IMECE2011-64975

INTEGRATION OF CLIMATE CHANGE IN THE ANALYSIS AND DESIGN OF
ENGINEERED SYSTEMS: BARRIERS AND OPPORTUNITIES FOR ENGINEERING
EDUCATION

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ABSTRACT

The goal of this paper is to begin mapping perspectives of engineering faculty on barriers and opportunities related to the integration of climate change in the analysis and design of engineered systems (CC&ES). Although both sustainability and renewable energy have been receiving increasing attention in engineering education for quite some time¹, climate change, especially as it relates to engineered systems, has yet to become a widely accepted topic of teaching and research. From recent literature on engineering education and from interviews with engineering faculty, a picture emerges of whether and how climate change is an important dimension in the analysis and design of engineered systems. From those sources, we begin to see what it might take to incorporate the relationship between climate change and engineered systems in engineering education, what the barriers and opportunities to this incorporation might be, and what strategies might be available to institutionalize this incorporation in engineering education.

Support for this paper comes from a larger research project on "Climate Change, Engineered Systems, and Society" which has the goal to develop conceptual and educational frameworks and networks of change agents to promote effective formal and informal education for engineering students, policymakers and the public at large. The project partners include the National Academy of Engineering (NAE), Arizona State University, Boston Museum of Science, Colorado School of Mines (CSM), and the University of Virginia. Within this larger team, the CSM team is planning to develop a testbed for the incorporation of CC&ES in engineering education. Hence, our first step is to find related curricular innovations in the engineering education literature and perspectives from engineering faculty on barriers and opportunities to the integration of CC&ES in engineering education.

METHODS

To develop a plausible map of barriers and opportunities that can later inform a more systematic attempt to generalized knowledge, we are triangulating data from three sources: related literature, individual interviews with engineering faculty, and participant observation during a faculty workshop. In this paper, we only use data from literature and interviews. Participant observation will take place during a faculty workshop in Spring 2012 after the ASME conference. Hence we are not able to report the results of that participant observation in this paper.

We conducted a comprehensive literature review using two databases—Engineering Village and Web of Science—and searched for the keywords "climate change" and "engineering education" in the full text of the articles. We selected those items that proposed a curricular intervention to educate engineering students about some aspect of climate change.

To design and conduct interviews, we searched for faculty in our school who had the words "climate change" in their resumes or websites as part of their teaching and/or research agendas. We then compared the results with our own and our peers' knowledge of faculty teaching and research interests. We identified and interviewed 13 faculty with the following characteristics:

- 3 instructors, 3 assistant professors, 3 associate professors, and 4 full professors
- 10 men and 3 women
- 2 mechanical engineers, 1 mining engineer, 2 geoscientists, 3 civil engineers, 2 electrical engineers, 2 environmental engineers, and 1 chemical engineer.

We then developed an interview protocol, which included the following questions:

- What classes do you teach at the undergraduate and graduate levels?
- Is climate change considered or covered in your course(s)? If so, to what degree did it become a part of your course? If not, has CC come up in other ways?

¹ See [1] for a historical overview of how sustainability and sustainable development became accepted areas of teaching and research in engineering.

- Please help me understand how you decided to include climate change? What was your motivation to include it? Or if it was not even considered, please help me understand how you decided not to include it?
- Could you imagine places where or ways in which you might include climate change as an explicit topic in your course(s) in the future?
- What other opportunities do you see for integrating climate change in your courses or in the curriculum? How might you do this? What would motivate you to do so?
- What barriers might exist to your including climate change in your courses?
- How might climate change or climate-related topics relate to your research? How is climate change discussed or considered in your field?
- How might climate change be considered as a dimension in the analysis and design of engineered systems?
- Do you mind emailing your syllabus to us? Do you know other faculty who explicitly address climate change in their teaching and/or research or other faculty we should talk with?

