Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #47262

The Global Context of Clean Energy Materials, an EOP aligned undergraduate engineering course

Dr. James Groves, University of Virginia

James Groves is a leading university educator in the field of sustainable development. In the classroom he engages with students across disciplines and educates them about sustainable energy systems. He helps students to appreciate the need for a timely energy system transformation. James Groves' scholarly interests include a focus on the impacts of climate change upon the mid-Atlantic region. He has recently been developing an engineering ethics case study related to his local climate change research.

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An EOP-aligned undergraduate engineering course

Abstract

An undergraduate course in materials science and engineering has been delivered that aligns with the Engineering for One Planet (EOP) framework, teaching about the challenges of reorienting the world's energy supplies to flow through alternative energy systems. Fabrication of such systems requires far more minerals than their fossil fuel counterparts, minerals sourced, refined, and disposed of globally. The course examines the materials employed, studies the functional justification for using those materials, considers the social, economic, and environmental sustainability challenges of using those materials, and highlights strategies to minimize the negative impacts associated with global-scale deployment. The course highlights the sociotechnical reality of sustainability, i.e., success depends upon social *and* technical advance.

The course is organized into learning modules. In each, relevant clean energy material properties, e.g., magnetic, mechanical, thermal, are introduced and their scientific bases illuminated. Then, select sustainable energy systems are explained to help students understand the system design and materials selection processes. Why is a given material used in that device solution?

Students are introduced to life cycle assessments (LCAs) and learn about major environmental *and* social impact categories. They develop familiarity with LCA processes and impact categories by examining the social and environmental implications of specifying one material or another for use in energy solutions. Students are asked to think critically as they consider the use of alternative energy systems that rely upon global supply chains. What are the implications of reorienting supply chains to potentially more sustainable materials, manufacturing, or recycling?

Students are challenged to appreciate the scale of the proposed transformation and grapple with the social and cultural, economic, and environmental impacts of achieving the transformation. Examples of social and technical strategies for moderating those impacts are examined, e.g., global governance, materials research and development, and industrial ecology best practices.

By course completion, students are asked to demonstrate achievement of key learning objectives. These include an ability to identify material properties relevant to sustainable energy systems and describe their scientific basis. Students should be able to link properties to specific system performance. Students should be able to review a material life cycle analysis and identify the most important sustainability challenges associated with a given materials selection. They should be able to highlight the equivocal impacts of materials used in energy systems from sustainable social, economic, and environmental perspectives. They should demonstrate critical thinking skills by communicating to non-technical audiences how corrections to the trajectory of the energy transformation can strengthen the undertaking. Strategies for and examples of student assessment are presented to illustrate course design that targets core student learning outcomes highlighted by the EOP framework.

Introduction

For decades, scientists and politicians have known that societal production of large volumes of greenhouse gases changes the Earth's climate in ways that, on balance, are not beneficial to living systems and the global economy [1, 2]. Since the start of the 21st century, there have been increasingly visible worldwide efforts to limit the anthropogenic release of greenhouse gases into the atmosphere. Many strategies recommend replacement of fossil fuel burning energy systems with alternatives referred to as sustainable, renewable or clean energy systems. The proposed replacement is contentious, and some who oppose the transformation question whether these alternative systems are in fact better for the environment and society [3].

The substance of some concerns is illustrated by two brief excerpts from the 2021 International Energy Agency report entitled, "The Role of Critical Minerals in Clean Energy Transitions" [4]. That report notes that, "A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant." The report also states, "Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewable has risen." In short, some opponents of the call for an energy transformation argue that these alternative energy systems are not better for the environment or society. Rather, the alternatives simply shift the form of energy system impact from greenhouse gas emissions during technology use to (more significant) impacts during the mining, manufacturing, and end-of-life stages of their life cycles.

To prepare students to critically evaluate the complexities of this high-profile, contentious aspect of alternative energy systems, an upper-level undergraduate engineering course has been developed and delivered which examines the science, engineering and broader environmental and societal impacts of the effort to advance such systems. This paper documents the form and focus of this three-credit hour, 3rd year undergraduate engineering course. It details major assessment activities delivered and outcomes assessed during five offerings of the course from 2019 – 2023. It also highlights how the course aligns with elements of the Engineering for One Planet (EOP) framework (Figure 1).

