

Article

An Integrated Approach to Energy Education in Engineering

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Abstract: What do engineering students in 2020 need to know about energy to be successful in the workplace and contribute to addressing society's issues related to energy? Beginning with this question, we have designed a new course for second-year engineering students. Drawing on the interdisciplinary backgrounds of our diverse team of engineering instructors, we aimed to provide an introduction to energy for all engineering students that challenged the dominant discourse in engineering by valuing students' lived experiences and bringing in examples situated in different cultural contexts. *An Integrated Approach to Energy* was offered for the first time in Spring 2020 for 18 students. In this paper, we describe the design of the course including learning objectives, content, and pedagogical approach. We assessed students' learning using exams and the impact of the overall course using interviews. Students demonstrated achievement of the learning objectives in technical areas. In addition, interviews revealed that they learned about environmental, economic, and social aspects of engineering practice. We intend for this course to serve as a model of engineering as a sociotechnical endeavor by challenging students with scenarios that are technically demanding and require critical thinking about contextual implications.

Keywords: energy; sustainability; engineering education; sociotechnical

1. Introduction

As we write this article in 2020, the world is besieged by the global pandemic COVID-19. This pandemic has revealed a political world order unprepared for the international collaboration required to address a global crisis, which has further exacerbated inequities shouldered heavily by vulnerable communities. Climate change poses a similar and inequitably larger threat to vulnerable communities. There have been quite a few articles written examining the impact COVID will have on the climate crisis [1–3]. We agree with journalist Meehan Crist that “The real question is not whether the virus is “good” or “bad” for climate, or whether rich people will take fewer airplane flights, but whether we can create a functioning economy that supports people without threatening life on Earth, including our own” [4].

We hope the answer to Crist’s question is “yes” to creating a sustainable future, but to do so we must change the way we train engineers. No longer can our classes have a narrow focus on technical problem solving. Instead, we must strive to train the sociotechnical engineer—someone capable of

addressing the intertwined social and technical elements of a problem [5–8]. To be successful in solving these problems, we argue that engineering students must learn to understand the complex cultures, ways of knowing, and ecosystems in which engineered systems exist [9,10]. Unfortunately, the current state of engineering education fails to address these global needs [11,12].

We see energy education as a key area in need of reform. Energy is commonly taught in foundational engineering classes such as *Thermodynamics* or *Circuits*. While it is well known that students struggle to find the relevance of the material in these “middle-year” courses [13], engineering faculties, nonetheless, are strongly opposed to changing them [14]. For example, the lead author of this paper completed his undergraduate studies in 2008, but was first introduced to energy concepts using a thermodynamics textbook written in the 1950s. In this paper, we argue for change in **what** we teach and **how** we teach engineering students about energy. We have developed *An Integrated Approach to Energy*, a second-year course designed to help engineering students develop an interdisciplinary understanding of energy topics. We present a case study of our course that focuses on our course design in terms of content and pedagogical approach as well as our experiences from the first offering in Spring 2020. Then, we use quantitative and qualitative methods to assess students’ learning and response to this class. Before discussing our course in detail, we set the stage with some relevant background on energy education and our institutional context.

2. Background

2.1. Energy Education

Energy is challenging to define. While many scientists, engineers, and philosophers have tried to define and neatly categorize the concept of energy in different ways [15], none seem to capture the complex nature of this phenomenon without becoming entangled in the arbitrary trappings of disciplinary delineations. The complexity around defining energy combined with limited theoretical exposure and a daily personal experience lead to a plethora of misconceptions around energy. For example, a study by Prince et al. [16] identified several misconceptions of engineering students, including the difference between temperature and energy, temperature and the perception of hot and cold, and the amount of heat transfer versus the factors that affect the rate—even after an entire semester of instruction on thermodynamics. Jewett [17–20] argues that students’ confusion around energy stems from their inability to relate the theoretical material to their physical world, which supports Solomon’s [21] theory that students tend to think in two domains, in which they readily grasp concepts related to everyday life more than those learned theoretically.

The typical energy education in engineering curricula in the USA is siloed within the engineering disciplines. Energy is usually introduced in the second year and based on an underlying assumption of fossil-fuel-driven power plants [22–28]. For example, within Mechanical Engineering *Thermodynamics* is heavily influenced by examples from the Industrial Revolution [29]. Students learn to read steam tables as they develop an understanding of steam engines and power cycles. Energy is divided into heat and work. Emphasis is placed on the fundamental laws of thermodynamics. Research has shown that students come to a thermodynamics course with the expectation of being exposed to real world content but traditional courses have not met those expectations [22]. Within Electrical Engineering, *Circuits* focuses on “power”—energy per unit time—rather than energy. Concepts such as conservation of power and maximum power transfer are emphasized. Sinusoidal steady-state and three-phase power calculations are typically covered near the end of the first circuits course [25]. The application or context for these topics is usually household power distribution from a fossil fuel powered plant.

Within Civil Engineering, the human consumption of energy is usually directly addressed more so than the concept of energy itself. Often, the only instances in which “energy” appears in a course title are in topics on energy efficiency in buildings. As a contrast to Mechanical Engineering, *Thermodynamics* is typically an optional or not a required course in Civil Engineering curricula. The concept of energy can be disjointed even between civil engineering courses, appearing in minor ways such as strain energy

in structural components, embodied energy in construction materials, in the kinematics of structural systems (indirectly addressing conservation of energy and momentum), or in the dynamic motion that civil systems must withstand (e.g., earthquake energy, hydrodynamic wave energy, hurricane energy, etc.) In upper-level electives or graduate courses that have a focus on sustainability, energy topics covered include civil infrastructure's greenhouse gas footprint, life cycle analyses and embodied energy of construction materials, environmentally informed design of transportation and building systems, energy efficiency (e.g., Leadership in Energy and Environmental Design (LEED) ratings), and the business case for sustainability through energy cost savings [28].

While energy concepts are typically taught using siloed approaches, there have been attempts to take a more interdisciplinary approach. Several universities, including Penn State [30], Indiana University—Purdue University Indianapolis [31], and UC Berkeley [32], offer a Bachelor of Science (B.S.) in Energy Engineering. While these programs expose students to energy concepts from across the curriculum, they usually require students to take standard engineering foundational courses such as *Thermodynamics* and *Circuits*. It is not until the third or fourth year that they introduce courses to synthesize information across disciplines.

