACI, CML and IMPACT 2002+." , J. Industrial Ecology, under review

Landis, A.E., Miller, S.A., and Theis T.L., 2007, "Life cycle of the corn-soybean agroecosystem for biobased production", Environ. Sci. Technol., 41 (4): 1457-1464

Lippiatt, B.C. and Boyles, A.S., 2001, Using BEES to select cost-effective green products, Int J LCA, 6 (2): 76-80

Lundquist, L., Leterrier, Y., Sunderland, P. and Månson, J.A.E. , 2000, Life Cycle Engineering of Plastics: Techonology, Economy, and the Environment, Elsevier

Miller, S.A. and Theis, T.L., 2006, Comparison of life-cycle inventory databases: A case study using soybean production, J. Industrial Ecology, 10 (1-2): 133-147

Miller, S.A., Landis A.E., and Theis, T.L., 2006, Use of Monte Carlo analysis to characterize nitrogen fluxes in agroecosystems, Environ. Sci. Technol., 40 (7): 2324 -2332

Pennington, D.W., Norris G., Hoagland, T. and Bare, J.C., 2000, Environmental comparison metrics for life cycle impact assessment, Environmental Progress, 19 (2): 83-91

Penningtona, D.W., Potting, J., Finnvedenc, G., Lindeijerd, E., Jolliete, O., Rydberga, T., and Rebitzer, G., 2004, Life cycle assessment Part 2: Current impact assessment practice, Environment International, 30 (5): 721-739

PRé Consultants, 2000, Eco-indicator 99 Manual for Designers: A damage oriented method for Life Cycle Impact Assessment", Dutch Ministry of Housing, Spatial Planning, and the Environment, October 2000

PRé Consultants: Goedkoop, M. and Spreinsma, R., 2001, Eco-indicator 99 Methodology Report, 3rd ed, PRé Consultants

PRé Consultants: Goedkoop, M., De Schryver, A., and Oele, M., 2008, Introduction to LCA with SimaPro, PRé Consultants

Rebitzer, G., Ekvallb, T., Frischknechtc, R., Hunkelerd, D., Norrise, G. Rydbergf, T., Schmidtg, W.-P., Suhh, S., Weidemai, B.P., and Pennington, D.W. , 2004, Life cycle assessment, Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environment International, 30 (5): 701-720

Suh, S. and Huppes, G., 2005, Methods for Life Cycle Inventory of a Product, J. Cleaner Production, 13 (7): 687-697

Sullivan, J.L., Williams, R.L., Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G., and Pomper, S.D, 1998, Life Cycle Inventory of a Generic U.S. Family Sedan : Overview of Results USCAR AMP Project , SAE Total Life Cycle Conference, paper #982160, Graz, Austria

Svoboda, S., 1995, Note on Life Cycle Analysis, National Pollution Prevention Center for Higher Education, University of Michigan

US EPA, 2006, Life Cycle Assessment: Principles and Practice (formerly LCA 101), US EPA, ORD, EPA/600/R-06/060, May 2006

Weidema, B., 2001, "Avoiding Co-Product Allocation in Life-Cycle Assessment.", J. Industrial Ecology, 4, no. 3 (2001): 11-33

Wenzel, H., Hauschild, M., and Alting, L., 1997, Environmental Assessment of Products, Vol 1. Methodology, tools and case studies in product development, Chapman & Hall

Williams, E., 2004, Energy Intensity of Computer Manufacturing: Hybrid Assessment Combining Process and Economic Input – Output Methods, Environ. Sci. Technol., 38 (22): 6166 - 6174

Material Flow Analysis

Brunner, P.H. and Rechberger, H., 2004, Practical Handbook of Material Flow Analysis, Lewis

Graedel, T.E., et al., 2004, "Multilevel Cycle of Anthropogenic Copper", Environ. Sci. Technol., 38 (4): 1242-1252

Jasinski, S.M., 1994, “The Materials Flow of Mercury in the United States”, US Department of the Interior , USGS, US Bureau of Mines Information Circular 9412

Klee, R.J. and Graedel, T.E., 2004, "Elemental Cycles: A Status Report on Human or Natural Dominance", Annu Rev Environ Res, 29: 69-107

Matthews, E., et al., 2000, The Weight of Nations: Material Outflows from Industrial Economies, World Resources Institute

Moll, S., Bringezu, S., and Schuetz, H., 2005, "Resource Use in European Countries", Wuppertal Institute for Climate, Environment, and Energy, Wuppertal Report No. 1., December 2005

Materials

Hwang, J.S., 2001, Environment Friendly Electronics: Lead-Free Technology, Electrochemcial Publications

Ku, A., Oetinscitan, O., Saphores, J.-D., Shapiro, A., Schoenung, J.M., 2003, "Lead-Free Solders: Issues of Toxicity, Availability and Impacts of Extraction", P. IEEE Electronic Components and Technology Conference, 27-30 May 2003, 47-53

Lagos, G., 2005, “Copper in Health and the Environmental: Evolving Issues and Market Impacts”, World of Metallurgy – ERZMETALL 58 (5), 279-282

Lincoln, J.D., Ogunseitan, O.A., Saphores, J.-D.M., Schoenung, J.M., Nixon, H., and Shapiro, A.A., , Environmentally Benign Materials for Electronics: A Review of Current Developments and Emerging Technologies, P. IEEE International Symposium on Advanced Packaging Materials: Processes, Properties and Interfaces, 16-18 March 2005, 139-143

Masini, A., Ayres, R.U. and Ayres, L.W., 2001, “An Application of Exergy Accounting to Five Basic Metal Industries”, INSEAD, Center for the Management of Environmental Resources, Working Paper, May 2001

Ogunseitan, O.A., Schoenung, J.M., Saphores, J.-D., Shapiro, A.A., Bhuie, A.K., Kang, H.Y., Nixon, H., and Stein, A.W., 2003, "The Devil that We Know: Pb Replacement Policies under Conditions of Scientific Uncertainty", P. Electronic Design, Manufacturing, and the Environment, Irvine, April, 2003

Schwartz, L.H., 1999, Sustainability: The Materials Role, Metallurgical and Materials Transactions A, 30 (4), 895-908

Shapiro, A.A., Bonner, J.K., Ogunseitan, O.A., Saphores, J.-D.M., and Schoenung, J.M., 2006, "Implications of Pb-Free Microelectronics Assembly in Aerospace Applications", IEEE Transactions on Components and Packaging Technologies, Part A, 29 (1): 60-70

Socolow, R. and Thomas, V., 1997, The Industrial Ecology of Lead and Electric Vehicles, J. Industrial Ecology, 1 (1): 13-36

Natural Resources

Graedel, T.E. and Klee, R.J., 2002, "Getting Serious about Sustainability", Environ. Sci. Technol., 36 (4): 523-529

Holland, H.D. and Peterson, U., 1995, Living Dangerously, Princeton University Press

Policy

Banerjee, A. and Solomon, B.D., 2003, Eco-labeling for energy efficiency and sustainability, Energy Policy, 31 (2): 109-123

Kang, H.-Y., Ogunseitan, O., Saphores, J.-D.M., Shapiro, A.A. and Schoenung, J.M., 2005, Toxic Use Reduction Act: Policy Recommendation for California, P. Materials and Life Management Issues Symposium, Materials Science and Technology, pp. 15-23

Mihelcic, J.R., Zimmerman, J.B., and Ramaswami, A., 2007, "Integrating Developed and Developing World Knowledge into Global Discussions and Strategies for Sustainability. 1. Science and Technology", Environ. Sci. Technol., 41 (10): 3415 -3421

Pollution Prevention, Fate & Transport

Norris, G.A., 2002, Impact Characterization in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, J. Industrial Ecology, 6 (3-4): 79-101

Rubin, E.S and Davidson, C.I., 2001, Introduction to Engineering and the Environment, McGraw-Hill

US EPA, 2001, An Organizational Guide to Pollution Prevention, US EPA, ORD, EPA/625/R-01/003, August 2001

US EPA, 2001, Guide to Industrial Assessments for Pollution Prevention & Energy Efficiency, US EPA, ORD, EPA/625/R-99/003, June 2001

Systems, Metrics, & Information Management

Chambers, N., Simmons, C. and Wackernagel, M., 2000, Sharing Nature's Interest: Ecological Footprints as an Indicator of Sustainability, Earthscan Publications

Gutowski, T.G., et. al, 2008, Environmental Life Style Analysis (ELSA), P. IEEE International Symposium on Electronics and the Environment, 19-21 May 2008, San Francisco USA

Huesemann, M.H., 2003, The limits of technological solutions to sustainable development, Clean Technologies and Environmental Policy, 5 (1): 21-34

Ossenbruggen, P.J., 1984, Systems Analysis for Civil Engineers, John Wiley & Sons

Pearce A.R. and Vanegas, J.A., 2002, "Defining Sustainability for Built Environment Systems: An Operational Framework", Int J Environmental Technology and Management, 2 (1-3): 94-113

Vanegas, J.A. (ed), 2004, Sustainable Engineering Practice: An Introduction, ASCE (American Society of Civil Engineers) Committee on Sustainability

Transportation

Graedel, T.E. and Allenby, B.R., 1998, Industrial Ecology and the Automobile, Prentice Hall

Mildenberger, U. and Khlare, A., 2000, Planning for an environment-friendly car, Technovation, 20 (4): 205-214

Wang, M., 2002, Fuel choices for fuel-cell vehicles: Well-to-wheels energy and emissions impacts, J. Power Sources. 112:307-321.

Wells, P. and Orsato, R.J. , 2005, Redesigning the Industrial Ecology of the Automobile, J. Industrial Ecology, 9, No. 3, pages 15-30

Urbanism and Urban Systems

Babbitt, B., 2005, Cities in the Wilderness: A New Vision of Land Use in America, Island Press

Water

Mays, L.W., 2007, Water Resources Sustainability, McGraw-Hill

Sustainable engineering technology

Energy & Power Generation

Barbir, F., 2005, PEM Fuel Cells: Theory and Practice, Elsevier Academic Press, Sustainable World Series

Boyle, G., ed., 2004, Renewable Energy: Power for a Sustainable Future, 2nd ed, Oxford University Press

Cassedy E.S. and Grossman, P.Z. , 1998, Introduction to Energy: Resources, Technology, and Society, Cambridge University Press

Duffie, J.A. and Beckman, W.A., 2006, Solar Engineering of Thermal Processes, 3rd ed, John Wiley & Sons

Goswami, D.Y., Kreith, F., and Kreider, J.F., 2000, Principles of Solar Engineering, 2nd ed, Taylor and Francis

Komp, R.J., 1995, Practical Photovoltaics: Electricity from Solar Cells, Aatec Publications, Ann Arbor, MI

Larminie, J. and Dicks, A. , 2000, Fuel Cell Systems Explained, John Wiley & Sons

Manwell, J.F., McGowan, J.G. and Rogers, A.L., 2002, Wind Energy Explained: Theory, Design and Application, John Wiley & Sons

Marion, W. and Wilcox, S., 1994, "Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors," , US DOE, NREL/TP-463-5607, DE93018229, April 1994

McDaniels, D.K., 1991, The Sun, Our Future Energy Source, Krieger Publishing

MIT, 2003, The Future of Nuclear Power, MIT

O'Hayre, R., Cha, S.-W., Collela, W., and Prinz, F., 2006, Fuel Cell Fundamentals, John Wiley & Sons