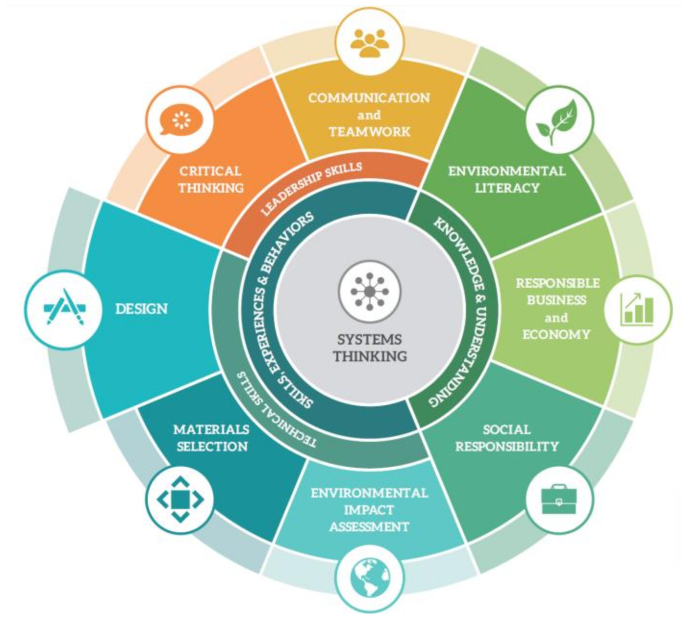

Figure 1 The Engineering for One Planet framework draws together knowledge elements that prepare students to contribute to a more sustainable world.

Course objectives and content

The course relies upon no-cost instructional materials to minimize educational expenses for students. Additionally, given the rapid evolution of the energy system technology space, the course points students to learning materials culled from recent internet materials and university library databases.

The beginning of course memo states that, by the end of the semester, students should be able to:

1. Identify material properties relevant to alternative energy systems and describe their scientific basis. Explain how specific material properties link to specific alternative energy system performance.
2. Use material life cycle analyses to identify sustainability challenges associated with the use of engineered materials in contemporary alternative energy system designs.
3. Illustrate the equivocal impacts of materials used in alternative energy systems - from sustainable social, economic, and environmental perspectives.
4. Describe how the accelerating energy transformation could be strengthened as the result of both social and technical corrections to its current trajectory.
5. Communicate effectively regarding the global nature and sustainable use of materials in alternative energy systems and regarding the ethical dilemmas embedded within the accelerating energy transformation.

The course examines the energy system transformation first from the perspective of materials science and engineering. Yet, in the spirit of the EOP framework, it employs a much broader systems thinking approach as it marries materials science instruction with teaching about sustainability and concepts in science, technology and society (STS). It examines different material properties, e.g., electrical, mechanical, and optical, and reviews the materials science underpinnings of each. It explains how specific atomic elements from the periodic table are thoughtfully leveraged into alternative energy systems via a deliberate materials selection process. The course proceeds to highlight the impacts of increased alternative energy system deployment upon the environment and society. It considers the sustainability of alternative energy systems by employing life cycle analyses (LCA) to inform many discussions. In the spirit of the STS field, the course examines the interplay of society and technology by considering how the adoption of alternative energy systems depends upon not only engineering and technology but also social psychology, finance, and domestic and global public policy.

In the course, sustainability has been defined as the use of resources in a manner that meets the needs of the present without compromising the ability of people and the planet to prosper – now and into the future. As in the EOP framework, the course asks students to think beyond just environmental sustainability to include consideration of social and economic sustainability. At an introductory level, the course centers discussions of environmental sustainability within the planetary boundaries framework pioneered by Rockström, *et al.* [5]. It defines social sustainability as including elements such as wealth, health, education, personal security, and food supply, broadly aligned with the United Nations' Human Development Index [6].

As encouraged by the EOP framework, the course seeks to be quantitative and structured in its consideration of environmental and social sustainability, asking students to examine the impacts of a product's full life cycle. While environmental life cycle analyses are increasingly mature methodologies for product evaluation [7], social sustainability life cycle analysis is an emerging construct. For social sustainability LCA, the course points students to guidelines published by the United Nations [8] and the social LCA database of GreenDelta [9]. Consideration of social and economic aspects of the energy system transformation aligns well with the intellectual perspective of STS studies. From the outset, the course sets the expectation that, as designers, future engineering professionals have the opportunity and obligation to think about a product's entire life cycle in a way that a typical consumer does not. They should understand and consider the interplay of alternative energy system development with the environment and society.