At the course level, several faculty members have developed textbooks that take a more interdisciplinary approach. We have found physicists Randolph and Masters' *Energy for Sustainability* to be a particularly useful reference [33]. This text introduces students to energy in the context of the environment and begins with foundational concepts relating to energy mechanics, heat and work, and conservation of energy. This foundation is used to explore more complex topics of home energy conservation, solar energy, and fossil fuel power plants.

2.2. Institutional Context

Our ability to do this work is heavily dependent on our institutional context, groundwork laid by forward-looking administrators at the University of San Diego (USD), and grant funding support. We are often able to buttress our work with a university mission, vision, and values that focus on peace, justice, sustainability, and confronting humanity's urgent challenges. Our private, contemporary Catholic institution prioritizes caring for our common home, advancing access and inclusion, and upholding a liberal arts education for the 21st century [34]. These university values are also reflected throughout the Shiley-Marcos School of Engineering, where only joint Bachelor of Science/Bachelor of Arts (BS/BA) engineering degrees are awarded, requiring graduates to have a robust education in both engineering and the liberal arts [35]. Our School of Engineering also received a USA National Science Foundation (NSF) Revolutionizing Engineering Departments (RED) grant several years ago entitled "Developing Changemaking Engineers". For us, changemaking focuses on seeing engineering as a sociotechnical endeavor including contexts of peace, social justice, and humanitarian practice [6,36].

To take this liberal arts integration one step further, our Integrated Engineering program was launched recently, with our first graduates in May 2019 [37]. The Integrated Engineering program is fundamentally different from the pre-existing discipline-specific engineering majors at USD as the curriculum was designed to provide a more flexible degree path as well as being an incubator for potential new engineering majors. Integrated Engineering students all begin with a shared set of major courses that focus on interdisciplinary engineering science through a sociotechnical lens, but then branch off into their respective concentrations. Currently, our major hosts concentrations in embedded software, sustainability, engineering and the law, biomedical engineering, and an individual plan of study that allows students to co-design a curriculum that prepares them for their unique career goals.

The interdisciplinary and sociotechnical nature of the major can be highlighted with several courses that are rarely seen in engineering requirements. Two classes, *User-Centered Design* and *Engineering and Social Justice*, fulfill the introductory and advanced level university requirements for diversity, inclusion, and social justice [7]. In the third year, students take *Experimental Engineering*, which is an interdisciplinary lab/lecture hybrid course that builds upon prerequisites in circuits, statics, computer programming, materials science, energy, and engineering math courses. While this

culminating third year experience is framed by a data acquisition and instrumentation content, technical writing and oral presentation skills play a large role in the course's learning objectives.

As the sociotechnical spine of our curriculum has solidified, we turned our gaze to the middle year engineering sciences, which ironically stem from sociopolitical origins. Leydens and Lucena argue that the engineering sciences in engineering curricula were elevated during the Cold War to become a body of knowledge prioritizing mechanics of solids, fluid mechanics, thermodynamics, transfer and rate mechanisms, and electrical theory, abstracted from their application to the real world [14]. These middle year engineering science courses have become untouchable by revision and innovation due to their "definitional and normative roles in what an engineer is and what engineering education should be about" [14], even with the rise of interdisciplinary engineering majors, such as environmental engineering or biomedical engineering. To further strengthen our program, we focused on transforming these foundational courses by answering the call from Lord and Chen to "make the learner and community an integral part ... Address diversity as part of the equation, not as an afterthought ... [and] Learn from decades of research on gender and race" [13]. Four faculty in Integrated Engineering (authors GDH, DAC, JAM, and SML) collaborated to obtain funding from the NSF's Improving Undergraduate STEM Education (IUSE) program to reimagine how an interdisciplinary energy course could address these deficiencies in the curriculum [38].

3. Course Design: Integrated Approach to Energy

In our design of *An Integrated Approach to Energy*, content (what we teach) and process (how we teach) are intertwined and strongly influenced by who we are. We aimed to give students an understanding of modern energy concepts that emphasized topics relevant to all engineering students regardless of their eventual career path. We also, and perhaps more importantly, sought to develop a course that challenged the dominant discourse in engineering. Leveraging the authors' diverse backgrounds, both in our engineering training and our personal identities, we wanted this course to be a model of sociotechnical thinking—challenging students with scenarios that were both technically demanding and required critical thinking about social implications.

3.1. What We Teach: Our Motivation for the Content

3.1.1. Modern: Renewables and Interdisciplinary

In considering what a "modern" energy course should include, we reflected on the typical characterizations of solar and wind as *Alternative Energies* (as in: alternatives to fossil fuels). This categorization, rather than the use of the term *Renewable Energies* or *Sustainable Energies*, inherently prioritizes fossil fuels over other options. In traditional engineering curricula, courses such as *Thermodynamics* or *Circuits* are often considered a fundamental required part of engineering education and typically focus on fossil fuel-based energy. Topics relating to renewable energy such as wind or solar power are usually left for upper division elective courses. Some thermodynamics textbooks have a final bonus chapter on "alternative" energy, but this is unlikely to be covered (and sometimes is not even included in the print version of the book). This delineation between energy types by their naming convention and their placement in engineering curricula indicate that what is considered a part of the energy canon has changed little in decades. We argue that this prioritization needs to be flipped: all engineering graduates in the 21st century need to have some knowledge of renewable energy and those who want to specialize in fossil fuel-based technologies can do so through electives.

3.1.2. Interdisciplinary: Beyond Engineering Silos

We also argue that energy education for engineering students should be interdisciplinary rather than siloed within engineering disciplines. We are fortunate to have an interdisciplinary team to work on this course design supported by an NSF grant [39,40]. The project team includes faculty with degrees in mechanical engineering (ME), civil engineering (CE), electrical engineering (EE), materials science

and engineering (MScE), and engineering education, who collaborated on the design of this course. For example, the ME with experience teaching *Thermodynamics* led the design of the course content around mechanical energy, the EE contributed to the solar energy section, and the CE took the lead on energy consumption. We also provided an outside perspective for concepts not typically within our disciplines, helping to make the material more accessible to the students, reconciling units and vocabulary, and clarifying the key concepts. This was challenging as we each realized how deep our disciplinary biases are. For example, the ME and CE wanted to prioritize the engineering laws governing energy while the others felt that students needed to see the application before and sometimes, instead of, the theory. The EE was used to units and equations for power while others were more comfortable with energy. We had internal struggles as we explored what we meant by “types of energy,” key units, and level of detail needed. Even in some minor cases, we found it was prudent to help students with “translating” between engineering disciplines. For example, the same variable “R” is used for resistance in electrical circuits and for thermal conductance in buildings. While this could initially confuse students, deconstructing and explaining that these symbols all represent a type of resistance (and would never be used in the same diagram) can help students see how concepts within different engineering disciplines are connected.

