Sustain Sci (2009) 4:7–15
DOI 10.1007/s11625-009-0065-5

SPECIAL FEATURE Education for sustainable development

Sustainable engineering education in the United States

**Brad Allenby · Cynthia Folsom Murphy ·
David Allen · Cliff Davidson**

Received: 28 August 2008 / Accepted: 18 December 2008 / Published online: 24 February 2009

Abstract Sustainable engineering is a conceptual and practical challenge to all engineering disciplines. Although the profession has experience with environmental dimensions of engineering activities that in some cases are quite deep, extending the existing body of practice to sustainable engineering by including social and cultural domains is a significant and non-trivial challenge. Nonetheless, progress is being made, as a recent study undertaken by the Center for Sustainable Engineering in the United States demonstrates.

Keywords Sustainable engineering · Industrial ecology · Engineering education · Sustainable engineering education

Introduction

Engineering education and sustainability

The idea of "sustainable engineering" is both powerful and challenging. It recognizes that appropriately designed products, technology systems, and services, and thus good engineering, are critical to better environmental and social performance across a globalizing economy. But it is one thing to appreciate the power of an abstract concept and entirely another to reduce it to a rigorous enough framework, a toolbox of methods, and sets of metrics so that it can be applied by professionals and taught to engineering students. The Center for Sustainable Engineering, a consortium consisting of Arizona State University, Carnegie Mellon University, and the University of Texas at Austin, has been exploring these issues in the context of American universities and educational practices. The results of this activity, reflecting both the uncertainty surrounding the concept itself and the nascent state of the field of sustainable engineering, are necessarily preliminary. Nonetheless, they establish that the engineering profession and engineering educators are moving forward, and suggest avenues by which sustainable engineering can be expanded significantly in both academia and practice. The data also indicate, however, that understanding the challenges summarized in the term "sustainable engineering" will be neither trivial nor quickly accomplished, and that further structured research, including integration of non-US engineering communities in this dialogue, is necessary.

Perhaps more than most professions, engineering because of its practical and applied focus reflects the immediate environment within which it operates. This has important implications for framing the idea of "sustainable engineering;" as we learn more about the environmental

---

B. Allenby (✉)
Department of Civil, Environmental, and Sustainable Engineering, Arizona State University, Tempe, USA
e-mail: Braden.Allenby@asu.edu

C. F. Murphy
Center for Energy and Environmental Resources, University of Texas at Austin, Austin, USA

D. Allen
Department of Chemical Engineering, University of Texas at Austin, Austin, USA

C. Davidson
Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, USA

and social impacts of our lifestyles, we need to re-think many of the assumptions that underlie our engineering decisions.

Technology systems in the anthropocene

Most importantly, perhaps, it is becoming clear that the industrial revolution and associated changes in human demographics, agricultural practices, technology systems, cultures, and economic systems have resulted in the evolution of an anthropogenic earth, in which the dynamics of major natural systems are increasingly impacted by human activity (Allenby 2005). We note much more integration of human culture, built environments, and natural systems now than ever before, producing emergent behaviors that could not have been predicted. Failure to appreciate the complexity of these interacting systems has serious consequences: for example, many of the difficulties of the climate change policy dialogues arise from the fact that climate change has been positioned as an "environmental" issue, when in reality it cuts across, and involves, numerous systems—including, importantly, foundational cultural systems, different value systems, and economic and technological frontiers. Within the climate change policy framework, the complexities of these integrated earth systems are well illustrated by dysfunctional policies that require the production and use of corn-based ethanol. These policies have resulted in much higher food prices, which is not surprising considering increasing fossil fuel prices, changes in diet to include more meat in developing countries, global commodity markets, shifts in planting patterns to reflect policy-driven changes in demand, and other factors. Rising food prices have, in turn, caused political instability in many nations, creating security issues. This interpenetration of human systems, especially technology, with natural systems can no longer be evaded or ignored; as the journal *Nature* put it in an editorial in 2003, "Welcome to the Anthropocene," or, roughly translated, the age of humans.