The course is organized into a set of modules each of which typically spans three or four 75-minute class sessions. Before each class, students are provided multimedia content to review and instructor notes that highlight the more important learning content of the assigned materials. The first module is entitled "Cornerstones of Understanding." It introduces definitions of sustainability and its major elements - environmental, social, and economic. It presents an overview of climate change and biodiversity loss and the related challenge posed by the materials intensity of alternative energy systems. It provides a scientific overview of material structures and properties at the subatomic, atomic, and bulk materials levels. The module introduces the concept of technology readiness levels [10] and finishes with a first introduction of a life cycle analysis.

Following the cornerstones module, the course explores up to seven modules of content organized around material properties. Table 1 presents the course modules in the order typically taught. Each module begins by explaining the material property and how material structure contributes to the essential properties exploited by different alternative energy systems. Specific atomic elements and molecules are highlighted in each module, helping students to appreciate that material selection is a deliberate process driven by an informed plan to leverage unique material properties into specific alternative energy system solutions. The goal is to teach students why particular materials are employed in each application.

Table 1 Course modules cover material properties, specific atomic elements and molecules, and associated alternative energy systems and applications

Order	Material property	Key Materials	Alternative energy systems, applications
I.	Optoelectronic	Si, Rare earths	Photovoltaics, LED lighting
II.	Magnetic	Rare earths, Fe	Electric generators and motors
III.	Electrochemical	C, Li, Ni, Co, Fe	Rechargeable batteries
IV.	Electrical	Cu, SiC	Power electronics, Electrical wiring
V.	Mechanical	C, Epoxy, Al	Turbine blades, Transport system bodies
VI.	Thermal	Refrigerants, Salts	Heat pumps, Concentrating solar power
VII.	Chemical	Pt, C, H_2, N_2, O_2	Power-to-X, Carbon capture and utilization
VII.	Optical	S	Atmospheric seeding

Following a consistent materials science introduction, different sustainability and STS topics are introduced in each module, with the focus in a given module determined by the importance of a particular sustainability or STS concept to the material systems and energy system applications under consideration. For instance, in the optoelectronic module, sustainability and life cycle discussions focus upon the manufacturing stage of silicon's life cycle where energy consumption and greenhouse gas emissions are quite significant during solar cell fabrication [11]. During the magnetic module, the environmental and social impact of rare earth element mining is examined to highlight the impact of motor / generator designs that employ strong magnets [12, 13]. In the electrochemical module, the environmental and social impact of lithium extraction in dry South American regions [14] and cobalt extraction in war-torn sub-Saharan regions [15] is considered as part of battery material mining. In the electrochemical and mechanical modules, end of product life recycling is examined, e.g., battery recycling [16] or composite structural material recycling [17]. In the electrical module, the magnitude of metal demand for alternative energy systems is considered, along with its environmental impacts [18]. Whenever possible, discussions are tied to LCA publications from the literature that quantify the environmental and social impacts of these various materials-intensive activities.

As students gain an appreciation of the environmental and social pressures imposed by global efforts to increase the use of alternative energy systems, the course considers strategies that could mitigate those pressures. The course examines how technology advances spurred by research and development (R&D) can mitigate the environmental and social impacts of alternative energy system production. For instance, the course examines the recent evolution of lithium-ion battery electrode chemistry for many applications from nickel-cobalt to iron-phosphate mixtures [19]. In the context of R&D, the course discusses technology readiness levels, to help students better assess technology maturity as they read announcements of breakthroughs. In the course, the development of perovskite-based solar cells is used as a case study for assessing the actual maturity of a promising but much-hyped technology development [20]. The course illustrates how corporate and nation-state decision-making can define supply chains and significantly modify the environmental and social impacts of energy system manufacturing. The global mining and refining of nickel in countries such as New Caledonia, Indonesia, and Russia is highlighted [21]. The U.S. domestic debates over project permitting and mining regulations are highlighted [22]. The course explains how public policy actions by governments can reshape supply chains and modify the environmental and social impacts of alternative energy system production, in international [23] and domestic [24] settings.