Sørensen, B., 2004, Renewable Energy: Its Physics, Engineering, Use, Environmental Impacts, Economy and Planning Aspects, 3rd ed, Academic Press

Stine, W.B. and Harrigan, R.W. , 1985, Solar Energy Fundamentals and Design: With Computer Applications, John Wiley & Sons

Tester, J.W., Drake, E.M., Driscoll, M.J., Goly, M.W., and Peters, W.A., 2005, Sustainable Energy: Choosing Among Options, MIT Press

Thomas, S. and Zalbowitz, M., 1999, Fuel Cells - Green Power, US DOE, Office of Transportation Technologies, LA-UR-99-3231

US DOE, 2004, Fuel Cell Handbook, 7th ed., US DOE, NETL (National Energy Technology Laboratory), November 2004

Zweibel, K., Mason, J. and Fthenakis, V., 2008, "A Solar Grand Plan", Scientific American, January 2008, 298 (1) 64-73

Transportation

Carney, D., 2004, "High-Performance Hybrids", Society of Automotive Engineering Magazine, March 2004, 50-56

Keith, D.W. and Farrell, A.E., 2003, “Rethinking Hydrogen Cars”, Science, 301 (5631): 315-316

Yamaguchi, J., 2006, Hybrids for Commerce, Automotive Engineering, November 2006, 66-68

Water

Economic and Social Commission for Asia and the Pacific, 1997, Guidelines on Water and Sustainable Development: Principles and Policy Options, United Nations, Water Resources Series, No 77, Renouf Pub Co Ltd

Pankratz, T.M., 2002, Seawater Desalination Processes: Operations and Costs, CRC Press

Sandia National Laboratory, 2003, Desalination and Water Purification Technology Roadmap, The National Academies Press, 2004., US DOE, DWPR Program Report #95

Traditional engineering

Building & Construction

ASHRAE, 2005, ASHRAE Handbook -- Fundamentals, American Society of Heating, Refrigeration and Air-Conditioning

Hudson, W.R., Haas, R., and Uddin, W., 1997, Infrastructure Management: Integrating Design, Construction, Maintenance, Rehabilitation and Renovation , McGraw-Hill

McQuiston, F.C., Parker, J.D. and Spitler, J.D., 2004, Heating, Ventilating and Air Conditioning Analysis and Design, 6th ed, John Wiley & Sons

Threlkeld, J.L, 1970, Thermal Environmental Engineering, 2nd ed, Prentice-Hall

Design

Cagan, J. and Vogel, C.M., 2002, Creating Breakthrough Products: Innovation from Product Planning to Program Approval, Financial Times/Prentice Hall

Dym, C.L. and Little, P., 2000, Engineering Design: A Project-Based Introduction, John Wiley & Sons

Eide, A.R, Jenison, R., Northup L.L., Mashaw L., and Eide, A., 2001, Introduction to Engineering Design and Problem Solving, 2nd ed, McGraw-Hill

Finkelstein, E., 2003, AutoCAD 2004 Bible, John Wiley & Sons

Jewell, T.K., 1986, A Systems Approach to Civil Engineering Planning and Design, Harper and Row

Otto, K.N. and Wood, K.L. , 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Prentice Hall

Energy & Power Generation

Angrist, S.W., 1976, Direct Energy Conversion, Allyn & Bacon, Series in Mechanical Engineering and Applied Mechanics

Bejan, A., Tsatsaronis, G., and Moran, M., 1996, Thermal Design and Optimization, John Wiley & Sons

de Swaan Arons, J., van der Kooi, H.J., & Sankaranarayanan, K., 2004, Efficiency and Sustainability in the Energy and Chemical Industries, Marcel Dekker

Decher, R., 1994, Energy Conversion: Systems, Flow Physics and Engineering, Oxford Engineering Science Series, Oxford University Press

Fanchi, J.R., 2004, Energy Technology and Directions for the Future, Elsevier Academic Press

Gyftopoulos, E.P. and Beretta, G.P., 1991, Thermodynamics: Foundations and Applications, Macmillan

Knebel, D.E., 1983, Simplified energy analysis using the modified bin method, ASHRAE (American Society of Heating, Refrigerating, and AC Engineers)

Mitchell, J.W., 1983, Energy Engineering, John Wiley & Sons
Moran, M.J., 1982, Availability Analysis: A Guide to Efficient Energy Use, Prentice-Hall
Sato, N., 2004, Chemical Energy and Exergy: An Introduction to Chemical Thermodynamics for Engineers, Elsevier
Sorensen, H.A., 1983, Energy Conversion Systems, John Wiley & Sons
Stoecker, W.F. and Jones, J.W., 1982, Refrigeration and Air Conditioning, McGraw-Hill
Stoecker, W.F., 1989, Design of Thermal Systems, 3rd ed., McGraw-Hill
Szargut, J. Morris, D.R., and Steward, F.R., 1988, Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Hemisphere
Turner, J.E., 2007, Atoms, Radiation, and Radiation Protection, 3rd ed., Wiley-VCH
Weston, K.C., 1992, Energy Conversion, West Publishing Co.

Humanities (philosophy, ethics, history)

ASCE, 2007, The Vision for Civil Engineering in 2025, American Society of Civil Engineers
Industrial Processes
Ashby, M., Shercliff, H. and Cebon, D., 2007, Materials: Engineering, Science, Processing and Design, Butterworth-Heinemann
Basel, W.D., 1990, Preliminary Chemical Engineering Plant Design, 2nd ed, Van Nostrand Reinhold
Felder, R.M. and Rousseau, R.W., 2000, Elementary Principles of Chemical Processes, 3rd ed, John Wiley & Sons
Logan, E., 1995, Handbook of Turbomachinery, Marcel Dekker, Inc.
Peters, M.S., Timmerhaus, K.D., and West, R.E., 2003, Plant Design and Economics for Chemical Engineers, 5th ed., McGraw-Hill
Schey, J.A., 1987, Introduction to Manufacturing Processes, 2nd ed, McGraw-Hill
Smith, R., 1995, Chemical Process Design, McGraw-Hill
Turton, R., Bailie, R.C., Whiting, W.B and Shaeiwitz, J.A., 2003, Analysis, Synthesis, and Design of Chemical Processes, 2nd ed, Prentice Hall/PTR
Ulrich, G.D. and Palligarnai, P.T., 2004, Chemical Engineering Process Design and Economics: A Practical Guide, 2nd ed, Process Publishing

Materials

Ashby, M.F., 2005, Materials Selection in Mechanical Design, 3rd ed, Elsevier Butterworth-Heinemann
Kalpakjian, S. and Schmid, S.R., 2008, Manufacturing Processes for Engineering Materials, 5th ed, Pearson Education

Policy

Reid, R.L, 2008, Special Report: The Infrastructure Crisis, Civil Engineering, 78 (1)

Systems, Metrics, & Information Management

Blanchard, B. and Fabrycky, W., 1998, Systems Engineering and Analysis, 3rd ed, Prentice Hall
Kornreich, P., 2008, Mathematical Models of Information and Stochastic Systems, CRC Press
Revelle, C.S., Whitlatch, E.E. and Wright, J.R., 2003, Civil and Environmental Systems Engineering, Pearson Prentice Hall

Transportation

Fricker J.D. and Whitford, R.K., 2004, Fundamentals of Transportation Engineering: A Multimodal Systems Approach, Pearson Prentice Hall

Garber, N.J. and Hoel, L.A., 2002, Traffic and Highway Engineering, 3rd, Brooks/Cole Publishing

Kapka, R.J., 2004, Megaprojects -- They are a Different Breed, US Department of Transportation, Public Highway Administration, Public Roads, July/August 2004, 68 (1)

Papacostas C.S. and Prevedouros, P.D., 2001, Transportation Engineering and Planning, 3rd ed, Prentice Hall

Pline, J.L. (ed), 1999, Traffic Engineering Handbook / Institute of Transportation Engineers , 5th ed., Institute of Transportation Engineers (ITE)

Robertson, H.D., Hummer, J.E., and Nelson, D.C. (eds), 1994, Manual of Transportation Engineering Studies/ Institute of Transportation Engineers, Prentice Hall

Roess, R.P., Prassas, E.S.and McShane, W.R., 2004, Traffic Engineering, 3rd ed, Pearson Prentice Hall

Transportation Research Board, 2000, Highway Capacity Manual 2000, National Research Council, Special Report (SR) 209

Water

Johnston, P.R., 1990, Fundamentals of Fluid Filtration: A Technical Primer, 2nd ed, Tall Oaks Publishing

Loucks, D.P. and van Beek, E., 2005, Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications, UNESCO Publishing

Table E.1. Websites, pg. 1 of 6

Sites mentioned multiple times are shaded yellow and the number of mentions is given in the last column; a blank represents a single mention
Repeat mentions of a host are shaded grey.

Host	Website Title	URL	#
American Society of Civil Engineerings	Code of Ethics	http://www.asce.org/inside/codeofethics.cfm	
American Society of Mechanical Engineers (ASME) Professional Practice Curriculum	Sustainability	http://www.professionalpractice.asme.org/communications/sustainability/index.htm	
American Solar Energy Society	home page	http://www.ases.org/	
ASEE (American Society for Engineering Education)	Statement on Sustainable Development Education	http://www.asee.org/about/Sustainable_Development.cfm	
Biothinking, E. Datschefski	Product Design: Quick Start: Chair Examples	http://www.biothinking.com/chairs.htm	
BP	Statistical Review of World Energy 2008	http://www.bp.com/productlanding.do?categoryId=6848&contentId=7033471	2
Bridges to Sustainability	Publications	http://www.bridgestos.org/publications.htm	
BuildingGreen, LLC	GreenSpec-Listed Green Building Products	http://www.buildinggreen.com/menus/index.cfm	
BuildingGreen, LLC	home page	http://www.buildinggreen.com/	
California Integrated Waste Management Board (CIWMB)	Green Building Home Page	http://www.ciwmb.ca.gov/GreenBuilding/	
California Integrated Waste Management Board (CIWMB)	Sustainable Building Guidelines	http://www.ciwmb.ca.gov/GreenBuilding/Design/Guidelines.htm	
Cambridge University, Engineering Department	Centre for Sustainable Development	http://www-g.eng.cam.ac.uk/sustdev/	
Carnegie Mellon University, Green Design Institute	EIO-LCA Tutorial	http://www.eiolca.net/tutorial/tut_1.html	
Carnegie Mellon University, Green Design Institute	EIO-LCA Tutorial	http://www.eiolca.net/	
Carnegie Mellon University, S. Matthews	Environmental Life Cycle Assessment (12-714 / 19-614)	http://www.ce.cmu.edu/~hsm/lca2006/	
CDC (Center for Disease Control)	home page	http://www.cdc.gov/	
Charles Sturt University, Chemistry	Production of materials: Fossil fuel products	http://hsc.csu.edu.au/chemistry/core/identification/chem921/chem921net.html	
Dream Green Homes	home page	http://www.dreamgreenhomes.com/	
earthdaynetwork	Earth Day Network Footprint Calculator	http://www.earthday.net/footprint/index.html	
Energy Justice Network	Primer on Landfill Gas as "Green" Energy	http://www.energyjustice.net/lfg/	
Energy Justice Network	The Basics of Landfills	http://www.ejnet.org/landfills/	
Energy Star	home page	http://www.energystar.gov/	
Engineering Pathway	home page	http://www.engineeringpathway.com	2