3.1.3. Sociotechnical (PESTEL)

We also aimed to teach energy within a sociotechnical framework so that our students would be prepared to create a sustainable energy future. Some of the previously reported interdisciplinary energy courses incorporate concepts beyond the technical, particularly policy and economics. We were especially interested in the PESTEL framework (political, economic, social, technical, environmental, and legal). This framework, which has developed organically over several decades with contributions from many scholars, is often taught in business planning and marketing courses [41]. We agreed that PESTEL is also extremely well suited for engineering students, as it is a simple framework that reflects the complex nature of engineering practice. By helping students analyze energy challenges using a PESTEL framework, we aimed to help them develop their critical thinking skills in areas that go beyond a narrow technical interpretation. Most importantly, we wanted our students to recognize that engineers have expertise in technical areas, but that consideration of (and collaboration within) the PESTEL framework is required to solve these complex problems.

3.2. How We Teach: Pedagogical Approach

3.2.1. Challenging the Dominant Discourse

While engineering is often perceived as objective and independent of culture, scholars argue that in reality, engineering has a dominant discourse—one that privileges masculine, Western, White, colonial knowledge over other ways of knowing [9,12,42]. For example, consider the classic engineering textbook problem about car pistons in thermodynamics, or the physics mechanics problem about calculating the projectile of a hunter’s bullet as a monkey falls out of a tree. Such problems tend to cater to stereotypes of male interests and, when the problems involve a human, usually present stereotypically male and White characters. We sought to develop a course that challenged the dominant discourse in engineering by bringing in examples from a diverse range of perspectives and cultural contexts outside of what has been traditionally taught in engineering curricula.

By approaching the design of this course as an interdisciplinary team, we already began challenging the traditional approach to engineering expertise, where one instructor is responsible for identifying and creating course content they believe to be the most important for students to learn. To reframe for students how engineering knowledge is constructed, it was critical that we practiced what we preached in creating any material we presented. We spent many hours thinking about not only the content, but also discussing how our preconceived notions about engineering perpetuated the dominant discourse and the ways in which we could deconstruct that discourse for our students and

ourselves. Reflexivity was central to engaging meaningfully and positively during these conversations. We share a commitment to helping students see engineering as a sociotechnical endeavor and making engineering education more socially just. We are all interested in engineering education research and incorporate evidence-based effective teaching practices such as active learning in our teaching. Thus, we bring these strengths to the design and teaching of this course.

We also leveraged the authors' backgrounds and personal identities [39]. Our diverse viewpoints played a large role in creating the tensions and revealing the hidden connections that drive interdisciplinary work. In addition to our varied educational backgrounds, we bring different perspectives in terms of gender, race/ethnicity, and age. Our team included two White women, one Asian-American woman, one Latino, and one White man. The team consisted of three pre-tenure faculty members, one tenured professor, and one post-doctoral scholar. Several graduate and undergraduate students have also made important contributions along the way. Working on this team has convinced us of the importance of ensuring that such diversity in engineering teams becomes the norm rather than the exception.

We also acknowledged the complexities of teaching content in ways that are not typical of engineering education. Certain racial and gender norms are made more visible in engineering education when women and faculty of color are tasked with teaching courses which include some social, cultural, or sociotechnical aspect [43]. With this in mind, along with the "sometimes hidden, sometimes overt climate" in engineering education that places women and faculty of color in precarious situations [43], we believed it was important to have a White male professor teaching the course. Strategically, it was important for the research team to demonstrate that culturally responsive education has a place in engineering education and reinforce the importance of allyship and diversity.

3.2.2. Learning from Culturally Sustaining Pedagogies (CSPs)

Since we were interested in helping our students develop a wider perspective, as course designers we looked outside of traditional pedagogies used in engineering to widen our own perspectives. We researched several culture-based and asset-based approaches, including culturally relevant, culturally responsive, and indigenous pedagogy. More about this exploration and key references can be found in Momo et al. (2020) [39]. This energy course was most informed by culturally sustaining pedagogies (CSPs). Culturally sustaining pedagogies are an educational approach which "seeks to perpetuate and foster—to sustain—linguistic, literate, and cultural pluralism as part of the democratic project of schooling" [44]. Paris and Alim (2017) argue that closing the so-called "achievement gap" is not just about getting working-class students of color to speak and write like middle-class White ones—it requires centering pedagogies on heritage and practices of students of color [45]. Our *Integrated Approach to Energy* course sought to highlight "linguistic, literate, and cultural practices" as examples of engineering not stemming from the dominant discourse of White, Western, masculine colonial knowledge. Our goal was to help students see that there are other ways of knowing and that engineering is not owned by a particular culture, nor is the topic of energy owned by a particular engineering discipline. It is through this approach that we sought to highlight the voices of those who are not traditionally part of the engineering curricula, connect to students' personal lived experiences, and uplift the plurality that exists in engineering (even when it is not legitimized in the traditional engineering cannon).

We also learned from indigenous scholars about the importance of place and acknowledging this fact in the classroom [46–48]. Thus, we specifically considered energy within our local context of San Diego in choosing course content. These scholars encouraged us to think about how an energy course in San Diego would be different from an energy course in a different location, moving towards a decolonizing rather than a colonizing mindset [49,50].

Based on this research and our own experiences and goals, we aimed to structure the class around contemporary practices that might resonate with the majority of our students through their shared upbringing in the USA and age group. We also aimed to integrate a more diverse worldview that

reflects the variety of ways engineering is used, if not defined, through cultures that are not White, Western, masculine, and colonial. It is important to recognize that this work is hard, and requires commitment and critical reflexivity. We recognize that this is a work in progress and that we have not yet achieved all of our goals. In the next section, we describe our experiences with the first implementation of this course.

4. Integrated Approach to Energy in Spring 2020

The first offering of this course was in Spring 2020, with eighteen students majoring in Integrated Engineering enrolled. Seventeen of the students were in their second year and one was in the third year. There were six women and twelve men. While all faculty-authors (GDH, DAC, JAM, and SML) were involved in developing the course, author GDH was the primary instructor and instructor of record. Moving forward, this course will be required for all Integrated Engineering second-year students.