Example modules

By the end of the semester, students should appreciate how the engineering of alternative energy systems builds upon an understanding of materials science. They should think about the entire life cycles of alternative energy systems and intuitively know that there are environmental, social, and economic sustainability considerations throughout the life of all alternative energy systems. They should appreciate that new energy system solutions take time to bring to market and that research and development investments and government policy and geopolitics can greatly influence the trajectory of alternative energy system adoption. To illustrate how several modules fit together, consider the following summaries of the optoelectronic, magnetic and mechanical modules.

Optoelectronic properties

- Science and technology
  - Band theory of solids
  - Conductors, insulators, semiconductors
  - PN junctions, solar cells and LEDs
- Sustainability
  - An introduction to environmental and social LCA
- Life cycle stage 2: Manufacturing
  - Polysilicon: Environmental LCA
  - China's silicon and solar supply chain: Social sustainability considerations
- Technology and supply chain evolution
  - Perovskites
  - Recycling

Magnetic properties

- Science and technology
  - The subatomic origins of magnetism
  - Rare earth elements and permanent magnets
  - Rare earth, permanent magnets for transportation and wind turbines
- Life cycle stage 1: Materials acquisition
  - Mining 101

China's rare earth element supply chain: Environmental and social LCA
Supply chain evolution
Australia's Lynas Corp.: An alternative supply chain,
Permanent magnet research and development

Mechanical properties
Science and technology
Thermosetting and thermosoftening plastics, composites
Wind turbine blades
Transportation system components: Composites and aluminum (aerospace, automotive)
Life cycle stages 2 and 4: Manufacturing and recycling
Carbon fiber synthesis, aluminum refining
End-of-life LCA
Supply chain evolution
Beyond thermosetting plastics
Recycling carbon fiber, aluminum

Course assessment
For each course offering, student learning was assessed via the following elements:

Formative assessment
Weekly homework quizzes (20%)
Class discussion and participation (15%)
Critical materials analysis assignment (10%)

Summative assessment
Personal learning experience
Mid-term project prospectus (5%)
Final project (20%)
Policy advocacy assignment (10%)
Final exam, comprehensive (20%)

Student evaluation was organized into both formative and summative assessment. Each week, students completed a five-question quiz drawn from the instructor notes provided with assigned course content. The assessment tool used for the quizzes provided question-level statistical summaries that could be used to check student engagement and learning and refine future instruction (Figure 2).

Additionally, early in the semester, students were assigned an exercise to assess their materials footprint. The assignment sought to raise awareness of the extent to which we rely upon specialized materials for technology solutions in our lives. The exercise asked students to catalogue their family's transportation systems, e.g., cars and e-bikes / e-scooters, and the number of computers, tablets, smartphones and televisions their family has owned in the past five years. It asked them to note if their home has rooftop solar and what type of air conditioner they have installed at home. After students catalogued these systems, the assignment provided estimates of the critical materials used in each, e.g., refrigerants in air conditioners, lithium and cobalt in battery systems, and copper and aluminum in vehicles. The students then estimated the mass and greenhouse gas emissions associated with the critical materials in their devices.

Consider the magnetism exhibited by an atom of argon and an atom of iron. Briefly, explain why the iron atom has a strong magnetic field and the argon atom does not. (1 -2 sentences)

Responses	Total Points Possible	Mean
9	4.0	3.88

This week, you listened to a two-part podcast on rare earth elements. The second of those two podcasts delves into some of the severe human and environmental impacts of rare earth element mining in China. Briefly summarize some of those impacts. (2 - 3 sentences)

Responses	Total Points Possible	Mean
9	4.0	2.55

One of our assigned articles this week highlighted three major shortcomings of the U.S. 1872 General Mining Law. Name two of those three shortcomings.

Responses	Total Points Possible	Mean
9	4.0	3.55

Figure 2 Homework quizzes assess student engagement and learning during the semester.