FINDINGS: LITERATURE

Engineering Organizations and Climate Change

Our literature review reveals that influential engineers and engineering organizations consider climate change to be a significant dimension in the analysis and design of engineered systems. Important US engineering organizations like the NAE have issued calls for adaptation and mitigation efforts to minimize the impact of climate change on society. On adaptation, the National Academy of Sciences (NAS) clearly states that

In the long term, adaptation to climate change calls for a new paradigm that takes into account a range of possible future climate conditions and associated changes in human and natural systems, instead of managing our resources based on previous experience and the historical range and variability of climate. This does not mean waiting until uncertainties have been reduced to consider adaptation actions. Actions taken now can reduce the risk of major disruptions to human and natural systems; inaction could serve to increase these risks, especially if the rate or magnitude of climate change is particularly large. [2], pp. 3-4. ²

Regarding mitigation, NAS clearly recognizes that a carbon pricing system will not be enough: “[We must] complement the carbon pricing system with policies to help realize the practical potential of near-term technologies; to accelerate the retrofit,

replacement or retirement of emission intensive infrastructure; and to create new technology choices” [5], p. 7³

Clearly, as NAS summarizes, climate change adaptation is both of national and international importance:⁴

First, it would help address questions of global equity as developing countries bear the consequences of climate change resulting from developed countries’ emissions. Second, it would open an opportunity for the United States to provide assistance for international humanitarian concerns as part of existing development goals. Third, international engagement could help to address national security issues that will arise from climate change. Fourth, coordination among countries could improve the effectiveness of adaptation efforts by reducing redundant activities or those that act at cross-purposes. Fifth, international engagement offers the United States opportunities to exchange lessons learned from the adaptation experiences. And sixth, international engagement would open expanded global market opportunities for U.S. adaptation technologies, systems, and services. [2], p. 7

So climate change, and the adaptation and mitigation that can happen through engineered systems, clearly enjoys attention by engineers and policymakers at the highest levels. Yet for us as engineering educators, a key question is what would it take to incorporate CC&ES in the education of engineers in the US?

Climate Change and Educational Reform

Influential thinkers have proposed that climate change and associated innovation in renewable energies and related technologies could be our next Sputnik.[11] The scientific and engineering challenges posed by CC, from mitigation in the form of renewable energy to adaptation of existing coastal infrastructures to geo-engineering climate, present significant challenges to engineering education. How might these challenges be met and welcomed by engineering educators?

³ For role of renewable energy systems in mitigation see [6]. The flooding of the Mississippi basin, in great part intentionally done by the US Army Corps of engineers to save larger populations downstream, clearly reflects how high level engineers have articulated the connections between climate change (global warming), natural phenomena (rise in river level) and the need to adapt engineered systems (opening levees). [7]

⁴ The relationship between CC&ES is not just a national issue. Engineering societies and engineers from other countries are in many ways ahead on this debate and dialogue. The European Union has created an EU-wide Adaptation and Mitigation strategies (ADAM) project. [8] In Canada, the Climate Change Impacts and Adaptation Directorate of the Canadian government has proposed significant changes in key engineering infrastructure and systems. [9] The British government created a cabinet level Department of Energy and Climate Change in 2008. [10]

² For multiple options for adapting to climate change in the ocean and coastal engineered systems, see [2] Table S.1 on p. 12. For how transportation systems will have to adapt to climate change, see [3] and for how engineering designers would need to learn to design under uncertainty, see [4].

Broadly speaking, higher education institutions seem ill equipped to deal with these changes. In [12], Bardaglio and Putman conclude that most universities are in the “Stone Age” when it comes to responding to new and important challenges like climate change. They argue that a new entrepreneurial culture will be required “to liberate the innovative spirit of learning and teaching in our campuses...to establish connections across disciplines, between student and academic affairs and between campus and community.” (p. 6)

What might be some of the specific barriers and opportunities to integrate climate change into higher education? In her study on barriers and opportunities toward sustainability education at the University of British Columbia, Janet Moore identified the following barriers:

- a *disciplinary environment* that determines organizational structure and budget/hiring allocations, promotes turf wars and discourages students from taking courses outside of their discipline;
- a *competitive environment* between and within students, faculty, departments and universities;
- *misdirected criteria for evaluation*; and
- *unclear priorities and decision-making structures*. [13]

As opportunities for the future of sustainability education, Moore outlined the following: transdisciplinary research and teaching, collaborative and transformative learning, and participatory evaluation.