The course description was crafted to show students from the beginning that this course was different from traditional engineering courses:

Ever wonder what “energy” really is? In this course you will learn the engineering behind both energy production and consumption. Our discussion of energy production will be grounded in a California context and highlight the fundamental operating principles of solar, wind, and natural gas power plants. We will also examine the global energy landscape and consider contemporary sociotechnical challenges related to energy. When thinking about consumption we will focus primarily on the residential and commercial sectors. You will learn a systems approach for analyzing energy consumption within buildings that can be applied to anything from your own home to a large manufacturing plant. By the end of the semester you will be able to identify, formulate, and solve a range of engineering problems related to energy.

As indicated by the description above, our goal was for the students to get a glimpse of the content of the course and the emphasis on the sociotechnical aspects of energy production and consumption. Prerequisites included required classes in the engineering curriculum, which should have been completed by the third semester, including the second Physics class in electricity and magnetism, two introductory engineering design classes, including one in user-centered design, and an engineering math class (focusing on linear algebra and ordinary differential equations) which could be taken concurrently.

4.1. Learning Objectives

Following best practices in education [51], we developed course-level learning objectives. By the end of the course, we hoped students would be able to:

1. Identify, formulate, and solve engineering problems related to a range of energy concepts (e.g., efficiency, heat, work, and appropriate units)
2. Categorize types of energy using appropriate engineering terminology (e.g., mechanical, internal, solar, electrical, chemical, and nuclear) and perform calculations related to energy transformations
3. Explain the fundamental operating principles of the most common types of electricity generation in California (e.g., natural gas, solar, hydroelectric, nuclear, and wind)
4. Describe contemporary challenges caused by or related to energy resources, such as economic impacts, sociopolitical tensions, and environmental impacts
5. Explain how various methods of both passive (e.g., evaporative cooling) and active (e.g., electric, fuel-powered, heat pumps) heating and cooling in buildings work
6. Analyze how the natural environment (e.g., tree shade, sun angles) and built environment (e.g., windows, insulation) impact heat transfer into and out of buildings, with consideration for cultural and climatic contexts

7. Apply concepts from class to inform decisions about energy consumption or conservation in your everyday life

These objectives reflect a few major themes we sought to address with the course. First, as one of the students' first engineering science courses, we wanted students to develop their engineering problem solving skills as captured by ABET Outcome 1 (see Table 1) [52]. Most of our objectives supported achievement of this outcome. Another important guiding principle in developing these objectives was that we sought to create a flexible framework that could be adapted as contemporary energy issues evolve. Within this framework, we identified electricity generation and energy consumption (in ways students have experienced, primarily in buildings and at home) as important areas to address for students. In particular, learning objectives 4 and 7 were developed to ensure we were helping students see the relevance of energy course concepts to both their own lives and the ways in which engineering decisions fit into the larger global context. These objectives align closely with ABET Outcomes 4 and 7 (Table 1). Our syllabus also included a land acknowledgement statement and inclusivity statement as additional signals to students about the importance of these issues.

Table 1. Course Learning Objectives and ABET Outcome Mapping.

ABET Outcome	Course Learning Objectives
1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics	1, 2, 3, 5, 6
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts	4
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies	7

4.2. Course Content

Guided by our learning objectives, we identified four major themes we wanted to address in our course: energy fundamentals, electricity generation, energy policy, and energy consumption (Table 2). We developed detailed learning objectives for each of these areas (available upon request). The class met twice a week for 80 min, with weekly homework and three exams. We developed active learning lesson plans that provided multiple opportunities for students to engage deeply with the material during class. We have the privilege of having small classes, which gave us considerable flexibility in designing the student experience. Roughly halfway through the semester, we had to adapt due to COVID-19 and move to an online learning environment (for more on this transition, see [53]). We continued with synchronous instruction through Zoom, though sessions were recorded for students who were unable to attend. Fortunately, attendance was quite high and there were typically only one or two students absent for each session. We were able to continue with our active learning approach utilizing tools such as Zoom breakout rooms, Google Docs, and Slack workspaces.

Table 2. Thematic Areas Addressed in Integrated Approach to Energy.

Topic Area	Course Time
Energy Fundamentals	30%
Electricity Generation	30%
Energy Policy	20%
Energy Consumption	20%

4.2.1. Energy Fundamentals

We began the semester by engaging students in a discussion about their existing knowledge of energy. We posed the question "What is energy?" and had students define the term for themselves.

Student definitions ranged from “Energy is a concept that is used to power and do work” to “Energy is a fundamental source which can be transferred and used or manifest in many different ways. It exists everywhere and has become a driving force behind human civilization.” We then guided the conversation to help students see that energy is a social construction that brings together concepts from multiple different lines of inquiry, (e.g., theory of mechanics, theory of heat, technology of machines and engines, theory of electromagnetism; see Lehman [54]).

Next, we had students examine the USA’s energy landscape using Lawrence Livermore’s Energy Flow Chart (Sankey Diagram) [55]. This led students to raise questions about climate change, a topic we had planned to cover later in the semester, so we decided to adapt and move that discussion earlier. Having set the stage with this larger framing, we then moved into technical topics of energy units and types of energy (e.g., mechanical, electrical, nuclear, etc.) For this section of the course, we adapted material from Chapter 4 of Randolph and Masters’ *Energy for Sustainability* [33].

4.2.2. Electricity Generation

After setting the stage, we turned our attention to electricity generation. While energy encompasses more than just electricity, we agree with the prevailing wisdom that a sustainable energy future is grounded in an “electrify everything” approach [56]. Before the start of the class, we surveyed a wide range of USD students on what energy topics they might be interested in learning about [15]. Wind and solar were two of the leading results, so we began the semester with a focus on these two technologies. We capitalized on resources that we had available right on campus—in particular, a small-scale solar and wind generator called the PrimoWind EnergiPlant (Figure 1) installed outside our engineering building that students walk by every day. We took a deep dive into this technology by using it as the context for wind and solar energy, beginning with a “field trip” to the EnergiPlant. Students developed a block diagram showing the key components of this system. We traced the energy flows through this block diagram, performing detailed analyses of the different energy conversions that occur from the primary resources of sun and wind to electrical energy. Students’ learnings from this small-scale system were extrapolated to large-scale wind and solar farms. We then turned our focus to heat engine-based power plants (e.g., Natural Gas, Coal, Nuclear, Geothermal, etc.). We focused on these power plants at a high level, discussing their block diagrams, basic operating principles, and high-level efficiency analysis. To conclude the section, we had students examine the economic and environmental aspects of these generating technologies. We had them calculate the costs of generating electricity, as well as the greenhouse gas emissions from different fuel sources.



