



Article

# A Place-Based Sustainability Approach to Learning about Photovoltaic Solar Energy

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**Abstract:** An ethical and effective engineering practice is inherently place-responsive and designs for a sustainable future. Engineering students must therefore be educated within a sustainable and sociotechnical paradigm. In the spring of 2022, the integrated engineering department of the University of San Diego offered a new photovoltaic solar energy course for junior and senior students. Informed by place-based pedagogies and culturally sustaining pedagogies, we designed the course to be relevant to the students' lived experiences by coupling the learning about the technical elements of solar energy with a focus on solar energy projects and sustainability on campus. Prior to running the course, we identified four potential new solar investment/upgrade projects for the university. We divided the class into four teams, with each team assigned to assess the feasibility of a solar project through (1) social, (2) technical, (3) economic, and (4) environmental analyses. Finally, the students integrated their findings and made recommendations to key university stakeholders about how to proceed with solar energy investments on campus. In this paper, we share the course project design, our findings from implementing it, and ideas for adapting it to other place-based sustainability learning experiences.

**Keywords:** higher education; photovoltaic solar energy; place-based pedagogies; sociotechnical engineering; sustainability; qualitative methods



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## 1. Introduction

Sustainability is often considered using the model of three pillars: environmental, economic, and social [1]. The environmental pillar is rooted in “place” and challenges us to be mindful of a given context—our surroundings, a geographic locale, and the whole world, or a part of it—as we strive towards, assess, or reflect on sustainability. In fact, we argue that this cultural context is all-encompassing and should always be considered. Analogously, an ethical and effective engineering practice is also inherently place-responsive and designs for a sustainable future. Engineering students, therefore, must be educated within a sustainable [2,3] and sociotechnical paradigm. The sociotechnical engineering paradigm equally values the “socio” (social context and considerations, including “place”) and the technical elements of engineering, compared to traditional engineering, which has historically been myopically focused on the technical [4–16].

Photovoltaics (PV), the generation of electrical energy from sunlight using solar cells, is an important technology in today's world. There is a wealth of research on these systems and efforts to optimize them (e.g., Lupangu and Bansal, 2017 [17]; Kannan and Vakeesan, 2016 [18]), and educational efforts to help students learn about PV, including laboratories (Nehme and Akiki [19], Axaopoulous et al. [20], and Zachariadou et al. [21]), simulations (Erdem 2013 [22]), software (Sharma 2014 [23]), and courses (Martinez 2010 [24]; Benda, 2004 [25]). Some of these courses are deeply technically focused, and Benda describes a challenge of PV being that it is broad and interdisciplinary. Nelson et al. (2011) [26] see these aspects as an advantage, arguing that PV may be particularly interesting and relevant

for today's students and may help them see the value of what they are learning. They encourage educators to "take advantage of new, innovative interventions that support students' sense of personal relevance and value of curriculum." (p. 2).

In the spring of 2022, the integrated engineering department of the University of San Diego (USD) offered a new place- and sustainability-focused PV solar energy course for junior and senior students that aimed to respond to the call of Nelson and colleagues. We designed the course with place-based and culturally sustaining pedagogies (CSPs)—connecting the students' lived experiences with their course experiences [27–29]—as the foundation. Although it contained significant technical content about how PV systems work, the course was not intended for electrical engineers and was not purely focused on the technical aspects. Rather, the course emphasized the importance of "place", which was operationalized for these students as their campus, and facilitated student learning experiences designed to be relevant to this context and their lives [30–34]. Specifically, student teams worked on a semester-long, team-based sociotechnical solar energy project for the campus while concurrently gaining technical insights through lectures and problem sets.

In this paper, we share the course and project design, our analysis approach, and the findings from our first implementation of this course. Our qualitative research examines student reflections and our own observations and reflections from teaching the course. We provide more context in the discussion and argue that this approach could be scaled and adapted to facilitate other place-based sustainability learning experiences for students across a wide range of ages and topics, such as explorations of local waste, water, or food sustainability.

## 2. Materials and Methods

### 2.1. Place-Based Context

The University of San Diego (USD) is a private, Catholic, liberal arts institution serving ~6000 undergraduates [35]. The campus currently has a ~1.2 MW photovoltaic solar system that spans 11 buildings and a carport and provides ~7% of the energy consumed on campus. Located in sunny, southern California, the campus setting is ideal for solar energy.