But what would it take specifically for engineering education schools or departments to undergo these kinds of changes and transformations required to effectively incorporate CC&ES? What would the barriers and opportunities to these transformations be? In a one-of-a-kind NAE workshop titled *The Acceptance and Diffusion of Innovation: A Cross-Curricular Perspective on Instructional and Curricular Change in Engineering*, sociologists and engineering educators came together in a joint exploration to find both barriers and opportunities for curricular innovation and adoption in engineering education. Prior to the workshop, participants had to research and write position papers on barriers and opportunities to innovation in engineering education. [14]

In her position paper, sociologist Mary Frank Fox found a) faculty autonomy, b) impetus of institution for status maintenance or mobility, c) subfields of faculty, and d) faculty and student composition to be both barriers and opportunities for innovation. [14] For our purposes here, *faculty autonomy* becomes a barrier if a directive to integrate CC&ES were to come from the administration and faculty would resist it. Faculty autonomy becomes an opportunity if the challenge to incorporate CC&ES comes from the faculty’s broader research and professional communities, which often exert great influence on faculty, and faculty would adopt CC&ES. In short,

research and professional communities have the potential to make the integration of CC&ES a *norm*, which will then influence how and what faculty members teach and research. Second, the *impetus of institutions for status maintenance or mobility* refers to actions that schools take to maintain a status position among peer institutions or moves that they make to position themselves as leaders in a new area. So unless an engineering school is determined to position itself as a leader in CC&ES, the impetus will likely act as a barrier, especially in schools with long-held reputations in high-carbon areas such as extraction and use of hydrocarbons. Third, the *subfields of faculty specialization* can be barriers if these subfields, and their associated organizational structures, are more in line with high-carbon energy sources (e.g., coal, oil, gas) instead of alternative forms of energy (e.g., wind, nuclear, solar). *Faculty and student composition* can be an opportunity if there is enough diversity in gender, race, ethnicity and geographical origins that interfaces with the capacity for institutional transformation with regards to incorporating CC&ES. For example, if most faculty and students come from regions whose economies and job markets rely heavily on fossil fuels and/or coal mining, it may be difficult to incorporate CC&ES within their institution. But if they come from areas where climate change has had significant impacts on people’s lives (e.g., loss of residential areas due to rise in sea levels), incorporation of CC&ES will likely be welcomed.

Another NAE workshop participant, Gerhart Sonnert, calls us to consider normative styles and presuppositions or that which is considered to constitute “good engineering” by those in positions of power in academic institutions. [14] If the *norms* held by those in power of academic engineering programs value well-defined disciplinary bodies of knowledge guiding research and teaching, measurable and predictable phenomena as criteria for engineering analysis and design, and the removal of political and contentious issues, like climate change, from engineering education and research, then the incorporation of CC&ES would be difficult to accomplish. For the norms to become opportunities, those in power of engineering programs would have to consider “good engineering” to include, for example, interdisciplinary research and teaching among engineering and social/behavioral sciences to analyze how technical systems interact with social behavior in contributing to CC, accept and learn to deal with unpredictable phenomena and political and contentious issues in engineering analysis and design.

CC and Best Practices in Engineering Education

We also wanted to see a) to what extent climate change had been incorporated (e.g., marginally, moderately, boldly) in courses in engineering education and b) to what extent developers of these courses considered institutional and normative aspects like those mentioned above. Our first

concern was motivated by preliminary interview findings (see below) where some respondents acknowledged that due to the political nature of CC, faculty often address CC under the umbrellas of sustainability, energy efficiency, and life cycle analyses. Yet it is not clear whether the same faculty view CC as a significant dimension in the analysis and design of engineered systems. The second concern was motivated by the NAE workshop participants (see above) who unequivocally state that although structural and cultural (norms) dimensions “such as prestige hierarchies, reward systems, and networks” are key determinants in hindering or facilitating innovation and change in engineering education, “these factors are frequently ignored in ‘best practice’ studies.”