Table E.1. Websites, pg. 2 of 6

Host	Website Title	URL	#
Environment Canada	Acid Rain and the Facts	http://www.ec.gc.ca/acidrain/acidfact.html	
European Chemical Industry Council (CEFIC)	Guidance on relationships between common acronyms related to effluent water: BOD, COD, ThOD, StOD, TOD, TOC, and DOC	http://www.cefic.be/activities/hse/rc/guide/11.htm	
European Environment Agency (EEA)	Indicator: Biochemical oxygen demand in rivers	http://themes.eea.europa.eu/Specific_media/water/indicators/bod/index_html	
Feather River Air Quality Management District	Pollution Sources	http://www.fraqmd.org/Pollutants.htm	
Georgia Tech, Center for Quality Growth & Regional Development	Megaregions	http://www.cqgrd.gatech.edu/megaregions/	
Global Footprint Network	home page	http://www.footprintnetwork.org/en/index.php/GFN/	
Global Issues	The demographic transition	http://www.globalissues.org/article/204/the-demographic-transition	
Green Energy Ohio	home page	http://www.greenenergyohio.org/default.cfm?Flash=true	
Greenblock	home page	http://www.greenblock.com/	
How Stuff Works	xHome Appliances	http://home.howstuffworks.com/home-appliances.htm	
Huf Haus	home page	http://www.huf-haus.com/gb/intro.html	
International Institute for Sustainable Development	Rio Declaration on Environment and Development	http://www.iisd.org/rio+5/agenda/declaration.htm	
Life-Cycle Services, Thomas Gloria, Ph.D	LCA Software links	http://www.life-cycle.org/LCA_soft.htm	
Max Planck Institute for Chemistry, Mainz, Germany, E. Uherek	Lower Atmosphere: Ozone and nitrogen oxides as key compounds	http://www.atmosphere.mpg.de/enid/05d4a3081bf366396df70117b26c496e,0/basics/3__Ozone_and_nitrogen_oxides_239.html	
McDonough Braungart Design Chemistry (MBDC) and the Environmental Protection Encouragement Agency (EPEA)	Introduction to the Cradle to Cradle Design Framework	http://www.chinauscenter.org/purpose/CradleDesign.pdf	
Missouri Botanical Garden	home page	http://www.mbgnet.net/	
National Association of Home Builders	home page	http://www.nahb.org/default.aspx	
National Atlas of the United States	home page	http://www.nationalatlas.gov/	
National Institute for Science and Technology (NIST) Manufacturing Extension Program	home page	http://www.mep.nist.gov/	
National Oceanic and Atmospheric Administration (NOAA)	home page	http://www.noaa.gov/	
National Pollution Prevention Roundtable	home page	http://www.p2.org/	
Oikos, Green Buidling Source	Green Building News	http://oikos.com/	
Paramont Classics	"An Inconveient Truth"	http://www.climatecrisis.net	

Table E.1. Websites, pg. 3 of 6

Host	Website Title	URL	#
Pollution Prevention Resource Exchange	home page	http://www.p2rx.org/	
Princeton University	Carbon Mitigation Initiative	http://www.princeton.edu/~cmi/resources/stabwedge.htm	
Product Ecology Consultants (PRé)	Eco-indicator 99 method	http://www.pre.nl/eco-indicator99/default.htm	2
Product Ecology Consultants (PRé)	home page	http://www.pre.nl/	
Redefining Progress	home page	http://www.rprogress.org/index.htm	4
Redefining Progress	Global Ecological Footprint Calculator	http://www.ecologicalfootprint.org/Global%20Footprint%20Calculator/GFPCalc.html	
Reuse Development Organization	home page	http://www.redo.org/	
Siemens Building Technologies	Energy Solutions	http://www.buildingtechnologies.usa.siemens.com/Services__and__Solutions/Energy__and__Environmental/energy_solutions.htm	
Stanford University	Asner Lab, Laboratory for Regional Ecological Studies	http://asnerlab.stanford.edu/index.shtml	
Texas Environmental Profiles	Point Source Discharges	http://www.texasep.org/html/wql/wql_2sfc_ps.html	
The Earth Policy Institute	home page	http://earthpolicy.org/	
The University Cooperation for Atmospheric Research	Tropospheric Ozone, the Polluter	http://www.ucar.edu/learn/1_7_1.htm	
U.S. Census Bureau, International Programs	World POPClock Projection	http://www.census.gov/ipc/www/popclockworld.html	
U.S. Climate Change Technology Program	home page	http://www.climatetechnology.gov/	
U.S. Department of Energy	home page	http://www.energy.gov/	
U.S. Department of Energy, EIA (Energy Information Administration)	Greenhouse Gases, Climate Change, and Energy	http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm	
U.S. Department of Energy, EIA (Energy Information Administration)	home page	http://www.eia.doe.gov/	2
U.S. Department of Energy, EIA (Energy Information Administration)	Long Term World Oil Supply, Presentation made in April 2000	http://www.eia.doe.gov/pub/oil_gas/petroleum/presentations/2000/long_term_supply/sld001.htm	
U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE)	Buildings Energy Data Book	http://buildingsdatabook.eren.doe.gov/	
U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE)	Buildings Energy Software Tools Directory	http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=444/pa	
U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE)	Green Power Markets	http://apps3.eere.energy.gov/greenpower/markets/pricing.shtml?page=0	
U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE)	Wind Powering America	http://www.windpoweringamerica.gov/wind_maps.asp	
U.S. Department of Energy, Lawrence Berkeley National Laboratory (LBNL)	Environmental Energy Technologies Division	http://eetd.lbl.gov/	

Table E.1. Websites, pg. 4 of 6

Host	Website Title	URL	#
U.S. Department of Energy, National Renewable Energy Lab (NREL)	home page	http://www.nrel.gov/	
U.S. Department of Energy, National Renewable Energy Lab (NREL)	National Solar Radiation Data Base	http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/	
U.S. Department of Energy, National Renewable Energy Lab (NREL)	U.S. Life-Cycle Inventory (LCI) Database: Life-Cycle Assessments	http://www.nrel.gov/lci/	5
U.S. Department of Energy, Oakridge National Laboratory (ORNL)	Carbon Dioxide Information Analysis Center	http://cdiac.ornl.gov/home.html	
U.S. Department of Energy, Oakridge National Laboratory (ORNL)	Carbon Sequestration in Terrestrial Ecosystems	http://csite.ornl.gov/	
U.S. Department of Energy, Sandia National Laboratories	home page	http://www.sandia.gov/	
U.S. Department of the Interior, U.S. Geological Survey (USGS)	Advisory Committee on Water Information	http://acwi.gov/swrr/	
U.S. Department of the Interior, U.S. Geological Survey (USGS)	Minerals Information	http://minerals.usgs.gov/minerals/	
U.S. Green Building Council	home page	http://www.usgbc.org/	4
U.S. Small Business Administration	Mission Statement	http://www.sba.gov/aboutsba/sbaprograms/sbdc/index.html	
University of Missouri, Extension	Understanding the Material Safety Data Sheet	http://extension.missouri.edu/xplor/agguides/agengin/g01913.htm	
University of Texas, D. Allen	Life Cycle Assessment	http://www.utexas.edu/research/ceer/che341/greenproduct/dfe/lca.htm	
University of Washington, J. Cooper	Inventory of LCA Inventory Data Sources	http://faculty.washington.edu/cooperjs/Definitions/inventory%20squared.htm	
unknown	LCA Food Database	http://www.lcafood.dk/	
US Code	Title 33, Chapter 26 (Navigable Waters: Pollution Prevention and Control)	http://www.4uth.gov.ua/usa/english/laws/majorlaw/33/ch26.htm	
US Dept of Health and Human Services, ATSDR (Agency for Toxic Substances and Disease Registry), CDC (Center for Disease Control)	Toxicological Profile Information Sheet	http://www.atsdr.cdc.gov/toxpro2.html	
US Environmental Protection Agency (EPA)	home page	http://www.epa.gov/	2
US Environmental Protection Agency (EPA)	Nonpoint Source Pollution: The Nation's Largest Water Quality Problem	http://www.epa.gov/nps/facts/point1.htm	
US Environmental Protection Agency (EPA)	Summary of the Clean Water Act	http://www.epa.gov/lawsregs/laws/cwa.html	
US Environmental Protection Agency (EPA)	Superfund, SARA Overview	http://www.epa.gov/superfund/policy/sara.htm	
US Environmental Protection Agency (EPA)	Toxics Release Inventory Program	http://www.epa.gov/tri/	3
US Environmental Protection Agency (EPA)	Toxics Release Inventory Program: TRI Explorer	http://www.epa.gov/triexplorer/	2

Table E.1. Websites, pg. 5 of 6

Host	Website Title	URL	#
US Environmental Protection Agency (EPA), Air and Radiation	National Ambient Air Quality Standards (NAAQS)	http://www.epa.gov/air/criteria.html	
US Environmental Protection Agency (EPA), Air and Radiation	Six Common Air Pollutants	http://www.epa.gov/air/urbanair/index.html	
US Environmental Protection Agency (EPA), Air and Radiation	The Clean Air Act	http://www.epa.gov/apti/course422/apc3.html	
US Environmental Protection Agency (EPA), Compliance Assistance	Sector Notebooks and Sector Publications	http://www.epa.gov/compliance/resources/publications/assistance/	
US Environmental Protection Agency (EPA), Compliance Assistance	Sector Publications, Construction	http://cfpub.epa.gov/compliance/resources/publications/assistance/sectors/construction/index.cfm	
US Environmental Protection Agency (EPA), Green Building	Green Building	http://www.epa.gov/greenbuilding/	
US Environmental Protection Agency (EPA), Indoor Air Quality	Organic Gases (Volatile Organic Compounds - VOCs)	http://www.epa.gov/iaq/voc.html	
US Environmental Protection Agency (EPA), Office of Policy, Economics, and Innovation (OPEI)	Sector Strategies Program	http://www.epa.gov/sustainableindustry/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Design for the Environment, Partnerships for Safer Chemistry	http://www.epa.gov/dfe/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Environmental Accounting Project	http://www.epa.gov/opptintr/library/pubs/archive/acct-archive/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Environmentally Preferable Purchasing (EPP)	http://www.epa.gov/opptintr/epp/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Green Chemistry	http://www.epa.gov/greenchemistry/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Green Engineering	http://www.epa.gov/opptintr/greenengineering/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Pollution prevention (P2)	http://www.epa.gov/opptintr/p2home/	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Pollution prevention (P2): Technical Assistance	http://www.epa.gov/opptintr/p2home/pubs/assist/index.htm	
US Environmental Protection Agency (EPA), Office of Prevention, Pesticides and Toxic Substances (OPPTS)	Pollution prevention (P2): Waste Minimization Resources and Programs	http://www.epa.gov/region02/p2/wastemin.htm	
US Environmental Protection Agency (EPA), Office of Research and Development (ORD)	Life-Cycle Assessment (LCA)	http://www.epa.gov/nrmrl/lcaccess/	4