Figure 1. The PrimoWind EnergiPlant, a solar and wind electric charging station installed on our campus.

4.2.3. Energy Policy

While we infused timely public policy discussions around topics throughout the semester, after concluding the electricity generation section, we took several classes to focus in detail on this area. We wanted students to see the ways in which engineering decisions are influenced by societal context. We engaged with policy in several different ways. We started this section by framing the discussion in the context of *Factfulness* [57]. As former USA President Barack Obama nicely summarizes, “Factfulness by Hans Rosling, an outstanding international public health expert, is a hopeful book about the potential for human progress when we work off facts rather than our inherent biases” [57]. (For a short summary, see Rosling’s TED Talk *How not to be ignorant about the world* [58]) In particular, Rosling’s Gap Minder bubble tool gave students a way to visualize relationships between energy and a wide range of economic, health, and other policy indicators. For one example, see Figure 2 which shows CO₂ emissions vs. income.

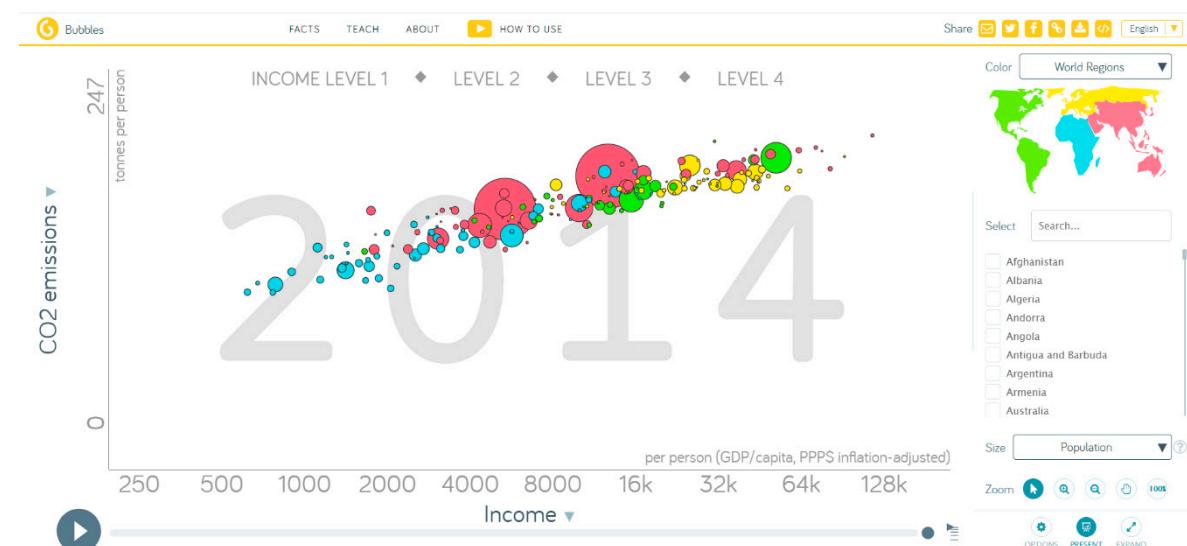


Figure 2. The Gap Minder Bubble tool allows students to visualize the relationships between energy, economic, health, and other policy indicators throughout time. Colors represent countries from different regions of the world. (Image source: Free material from www.gapminder.org).

With this framework for critical thinking, we then engaged in several different activities. Students did a jigsaw activity with several articles from the *New York Times*’ Carbon Casualties series. These articles discussed the already substantial impacts of climate change on primarily indigenous communities around the world [59]. We examined two local examples (within 60 miles of our campus) of challenging policy situations: the troubled life of the San Onofre Nuclear Generating Station and the challenges faced by Native Americans trying to build a wind farm on their reservation. We had students watch *The New Fire*, a 2019 documentary that argues for nuclear as a key technology in the fight against climate change [60]. Students then read Professor Gregory Jackzo’s op-ed “I oversaw the U.S. nuclear power industry. Now I think it should be banned” [61]. These activities were all designed around our fourth learning objective: “describe contemporary challenges caused by or related to energy resources, such as economic impacts, sociopolitical tensions, and environmental impacts.”

4.2.4. Energy Consumption

Towards the end of the semester, we turned our attention to energy consumption. We revisited the energy flow charts from the beginning of the semester and provided a short, high-level overview of the categories we use in the USA to categorize energy use: residential, commercial, industrial, and transportation. We then focused on energy use within buildings, discussing the primary areas of energy consumption in these spaces: heating, cooling, and ventilation. We compared electric,

natural gas, and heat pump heating by tracing energy flows and efficiencies through these systems from site to source. In particular, students learned how to analyze heat pumps, refrigerators, and air conditioners using the refrigeration cycle. We had planned to incorporate heat transfer into this module as well, however, because of COVID-19, we did not get as far as we had hoped. Thus, learning objective 6 was not fully covered or achieved in this first implementation of the course.

4.3. Pedagogical Approach in Context

4.3.1. Engaging Students' Lived Experiences

For education to be successful and resonate with students, it needs to be centered on students' lived experience. Best practices in education call for making course content relevant to students for a myriad of reasons [51]. We see our role not as delivering content, but as creating a space for knowledge construction. This is consistent with an asset-based approach that recognizes students' existing abilities as opposed to focusing on their deficits [62–65].

Aligned with this idea, proponents of CSPs emphasize the importance of understanding and sustaining students' own cultural practices. This means that the course experience should be different depending on who is in the classroom and where it is taught. Another related lesson we took from our research into CSPs was the importance of including students in the course design process. Towards this end, we conducted a survey of students at our institution to understand their relationship towards energy [15]. This survey revealed strong interest in both sustainable and nuclear energy technologies, so we made sure to include these in the course although we had initially not planned on including nuclear energy. As our school is located in southern California and we have many Californians in class, we placed an emphasis on California energy issues. We sought out local examples to help students connect and see the relevance of this material. This is why we selected the EnergiPlant (Figure 1) as a central theme early in the course—it was something the students walked by every day, but probably had never thought about from an engineering perspective.

Another lesson we took from CSPs was the importance of providing flexibility for students to bring their own identity into their engineering work. Towards this end, we asked students a reflection question on every homework assignment to help them connect their own perceptions to the course material (e.g., "What is the most interesting thing you learned about energy this past week (could be from class, homework, or somewhere else)? Explain this concept and what you found interesting about it.") We also designed open-ended assignments that allowed students to exercise choice. For example, in one assignment students analyzed their own personal energy bill, and in another they did a power analysis of their personal electronic devices. Students were quite engaged in these assignments and many commented on how it brought the material to life.