Marginally: Acknowledgement that CC happens but no further inclusion or conceptualization with respect to course content or engineered systems.

In her course “Analysis of the Structure of Materials” Luisa Dempere acknowledges that “critical topics such as global warming, climate change, green practices and sustainable engineering solutions are central to recent changes to regulations and policies impacting the practice of engineering.” She wants to teach students about sustainability through reverse engineering by disassembling an engineered product and analyzing the triple bottom line of sustainability: environment, society, and economy. Although students had to analyze the life cycle of the products, their focus was mostly on the use and disposal of the product, not on the energy used in the extraction of raw materials, manufacturing and transportation and its effects on the climate. Hence connections between CC and the selection of materials were marginal at best. [15]

In a comprehensive survey of renewable energy education in Australia, Philip Jennings claims that “many excellent courses have been developed to train engineers and technicians to design, install and maintain conventional energy systems. However, these systems are now the subject of controversy over issues such as global warming, energy security, public health, air pollution, waste disposal and ecological damage.” Without engaging CC any further, he goes on to treat the problem as one of increasing demand for experts in renewable energy and lack of sufficient supply of related courses or programs. His review of initiatives includes technical education courses, programs in energy studies, renewable energy engineering, environmental architecture programs and short and online courses. Although it is impossible to assess the content of every individual course covered in this review with respect to their treatment of CC, an explicit connection to CC or a treatment of CC as an explicit dimension of renewable energy systems is missing in this review. [16]

Moderately: Acknowledgement that CC is happening might be important for engineered systems, but it is not clear how.

In her “Introduction to Environmental Engineering” course, Angela Bielefeldt asked students to read part of the document “Global Climate Change Impacts in the United States,” included slides with evidence for climate change during a sustainability module that encompassed the second and third lectures in the course, assigned a written homework worth 12% of the total course grade, and surveyed students to rate how severe they thought problems related to global climate change will be. Yet the course description or its contents do not make it clear how CC relates to engineered systems.[17]

From an unexpected institutional and geographical location, Lana Chaar and Lisa Lamont review their course on renewable energy offered at the Petroleum Institute of the United Arab Emirates (UAE). To justify the importance of renewable energy in the land of oil, the paper courageously begins by revealing data positioning the UAE as the world’s second largest producer of CO₂ emissions per capita per year and then describing the course objectives which calls for students to “understand the environmental consequences of energy conversion and how renewable energy can reduce air pollution and global climate change.” Yet the authors do not include this objective as part of the measurable outcomes for the course, and do not show whether or how students met this objective. Instead they show how the course influenced students’ choices for participation in activities after completing the course (internships, solar energy workshop, educating school children) and career pathways after graduation (MS in renewable energy, renewable energy employment, other employment).[18]

Boldly: Acknowledgment that CC is a serious planetary problem, cause for change in engineered systems and motivation to rethink engineering curricula. Fragacy et al. state that “the global climate change crisis...links anthropogenic effects to the stability of the earth’s climate, resulting in significant and potentially catastrophic warming of the earth’s atmosphere and oceans, and the concomitant rise in sea levels... The effects of current use of fossil fuels, however, are a more immediate problem. The tie between fossil fuel use and global warming through increased CO₂ is well recognized by climate modelers.” Hence they propose “to identify salient issues related to energy geotechnology, the sustainable use of geomaterials, and the potential impact of climate change in geosystems.” In their paper they analyze the geotechnical consequences of climate change that include “flooding and erosion control for coastal areas and along river margins; engineering hydrogeology to prevent salt-water intrusion and the contamination of fresh water reservoirs; instability of geosystems associated with the melting of the permafrost and snow caps ... failures of infrastructure...evolution of the physical properties of soils as a function of changing weather

conditions" to name a few. They conclude that these consequences "will extend and profoundly change geotechnical engineering analysis and design [and] these changes will require renewed engineering curriculum, adapted continuing education programs for practitioners, and increased public awareness and expectations for civil engineering infrastructure." They clearly call to "modify the geotechnical curriculum to cover the fundamental scientific principles involved in geomaterials subjected to hydro-chemo-thermo-bio- and/or mechanical loading" and propose a specific way to redesign intro courses in geotechnical engineering. [19]