Table E.1. Websites, pg. 6 of 6

Host	Website Title	URL	#
US Environmental Protection Agency (EPA), Wastes	Reduce, Reuse, Recycle	http://www.epa.gov/epawaste/conserve/rrr/index.htm	2
Victoria University of Wellington, New Zealand	Embodied Energy Coefficients	http://www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf	
Vienna TU, Institute for Engineering Design	Ecodesign Online Pilot	http://www.ecodesign.at/pilot/ONLINE/ENGLISH/PDS/INDEX_W.HTM	
World Health Organization	home page	http://www.who.int/en/	
World Resources Institute	home page	http://www.wri.org/	

Table E.2. Software, pg. 1 of 2

CHE = Chemical, Bio-, Materials, CAE = Civil, Architectural, Environmental, MAM = Mechanical, Aero-, Manufacturing, ISS = Industrial, Systems, Sustainable, GEN = General Engineering and Other

	Software	Distributed By	URL	CHE	CAE	MAM	ISS	GEN	TOTAL
LCA	EIO-LCA	CMU, Green Design Institute	www.eiolca.net		4	4	1	3	12
LCA	SimaPro	PRé Consultants	http://www.pre.nl/			3	4	2	9
LCA	GaBi 4 LCA software	PE International	http://www.pe-europe.com/			1			1
LCA	Umberto	ifu, Hamburg, GmbH	http://www.umberto.de/en/			1			1
LCA	GREET	US DOE, Argonne National Laboratory	http://www.transportation.anl.gov/software/GREET/	1					1
			LCA TOTAL	1	4	9	5	5	24

	Software	Distributed By	URL	CHE	CAE	MAM	ISS	GEN	TOTAL
Design and General	Cambridge Engineering Selector	Granta Design	http://www.grantadesign.com/	2		1			3
Design and General	COMSOL Multiphysics	COMSOL AB	http://www.comsol.com/products/multiphysics/			2			2
Design and General	Aspen	Aspen Technology	http://www.aspentech.com/products/	2					2
Design and General	Office Project	Microsoft	http://office.microsoft.com/en-us/project/default.aspx	1	1				2
Design and General	Process Engineering Suite (PES)	SimSci-Esscor	http://www.simsci-esscor.com/us/eng/products/productlist/proII/default.htm	1					1
Design and General	ChemCad	Chemstations	http://www.chemstations.net/	1					1
Design and General	AutoCAD	Autodesk	http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=2704278		1				1
Design and General	STELLA	isee systems	http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx		1				1
Design and General	Mathcad	Parametric Technology Corporation (PTC)	http://ptc.com/products/mathcad/			1			1
Design and General	MATLAB	The MathWorks	http://www.mathworks.com/			1			1
Design and General	Cambridge Materials Selector	Granta Design	http://www.grantadesign.com/				1		1
Design and General	Vensim	Ventana Systems	http://www.vensim.com/software.html				1		1
			Design and General Engineering TOTAL	7	3	5	2	0	17

Table E.2. Software, pg. 2 of 2 CHE = Chemical, Bio-, Materials, CAE = Civil, Architectural, Environmental, MAM = Mechanical, Aero-, Manufacturing, ISS = Industrial, Systems, Sustainable, GEN = General Engineering and Other

	Software	Distributed By	URL	CHE	CAE	MAM	ISS	GEN	TOTAL
Environmental	Air CHIEF	US EPA, Technology Transfer Network	http://www.epa.gov/ttn/chief/software/	1					1
	ChemSTEER	US EPA, OPPTS	http://www.epa.gov/oppt/exposure/pubs/chemsteer.htm	1					1
	EPI Suite	US EPA, OPPTS	http://www.epa.gov/oppt/exposure/pubs/episuite.htm	1					1
	Green Chemistry Expert System	US EPA, OPPTS	http://www.epa.gov/greenchemistry/pubs/gces.html	1					1
	BAHM (Bay Area Hydrology Model)	Clear Creek Solutions	http://www.bayareahydrologymodel.org/		1				1
	BioWin	EnviroSim	http://www.envirosim.com/products/bw32/bw32intro.php		1				1
	E-COMMUTair	UC, Berkeley, Green Design and Mfg	http://cgdm.berkeley.edu/telework/		1				1
	CMU Equivalent Toxicity Calculator	UC, Berkeley, Civil and Environmental Eng	http://www.ce.berkeley.edu/~chester/cmuet/		1				1
	HEC-RAS	US DOD, Army Corp of Engineers	http://www.hec.usace.army.mil/software/hec-ras/		1				1
	WEAP (Water Evaluation & Planning)	Stockholm Env. Inst. US Center (SEI-US)	http://www.weap21.org/		1				1
	HOMER	US DOE, NREL	https://analysis.nrel.gov/homer/			1			1
			Environmental TOTAL	**4**	**6**	**1**	**0**	**0**	**11**

	Software	Distributed By	URL	CHE	CAE	MAM	ISS	GEN	TOTAL
Buildings	ESim	Univ. of Dayton, Mech & Aero. Eng.	http://www.engr.udayton.edu/faculty/jkissock/http/research/ESim.htm			3			3
	LightSim	Univ. of Dayton, Mech & Aero. Eng.	http://www.engr.udayton.edu/faculty/jkissock/http/research/LightSim.htm			3			3
	Energy-10	Sustainable Buildings Industry Council	http://www.sbicouncil.org/displaycommon.cfm?an=1&subarticlenbr=112			1			1
	Energyplus	US DOE, EERE, Building Tech Prgm	http://www.eere.energy.gov/buildings/energyplus/			1			1
			Building and Architecture TOTAL	**0**	**0**	**8**	**0**	**0**	**8**

	CHE	CAE	MAM	ISS	GEN	TOTAL
TOTAL	**12**	**13**	**23**	**7**	**5**	**60**

Appendix F. Sample Modules

Two example modules from the CSE project are presented.

The first is module is entitled “Wind and Photovoltaic Solar Electricity Generation” by Daniel Giammar of Washington University. In addition to discussions of wind and solar power, the module includes information on conventional coal-fired power plants for comparison and presents a number of quantitative problems.

The second module is "Terephthalic Acid Synthesis in High-Temperature Liquid Water" by Phillip Savage at the University of Michigan. Terephthalic acid (TPA) is used in making polyethylene terephthalate (PET) which is widely used in making water bottles and other beverage containers. The module discusses replacing acetic acid with high temperature water in TPA synthesis to reduce environmental hazards as well as other benefits.

Wind and Photovoltaic Solar Electricity Generation

Daniel Giammar
Washington University
August 14, 2008

1. Introduction

Electricity consumption in the United States has increased in almost every year for at least the last 50 years (Figure 1). Currently electricity generation is responsible for about 40% of the primary energy consumption in the United States. Combustion of coal is responsible for the largest amount of electricity produced, contributing 49% of U.S. electricity in 2007 (Energy Information Administration, 2008a). Natural gas is the second largest source of electricity generation. Combustion of coal and natural gas emits carbon dioxide to the atmosphere. Coal combustion is currently responsible for 36% of of U.S. carbon dioxide emissions (Energy Information Administration, 2008a). Concerns about global climate change are motivating governments and industries to reduce carbon emissions.

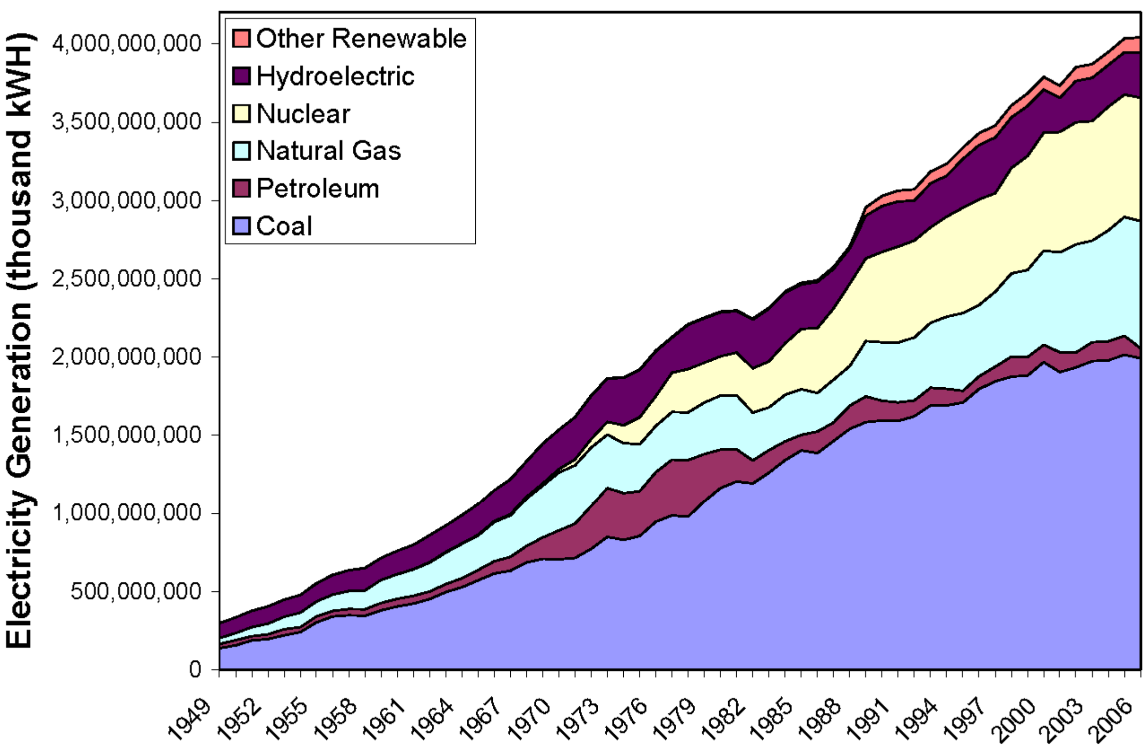


Figure 1. Sources of U.S. electricity. Data are from the Energy Information Adminstration (www.eia.doe.gov).

Numerous options are available for carbon-free generation of electricity. Of these, hydroelectric and nuclear are the only two that contribute appreciable amounts to United States electricity generation. The component labeled “other renewable” in Figure 1 includes wind, solar, geothermal, and renewably produced biomass. Other technologies being explored for development include tidal and wave energy and ocean thermal energy conversion. The term "carbon free" should be used with caution as the overall life cycles of these technologies most certainly involve carbon emissions.

The following sections will examine electricity production from solar and wind energy resources. The mass and energy conservation principles involved in each technology will be presented, and then an example will be presented for the production of 1000 megawatts (MW) of electricity in a specific location. Before examining wind and solar energy, it will be valuable to review a few concepts from physics on energy and power.

2. Power and Energy of Electricity

Electricity is often expressed in terms of the energy contained in the electricity or the power delivered. It is helpful to remember that power is the rate of useful energy delivered, and consequently power is energy divided by time (equation 1).

$$Power = \frac{Energy}{Time} \qquad (1)$$

The SI unit of energy is the Joule (J) and that of power is the Watt (W). The two are related by the conversion that 1 W = 1 J/s.