4.3.2. Countering the Dominant Discourse

The first step we took in countering this dominant discourse and approaching a CSPs-based curriculum was to present more human examples to demonstrate typical engineering concepts. In particular, we tried to be intentional in directly confronting the Whiteness of engineering. Not only did we replace kinetic energy examples of bullet projectiles with kids on swings, but we also intentionally searched for diverse faces to include on our class slides. It is worthwhile to note that even the trivial task of finding an image of a child of color on a swing, and the consequential conversation that ensued, illustrated the differences in lived experience on our team. While being intentional about selecting images with diverse faces is certainly not groundbreaking, this experience helped our White male ally comprehend a dose of the frustration the rest of the team members feel regularly when it comes to representation in engineering as their authority at the front of the classroom is questioned [43]. The learning experience illustrated by this small task hints at the exclusion a non-White student (layered upon other minoritized identities) might feel in a traditional engineering classroom.

We sought to confront the White, Western, masculine, and colonial (re)presentation of engineering knowledge by choosing a broader range of examples than the traditional ones throughout the course. In one instance, we examined Sankey Diagrams that illustrated Mexico's energy flow and compared and contrasted it with that of the USA. The activity highlighted how Sistema de Información Energética de Latinoamérica y El Caribe (sieLAC), the equivalent to the USA Energy Information Administration (EIA), uses a different framework to depict its energy types, energy use, and energy sectors. Additionally, the fact that the graphic was labeled in Spanish emphasized that English is not the only language for disseminating technical knowledge. Other examples included China's Three Gorges Dam rather than a USA hydroelectric plant and using a hair dryer rather than a car engine to introduce a system block diagram, among others.

We also designed larger contextualized activities that showed the interaction between engineering and society. For example, the New York Times activity around climate change (discussed previously) emphasized the ways in which indigenous communities are being negatively impacted and the steps they have taken to address the problem. Discussing *Factfulness* in parallel allowed us to directly confront the narrative of "developing" versus "developed" countries, and instead help students see the continuum of development both between and within countries. To begin to challenge the source of engineering knowledge, we introduced voices of authority that illustrated examples of non-Western energy expertise. We set the stage for these conversations by emphasizing the ways in which energy is a social construction. This framing was important because it helped students recognize, starting in the first week, the ways in which energy education (and engineering in general) is not a product of objective truths, but rather is based on social constructions and convention agreements. For example, we reinforced this idea in our lesson on units. Units are a cultural phenomenon—throughout history, nearly every culture has developed a unit system based on body measurements (e.g., feet, hands, fingers). There is no one "correct" unit for length or any other quantity; rather, unit systems vary culturally. This showcases how units are not objective knowledge—they are part of knowledge constructions that are neither static nor constant. We then briefly explained the evolution of these systems into what is now the Système international d'unités (SI Units) which many countries have agreed to use to simplify analysis and communication. This was a particularly salient example because the USA still does not fully participate in this system, a fact that roils every new generation of engineering students from the USA.

One concern we had in elevating non-Western ways of knowing was avoiding cultural appropriation—we did not want students to falsely attribute these "new" (to them) ideas to the White male instructor. Therefore, we tried to incorporate these examples using the engineers' own voices by showing videos or reading articles in each authors' own words. In our module on wind energy, students watched a short video about wind turbines, built over 1000 years ago and still active in Iran, which inspired the creation of current Dutch windmills [66]. In a more involved module, students watched Rose Mutiso's TED talk on "How to bring affordable, sustainable energy to Africa" [67], which highlighted common Western misconceptions about Africa's energy needs and proposed a path forward. In particular, Mutiso criticized the naïve narrative that Silicon Valley has inspired regarding Africa "leapfrogging" dowdy infrastructure by implementing off-grid technology. However, she said, ultimately, no approach can succeed in solving energy poverty unless we confront the complex socioeconomic and political contexts which have created the broader macroenvironment. Mutiso states that we are "misdirecting concerns about climate change ... and these are leading us to impose a Western debate on the future of energy and falling back on paternalistic attitudes towards Africa" [67].

This video provided an opportunity for discussion of engineering as a sociotechnical endeavor, but it also helped students see how Western values and beliefs are not inherently better than or transferable to engineering knowledge in other cultures. Mutiso states several examples of new renewable infrastructure projects across the continent, which capitalize on Africa's vast natural resources in an effective and efficient way. Rather than abiding by Western ideas of how energy

should be sourced and used, and dismissing colonialist myths about how “allowing” Africa to develop economically will spell disaster for climate change, Mutiso captures the reality surrounding the hierarchy of knowledge in energy and in engineering.

5. Methods

To analyze student learning and the impact of our course, we utilized quantitative and qualitative approaches. All 18 students enrolled in the class consented to participate in our research project. We collected a range of data in the form of student work (homework and exams), a pre/post survey with knowledge-based energy questions, and interviews with 11 students. For this paper, we focused on the pre/post survey, final exam questions, and interviews.

5.1. Pre-/Post-Assessment

On the pre-/post-exam we asked students 19 knowledge-based energy questions. The pre-assessment was administered on the first day of class, the post-assessment was administered during one of the semester’s final classes. The questions were based on an energy knowledge survey developed by DeWaters [68] and adapted to focus on material covered in our energy course, including types of energy fundamentals, electric generation, and energy policy. For example, one question asked, “Complete the following energy conversion for a battery-powered flashlight: _____ energy -> electrical energy -> light energy.” The full survey can be made available upon request. Student responses to the survey were analyzed using the software package R. We calculated students’ scores on each assessment as a percentage, the difference between the means, and a standard deviation on the difference of the means. We compared each student’s overall score between the pre- and post-assessment using a paired *t*-test, as well as computing the same test for three subcategories of questions: energy fundamentals (6 questions), electric generation (4 questions), and energy policy (8 questions) [69,70].

5.2. Final Exam

The final exam had two parts: 15 multiple-choice questions and three free-response problems. The exam covered the entire semester but emphasized the material from the last third of the course. Due to COVID-19, the exam was administered as open-book and students were given 24 h to complete the exam to reduce anxiety (though most completed it within ~3 h). In the multiple-choice section, we selected five questions from a heat and energy concept inventory developed by Prince [16] that were addressed by our course learning objectives. These questions were designed explicitly to identify students’ common misconceptions, thereby assessing whether students have a true understanding of the phenomenon in question. While Prince developed a robustly validated instrument, we cannot compare directly to their results as we selected only those questions relevant to our course.