Unapologetically, Wei and Backer justify their new "green engineering" curricula and research at San Jose State University (SJSU) by stating that "climate change is a pressing issue for the world today. There are an increasing number of technological by-products posing a threat to the stability and quality of the world environment. According to the United Nations' Intergovernmental Panel on Climate Change (IPCC), global warming appears to be accelerating, resulting in higher increases in global temperature and higher rises in the sea level. To effectively address this problem, there is a need for transdisciplinary, transnational approaches, reflecting the complexity of the problem and the interdependence of people's lives around the world." [20] Wei and Backer propose that "given the dire consequences of climate change, the Davidson College of Engineering (CoE) at SJSU has identified green and sustainability engineering as the overarching theme for focused development." Furthermore, they acknowledge that a new form of engineering, one that cuts across disciplinary lines, is needed to deal with the challenges of CC: "Green engineering cross-cuts all engineering disciplines. It covers not only discipline-specific but also interdisciplinary courses and projects. The discipline-specific courses at SJSU include mechanical engineering courses in Solar Energy, Fuel Cell Energy, and Alternative and Renewable Energy; civil engineering courses in Environmental Engineering; and technology courses in Green Manufacturing. We also offer an interdisciplinary curriculum path, a green engineering minor degree." The SJS initiative also includes a project-based Climate Solutions Initiative (CSI) open to all majors, the development of a "Global Green documentary to mobilize college students in the U.S. and China, the world's two biggest energy users, to develop climate change solutions."

As NAE workshop participants warned us, there was no consideration of structural and cultural (norms) dimensions in the curricular best practices that were researched and reviewed for this paper. To begin mapping these, particularly when introducing CC&ES, we focused our interview questions on structural and cultural elements of engineering education.

FINDINGS: INTERVIEWS

Barriers

During our preliminary interviews with faculty⁵, we found four types of barriers to the integration of CC&ES: **institutional, curricular, epistemic, and political.**

The three main **institutional barriers** referred by our interviewees were a) budget b) faculty availability, and c) time. Many of our interviewees described the lack of departmental funds as a barrier since new funds would have to be made available to pay an adjunct faculty, for example, if a tenure-track faculty were to dedicate his/her time to a new course related to CC. Even if funds were to become available, it is not clear whether faculty would be available to teach a new CC-related course given existing commitments to teach required courses and the need for faculty training time.

The main **curricular barriers** found were a) course fit, and b) resistance to take out existing course content. Overwhelmingly, interviewees indicated that there would be resistance to take out content perceived by faculty to be part of the canon of a particular engineering course. Some respondents indicated that ABET requirements or Fundamentals of Engineering exam topics dictate course content, so they are reluctant to take anything out. Others indicated that ABET requirements are quite broad, and CC-related content, if specified, could be incorporated into the curriculum somewhere, not in specific courses. Clearly, there is no consensus among engineering faculty on what ABET requirements mean for the integration of CC&ES.

Some respondents indicated that, given the interdisciplinary content probably required in a CC&ES course, it would be difficult to decide which department would host the course since i) the course would cross many disciplinary boundaries, ii) involve faculty from many academic units, and iii) it would not be clear how to count it towards graduation. "Engineering courses are very technical" (Mario), said one faculty, to indicate that perhaps an interdisciplinary course in CC&ES would be difficult to justify towards graduation from an engineering degree.