Technology in many ways functions as the mechanism by which humans perceive, and interact with, each other and their external environment. Understood this way, technology is far more than products and artifacts, or even the commercial services for which physical systems serve as platforms; rather, technology must be considered a powerful force that acts across institutions and is transformative across cultures (Bijker et al. 1997).

Consider a familiar technology such as the railroad (Allenby 2007a). In the middle 1800s as railroad technology began its rapid expansion phase, it included the most impressive pieces of machinery most people ever saw. However, few could have predicted that it would turn out to be the mechanism for unprecedented institutional and social change. As a regional and then national network requiring close coordination, railroads required a uniform, precise system of time, and thus created "industrial time" and its associated culture. [Before railroads, times often differed by a random number of minutes between neighboring towns. There was no pressure against this, because contemporary society and commerce had no need of coordinated time; there were no systems that needed that kind of coordination (Schivelbusch 1977)]. Similarly, railroad technology required coordination of communication across their networks, and thus it created the need for, and co-evolved with, the telegraph as the first national-scale communications system.

But the changes wrought by railroad technology were not just in other technologies, but also in institutions; railroad firms required a hitherto unprecedented accumulation of capital and thus created modern capital and financial instruments and markets (railroad construction was the single most important stimulus to industrial growth in Western Europe by the 1840s). Railroads also required unprecedented complexity and scale in the firms that were to operate them, thus creating modern managerial capitalism (modern accounting, planning, and administration systems) (Freeman and Louca 2001). Railroads were also environmentally transformative: not only did they have relatively direct environmental impacts, as policymakers worried about the deforestation they caused, but huge indirect effects on the hinterlands of major railroad termini: Chicago existed, and restructured the entire American midwest from a wild swamp to a gridded agricultural region, because of railroads (Cronon 1991). But even more fundamentally, railroads in the US became a potent symbol of national power, validating the US integration of religion, morality, and technology, as well as the belief in manifest destiny, the idea that America had not just the ability. It is more than coincidence that the concept of manifest destiny—the right and duty of Americans under god to extend civilization across the continent—originated in the 1840s in the middle of the railroad expansion (Nye 1994). Thus, the railroads fundamentally changed what it meant to be an American, and what America meant: railroads dramatically changed the underlying character of American culture from an edenic teleology of Jeffersonian agrarianism to the fundamentally different teleology of a technology-driven New Jerusalem, a cultural schism that replays itself today in the continuing environmentalist challenge to technology (Marx 1964).

The railroad example makes several points clear. Most importantly, it refutes the idea that sustainability can be understood, studied, or indeed even conceptualized without understanding technology; this puts a substantial burden on engineers and on those who teach them. It is also a serious warning flag to the portions of the sustainability community that tend to be neutral on technology, if not technophobic. Second, it warns that technological change, especially when it involves fundamental systems, is profoundly destabilizing and unpredictable: who would have predicted that railroads would create our modern sense of time? Or managerial capitalism? This is important given that not just one foundational technology, but five—nanotechnology, biotechnology, robotics, information and communication technology, and applied cognitive science ("NBRIC")—are undergoing rapid evolution. Some are pessimistic about the implications (Joy 2000), some optimistic (Kurzweil 2005), but for the engineering community it is sufficient to recognize that these converging technologies, with their mutually reinforcing integration across technological frontiers, have become major earth systems in their own right. Indeed, the implications of NBRIC may be more fundamental than previous "long waves" of technological innovation because, taken together, these technology systems offer a potential for designing the human in ways that have hitherto been infeasible. This raises the additional complexity in long-range engineering (such as engineering large resource regimes, food and fuel supply systems, carbon cycle engineering and management) that not just the system of interest, but also the engineers interested in it are simultaneously subject to design. Thus, what is most challenging, perhaps, about technological convergence is not merely its effect of turning natural systems, from the carbon and climate cycles to biology at all scales, into design spaces (and commodities). Rather, it also turns the human into a self-reflexive design space. In doing so, the feedback systems, and concomitant increases in system complexity, become truly daunting.