We wrote the remaining ten multiple choice questions ourselves to cover energy conversion (e.g., “Complete the following for a wind turbine: mechanical energy (wind) > _____ -> electrical energy”), efficiency (e.g., “What does it mean if an electric power plant is 35% efficient?”), and energy policy (e.g., “The term “climate change” refers to … ”)

The three free response questions addressed energy conversion (a mechanical energy storage problem), energy policy (a critical analysis of a policy issue they chose from a list), and energy consumption (a refrigeration problem). Questions were scored using a holistic rubric.

On the final exam, we asked students to “Choose a challenge below (e.g., “Where should we install wind turbines?”) and write a critical analysis that explains the political, economic, social, technological, environmental, and legal issues surrounding the choice (PESTEL). Specifically, students were instructed to write approximately 300 words and address at least 4 of the 6 PESTEL elements in their responses. Student answers were coded for the areas they addressed in their answers. Students’ responses were analyzed using a deductive coding approach with a list of a priori codes [71] that were relevant to the research (e.g., political, energy).

5.3. Semi-Structured Interviews

All students within the class were invited to participate in semi-structured research interviews with LAG, a postdoc who had been observing the class until the transition to remote learning. Eleven students agreed and were interviewed. Students were informed of the opportunity by the instructor during class and provided with a link to a Google Form. Students who wished to participate responded to the form and LAG scheduled individual interviews over Zoom. Participants were briefed on the purpose of the research, reminded that they could refuse to answer interview questions and/or rescind participation at any time, and given the opportunity to ask questions before, during, and after the interviews. Additionally, students were reminded that participation did not have an effect on their grades. To ensure confidentiality and privacy of participants, the instructor was only made aware of how many students elected to participate (not who participated). Additionally, results and themes were not discussed among the authors until after grades were submitted. When interviews were completed, participants were compensated with a \$50 Amazon gift card.

Interviews were semi-structured and conducted over the course of two weeks in April 2020, ranging from 30–45 min in length. Using semi-structured interviews allowed flexibility to explore the participants' lived experiences and the aspects of the curriculum content most salient to them. These interviews were audio-recorded and later transcribed. Some of the interview questions included: "what was the most and least interesting part of class?", "what was the most important thing you learned from the class?", and "describe a moment where the class content clicked or resonated with you." Additionally, at the end of the interviews, students were allowed the opportunity to talk about their experiences with remote learning in light of COVID-19 [53]. (For more information on our experiences with transitioning to emergency remote teaching, see Gelles et al. [53].)

6. Results and Discussion

6.1. How Did Students Learn the "Technical" Content?

One common criticism of this kind of curricular change is that "the bridges will fall down" if any "technical" content is removed to make space for other aspects of engineering practice—particularly social aspects. Contrary to the idea that the integration of sociotechnical aspects could hinder the learning of technical concepts, our data show that our approach did not interfere with our students learning the technical content. We assessed this learning in two quantitative ways: a pre-/post-assessment with knowledge-based energy questions and a final exam question (see Methods for more information).

Student scores on the pre-/post-assessment increased on average by 9 percentage points ($\sigma = 12$) from 66% to 75% (see Figure 3). This change was measured to be statistically meaningful using a paired *t*-test ($t = 3.06$, $p < 0.01$, 95% confidence interval on the difference of the means [2.8 to 15.2]). We further investigated student improvement by examining groups of questions in three categories: energy fundamentals, electric generation, and energy policy. We were able to measure a statistically significant increase in student performance on energy fundamentals (pre: 75% post: 88%, paired *t*-test, $t = 2.74$, $p = 0.02$). Although students' scores on questions about electric generation (pre: 57% post: 71%, paired *t*-test, $t = 1.77$, $p = 0.10$) and energy policy (pre: 63% post: 68%, paired *t*-test, $t = 1.06$, $p = 0.31$) increased, these increases were not statistically meaningful.

Students also did quite well on the technical content of the final exam. Students averaged 92% on the multiple-choice section ($\sigma = 7.6\%$), including averaging 92% ($\sigma = 10\%$) on the 5 questions taken from an energy concept inventory. While we cannot compare directly to results reported by Prince et al. for the concept inventory as a whole, we took it as a promising sign that most students selected the correct answers rather than those associated with common misconceptions.

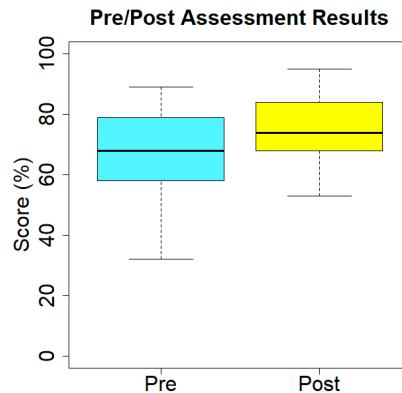


Figure 3. A box-and-whisker plot showing student improvement on the pre/post assessment. Student scores increased on average by 9 percentage points from 66% to 75%.

On the technical free-response problems, all students scored within the top two categories (of five levels) of our rubric. Students demonstrated command of the material and appeared to meet the technical learning objectives of the course. It seems unlikely that any bridges will collapse due to our curricular changes.

The interview data reinforce that students believed they learned about technical aspects of energy in this class. When asked to describe a moment that 'clicked' or resonated with them, one participant said:

"I never really understood the equations for energy and power. I felt like I was memorizing them up until this class. And I think that he [the instructor] did a really good job and continues to do a good job of explaining how to convert between one and the other, given certain components like time and then either energy or power. And I think he just did a good job of using examples and having us really understand what it means for charges to flow. And I just think he did a really good job of having us not just memorize things."

This participant goes on to describe how she now has a better understanding of the relationship between energy, power, and time. She had the unique perspective compared to her peers of having already taken a thermodynamics course and when comparing the two she stated, *"We focused on systems and surroundings and cycles [in Thermodynamics], like the Rankine cycle and other cycles. Whereas this class is more integrated, and it's kind of understanding those cycles and applying them to bigger concepts which I've really enjoyed."*

When asked the same question, another participant described how studying the example of the EnergiPlant on campus helped him learn about energy flows. He stated:

"It gets taken in by the propeller or whatever and then pushed down through the whole system, and then you can see where it's outputted. And I think just going through the whole systems like that, where you can kind of see how the energy's moving and how it gets transformed from AC to DC, DC to AC, whatever it may be. I thought that was really a good basis for me to kind of just see how energy was moving through a system, because I was beginning to like more complex systems as the year's gone on since then. I think that was really a very helpful part that kind of clicked immediately that definitely helped with the rest of the semester."