The **epistemic barriers** found thus far include a) unpredictability of inputs, b) the nature of design criteria for engineered systems, c) indeterminacy and unpredictability of CC, and d) conceptual overlapping. For engineering faculty who are used to dealing with very predictable inputs and outputs when teaching students how to analyze or design a system, CC presents a significant challenge as they do not know how to model unpredictability. The

⁵ Note: at this stage of our research, we are summarizing interview findings instead of providing full direct quotes from individual interviewees as interviews have not been fully transcribed or coded.

math becomes messy and complex, perhaps too sophisticated for undergraduates (Joan). Another respondent clearly described that engineered systems design is based on past data and decisions to build systems happen fairly quickly, at least in geological time. Yet forecasting CC consequences always involves future projections since past climatic events do not necessarily reflect what will happen in the future. So how are engineers supposed to use these future events as data to design systems? Also, if one goal of an engineered system is to have as little impact as possible on the climate, how are engineers supposed to know if this is actually happening since CC happens so slowly?

Furthermore, many respondents agree that CC's relationship to engineered systems is not exact, and few do not consider it a science, since it also includes policy decisions, geographical considerations, societal behaviors, and in some cases politicized interpretations. So most respondents found it puzzling to try to incorporate CC in the analysis and design of engineered systems.

The most common epistemic barrier among respondents was conceptual overlapping that emerged from equating CC to sustainability or to sustainable engineering. Some faculty used both CC and sustainability interchangeably as if they meant the same thing or assumed a positive relationship between sustainability and CC (e.g., more sustainable practices lead to less climate change). Yet others shied away from using sustainability at all because of its vagueness and lack of definition (Tim). One of those preferred to discuss increasing energy efficiency and reducing energy use. After all, these can be measured in precise terms. Other respondents preferred to include CC as part of a larger concept called "sustainable engineering" which includes CC as one among other constraints to be considered (Nick).

The **political barriers** found thus far include a) "passive resistance" (John), b) institutional affiliations with industry, and c) concerns about being associated with CC given its political nature. Passive resistance refers to faculty's reluctance to even bring CC as a peripheral class topic due to personal skepticism about CC, to worries about barriers b) and c), or any of the barriers outlined above. Our university's close association with oil, gas, and mining industries creates two barriers. Some respondents described an underlying belief held by some faculty with close ties to these industries that CC is not happening. So if CC is not a real physical phenomenon, why should faculty take it seriously, teach it to students, or consider it a significant dimension in the analysis and design of engineered systems? Second, some respondents raised concerns about whether these companies would continue contributing financially to the school if they knew that CC is being taught and taken seriously in the analysis and design of engineered systems. Interestingly, concerns over these political barriers

lead some faculty to suggest that hiding CC behind concepts (e.g., sustainability and energy efficiency) that are more acceptable to certain industries and faculty and students skeptical of CC might be a good strategy. Hence conceptual overlapping could be a barrier or a strategy, depending on who does it and how is done.

Opportunities

During our preliminary interviews with faculty, we also found four types of opportunities to the integration of CC as a dimension in the analysis and design of engineered systems: **institutional, curricular, epistemic, and political.**

The main **institutional opportunities** included a) funded research, b) possibilities for inter-institutional collaborations, c) the use of media technologies, and d) future workforce development. Some faculty members described that if large funded grants, for example to create a research center, were to include CC&ES, this could open opportunities and resources for faculty to teach courses that include such connection. CC skeptics will probably not question courses developed under major research grants (Joan). One faculty member proposed to complement what a nearby larger research university is doing with respect to climate change: "we cannot compete with CU-Boulder in covering modern climate change...but we can complement them covering paleoclimate." (Brian) The same faculty member has developed instructional technologies to reach out to students and colleagues and cover what cannot be covered in class. He described how these technologies allow him to do outreach without sacrificing much class time (Brian). Other respondents pointed to the opportunity to prepare future engineering leaders in CC&ES, a field where the design criteria are very likely to change over the coming years (Nick).

The main **curricular opportunities** included a) revamping the content of existing courses to include CC&ES, b) incorporating CC&ES in homework and projects, and c) complement the curriculum with CC&ES extra-curricular activities. In our institution, a new Minor in Energy, for example, has created the space for CC&ES to be included in its courses without excessive scrutiny from CC skeptics. Also, respondents identified specific required courses – for example, Mass and Energy Balances (John), Fundamentals of ESE (Joan)—and specific places in these courses—e.g., water cycle or LCA analysis of water systems—where CC&ES can be introduced. Two respondents ventured to propose new courses that would have CC&ES at their core: a course on how to produce energy from wastewater (Joan) and an energy systems course. "Just be careful not to title it 'Energy Systems and Climate Change'", said the respondent. Respondents also proposed the possibility to include CC&ES as a topic in homework and projects. Another respondent proposed CC-oriented speakers in departmental seminars to deal with time constraint issues inside of courses,

institutional politics and with concerns about being associated with CC by letting outsiders do the work for you.