This allows the identification of three major systems impacts of technological evolution in the age of the anthropogenic earth, and earth systems engineering and management (Allenby 2007b): destabilization (social, technological, institutional, and economic), accelerating complexity, and radical contingency. Each affects engineering in different ways. The destabilizing effects of technology, not only within the limited domains of existing technological practice and economic behavior, but institutionally and culturally, are well illustrated by the railroad example.

The complexity of technological evolution, with its challenging philosophic, religious, ideological, and economic implications, is just beginning to be recognized. Even very sophisticated projects, such as the work of the Intergovernmental Panel on Climate Change (IPCC), show very little appreciation for the transformative power of technology and its complexity once one is working in the domain of integrated human/built/natural earth systems. This complexity expresses itself in four different guises. The first, and intuitively most obvious, can be categorized as static complexity and is a measure of what the system looks like at any point in time—the number of components, stakeholders, interactions among different infrastructure, and linkages among them, for example. Since these systems constantly evolve, dynamic complexity arises as these factors interact in new and unanticipated ways; dynamic complexity can be quite unpredictable even in systems that are fairly simple statically. A third form of complexity arises as systems include human components, as of course all technology systems do; "wicked" complexity arises as systems dynamics change to reflect the reflexivity and intentionality of human systems and institutions. Finally, as one moves to the level of earth systems, scale complexity also increases; not only is the emergent behavior of these global scale systems different in complexity from the behavior of subunits, but the problem of understanding and managing multiscale phenomena becomes more problematic.

It should not be thought that questions of complexity are merely academic. Consider two very different examples. One, mentioned above, is the problem of climate change; a major reason for the failure of the Kyoto process is that it conceptualized climate change as a "scientific" problem, not a multidomain, multicultural, social, and cultural issue—or, in other words, it understated the complexity of the phenomenon it purported to address. The second is geopolitical: Marxism in the Soviet Union and China collapsed not from external conquest, but because the centralized economic model adopted by large Marxist societies simply became incapable of managing the complexity inherent in a modern (post) industrial economy. And economies, financial networks, and technologies have become far more complex since then.

The combined effect of accelerating technological change and increasing complexity is a profound and radical contingency, in that not just the external systems, but also that which interacts with them, and attempts to design, engineer, maintain, operate, and manage them, are rendered uncertain and unpredictable in shorter and shorter time frames (Allenby 2006a). As the system becomes more complex, in other words, it undermines the stability of the cultural and institutional frameworks within which engineers, and others, operate. Thus, the modern engineer faces a world where it is not just his or her discipline that has become far more complicated, but also the environment within which the engineer must practice, including the variables that now become part of the engineering process.

Defining sustainability for engineers

This dramatic increase in complexity is confounded by the challenge of a very ambiguous term, "sustainability." If one is going to approach this concept as an engineer, it is necessary to understand at least something about its origin. In this, the history is fairly clear: sustainability is a classic example of a cultural construct, a symbol, idea, or phrase by which societies create and transmit meaning (Allenby 2006b). The concept was initially popularized in the book *Our Common Future* (WECD 1987), and was in large part created to try to reduce conflict between two important discourses: the economic development discourse that sought to encourage economic growth, especially in developing countries, and the environmental discourse that sought to preserve as much biodiversity and unspoiled land as possible. In a cultural sense, the concept has proved successful in that, in less than 20 years, the idea of "sustainability" has evolved into a major policy discourse. Unfortunately, this has in part been accomplished by a considerable increase in ambiguity, as various stakeholders and institutions configure a fairly malleable idea to fit their own agendas.

Especially at the beginning, "sustainability" or "sustainable development"—the two tend to be interchangeable in use—embodied two major themes: egalitarianism and redistribution of wealth within and among generations, and environmental preservation and protection (WECD 1987). But although this fairly clear, if normative, focus has significantly eroded over time, the attractiveness of "sustainability" does not appear to have suffered, as the increasing popularity of "sustainable engineering" itself suggests. This has led some so suggest that the value and attractiveness of sustainability arise from the fact that it provides a modern foundational narrative that helps individuals make sense of a complex and unpredictable world. As Walker (2007 at 1, 8) comments:

> Sustainable development can be seen as our modern myth, emerging from a culture of science, technology and reason… (It) represents much more than simply an analytical approach to environmental auditing or improving business accountability. It also encompasses and represents a way of acknowledging our values and beliefs, and ascribing meaning to our activities. In this sense, sustainable development offers a contemporary way of, at least partially, filling the void left by the demise of religion in public discourse. On the other hand, it must also be acknowledged that sustainable development is both ideological and immature. As such, it has neither the breadth nor the profundity of the traditions that, to an extent, it supersedes.