As this representative excerpt indicates, students in the class appreciated making some of those "abstract" concepts more tangible through the examples provided in class. Moreover, these examples contributed to the students' understanding of energy as an amalgam of concepts necessary to produce an output. This holistic understanding of concepts also contributed to the students' sense-making of the world around them through critical thinking.

6.2. How Did Students Learn the Remaining PESTEL Aspects of Engineering Practice?

In addition to the technical elements, we were also interested in how students engaged across the political, economic, societal, environmental, or legal aspects of engineering practice. We assessed student learning on these topics in two ways: a free-response essay question on the final exam and through one-on-one semi-structured interviews.

6.2.1. Final Exam Question

On the final exam free-response question, students were required to address 4 of the 6 PESTEL elements in their responses. Table 3 shows which areas students chose to address. In their analyses, all but one student included a focus on economic issues (94%), which was higher than even the percentage that addressed technical issues (83%). Social and environmental issues were also heavily emphasized by 67% of the students. This was not surprising as many students expressed interest in environmental issues before enrolling in the class and seven are pursuing a concentration in sustainability. Putting environmental concerns in conversation with social issues was a frequent discussion topic in class. It is not surprising that legal issues were the least addressed since this was not discussed as much throughout the class.

Table 3. Political, Economic, Social, Technical, Environmental, and Legal (PESTEL) Areas Addressed by Students in Their Final Exam.

PESTEL Area	Addressed in Essay Response (% of Students)
Economic	94%
Technological	83%
Social	67%
Environmental	67%
Political	50%
Legal	22%

Overall student responses to this exam question were well thought out and the average score was 92%. Students demonstrated willingness to critically engage in conversations around topics typically outside of the engineering classroom. This suggests that our approach of including these types of questions in both class discussion and on homework assignments was successful in getting students to start considering these other elements of engineering practice.

6.2.2. Interviews

A deeper understanding of students' learning about political, economic, societal, environmental, or legal aspects of engineering practice can be gained from the interviews we conducted. Students prioritized economic over social aspects in their interviews, which was consistent with final exam responses. For example, during their interviews, students were prompted to imagine they were designing a hypothetical power plant and were not provided with any contextual information or design constraints. Students were asked what information they would need to inform their design. Many students prioritized technical and economic factors over any other. For example, when prompted with this question, one student prioritized cost by stating it first:

"I mean, first of all, I'd want to know their budget range, which is important. Not only upfront for building the project and designing the project, but also for upkeep. Do they want something that would run on solar or sun for nothing and they just want to pay something upfront or do they want to pay more ongoing?"

Another student also described economic and technical factors. She stated:

"Price. I'd definitely want to know price. Materials that I would need to use. What kind of drawbacks there will be if something goes wrong, maybe. Oh, gosh, that's so vague. Man, maybe how big it is, how much space is it taking up. Does it need to look aesthetically pleasing, kind of like the EnergiPlant. How much power do I need to be producing? How efficient it is, stuff like that."

This focus on cost and technical factors did not preclude mentioning environmental, social, political, and legal factors. However, students predominantly prioritized technical and economic factors by describing them first and in greater detail.

6.3. Impact of the Pedagogical Approach

In the interviews, students described the impact of the pedagogical approach that was informed by CSPs. Students felt that material in class resonated with their lived experience. Many students described the EnergiPlant in their interviews and how they passed by it every day. Other students brought up the activity where they looked at their own or the instructor's energy bill. When asked about what the most important thing she learned was, one student focused on "practical things" that connected to her everyday experience. She specifically highlighted a class activity where they used datasheets to look at the five appliances she regularly uses. When asked to compare this class to other engineering classes, many students commented on how the class discusses current issues and the real-life applicability of the curriculum and activities. For example, when discussing the most interesting aspect of the class, one student stated:

"What I like most about the course is its real-world application. We're learning about actual things that we use every day and not just the math behind it or the theory or the science. It's like we're actually learning about things we use every day or see every day. And I think that's pretty neat. Most classes, they don't apply what we learn to everyday life. And I like that. That helps me learn, for sure."

Students also described how it was easier to learn and retain knowledge in this class compared to others because of the way course material was presented and connected. One student commented, "[...] it was stuff that I didn't feel like I would forget right after the test".

7. Conclusions

In this paper, we described our approach to designing and teaching energy from an "integrated" perspective, the challenges in doing so, and the results obtained during our first course offering. Beginning with the question of "What do engineering students in 2020 need to know about energy to be successful in the workplace and contribute to addressing society's issues related to energy?", we drew on the interdisciplinary backgrounds of our diverse team to provide a class that challenged the dominant discourse in engineering by valuing students' lived experiences and incorporated examples from different cultural contexts. Quantitative assessments demonstrated that students achieved the learning objectives in technical areas although there is still room for improvement. Interviews revealed that students learned about environmental, economic, and social aspects of engineering practice. Students, however, still prioritized the technological and economic aspects. This suggests that we still have more work to do to help students to see engineering as a sociotechnical endeavor.

It is important to acknowledge that what we have presented in this paper is still a work in progress. The changes we are trying to achieve in engineering through this course require a significant commitment and consist of multiple iterations, reflection, and critical engagement. We aim to develop a truly inclusive engineering pedagogy, and we acknowledge that this will take time and hard work. We believe our new energy course is a step in the right direction, but there is certainly more to be done. Even for us, as an interdisciplinary and diverse team, it is challenging work to agree on interdisciplinary content and figure out how to incorporate voices from outside of the traditional engineering canon. We recognize that we still have our own biases to overcome—sometimes the product of our own

training as engineers embedded in the dominant discourse—a topic we will be tackling in depth in future papers. We, as faculty members, continue to be part of an institution that is doing what it was meant to do. Challenging that status quo while being part of it is taxing but necessary to achieve the changes we desire.

The course we have presented here engages students through contemporary practices, connects to their lived experiences, takes an interdisciplinary approach, and is framed within a sociotechnical context. While each element alone is not a radical change to the engineering curriculum, we believe that taken together this is an important advancement in the field of energy education. Energy is an incredibly important topic with direct connections to some of the thorniest problems facing society today. From our vantage point, the status quo seems unsustainable, future generations are counting on us to reimagine how we train engineers in this area.

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