The main **epistemic opportunities** included a) challenges posed by the unpredictability of CC and b) the complexity of engineered systems if conceptualized as socio-technical systems. One faculty member explained how unpredictable inputs present a great challenge for control theory: control theory is well-equipped to handle questions of robustness to uncertainty.”(Liz) Another opportunity comes from changing the way in which engineering students traditionally learn about engineering systems, from a complex collection of interconnected technical components to socio-technical systems with significant political, economic, social, and institutional dimensions (Hughes and Hughes 2000).

The main **political opportunities** included a) intervention in the development of the future generation of engineers and b) questioning the commonly accepted term “sustainability” for its contribution to CC. “Hopefully they will make a difference,” said one respondent. A faculty member also mentioned how important it would be to include CC&ES as a counter-voice to the prevalent “profit-making resource-gathering mindset” (Rick). Another respondent reminded us that today’s engineering students are much more highly motivated by wanting to “make a difference” than engineering students in the past. Finally, one respondent who is skeptical of the term “sustainability” proposed that exploring the associations between sustainability and CC would allow us to formulate serious questions about sustainability, e.g., how much does recycling, for example, which many people view as a part of sustainability, contribute to minimizing CC?

CONCLUSIONS

How might engineering education need to change in order to accept, disseminate and institutionalize the incorporation of CC&ES?

First, engineering educators need to acknowledge that CC is no longer the concern of just progressive or radical environmental groups but a well-documented priority of important national and international engineering organizations, especially as in its relationship with engineered systems.

Second, we should seize the challenges that CC present to academic teaching and research, particularly the creation of truly inter- and transdisciplinary and collaborative and transformative learning.

Third, we need to seriously consider structural and cultural dimensions such as faculty autonomy, impetus of institution for status maintenance or mobility, subfields of faculty, faculty and student composition, and norms of what those in power consider to be “good engineering.” Structural and cultural barriers can be turned into opportunities, not only by single faculty members working alone, but through inter- and trans-disciplinary collaborations,

especially organized around research and teaching centers (institutions within institutions). Centers that make the CC&ES relationship visible, teachable and researchable (e.g., Center for Climate Change Adaptation of Engineered Systems) could motivate engineering schools to create new impetus to excel in new areas. As one respondent said, “I think this university could design a program toward a specialty in climate adaptation engineering. I don’t know of a specific program that’s doing that right now. And we do have faculty capable of addressing many of those issues.” (CS)

Fourth, bold acknowledgements of CC as a planetary problem, and perhaps even caused by humans, have a better chance for becoming catalysts for curricular innovations when accompanied by collaborations between deans, policymakers, and faculty, as the exemplary program at San Jose State University (SJSU) clearly shows. These centers and programs can serve as organizational mechanisms to deal with the institutional barriers of budget, faculty availability, and time.

Fifth, curricular barriers like course fit and resistance to take out existing course content can be dealt with by learning to interpret ABET requirements and the desire to teach to the FE Exam in ways that make the inclusion of CC&ES legitimate. For example, ABET program outcome c) includes design with consideration of economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability constraints while outcome h) calls for the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context. Clearly the incorporation of CC&ES helps to meet these outcomes.

Sixth, epistemic barriers, such as unpredictability of inputs, the nature of design criteria for engineered systems, indeterminacy and unpredictability of CC can be turned into opportunities for cutting-edge research, and for pushing the boundaries of engineering theorizing, modeling, and teaching.

Seventh, political barriers can be overcome if faculty find in these centers and programs the space where they can freely and unapologetically associate themselves to CC.

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