Framing sustainability as an evolving myth helps explain some of the metaphorical language that surrounds it, which in turn helps engineers understand what is being demanded of them when stakeholders insist on "sustainable engineering." Consider, for example, the language of McKibben (1989 at 180), who insists that "the planet" is "suffering." This makes no sense to a scientist or engineer, because planets cannot suffer in any commonly understood sense of the word, but in mythic structures the suffering of nature, the individual, and society are frequently conflated. This is metaphor, not rational dialogue—and as an engineer, it is important to understand that the construct of sustainability is an objective façade over a normative structure; otherwise, it can significantly mislead those who attempt to apply what they believe is an objective set of criteria to technological or engineering situations.

In fact, it is the misunderstanding of "sustainability" as an objective function, rather than as a guiding myth, that perhaps causes the major conceptual problems regarding sustainable engineering. Engineers are basically problem solvers; an engineer's primary responsibility is to produce a solution that works in the real world, with all the attendant constraints—competitive, ergonomic, regulatory, economic, consumer friendly, and temporal (such as time to market). In addition, most engineering activities must appropriately consider other stakeholders as well: this is most critical where workers, and the public at large, are involved. To enable solutions in such complicated spaces, engineers and engineering methodologies are highly quantitative. Especially regarding sustainability, a concept that to some extent is validated by its ambiguity, this obviously poses substantial challenges, because the luxury of constructive ambiguity does not exist for engineers: whatever they design and build has to work.

On the other hand, it has always been the case that engineering changes as society and technology change. Traditionally, engineers have been relatively instrumental, in that they were presented with, and created solutions for, problems arising from design, manufacture or construction, operation, and management of technological artifacts of all types and scales. But the increasing interest in sustainable engineering indicates that engineers, engineering managers, and technologists generally are now being tasked with understanding the broader social, economic, and environmental implications of their work as well, with an implication that they have some responsibility for those dimensions. Thus, for example, an engineering firm building a road in a tropical rain forest might find itself responding to questions about how their road might change future settlement patterns in nearby sensitive locations; engineers and scientists working on biotechnology or nanomaterial projects find themselves being quizzed on the social and environmental performance of the underlying technology systems.

This is a subtle change, but it has potentially huge implications for the engineering profession and for engineering education. These include a serious increase in the complexity of the ethical dimensions of engineering activities and engineered systems, a subject not dealt with in detail here, but which one of us has discussed in an earlier issue of this journal (Allenby 2006a). It also requires broadening engineering education, a difficult challenge given the already full curriculum of engineering education at the undergraduate level. It requires teaching engineers about technology systems as well as about engineered systems; the two are not synonymous and, indeed, involve different domains. Finally, it means that engineers must also be taught to be leaders rather than simply technical members of large teams, a challenge not just for students, but for their professors, who are not trained to, or experienced in, delivering such training.

The challenge to engineering educators

"Sustainable engineering" thus poses a difficult set of challenges for engineering educators. From a conceptual perspective, there is the need to rephrase "sustainability"—a mythic, qualitative, highly normative construct—in language that is culturally acceptable, and reasonably useful, for the supremely applied, pragmatic, problem-solving engineering disciplines. In particular, this requires that vague statements such as "protecting the planet" or "sustainable solutions" be translated into quantitative, algorithmic procedures that enable engineers to derive designs and technologies that, on some objective basis, can be ranked.