When referring to power plants, it is common to describe them based on their electric power production. For example, a large coal-fired power plant can produce 1000 megawatts (MW) of electricity, which means that it is producing 1000 megajoules (MJ) of electricity every second. It is important to note that power plants are rated based on the electric energy that they produce and not the input energy that they use. This issue is revised below when efficiency is discussed.

The other commonly used unit for electricity is the kilowatt-hour (kWH), which is the amount of energy when 1 kilowatt (kW) of power is produced for 1 hour. From equation 1, power multiplied by time is energy, which means that the kilowatt-hour is a unit of energy. Equation 2 illustrates the conversion of kilowatt-hours into Joules.

$$1\,kW-h = 1000\,W \cdot 1\,h \cdot \frac{1\,{}^{J}\!/\!{}_{s}}{1\,W} \cdot \frac{3600\,s}{h} = 3600000\,J = 3600\,kJ \qquad (2)$$

As noted before, the stated power of a power plant is the amount of electricity produced. Because of the second law of thermodynamics, which states that conversion of energy from one form into another will always involve losses, the input energy to the power plant will be greater than the electric energy that it produces. The percentage of input energy converted into useful energy, which in this case is electricity, is the efficiency (equation 3).

$$Efficiency = \eta = \frac{energy\ out}{energy\ in} \qquad (3)$$

For a coal-fired power plant, the production of electricity from coal involves multiple conversions. The internal chemical energy of the coal is first converted to energy in the form of heat, which is used to produce steam that drives a turbine that has kinetic energy. This kinetic energy is finally converted into electric energy by a generator. Each of these conversions involves losses of energy that can be characterized by an efficiency for that step. The overall conversion of the chemical energy in the fuel into electricity is the overall efficiency for the power plant. Excellent discussions and examples of electricity production from fossil fuel-based power plants are included in books on engineering and the environment (Masters and Ela, 2008; Rubin, 2001).

Example 1: Electricity produced by a coal-fired power plant.

A 1000 MW coal-fired power plant has an efficiency of 33% and uses sub-bituminous coal with an energy content of 20,000 kJ/kg. The carbon content of the coal is 48% by mass. The electricity is used by a population that has a per capita electricity use of 36 kHW/d.

a. If the coal-fired power plant operates at 100% capacity, how many people can it supply? For this problem, assume that there are no energy losses in transmission of the electricity.
b. In one day, what mass of coal is used and how much carbon is emitted?

Solution: To find the number of people that can be supplied, the energy produced by the power plant in one day must be found.

$$\textit{electric energy} = 1000\,MW \cdot 1\,d \cdot \frac{1000\,kW}{MW} \cdot \frac{24\,h}{d} = 2.4 \cdot 10^7\,{kWh}/{d}$$

The population supplied can then be determined from the per capita use.

$$\textit{population} = \frac{2.4 \cdot 10^7\,{kWh}/{d}}{36\,{kWh}/{person \cdot d}} = 670000\,\textit{people}$$

To find the amount of coal used in one day, the electric energy output will first be expressed in units of kJ, and then the input energy to the power plant can be calculated using the efficiency.

$$\textit{electric energy} = 2.4 \cdot 10^7\,kWh \cdot \frac{3600\,kJ}{kWh} = 8.64 \cdot 10^{10}\,kJ$$

$$\textit{fuel energy in} = \frac{\textit{electric energy}}{\textit{efficiency}} = \frac{8.64 \cdot 10^{10}\,kJ}{0.33} = 2.62 \cdot 10^{11}\,kJ$$

By converting the energy into units of kJ, the masses of coal and carbon can then be found.

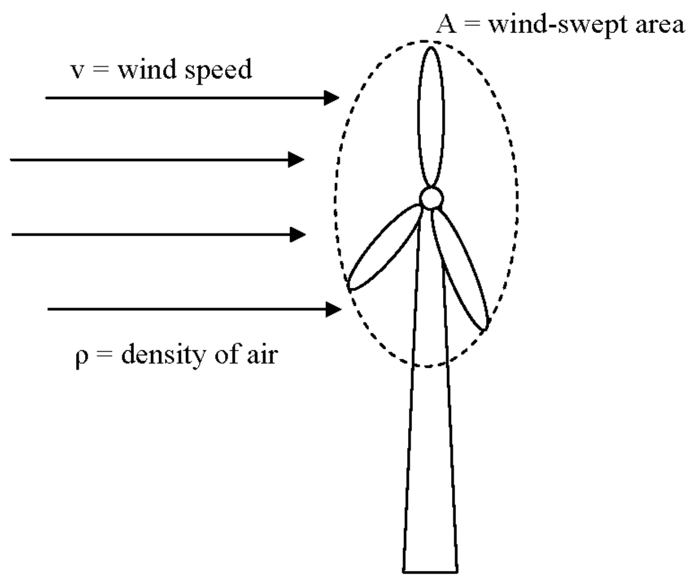
$$\textit{coal} = 2.62 \cdot 10^{11}\,kJ \cdot \frac{1\,kg}{20000\,kJ} = 1.31 \cdot 10^7\,kg = 13100\,\textit{metric tons}$$

$$\textit{carbon} = 1.31 \cdot 10^7\,kg\,coal \cdot \frac{0.48\,kg\,C}{kg\,coal} = 6.28 \cdot 10^6\,kg = 6280\,\textit{metric tons}$$

The preceding example was based on several assumptions. One important assumption was that the electric energy is produced and used at a constant rate. In this case the power plant was always producing 1000 MW of electricity and each person was always using 1.5 MW (1000 MW divided by 670000 people). In reality, the demand for electric power is subject to daily and seasonal cycles, and electricity generators are constantly varying production in order to meet the demand without producing any more electricity than is needed. Electricity demand and supply can be characterized as either base or peak. Base demand or base load is electricity that is required continuously, and it is largely supplied by big power plants that have low costs and are not easy to start up or shut down. In contrast, peak demand is electricity required beyond that of the base demand and can fluctuate rapidly. Peak demand is met by electricity generating systems with outputs that can be rapidly varied to match the demand. The concept of base versus peak electricity demand is an important factor in evaluating the potential for solar and wind electricity generating technologies to contribute to electricity supply.

3. Electricity from Wind

Wind energy is the fastest growing sector of renewable energy technologies, and in some regions its costs are competitive with those of combustion-based power plants. Unlike electricity generation from combustion-based power plants whose outputs are determined by their efficiencies and rate of fuel combustion, the generation of electricity from wind is highly dependent on location and season.



In generating electricity from wind, the kinetic energy (KE) of the wind is first converted into the kinetic energy of a spinning turbine, which is then converted into electricity by a generator. The kinetic energy contained in moving air (wind) depends upon the mass of air (m) and its velocity (v).

$$kinetic\ energy = KE = \tfrac{1}{2} \cdot mass \cdot velocity^2 = \tfrac{1}{2} mv^2 \qquad (4)$$

A wind turbine (Figure 2) taps the kinetic energy of the wind, so it is helpful to determine the rate at which air passes through the swept area of the turbine. The volumetric flow rate of air (Q) is equal to the swept area of the turbine (A) multipled by the velocity, and the mass flow rate of air is then determined by considering the density of air (ρ), which is approximately 1.2 kg/m^3.

$$\frac{volume}{time} = \frac{V}{t} = Q = vA \qquad (5)$$

$$\frac{mass}{time} = \frac{m}{t} = \rho \cdot \frac{V}{t} = \rho vA \qquad (6)$$

By substituting the rate of mass flowing through the turbine from equation 6 into equation 4, equation 7 becomes the rate of kinetic energy passing through the turbine, which is the same as the "power" of the wind (P_{wind}).

$$\frac{KE}{t} = \frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho vAv^2 = \frac{1}{2}\rho Av^3 = P_{wind} \qquad (7)$$

The electricity produced by the wind turbine is then determined by the overall efficiency of the turbine at converting the kinetic energy of the wind into electric energy (equation 8).

$$P_{elec} = \eta \cdot P_{wind} \qquad (8)$$

There is a theoretical limit to the amount of kinetic energy of a moving fluid that can be captured by a turbine (consider what would happen to the wind speed behind a turbine if the efficiency approached 100%), and the component of efficiency associated with this conversion is much greater than that of converting the spinning turbine kinetic energy into electricity. An overall efficiency of 25% is a reasonable value.

Equation 7 indicates that the electricity produced by a wind turbine depends upon both the size of the turbine and the wind speed. Because the power is proportional to the wind speed raised to the third power, the impact of wind speed is much greater than that of area. Consequently, location selection is critical to having an effective wind turbine. Maps of wind speeds are available from various sources, including online sources maintained by the National Renewable Energy Laboratory (http://rredc.nrel.gov/wind/pubs/atlas/maps.html and http://www.eere.energy.gov/windandhydro/windpoweringamerica/wind_maps.asp).

Wind turbines are often described based on the maximum power that they can produce. However, such values should be interpreted cautiously because the actual power produced depends upon the real wind speed and not the maximum operating wind speed.

Example 2. Electricity generated by a "1 megawatt wind turbine."

A wind turbine has been rated at 1 MW based on a maximum operating windspeed of 12.5 m/s (about 28 miles per hour) and an overall efficiency of 25%.

a. What is the diameter of this wind turbine?
b. What is the electric power generated by this wind turbine when the wind speed is 7 m/s (the maximum wind speed classification in Missouri)?
c. How many wind turbines would be needed at this location to provide 1000 MW of electricity?

Solution: In order to track the units involved in the calculations, the power will first be converted into units of kg, m, and s. Working backwards from 1 W being equivalent to 1 J/s, recall that 1 J is 1 N·m and that 1 N is 1 kg accelerated at 1 m/s^2. Consequently 1 W = 1 kg·m^2/s^3. The value of P_{wind} is determined from P_{elec} and the efficiency.

$$P_{wind} = \frac{P_{elec}}{\eta} = \frac{1000000 \, {kg \cdot m^2}/{s^3}}{0.25} = 4000000 \, {kg \cdot m^2}/{s^3}$$

5

Equation 7 with the wind speed set at 12.5 m/s is then solved for the wind-swept area of the turbine, and the diameter is then calculated.

$$A = \frac{P_{wind}}{\frac{1}{2}\rho v^3} = \frac{4000000 \, {}^{kg \cdot m^2}\!/_{s^3}}{0.5 \cdot 1.2 \, {}^{kg}\!/_{m^3} \cdot \left(12.5 \, {}^{m}\!/_{s}\right)^3} = 3410 \, m^2$$

$$A = \pi \cdot \frac{d^2}{4}, \qquad d = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 \cdot 3410 \, m^2}{3.14}} = 66 \, m$$

To determine the power generated when the wind speed is only 7 m/s, equation 7 could be computed for the actual wind speed and the area just determined. Alternatively, the power can be calculated by noting that the power is proportional to the wind speed to the third power.

$$\frac{P_{elec,1}}{P_{elec,2}} = \left(\frac{v_1}{v_2}\right)^3$$

$$P_{actual} = P_{\max}\left(\frac{v_{actual}}{v_{\max}}\right)^3 = 1 \, MW \cdot \left(\frac{7 \, {}^{m}\!/_{s}}{12.5 \, {}^{m}\!/_{s}}\right)^3 = 0.18 \, MW$$

The cubic dependence of power on wind speed consequently makes this “1 MW turbine” only generate 180 kW at optimal conditions in Missouri.