In the spring of 2022, a new photovoltaic solar energy course was developed and taught by two faculty members in the Shiley-Marcos School of Engineering integrated engineering (IntE) department. The lead instructor has a background in electrical engineering and materials science as well as engineering education research. The other instructor (who has since switched to the mechanical engineering department) has a background in environmental engineering. Both have experience with active learning and engaged pedagogies. Fourteen students majoring in integrated engineering, including five juniors and nine seniors enrolled in this elective course. There were five women and nine men. Eight students identified as White, one as African American, one as Latinx, two as Asian, and two as mixed race. One student was international. Both instructors were White women.

Students in the IntE department complete core liberal arts and engineering requirements in addition to a concentration (biomedical engineering, embedded software, sustainability, law, or a concentration of their design) [36]. This course satisfied a requirement for an upper-division elective within the sustainability concentration, which most students were pursuing. The department faculty emphasizes sociotechnical engineering learning approaches (such as utilizing the PESTEL framework (political, economic, social, technical, environmental, and legal)) [37], sustainability, and eco-social justice [38–43] across all courses. We have shared about other sociotechnical engineering courses from the department in previous publications [44–48].

### 2.2. Course Design

The course lecture and homework topics spanned (1) solar cell materials and operation, (2) PV modules and arrays, (3) grid-connected PV systems, (4) stand-alone PV systems, and (5) economic, environmental, and social considerations (including case studies). These topics mapped to the following course learning objectives:

1. Describe, using diagrams and appropriate equations, the operation of solar cells.
2. Explain the operation of photovoltaic (PV) modules and arrays.
3. Compare grid-connected and stand-alone PV systems.
4. Explain important economic, environmental, social, and technical considerations for the design and use of PV systems.
5. Identify at least two topics related to photovoltaic solar energy on campus.
6. Conduct effective research including critically evaluating technical papers, reports, podcasts, videos, or websites and expressing information orally and in writing.

The first three objectives were the focus of the beginning of the semester. The textbook, *Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems* [49], detailed lecture handouts, including exercises, and cooperative learning homework assignments [50] were used to support these objectives. The fourth goal was addressed throughout the course, primarily in the on-campus project, which is described below. In addition, to help students appreciate the importance of place for the design and use of PV systems, we worked with an alumnus in South Sudan who owns a solar energy company. Students completed modules that he developed [51] and then participated in a video call with him.

To address the fourth, fifth, and sixth course goals, student teams completed a class project which included the exploration of potential solar investments/upgrades (detailed below) that the university is considering as part of the campus goal to reach carbon neutrality by 2035. The project comprised 60% of the course grade; the other 40% was based on exam and homework performance. Each team investigated the sociotechnical viability of their assigned solar project through a series of feasibility analyses focused on the technical project components and the three pillars of sustainability (economic, environmental, and social). Finally, teams integrated their findings and collaborated on an all-class presentation with final solar project investment recommendations for key university stakeholders at the end of the semester. These stakeholders included the Provost, the Director of Sustainability, a member of the Board of Trustees, the Director of University Design, the Assistant Vice President for Facilities Management, three Senior Project Managers, the Director of the Care of Our Common Home Strategic Plan Pathway, and the Engineering Director of Development, in addition to several other engineering faculty members. Some attended remotely, while others attended in person.

### 2.3. Four Potential University Solar Investment/Upgrade Projects

Before the start of the semester, we investigated the current state of solar energy at the university and spoke with the Director of Sustainability about potential avenues to expand photovoltaic solar energy on campus. We identified four potential solar investments/upgrades that the university could pursue and sculpted them into team project assignments. Below, we provide an abbreviated prompt for each project that we gave to the students. We assigned students to these projects in two teams of three and two teams of four. One team comprised all seniors, and the other teams included at least one junior.

- Project 1: Solar Panel Upgrading Options
  - The university has been leasing the solar panels located on roofs across campus from [a solar company] for years through a Power Purchasing Agreement (PPA) and more efficient solar panels are available for lease or for purchase. Explore whether the university should: (1) continue to lease the same, less efficient panels, (2) lease new, more efficient solar panels, or (3) buy new, more efficient solar panels.
  - Additionally, how many panels could and should we add? Where? How much additional solar would that produce and what percentage of the university's energy portfolio would be comprised of solar?