Beyond the serious "two culture"[1] problem posed by the very framing of "sustainable engineering," there are other issues that any educational institutions seeking to instruct students in "sustainable engineering" must address. First is the fact that, because engineering is perhaps the last profession where an undergraduate degree is also considered to be the professional degree, the engineering curriculum is already full; there is simply no room for additional courses until major changes in engineering education are undertaken on a systemic level. Recognizing this, the Center for Sustainable Engineering (CSE), a consortium consisting of Carnegie Mellon University, Arizona State University, and the University of Texas at Austin, have focused their curriculum development efforts on the creation of sustainable engineering modules that can be inserted in existing classes, rather than the development of new classes. In some cases, however, engineering schools have developed sustainable engineering courses, and designed and certified them to meet distributive requirements so they augment, but do not replace, existing engineering courses. Thus, for example, the required senior-level undergraduate course on Earth Systems Engineering and management taught at ASU's Department of Civil and Environmental Engineering meets the humanities and fine arts distributional requirement. Nonetheless, how to inject substantial new content into existing engineering programs is a major challenge.

A related challenge is posed by the educational structure that surrounds engineering, which has substantial inertia. To some extent, this is simply a matter of scale, the sheer size of the engineering education system, especially given globalization. Although different standards and expectations of graduates make numerical comparisons suggestive rather than definitive, there is no question that huge numbers of engineers are graduated annually; the US alone produces roughly 70,000 engineering graduates per year; India, perhaps 350,000; China, some 600,000.[2] This makes quality control critical, and most countries have accrediting institutions, such as the American ABET, Inc., which was renamed in 2005 from the more descriptive Accreditation Board for Engineering and Technology. More subtly, many schools pay serious attention to the numerous services that use various criteria to produce annual rankings of engineering schools, usually by specialty; when a new area such as "sustainable engineering" appears, it is obviously not part of the ranking process and, more importantly, anything that draws resources and energy from traditional programs, thus potentially hurting their rankings, will be disfavored. Finally, there are cultural issues, such as the dynamic created by the anti-technology bias of much sustainability literature, which has the predictable effect of reducing the interest among many practicing engineers and professors in "sustainable engineering." To be fair, most of these institutions do understand the need for change. The problem is simply that the complexity and size of the global engineering education enterprise, and the importance of assuring professional competence among graduates, make any change slow and difficult.

There are also a number of substantive challenges. Most obviously, perhaps, "sustainable engineering" poses the same sort of problem as "environmental sciences" does: in an academic world expert at teaching within a disciplinary landscape, where do these sorts of integrative programs fit, and how does one teach them with appropriate rigor? The answer depends on whether one decides to teach it as its

---

[1] The phrase arises from the famous essay by C. Snow (1959) entitled "The Two Cultures" where he analyzed the cultural differences between the social sciences and the physical sciences.

[2] These numbers were cited in the 2007 report, Rising Above the Gathering Storm done by a committee of the US national academies, which were in turn drawn from Chinese and Indian government figures. They have been criticized, in part because the US appears to define engineering graduates differently than either China or India for statistical purposes.

own specialty, or as a necessary component of other engineering disciplines. For example, by teaching the ASU earth systems engineering course as part of the civil and environmental engineering curriculum, one knows that students will have a rigorous preparation in a recognized discipline, and that this is being enhanced and augmented, rather than replaced, by a course with an expanded sustainable engineering focus. But that is far more simple conceptually than creating a "sustainable engineering" discipline alongside the others; moreover, to do so would imply that sustainable engineering was a particular kind of engineering, not a competence to which all engineering students needed exposure. These sorts of positioning discussions are by no means resolved.