With this 180 kW value, the number of “1 MW turbines” that should be built in Missouri to replace the electric power produced by the 1000 MW coal-fired power plant is determined.

$$turbines = \frac{1000 \, MW}{0.18 \, {}^{MW}\!/_{turbine}} = 5600 \, turbines$$

As noted earlier, site selection is critical to generating optimal wind power. The cost of constructing a wind turbine will vary minimally from location to location (not considering the increasingly popular version of off-shore turbines), but the electric power produced will vary dramatically. Consequently, the cost of electricity from wind will be location-specific. The role of wind power in the overall mix of electricity generating sources must also consider base versus peak power. Unlike fuel-based power plants, a wind turbine can not be turned off or on. Wind power represents a form of base generating capacity that must be complemented by additional generating methods to provide peak power as well as base power during periods of low wind speed.

4. Electricity from Solar Energy

In a sense, nearly all of the major forms of electricity generation are solar powered. The coal and natural gas that make up the majority of U.S. electricity generation are ultimately the products of prehistoric plants that relied on the sun to drive photosynthesis. Hydroelectric power generation relies on the hydrologic cycle, which is driven by the input of solar energy. The pressure gradients that produce winds are the products of uneven heating of the earth by the sun. However, solar power is usually referred to as more direct conversions of solar energy into other useful forms. This module only examines photoelectric solar energy, but there are also thermoelectric methods that convert the sun's energy into heat to produce steam to spin a turbine and simpler solar hot water heating that directly converts the solar energy into hot water for use.

For photoelectric solar energy, the radiant energy contained within the sun's light is directly converted into electricity by semiconducting materials. Currently the most widely used semiconductors for photovoltaic solar energy are based on multicrystalline silicon wafers. A typical overall efficiency for these materials is 15%. For specialized materials, efficiencies greater than 40% have been achieved (National Renewable Energy Laboratory, 2008).

As with wind, the electricity generated by a photovoltaic system is highly dependent on the location of the installation and on daily and seasonal variation. The electric power generated by a system is proportional to the density of incoming energy (P_{sun}), the efficiency (η), and the area (A) of the photovoltaic array (equation 9).

$$P_{elec} = \eta \cdot A \cdot P_{sun} \tag{9}$$

Also similar to wind electricity, systems are often rated based on conditions that may not actually be reached in a specific setting. Photovoltaic solar systems are generally rated based on the electricity produced when the system is irradiated in a controlled setting with light with an area-based power density of 1000 W/m^2; this roughly corresponds to the incoming solar energy on a tilted south-facing surface in the United States at the spring or autumn equinox. Maps of available solar energy resources for different solar panel configurations are available from the National Renewable Energy Laboratory (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/).

Example 3: Electricity generated by photovoltaic system

Photovoltaic cells with an efficiency of 15% are to be installed in Missouri in a configuration of a tilted flat plate. For this configuration, the average annual incoming solar radiation is 210 W/m^2 in Missouri. Note that this average includes nighttime, when no electricity will be produced, as well as daytime.

a. What will be the average electric power output of a "10 kW photovoltaic system" at this location?
b. How large of an area must be covered with solar cells to equal the average electric power output of the 1000 MW coal-fired power plant?

Solution: The first step will be to determine the area of the "10 kW photovoltaic system" using equation 9. The rating is based on an incident irradiation of 1000 W/m^2.

$$A = \frac{P_{elec}}{\eta \cdot P_{sun}} = \frac{10000\,W}{0.15 \cdot 1000\,{}^{W}\!/_{m^2}} = 67\,m^2$$

7

When irradiated with the average Missouri solar radiation of 210 W/m^2, the power is calculated for this area.

$$P_{elec} = \eta \cdot A \cdot P_{sun} = 0.15 \cdot 67\, m^2 \cdot 210\, W/m^2 = 2100\, W = 2.1\, kW$$

On average this "10 kW" system will only produce 2.1 kW of electricity; however, during periods of peak solar intensity such as midday during the summer, the system will produce much more than this average value.

A similar calculation is done to calculate the area required to generate electric power at an annual average of 1000 MW.

$$A = \frac{P_{elec}}{\eta \cdot P_{sun}} = \frac{1000 \cdot 10^6\, W}{0.15 \cdot 210\, W/m^2} = 3.2 \cdot 10^7\, m^2 = 32\, km^2$$

This area is equivalent to about 12 square miles.

The location of a solar installation dramatically affects the electric power produced as well as the cost of producing the associated electricity because the capital cost of a photovoltaic system is essentially independent of location. Although photovoltaic solar electricity can not be turned off and on to meet fluctuations in peak power demand, it does have the advantage of maximum production during the periods of the day when electricity demand is highest.

5. Overview of Course Project – Reducing Carbon Dioxide Emissions Associated with Electricity Production for U.S. Universities.

To continue exploring options for solar and wind generation of electricity, a course project description is included in the appendix. The objective of the project is to propose a strategy for reducing by 20% the carbon dioxide emissions associated with a university's electricity consumption. Available options are photovoltaic solar, wind, and conservation. The first step in the project is estimating the current carbon emissions associated with electricity use by the university. To make this estimate, several assumptions are usually made. One is to provide a per student electricity use value. Another is to assume that electricity used by the university comes from a variety of sources with the same proportion as for the generation of electricity in the state. Detailed records of state electricity generation by source are available from the Energy Information Administration (Energy Information Administration, 2008b).

An element of the project not addressed in the module is that of costs. The project includes typical costs for electricity production from coal, natural gas, and nuclear on the basis of \$/kWh. In contrast, the costs associated with wind and solar are given in \$/m^2 for capital costs and \$/kWH for operating costs. The capital costs are given on an annual levelized basis that accounts for the anticipated useful life of the installation. For courses that include engineering economics, the calculation of annual levelized capital costs could be included as part of the project.

Bibliography

Energy Information Administration. (2008a) Annual Energy Review 2007.

Energy Information Administration. (2008b) State Historical Tables for 2006. U.S. Department of Energy,.

Masters G. M. and Ela W. (2008) *Introduction to environmental engineering*. Pearson Education, Inc.

National Renewable Energy Laboratory. (2008) NREL Solar Cell Sets World Efficiency Record at 40.8 Percent.

Rubin E. S. (2001) *Introduction to engineering and the environment*. The McGraw-Hill Companies, Inc.

Appendix – Course Project on Reducing Carbon Emissions from University Electricity Use

Objective: To propose a strategy for reducing by 20% the carbon dioxide emissions associated with a university's electricity consumption.

Groups: Groups of 4-5 students are assigned. Groups will select one of the following universities in class.

Universities:
Arizona State University, Drake University, Emory University, Harvard University, University of Hawaii

Deliverable: Written Report.

Due Date and Time: At the beginning of class on <u>due date</u>.

Elements of a Successful Report

1. <u>Executive Summary</u>. In a one page summary, communicate all of your key points to a busy reader who may only read this page of your entire report.
2. <u>Body of the Report</u>. Include the information described in more detail on page 2.
   a. Introduction to University, Current Electricity Use, and Associated Carbon Emissions
   b. Potential Strategies for Reducing Carbon Emissions
   c. Method for Determining Recommended Strategy
   d. Summary and Conclusions
3. <u>Appendices</u>. Provide supporting information and data that may be of interest to your reader, but that do not need to part of the main body of the report. Possible items for the appendices include any calculations performed as part of the work and tables of data used in the body of the report.

Length and Format. Use 11 point font, double spacing, and 1" margins. The total length (including tables, figures, and the executive summary; not including references and appendices) should be 7-12 pages. Include page numbers in your proposal. Tables and figures such as maps and charts can be useful elements of the report. Tables should be single spaced.

Project Grading and Evaluation.

<u>Grading Criteria</u>:	Inclusion of required information	30%
	Quality of estimations and calculations	30%
	Clarity of presentation	20%
	Length and quality of writing	20%

<u>Peer Evaluation</u>: After turning in the written report, each group member will have an opportunity to evaluate the other members of the group. Details of the peer evaluation process are given on page 5. The final project score will be adjusted for each group member by multiplying the group score by an individual's average peer evaluation rating divided by 10. Individual scores will be capped at 100.

INFORMATION TO INCLUDE IN REPORT

1. **Introduction to University, Current Electricity Use, and Associated Carbon Emissions (1-2 pages)**
   a. University Information. Location and estimated full-time student population.
   b. Current Electricity Use. Estimate electricity consumption based on an approximate value of 10,500 kW-h per full-time student per year. This does not mean that each student individually uses this amount, but rather that the entire university is using this amount of electricity for all activities (e.g., residence halls, classrooms, administrative offices, research facilities, etc.).
   c. Associated Carbon Emissions. Assume that the university currently gets electricity from coal, natural gas, nuclear, and hydropower. The proportion from each source is the same as the relative proportions used for electricity generation in the state where the university is located. See the Energy Information Administration data on electricity (http://www.eia.doe.gov/fuelelectric.html). Also use the information on electricity generating methods in the attached sheets.

2. **Potential Strategies for Reducing Carbon Emissions (2-4 pages)**

   Available options in this project for reducing carbon emissions are to use electricity from solar or wind generation and to decrease electricity usage by implementing conservation methods.

   a. Descriptions of Strategies.
      i. Develop a strategy based on increased use of wind power. This strategy may be done either with or without the simultaneous implementation of conservation methods. Identify the location, number, and size of the wind turbines used. Wind turbines must be located within 250 miles of the university. Off-shore sites are permissible within 20 miles of the coast.
      ii. Develop a strategy based on increased use of photovoltaic solar power. As with wind, this may be done with or without the simultaneous implementation of conservation methods. Identify the location and size of the solar facility. Solar panels must be located within 250 miles of the university. Off-shore locations are not permissible, but roof-mounted systems are allowed.

3. **Method for Determining Recommended Strategy (2-3 pages)**
   a. Identify and describe the criteria that you will use to determine the best strategy.
   b. Evaluate your two strategies according to these criteria.

4. **Summary and Conclusions (1-2 pages)**
   a. Identify your recommended strategy and summarize why it is your selection.
   b. Identify any other strategies that you would recommend the university consider as possible methods for reducing their carbon emissions.

INFORMATION ABOUT ELECTRICITY GENERATION FROM DIFFERENT SOURCES

Definitions

total levelized cost – total cost per unit of electricity production (includes fuel, operating and maintenance, and capital costs distributed over expected the life of a facility).

annual levelized capital cost – capital costs (e.g., construction and installation) distributed over the expected the life of a facility.

Coal
- Efficiency is 33%.
- Use composition and energy contents on next page.
- Total levelized cost is $0.045/kW-hr.

Natural Gas
- Efficiency is 35%.
- Use composition and energy contents on next page.
- Total levelized cost is $0.055/kW-hr.

Nuclear
- Total levelized cost is $0.09/kW-hr.

Photovoltaic Solar
- Use solar maps from the Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/).
- Use the instrument orientation "Two Axis Tracking Flat Plate"
- Efficiency is 15% (solar radiation to electricity).
- Annual levelized capital cost = $48/m^2-y.
- Operating and maintenance cost = $0.015/kW-hr.