- Project 2: Main Parking Structure Solar Carport
  - Explore the possibility of increasing the university's carbon neutrality and reliance on solar energy by adding a solar carport (roof structure with solar panels) to the top floor of the main parking structure on campus.
- Project 3: Athletic Stadium Solar Panels
  - Explore the feasibility of increasing the university's carbon neutrality and reliance on solar energy by adding solar panels to the athletic stadium, such as on a roofing structure over the audience seating.
- Project 4: Solar Heating for Outdoor University Pool
  - Explore the feasibility and impact of transitioning the campus pool heating system (currently a natural gas boiler) to PV, solar thermal, or hybrid (i.e., panels that can do both thermal and PV). Additionally, explore the possibility of and need for including a battery in the system for poor weather.

#### 2.4. Project Design

We guided the students in completing their semester-long (~14 weeks) project over the course of five phases, each lasting approximately two weeks and culminating in a team-written report and class presentation (Table 1).

**Table 1.** Project Phases.

Project Phase	Topic
0	The Current State of Solar Energy at the University
1	Project Definition and Social Contextualization
2	Technical Feasibility Analysis
3	Economic Feasibility Analysis
4	Environmental Feasibility Analysis
5	Integrated Analysis and Final Recommendation

Prior to beginning work on their individual projects, the class worked together to assess the current state of solar energy at the university (Phase 0). The students explored the university's Energy Master Plan (EMP) as their first individual homework. This provided an overview of the current state of solar on campus and plans for the future. Teams then began to work on their individual projects by gathering background information to clarify and define their assigned projects in greater detail, including their social contexts (Phase 1). Next, the teams conducted feasibility analyses for their projects with respect to three key areas: 1) technical (Phase 2), economic (Phase 3), and environmental (Phase 4). After completing their analyses in each of these areas, they integrated their findings into a final summative feasibility analysis and recommendation for the university (Phase 5). The instructors supported the students in completing the analyses by providing guiding questions and detailing deliverable expectations for each phase. We also provided some in-class time for students to collaborate on the project and were available to the teams for guidance/troubleshooting/workshopping during that time.

#### 2.5. Integrated Engineering Reflection

In addition to the more traditional project deliverables of written reports and presentations, we also integrated reflective practices throughout the semester. As sociotechnical engineers designing in complex, real-world settings, it is important to recognize that not everything can be quantified or captured in feasibility analyses. As such, a responsible engineering practice incorporates a process of reflection to consider who and what are being forgotten or left out of estimates, designs, and recommendations [52]. To help cultivate the students' development as reflective practitioners, we prompted them to complete a half-page to one-page reflection at the end of each project phase. The reflections were completed collaboratively by each team. However, following the final project phase, "integration", we

required that students complete their reflections individually and that they respond to the following prompt:

“What is not included in our analysis for this phase that should be taken into consideration?”

We also hinted that the students should “think about ‘invisible’, long-term, or ripple effects. Think about hidden costs, people not considered, and/or impacts to an ecosystem.”

### 2.6. Analysis

We analyzed the final individual student reflections using an inductive thematic analysis [53]. To maintain student anonymity, we employ pseudonyms as we share quotes from the fourteen students in this paper. As the students were given a specific prompt for the reflection, we anticipated that their responses would be thematically grouped in relation to that prompt. Instead, the student reflections touched on a wide range of topics, many of which had nothing to do with the prompt. As such, we let themes emerge authentically rather than forcing relation to the original prompt. We identified preliminary themes and then went through an iterative process of mapping the student reflections to the themes, adjusting and then finalizing four themes. We list the themes and sub-themes in Table 2 and share our findings across the four themes in the sections below.

**Table 2.** Identified Themes and Sub-Themes.

Theme	Sub-Theme
1. Course Commentary	i. Course Structure ii. Sociotechnical Course Nature iii. Three Pillars of Sustainability and the Engineering Design Process
2. Student Takeaways and Personal Development	
3. Students’ Self-Criticisms and Project Shortcomings	i. Project Aspects Overlooked ii. Unsureness of Findings
4. Student Perceptions of Project Broader Impact	

## 3. Results

In the following sections, we summarize our findings related to each theme and the corresponding sub-themes.