A second, and very important, substantive challenge for sustainable engineering derives from its roots. Most of the engineering fields that contribute in some way to the development of sustainable engineering—ranging from "green engineering" as developed in places like Carnegie Mellon University, to industrial ecology, to pollution prevention—as well as the most familiar methodologies, such as design for environment (DFE) and life cycle assessment (LCA), almost always have arisen from exclusively environmental concerns. Thus, engineers and educators are substantially more used to identifying and considering environmental issues than they are social and cultural issues. In part, this reflects the fact that environmental issues, which can be more easily defined and quantified than social or cultural issues, are therefore more tractable to engineering cultures and frameworks. It also reflects the fact that, even for policymakers and social scientists, social and cultural issues are difficult to define with precision, are invariably normative, and are usually highly conflictual. Thus, for example, one can relatively easily develop product design heuristics to address the environmental dimensions of product sustainability, such as better energy efficiency during use, reduction in toxic materials, and establishing a used product takeback system. When it comes to the social and cultural domains, however, there are many opinions (often stated as self-evident facts), but few heuristics. Moreover, many of the stakeholders with self-declared interests in sustainable products or engineering actively oppose the few heuristics that do exist, such as regulatory compliance and consumer acceptance. A classic example of this is the Greenpeace report on the Apple iPhone, which criticizes the device for containing certain chemicals, even though they are legal (www.greenpeace.org/use/news/iphone-s-hazardous-chemicals), as is the phone itself, which shows no indication of being hazardous, and, based on consumer response, obviously has a high social value. So who gets to decide what is socially preferable: consumers, stakeholders, or activist groups? And this highlights a final difficulty with sustainable engineering as opposed to environmental engineering: the skills necessary to evaluate environmental issues are part of the engineer's training already; the skills necessary to navigate the minefield of social and cultural preferences and value conflicts are not.

That said, there are an increasing number of efforts to extend approaches such as industrial ecology, which have in the past had a heavy environmental focus, to include sustainable engineering. Thus, for example, industrial ecology is defined in the leading engineering textbook in the field as "the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution" (Graedel and Allenby 2003, at 18). The third edition of that textbook, which is currently being prepared for the publisher, is being expanded to explicitly cover sustainable engineering as well as the more traditional industrial ecology subjects. Thus, an engineer would first use the methodologies of industrial ecology, such as life cycle assessment, material flow accounting, or product and process matrix analysis, to determine relevant social and environmental considerations, and then use existing design and engineering methods to integrate that knowledge into process, product, and infrastructure development. And, arguably, green engineering provides guidance for sustainable engineering, because if a product is designed to be environmentally responsible, and also meets social and cultural preferences well enough to succeed in the marketplace, it is to first approximation sustainable.

Industrial ecology is even defined appropriately. Certainly, the early history of industrial ecology is essentially a history written in terms of sustainable engineering: the first industrial ecology Ph.D. in 1992, titled "Design for Environment: Implementing Industrial Ecology," explicitly included analysis of social as well as environmental considerations (Allenby 1992). The longest publication record in industrial ecology and sustainable engineering is that of the proceedings of the IEEE annual symposium on electronics and the environment, which has been held since 1993. Moreover, technology intensive firms, especially AT&T and its Bell Laboratories, were critical early supporters of industrial ecology, and many of the early tools were developed and tested by engineers in such firms. Institutionally, it is also noteworthy that the US National Academy of Engineering not only was an early champion of industrial ecology, but continues to support initiatives on sustainable engineering to this day. In addition to the IEEE's activities, most of the major professional engineering organizations, drawing on industrial ecology, pollution prevention, design for environment, and green chemistry literature, have sustainability initiatives, although these have in general yet to lead to robust methodologies or educational initiatives, either at the university or the continuing education/professional levels [examples include the ASCE PERSI (practices, education, and research for a sustainable infrastructure) initiative, and the AIChE Institute for Sustainability].

Benchmarking sustainable engineering education: preliminary results[3]

In 2007, with support from the US EPA, the CSE developed two e-mail 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 1,500 surveys were sent out to department and program heads, and more than 300 responses were received. Based on recommendations from department and program heads, as well as publication records and attendance at NSF and CSE workshops, a total of 327 more detailed surveys were sent to individuals identified as sustainable engineering champions. About 137 valid responses were received, for a response rate of 43%, representing 97 separate US institutions with engineering programs out of a population of 365 (a 27% institutional response rate).

In interpreting the information below, the reader should bear in mind two caveats. First, while the survey and survey 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 survey 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 survey made us aware of 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 our analyses during this process provide a basis for holding at this point 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.”