Wind
- Use wind maps from the Wind Energy Resource Atlas of the United States (http://rredc.nrel.gov/wind/pubs/atlas/maps.html)
- Efficiency is 25% (wind energy to electricity).
- Annual levelized capital cost = $30/m^2-y (where m^2 is the cross-sectional area through-which the wind turbine spins). Increase this value by 50% for off-shore facilities.
- Operating and maintenance cost = $0.01/kW-hr. Increase by 50% for off-shore facilities.
- Required area for wind facilities is 30 hectares/4000 m^2 turbine area$_k$, but the turbine structures themselves only occupy 5% of the total land area.

Conservation
These are capital improvements that cost a certain amount of money per full-time student per year. The cost depends upon the percentage reduction of electricity consumption. The cost (C) in units of $/student-year for a k% reduction in per capita electricity use is $C = 15(e^{0.183k} - 1)$ (example: a 10% reduction in per capita electricity consumption costs $78.51/student-year).

Costs of Carbon Emissions
- Currently there are no regulations on carbon emissions.
- Potential future costs of carbon emissions (either from a carbon tax or from a trading system) may be in the range of $15-$75 per metric ton of carbon emitted.

USEFUL SOURCES OF INFORMATION

Fuel Property	Coal (Bituminous)	Natural Gas
Lower Heating Value (kJ/kg)	25,600	51,700
Composition (wt%)		
Carbon	67.0	74.1
Hydrogen	5.0	23.9
Sulfur	1.5	0.0
Nitrogen	1.5	1.7
Oxygen	8.7	0.3
Ash	9.8	
Moisture	6.7	

Washington University Libraries. In the digital age it is important to remember that there is a lot of very useful information still in hardcopy form in libraries.

Course Notes and Readings.

Links Available from the Course Website

SUGGESTIONS FOR SUCCESSFUL GROUP WORK

Distribute Workload. Identify sections of the project that individual members can complete, and then distribute tasks among the members.

Assign or Nominate Members for Group Roles. Groups often function best when individuals are playing distinct roles. It may be useful to elect a group leader who will coordinate meeting times and the distribution of the workload. Other useful roles are a designated note taker and a primary author for the report.

Set Internal Deadlines. Sometimes groups put the final pieces of a project together the night before it is due, which often results in a poorly organized, redundant, or inaccurate project. By setting internal deadlines, your group assures itself that continuous progress is made on the project.

Review all Work. One of the great advantages of working in a group is that there are more people to review and check the final work. All calculations should be checked by at least one group member other than the one who performed them. Likewise, all written work should be reviewed and edited by multiple group members. Avoid simply cutting and pasting.

PEER EVALUATION FORM

Name ______________________________ Group ____________________

Please assign scores that reflect how you really feel about the extent to which the other members of your group contributed to your learning and/or your group's performance. This will be your only opportunity to reward members of your group who actually worked hard on your behalf.

Instructions: In the space below, please rate each of the other members in your group. To complete the evaluation, you should:

1. List the name of each of the members of your group in alphabetical order.
2. Assign an average of ten points to the other members of your group.
   If your group has 4 people in it, you will assign 30 points.
   If your group has 5 people in it, you will assign 40 points.
3. The lowest score can be 8 points and the highest 12 points.

Group Member Score

1.

2.

3.

4.

Additional Feedback:

In the space below, would you also briefly describe your reasons for your highest and lowest ratings. These comments, but not information about who provided them, will be used to provide feedback to students who would like to receive it.

1. Reason(s) for your highest rating(s):

2. Reason(s) for your lowest rating(s):

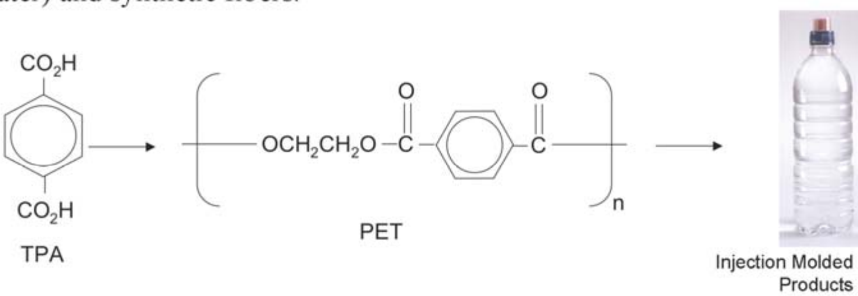
3. If you were to assign points to yourself on this scale, what do you feel you would deserve? Why?

Terephthalic Acid Synthesis in High-Temperature Liquid Water

Phillip E. Savage
University of Michigan
Chemical Engineering Department
Ann Arbor, MI 48109-2136

1. Introduction

Terephthalic acid (TPA) is a bulk, commodity chemical. Billions of pounds are produced every year. The main use of terephthalic acid is in the subsequent production of polyethylene terephthalate (PET). This polymer is used to make disposable beverage containers (e.g., for bottled water) and synthetic fibers.



The basic components in the commercial chemical process for terephthalic acid synthesis have been in use for about 50 years. Incremental improvements have been made continuously over this time span via R&D efforts in several different corporate labs. Briefly, the synthesis involves the homogeneously catalyzed oxidation of p-xylene to terephthalic acid. Air is used as the oxidant, a Co/Mn/Br mixture serves as the catalyst, and acetic acid is the solvent. The reactor temperature is around 200 °C and the reaction time is on the order of an hour or two.

After the reaction is complete, the crude terephthalic acid crystals are recovered, dissolved in hot liquid water, and purified by a catalyzed hydrogenation reaction. This purification step is done to remove undesired color bodies (from intermediate oxidation products) and generate white purified terephthalic acid crystals.

There are several reasons that a commercial process that used water as the solvent (instead of acetic acid) would be advantageous.

- Water is a byproduct in the oxidation reaction. Therefore, as the reaction progresses, the reaction medium changes from pure acetic acid to an acetic acid-water mixture. The water

1

formed during the reaction must be separated from the acetic acid so that the solvent can be recycled. Acetic acid and water are difficult to separate by distillation, however, because they are both molecules that form hydrogen bonds and they have similar boiling points. This separation requires a large distillation column (both in height to provide an adequate number of stages for the separation and in diameter to provide adequate capacity for the large volumes that must be processed). The column is not only large, it must also be lined with titanium to provide the corrosion protection necessary for this system, which contains halide (Br) at elevated temperatures. The net result is that the separation system required to recover the acetic acid solvent is expensive both to purchase and to operate. If water were the reaction medium for the oxidation reaction, the need for this costly distillation column would vanish.

- ☐ As the oxidation of p-xylene proceeds in the current commercial process, a portion of the acetic acid solvent also gets oxidized. This oxidative loss means that make-up solvent must be purchased and added, which adds to the cost of production. If water were the solvent, there would be no oxidative solvent loss.

- ☐ The acetic acid solvent reacts with the bromide present in the system (as part of the catalyst) to form small amounts of methyl bromide. The compound is a pollutant, so the process requires waste treatment methods to deal with it. Even so, there are releases of methyl bromide into the environment, as documented by the Toxic Release Inventory. If water were the solvent, there would be no methyl bromide formation.

- ☐ The current process uses different solvents in the oxidation and the purification stages. If water were used in the oxidation stage, then the same solvent would be used throughout. This adoption of a single solvent could lead to a more streamlined process.

The advantages of using water for this synthesis are clear. They involve both economic and environmental considerations. In fact, solvent substitution (that is, replacing organic solvents with environmentally friendlier solvents like water) is one of the principles of Green Chemistry [1]. The question then, is whether the synthesis reaction can be adequately done in water. Both p-xylene and terephthalic acid become increasingly soluble in water as the temperature increases, so it is possible to get significant amounts of the organic material into solution at elevated temperatures. Of course, if the system temperature exceeds the thermodynamic critical point of the mixture, then a single phase containing all of the components will exist. The critical temperature for water is 374 °C, but the critical temperature for water-p-xylene mixtures is lower and it is a function of the p-xylene concentration. We will use the term high-temperature water (HTW) to refer to liquid water below its critical temperature, and we will use supercritical water (SCW) to refer to water above its thermodynamic critical temperature and pressure. Water at these conditions has been widely explored [2,3] as part of developing a more sustainable chemical industry.

2. Selected Research Results

Holliday et al. [4] were the first to publish a refereed article in the chemical literature on p-xylene oxidation to terephthalic acid in HTW. The product yield they obtained was low, but the experiments did demonstrate the feasibility of the synthesis in HTW.

Research groups led by Poliakoff and by Savage performed much more extensive experiments for the synthesis in water. Poliakoff and coworkers [5 - 8] focused on synthesis at supercritical conditions whereas Savage and coworkers [9 – 14] focused on synthesis at milder conditions. Both groups published reports indicating that terephthalic acid could be made in high yields (> 90 %) and high selectivities (> 95%) by synthesis in HTW or SCW. Interestingly, $MnBr_2$ was found to be the most effective catalyst. The addition of Co to the system, which is needed in the acetic acid based process, did not improve reaction rates or product yields. Therefore, it seems that the details of the catalytic chemistry in water are different from those in acetic acid.

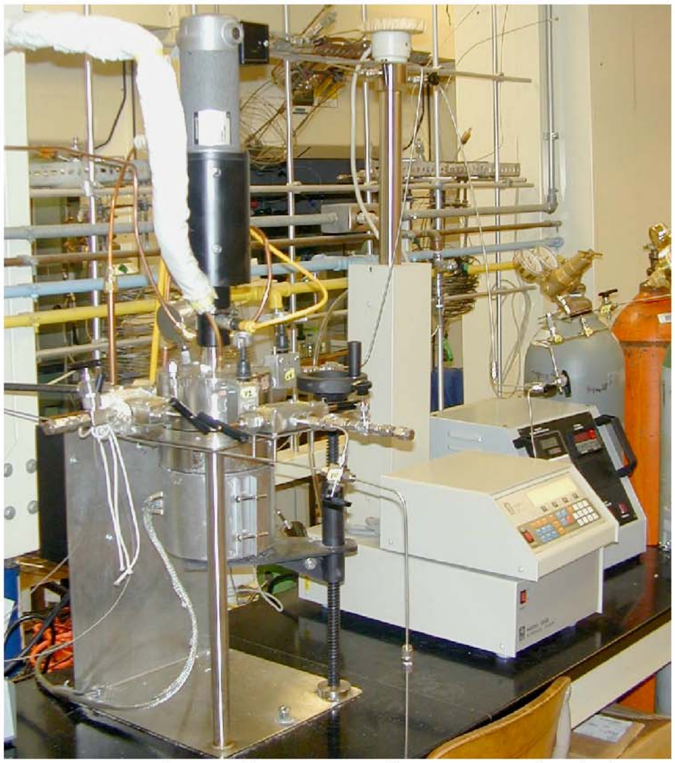


Figure 1: Experimental apparatus for TPA synthesis in HTW

The figure above shows the experimental system used by Dunn and Savage [12]. A batch reactor (left in photo above) was used in the experiment. Water and air were loaded into the reactor, and then it was heated and pressurized to the desired reaction conditions. After the reactor reached those conditions, a solution of p-xylene and catalyst ($MnBr_2$) was quickly added into the reactor by a syringe pump (right in photo above). The addition of the reactant marked time t = 0. Samples were withdrawn from the reactor periodically and analyzed. The analysis revealed which chemical compounds were present and in what amounts.