After students reported their materials footprints, they were asked a set of reflective questions designed to qualitatively assess their appreciation of critical minerals in modern lifestyles. Reflective questions included the following:

- What is your reaction to knowing that all these materials are mixed together to make your systems run? Imagine the challenge of separating those materials again, as part of recycling? Consider all the people around the globe who have these same devices or would like to have them. Do you now think differently about these "clean" energy systems?
- Emerging, full battery electric vehicles (BEVs) employ 60 – 70 kWh battery packs. Study the table provided which shows BEV demand for lithium and cobalt in kg / kWh. Comment upon the relative amounts of lithium and cobalt needed for your personal electronics versus tomorrow's battery electric vehicles. What if you decided not to buy a

battery electric vehicle in the future but instead committed to e-micromobility, how would your lithium and cobalt needs of transport vs. personal electronics then compare?

In the second half of the semester, student evaluation transitioned to more summative assessment. For a personal learning experience, students were asked to select a topic related to the course and complete a “deep dive.” The assignment asked students to teach themselves about a topic and demonstrate their learning in an end-of-semester paper. The paper was not required to cover all aspects of the selected topic: science, engineering, environmental sustainability, social sustainability, supply chains, and geopolitics. Rather, students were allowed and encouraged to select a subset of these course themes so that they might dig into their topic beyond a purely introductory overview. Papers were assessed qualitatively to evaluate the extent to which students demonstrated an ability to apply course learning to the specific topic chosen.

The focus of student writing was guided via the following prompts:

- If exploring the science, explain why a select set of natural elements, organized into a specific *material structure* is central to the *material properties* that power these systems.
- If exploring the engineering, explain how the materials are incorporated into sustainable energy systems that achieve necessary device *performance*.
- If exploring environmental sustainability, apply a life cycle analysis framework for your analysis.
- If exploring social sustainability, identify who could be harmed and how. Categorize the harms using life cycle frameworks presented in class.
- If considering how future solutions can be more sustainable, identify the broader, key takeaways from your investigations.
- If examining STS issues related to supply chains and geopolitics, articulate how can they become more effective and sustainable.

During recent offerings of the course, student paper topics included:

- *Engineering focus*: Geothermal energy systems: Minimizing operational corrosion for enhanced energy recovery.
- *Environmental sustainability*: The environmental impact of platinum mining in South Africa with a focus upon three LCA indicators: global warming potential, particulate matter formation potential, and abiotic depletion potential (water).
- *Environmental sustainability*: The full life cycle environmental impact of cadmium telluride and perovskite photovoltaics with a focus upon two LCA indicators: global warming potential and human toxicity potential.
- *Environmental sustainability*: Minimizing green sacrifice zones through enhanced mining and recycling practices.
- *STS*: Supply, demand and geopolitical challenges associated with vanadium use in redox flow batteries.

- *STS and sustainability*: Geopolitical considerations and the environmental and social impacts associated with copper extraction in Chile and platinum extraction in South Africa.

During the final month of the course, students considered how public policy plays an important role in determining the direction and speed of alternative energy system adoption. Students were asked to write a policy advocacy letter to one or more key individuals in the U.S. federal government, laying out the case for why action is needed to ensure a responsible alternative energy system transformation. They were expected to identify a policy action that they want to see the U.S. federal government take in support of the transformation. The assignment did not require that students take a particular advocacy position on the transformation. Rather, they were expected to take some position and support their position with strong logic and high-quality references.

During the most recent offering of the course, students advocated for U.S. government policy efforts that would:

- Boost domestic extraction and processing and responsible international trade of critical mineral resources.
- Address social sustainability and Chinese control concerns surrounding the extraction of cobalt in the Democratic Republic of Congo.
- Promote critical mineral recycling and investment in alternative materials research and development.
- Reduce geopolitical risks and human rights abuses through an increase in domestic critical mineral mining and refining.
- Track more closely the environmental and social impact of America's critical mineral supply chains.

Finally, the semester closed with a comprehensive exam that asked questions evenly across all course modules. The final exam included questions that evaluated if students understood:

- The expected trends in material demand that will result as greater alternative energy systems are adopted.
- The scientific, material property underpinnings of each class of materials employed in alternative energy systems.
- Key concepts in environmental and social sustainability, with a particular emphasis upon product life cycles and life cycle analyses.
- The role of international and domestic politics in shaping critical mineral supply chains.
- The role of research and development in shaping critical mineral supply chains, with demonstrated knowledge of technology readiness levels to assess the maturity of emerging solutions.