In the area of research, respondents self-identified a total of 238 sustainable engineering projects with more than a quarter of a billion dollars (some $235,000,000) worth of funding. The average project length is 30 months, and the average annual funding per project is a little over $240,000 per year. Nearly half of the funding is from the US National Science Foundation (NSF), with NSF plus the Department of Defense (DOD) accounting for nearly 70% ($162 M) of the total funding. If sponsorship is evaluated by funding rates, these two sponsors account for more than 60% at 31.3 million dollars per year (Fig. 1).

More than 500 graduate students are involved in this research, with 388 being fully supported by these grants, and the rest partially or not supported. Over 500 undergraduates are also involved in the research, with 89 fully supported, and the rest either partially or not at all supported.

The questionnaire participants were also asked about the conferences they regularly attend. The largest single events are the IEEE International Symposium on Electronics and the Environment (now renamed the International Symposium on Sustainable Systems and Technology, reflecting in part the need to extend from environmental to sustainability issues), reported by 17 respondents, and the International Society for Industrial Ecology, reported by 9; other meetings included those of the various professional societies, such as the AIChE and ASME. The two most widely read journals are *Environmental Science and Technology* (identified by 32) and the *Journal of Industrial Ecology* (25). While these meetings and scholarly journals are identified as having a plurality of activity, no single meeting or journal is dominant.

Respondents identified and described 160 relevant courses, and provided 49 syllabi. These will be placed on the CSE website, which is being designed as a one-stop

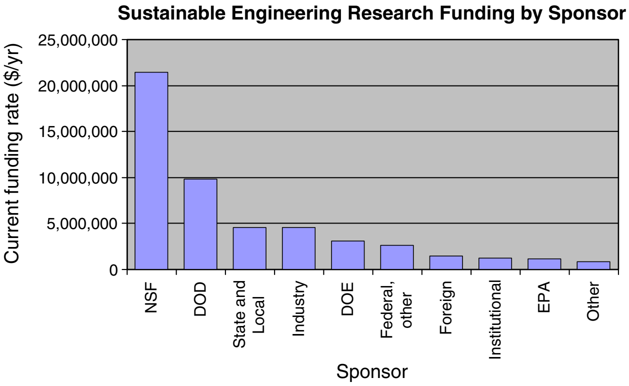

Fig. 1 NSF and DOD are the largest current sponsors of sustainable engineering research, based on CSE questionnaire responses

---

[3] This section draws heavily from a preliminary analysis of the data by Cynthia Folsom Murphy of the University of Texas.

resource for those desiring to teach courses in sustainable engineering. Most of the courses are designed for upper division undergraduate or graduate students: only 15 were made up of 50% or more freshmen and/or sophomores. Almost two-thirds of all courses are described as stand-alone offerings rather than part of a sequence or degree plan. Note that this process does not identify traditional courses that might increasingly include sustainable engineering components.

The participants in the questionnaire were asked to identify educational materials used in the courses. This information was provided directly through the survey process, and obtained from course web sites and syllabi under four categories: textbooks, readings, web sites, and software. Data from all three sources were combined and reconciled. Because the respondents varied in their interpretation of what constituted a textbook and what should be listed as a reading from a book, all books were treated as a single category.

Regarding educational material, 102 of the 160 courses listed one or more books as a text or as a source of readings. With the exception of five titles, very few publications were listed more than once or twice; the five books that account for 53 (21%) of the 249 listings are:

- *Industrial Ecology*, Graedel and Allenby (14 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).

The category mix of books used in the teaching of sustainable engineering courses reflects experimentation. For the purpose of analysis, each was placed in one of eight categories. Four engineering categories are used: sustainable engineering, sustainable engineering technology (e.g., wind, solar, fuel cells, etc.), traditional environmental engineering, and standard engineering; four non-engineering categories are also used: social science/business/policy, architecture/land use/human ecology, natural/physical science, and history/ethics/philosophy.

As indicated in Table 1, engineering books exceed the number of non-engineering, with a roughly even split between sustainable engineering and standard engineering. However, it is striking to note that 98 (39%) of the listings are non-engineering/non-science books. This probably reflects the fact that sustainable engineering by definition brings in more consideration of environmental and social context, and thus requires students (and professors) to reach beyond traditional categories.