Figure 2 shows experimental results from p-xylene oxidation in HTW at 300 °C. The initial p-xylene concentration was 0.02 mol/liter. It takes only a few minutes for terephthalic acid (tpa) to form in high yields. The yields of intermediate oxidation products are low, and after 15 minutes these intermediate products are no longer detectable. Only terephthalic acid is present, and in essentially 100% selectivity. These results show the synthesis of terephthalic acid in high yields and high selectivity is feasible in HTW.

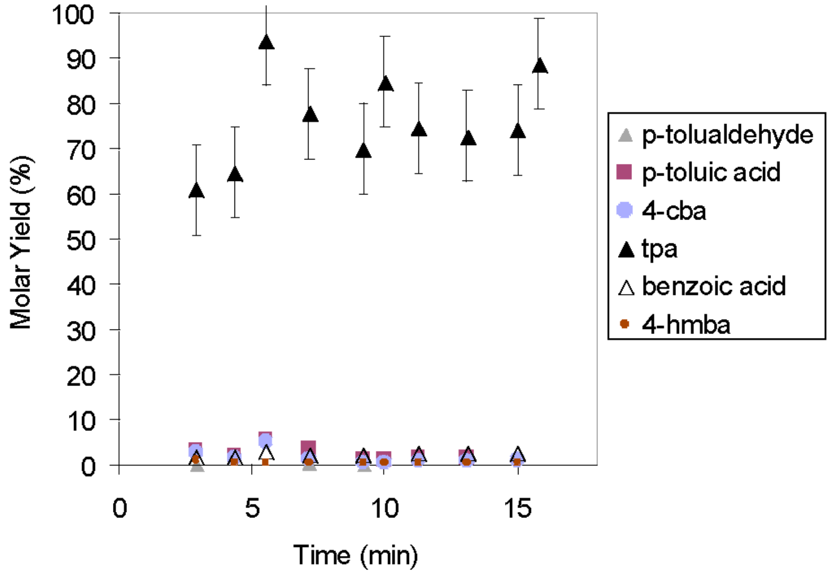


Figure 2: Experimental results for TPA synthesis in HTW at 300 °C [12]

Table 1: Results for TPA synthesis in HTW at 300 °C and high p-xylene concentrations [14]

Run	conditions			selectivity (mol%)					
	O_2 step[b]	final O_2 /*p*-xylene (mol/mol)	$MnBr_2$ (mol L^{-1})	**TPA**	*p*-xylene	*p*-tolu aldehyde	*p*-toluic acid	4-CBA	BA
1	0.5	9	0.014	**97.6**	0.0	0.2	0.1	0.0	2.1
2	0.5	9	0.028	**94.7**	0.0	0.7	0.7	0.4	3.5
3	1.0	9	0.028	**96.1**	0.0	0.8	1.4	0.1	1.6
4	cont[c]	6	0.028	**7.3**	87.9	1.4	3.5	0.0	0.0
5	cont[c]	6	0.028	**31.4**	59.7	5.4	3.5	0.0	0.0
6	cont[c]	6	0.028	**31.1**	59.4	5.4	3.4	0.7	0.0
7	cont[c]	6	0.028	**31.8**	65.6	1.0	1.0	0.0	0.6

(CBA = carboxybenzaldehyde, BA = benzoic acid)

More recent experiments [14] showed that the synthesis can also be conducted at even higher p-xylene concentrations. Using higher concentrations is desirable because it will allow more terephthalic acid to be produced per unit reactor volume. Table 1 shows results from p-xylene oxidation in water at 300 °C at a higher concentration of 0.2 mol/liter. In these experiments oxygen was added incrementally throughout the reaction rather than all at the start as had been done in the previous experiments. This protocol revealed that the reaction is very sensitive to the manner in which oxygen is added. Adding it in short discrete bursts leads to high selectivities at the end of the experiment (Runs 1 – 3 in the table above). Adding oxygen continuously leads to low selectivities (Runs 4 – 7).

3. Environmental and Economic Assessment
The laboratory research results published in the literature demonstrate that the desired synthesis reaction proceeds in HTW and in SCW. Thus, the alternative process seems capable of clearing the hurdle of technological feasibility. Other hurdles remained to be examined, however. These are the hurdles of economic and environmental feasibility. These considerations form two of the components of the triple bottom line of sustainability.

Dunn and Savage [11] examined economic and environmental aspects of terephthalic acid synthesis in HTW and SCW. A quantitative assessment is required to understand the tradeoffs involved. For example, a HTW or SCW process will require higher temperatures and pressures than the current commercial process. More severe conditions tend to be more costly. However, the current commercial process has solvent losses (due to oxidation), and the cost of solvent replacement would be eliminated in the HTW or SCW process. Understanding these and other tradeoffs requires a quantitative framework.

Dunn and Savage considered four different conceptual processes for the synthesis, two each for SCW and HTW conditions. One of the two variations included an air separation plant to generate pure oxygen for the oxidation reaction. The other variation used air as oxidant. The tradeoff here is the cost of the air separation plant vs. the cost of compressing and transporting large volumes of nitrogen (in air) throughout the entire process. Each of the four processes was simulated using ASPEN Plus, a commercial chemical process simulation software package. These simulations provided information needed to determine the sizes of the different pieces of equipment and the energy requirements for each process. A summary of results for the economic analysis of the four different water-based processes appears in Table 2 along with the related values for the commercial acetic-acid based process. Values for the current process were taken from the literature.

One can see that the capital costs for the process without air separation are much higher than those that include this operation. Air separation is not done in the current commercial process, but the higher pressures needed for HTW and SCW-based processes make it the more economical choice for the aqueous-phase processes. With air separation, the HTW and SCW processes have a total capital investment similar to that of the current technology.

Energy intensity, embedded energy, or embodied energy is a metric often used to assess sustainability. It gives a quick indication of the energy resources required to make a fixed amount of some product or material. The table below gives the energy intensity (e.g., amount of energy required in the process to make each kg of terephthalic acid) for the different processes. Note that this value does not include the energy requirements in other parts of the lifecycle of the reactants and materials used in the process. The process-based energy intensity is much lower for the processes that include air separation. The values for the HTW (2) and SCW (4), and Acetic Acid processes are all similar, but the value is lowest for HTW (2). This assessment of the capital costs and energy intensity revealed that HTW (2) was the preferred water-based process and that its metrics were very similar to those of the current acetic acid-based process.

Table 2: Process Summaries, Capital Cost Analysis (million $), and Energy Intensities (MJ/kg of terephthalic acid) (results taken from Ref [11])

Process	HTW (1)	HTW (2)	SCW (3)	SCW (4)	Acetic acid
Reaction Temp. (°C)	300	300	380	380	200
Reactor Pres. (bar)	150	100	250	250	30
Air Separation?	No	Yes	No	Yes	No
Reactor Residence Time (min)	30	30	0.20	0.20	60
CAPITAL COSTS					
Oxidation Section Capital Investment	170	170	150	150	96
Compression Plant	390	53	470	100	150
Air Separation Plant		55		55	
Total Capital Investment	560	280	620	310	250
ENERGY INTENSITY					
Furnace	9	9	10	10	
Compression Plant	44	6	53	11	
Air Separation Plant[a]		2		2	
Total	53	17	63	23	19

The environmental assessment used Toxics Release Inventory data to calculate the pollution intensity of methyl bromide for an acetic-acid-based process. BP's 1.3 billion kg/yr capacity terephthalic acid plant in Cooper River, South Carolina emits 41,600 kg/yr of methyl bromide after process gases are incinerated. Actual production of methyl bromide from the process is therefore greater than this figure. The majority of methyl bromide forming in the current process derives from acetic acid. HTW will not react with Br^- to form this pollutant and, consequently, one expects essentially no methyl bromide production in HTW.

Emissions of CO_2 from the process will also decrease with HTW substitution. Since 0.07 kg of acetic acid per kg of terephthalic acid undergo oxidation in the reactor in the current process, then 0.10 kg of carbon dioxide per kg of terephthalic acid result from this oxidation of solvent.

A final consideration is water usage. A HTW-based process will require large amounts of water, and, if the water is not recycled, it will have a greater water intensity than the acetic-acid-based process. However, it is likely that the water can be recycled without much replenishment. Additionally, the oxidation reaction that makes terephthalic acid generates two moles of water for every mole of terephthalic acid. Thus, there is a natural production of solvent during the reaction.

4. Summary

That terephthalic acid synthesis can proceed to high yields in HTW is very encouraging. One must recognize that only a fairly small number of academic researchers have been investigating this synthesis in water, and that the current commercial process has benefited from countless man-hours of R&D over the last 50 years. Much more work will be required for a HTW- or SCW-based process to displace the current commercial process, but it appears that there is merit in investing in this additional work. It is very difficult for a new process technology to supplant an existing one, especially when the existing one works quite well, is profitable, and is familiar.

5. References

1. Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press New York, 1998.
2. Savage PE. Organic chemical reactions in supercritical water. *Chem Rev.* 1999;99:603-621.
3. Akiya N, Savage PE. Roles of water for chemical reactions in high temperature water. *Chem Rev.* 2002;102:2725-2750.
4. Holliday RL, Jong BYM, Kolis JW. Organic synthesis in subcritical water oxidation of alkyl aromatics. *J Supercrit Fluids.* 1998;12:255-260.
5. Hamley PA, Ilkenhans T, Webster JM, Garcia-Verdugo E, Venardou E, Clarke MJ, Auerbach R, Thomas WB, Whiston K, Poliakoff M. Selective partial oxidation in supercritical water: the continuous generation of terephthalic acid from para-xylene in high yield. *Green Chem.* 2002;4:235-238.
6. Garcia-Verdugo E, Venardou E, Thomas WB, Whiston K, Partenheimer W, Hamley PA, Poliakoff M. Is it possible to achieve highly selective oxidations in supercritical water? aerobic oxidation of methylaromatic compounds. *Adv Synth Catal.* 2004;346:307-316.
7. Garcia-Verdugo E, Fraga-Dubreuil J, Hamley PA, Thomas WB, Whiston K, Poliakoff M. Simultaneous continuous partial oxidation of mixed xylenes in supercritical water. *Green Chem.* 2005;7:294-300.
8. Fraga-Dubreuil J, Poliakoff M. Organic reactions in high-temperature and supercritical water. *Pure Appl Chem.* 2006;78:1971-1982.
9. Dunn JB, Savage PE. Terephthalic acid synthesis in high-temperature liquid water. *Ind Eng Chem Res.* 2002;41:4460-4465.
10. Dunn JB, Urquhart DI, Savage PE. Terephthalic acid synthesis in supercritical water. *Adv Synth Catal.* 2002;344:385-392.
11. Dunn JB, Savage PE. Economic and environmental assessment of high-temperature water as a medium for terephthalic acid synthesis. *Green Chem.* 2003;5:649-655.
12. Dunn JB, Savage PE. High-temperature liquid water: a viable medium for terephthalic acid synthesis. *Environ Sci Technol.* 2005;39:5427-5435.

13. Savage PE, Dunn JB, Yu J. Recent advances in catalytic oxidation in supercritical water. *Combust Sci Technol.* 2006;178:443-465.
14. Osada M, Savage PE. Terephthalic acid synthesis at higher concentrations in high-temperature liquid water. 1. effect of oxygen feed method. AIChE J. 2008. (accepted)