The first half of the final exam included multiple / many choice, fill-in-the-blank, and short answer questions (Figure 3). Students were expected to demonstrate a knowledge of terminology used and concepts covered in the course.

Which of the following elements are rare earth elements. (Mark all that are correct.)		
Answer Options	**Correctness**	**Number of Responses**
Neodymium	Correct	9
Iron	Not Correct	0
Dysprosium	Correct	9
Boron	Not Correct	0
Cerium	Correct	8
9 Responses, **88%** Answered Correctly		

In the lithium triangle of South America, lithium is extracted from salt brines via evaporation processes that use extensive amounts of scarce groundwater in the region. Think about a life-cycle analysis of this water-intensive process in one of the driest places on Earth. Which of the following environmental impact categories should be scrutinized very closely?		
Answer Options	**Correctness**	**Number of Responses**
Abiotic depletion potential	Correct	9
Eutrophication potential	Not Correct	0
Acidification potential	Not Correct	0
Marine water aquatic eco-toxicity potential	Not Correct	0
9 Responses, **100%** Answered Correctly		

Cobalt mining in the Democratic Republic of Congo has been considered highly problematic for years. From the perspective of social sustainability, describe sustainability concerns that manifest themselves for any two of the following stakeholder groups in the country.

1. Workers
2. Consumers
3. Local community
4. Society
5. Value chain actors

Responses	Total Points Possible	Mean
9	6.0	5.33

Figure 3 For the final exam, students are expected to demonstrate more complete knowledge and understanding of the core topics covered in the course.

The second half of the exam required students to read several short articles related to the energy system transformation. They were then asked to identify topics discussed in the articles which were also covered in the course. For instance, if an assigned article described a particular mining issue discussed in class, students should note its mention. If the article described policy issues discussed in class, they should note the issue. The goal of these exam questions was to assess the level of awareness of the students to key issues influencing the speed and direction of the transformation of energy systems.

Alignment with the EOP Framework

In alignment with the EOP Framework, this course has endeavored to advance student systems thinking, knowledge and understanding, and skill, experiences, and behaviors in the realm of engineering sustainability. The interdisciplinary approach of the course asks students to think beyond materials science and engineering. It focuses upon environmental and social sustainability via frequent reference to and consideration of life cycle analyses. Students are expected to understand the four stages of an LCA and be aware of important environmental and social sustainability LCA categories. Additionally, students are asked to consider STS concepts, particularly in the realm of public policy, geopolitics, finance, and social psychology.

This course teaches and assesses many EOP Framework learning outcomes. For example, it:

- Explains interconnectedness and how all human-made designs and activities rely upon and are embedded within ecological and social systems.
- Applies environmental and social LCA at various length, time, and impact scales.
- Explains abiotic assets (e.g., critical minerals) and flows (e.g., supply chains).
- Identifies relevant environmental laws, ethics, and policies at the regional, national, and global levels, and considers ethical and cultural implications beyond current environmental compliance and political boundaries.
- Compares material properties and performance alignment with end-use applications via the course's organization around material properties modules.
- Discusses sustainability data extensively as it draws on LCA research.
- Identifies innovation gaps in existing materials options and strategies to spur needed research and development.
- Highlights how engineering design can incorporate whole life cycle and systems thinking.
- Discusses how to incorporate relevant quantitative research (e.g., LCA data) into the decision-making process.
- Communicates through audience-specific written skills (e.g., the course's policy advocacy assignment).

Conclusion

When this course was brought forward for approval, the undergraduate curriculum committee required that it either be classified as a technical elective or a humanities / social science course. While the committee recognized that the course delivered both engineering technical and broader impact instruction, they said it could not be used to simultaneously satisfy student learning requirements in both areas. Ultimately the course was slotted into the humanities / social sciences category.

Yet, the course intentionally asks students to think simultaneously about technical materials science concepts and important concepts in sustainability and STS. That structure embodies the spirit of the EOP Framework and its emphasis upon systems thinking. As the EOP Framework document asks, “What technical and professional skill must all engineers have to become competent in sustainability?” For this course, students need to understand materials science and technology, sustainability, *and* key concepts in STS.

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