Table 1 Sustainable engineering courses draw primarily on existing engineering texts, including relatively new texts on sustainable engineering and industrial ecology, but are also notable among engineering courses for reaching into relatively unfamiliar fields, such as social sciences and the humanities

Book category	Number of listings
Sustainable engineering	48
Sustainable engineering technology (e.g., wind, solar, fuel cells, etc.)	16
Traditional environmental engineering	23
Standard engineering textbooks	49
Total engineering	136
Social science/business/policy	61
Natural/physical sciences	15
Architecture/land use/human ecology	19
History/ethics/philosophy	18
Total non-engineering	113
Total number of book titles	249

Conclusion

The intellectual and cultural challenges of teaching sustainable engineering are considerable. While there is much that can be learned from existing experience in related fields, such as green engineering and industrial ecology, and associated methodologies, such as design for environment and life cycle assessment, there is an often underestimated substantive gap between these areas of study and sustainable engineering. Most obviously, this is because sustainability engages social dimensions that are less quantifiable and more normative and subjective compared with the material and methods most engineering professors are familiar with and are comfortable teaching. Initial data drawn from a US survey indicate, nonetheless, that considerable progress is being made, with numerous courses being developed and reliance on what is beginning to be a core of curricular material possible. Nonetheless, the survey also indicated substantial differences in the ways that different faculty and schools interpret the concept of sustainable engineering and choose to address it; most noteworthy is the split between those that integrate sustainability issues and examples into existing courses and those who choose to offer dedicated courses in sustainable engineering.

Acknowledgments This research was supported in part by EPA grant no. X3-83235101-0 and NSF grant no. 0442618.

References

Allenby BR (1992) Design for environment: implementing industrial ecology. University Microfilm International, Ann Arbor

Allenby BR (2005) Reconstructing earth. Island Press, Washington, DC

Allenby BR (2006a) Macroethical systems and sustainability science. Sustain Sci 1(1):7–15

Allenby BR (2006b) The real death of environmentalism. Environ Qual Manage 16(1):1–10

Allenby BR (2007a) From human to transhuman: technology and the reconstruction of the world. Templeton research lecture, available at www.asu.edu/clas/lincolncenter/documents/hottopics_humantotranshuman.pdf. Accessed June 2008

Allenby BR (2007b) Earth systems engineering and management: a manifesto. Environ Sci Technol 41(23):7960–7965

Bijker WE, Hughes TP, Pinch T (eds) (1997) The social construction of technological systems. MIT Press, Cambridge

Committee on Prospering in the Global Economy of the 21st Century (constituted by the US National Academy of Sciences, National Academy of Engineering, and Institute of Medicine) (2007) Rising above the gathering storm: an agenda for American science and technology. National Academy Press, Washington, DC

Cronon W (1991) Nature's metropolis: Chicago and the great West. W. W. Norton, New York

Freeman C, Louca F (2001) As time goes by: from the industrial revolutions to the information revolution. Oxford University Press, Oxford

Graedel TE, Allenby BR (2003) Industrial ecology (2nd edn). Prentice-Hall, Upper Saddle River

Joy B (2000) Why the future doesn't need us. Wired 8(4), available at www.wired.com/wired/archive/8.04/joy.html

Kurzweil R (2005) The singularity is near. Viking, New York

Marx L (1964) The machine in the garden: technology and the pastoral ideal in America. Oxford University Press, Oxford

McKibben B (1989) The end of nature. Random House, New York

Nature (2003) Welcome to the anthropocene. Nature 424:709

Nye DE (1994) American technological sublime. MIT Press, Cambridge

Schivelbusch W (1977) The railway journey: the industrialization of time and space in the 19th century. University of California Press, Berkeley

Snow CP (1959) The two cultures. Cambridge University Press, Cambridge

Walker S (2007) Sustainability—the evolution of a contemporary myth. Proceedings of the 5th European Academy of Design conference, Barcelona, Spain, retrieved 11 Jan 2007, from www.ub.es/5ead/PDF/5%20/walker.pdf

WECD (World Commission on Environment, Development, the "Brundtland Commission") (1987) Our common future. Oxford University Press, Oxford