### 3.1. Course Commentary

Numerous student reflections included commentary on the course, its structure, content, and sociotechnical nature. The students additionally discussed the three pillars of sustainability and the engineering design process as they related to the course and project.

#### 3.1.1. Course Structure

The students commented on the overall course structure, which first emphasized technical content before ramping up the project emphasis. This front-loaded technical focus and sectioning of the course was liked by students; in Rob’s words, “being able to focus on the project made the work and deliverables much higher quality”.

The students also acknowledged the necessity of the foundational technical material in making it possible to take on a project of this nature:

*The lectures, handouts, and homework we worked through during the first few weeks of this course helped me build a foundation of knowledge on PV solar energy that was crucial to my [project] efforts. (Adam).*

### 3.1.2. Sociotechnical Nature of the Course

There was one student request for additional coverage of technical content with respect to power storage because having that knowledge would be “very beneficial” to the student’s future. However, there were many more student comments that expressed an appreciation for and the benefits gained from the sociotechnical nature of the course and its non-technical components. For example, Charles stated:

*I really appreciated the focus on economic, environmental, and technical aspects that we had to focus on for this project. I have been exposed to lots of technical and economic situations over time, but the environmental aspects have always been a bit foreign to me due to the culture I grew up in.*

This student went on to say that he plans to bring the environmental perspective into his work as he “begins to design systems for his local community” in “Mexicali” (the border of Mexico/California). Rob praised the benefits of integrating findings across the social, environmental, economic, and technical analyses:

*[It was] very satisfying to put it all together. We reconsidered the work we had done in the past and analyzed our best possible options. It felt like all the work we had done over the semester was becoming a coherent, viable project. [The final phase] showed the breadth of our knowledge over solar and I could not believe I was part of writing this only three months after barely knowing anything about solar.*

### 3.1.3. The Three Pillars of Sustainability and the Engineering Design Process

Several students commented on the sociotechnical nature of the course and their experiences with the engineering design process and three pillars of sustainability through the project. In a previous study [54], we heard students grasping for the words to describe sociotechnical engineering by describing what it is not (e.g., “not just technical”), or describing it as “more than” technical. We found echoes of that sentiment in this study. For example:

*This course was more than just a class on solar energy and solar panels. [It also] shifted into a real-world project replicating what we might be faced with upon entering the engineering workforce. (Dane).*

Other students noted that their fluency with the three pillars of sustainability and the engineering design process were critical to their capability to complete the project. All but one of the students had already taken an engineering sustainability course and an energy course that introduced the three pillars. For example, Adam noted that he was able to make a solar recommendation “because of [his] education on common engineering subjects, the engineering design process, and the three pillars of sustainability”.

In summary, the students wrote favorably about the course and its structure. This finding is not a surprise, given that the enrolled students had self-selected the integrated engineering department, which is known for teaching courses with sociotechnical and integrated pedagogical approaches.

### 3.2. Student Takeaways and Development

The students described the benefits they obtained from the course, such as the skills they developed, including technical writing and public speaking and development as a sociotechnical engineering practitioner, and the opportunity to work on a real-world project. For example, Rob described the growth he experienced from the project presentations, which occurred at the end of each project phase (approximately every two weeks):

*The public speaking part of this project helped me grow tremendously. I do not like public speaking and the biweekly presentations forced me out of my comfort zone. The presentations gradually got better and better and I got more confident in articulating myself clearly.*

Dalia conveyed development of the sociotechnical and reflective mindset that we hoped to cultivate in the students:

*As a sociotechnical engineer, I realize that not every aspect of an engineering project can be quantified or captured in feasibility analyses. Therefore, I must practice the responsible engineering process of reflecting on who and what my team may have forgotten or left out as a part of our estimates, designs, and recommendations. In this reflection, I will consider whose voices were left out throughout the entirety of my team's project as well as what role I can play as an integrated engineer to incorporate these voices in the future.*

Tony noted that, “working on this project really opened my eyes to all the considerations that go into developing a project proposal”, while Adam saw the project as “an extremely valuable experience” because it provided him with “an opportunity to develop an applicable, real-world plan for implementing a commercial photovoltaic solar system”. Christian, who had switched to IntE because he found it to be a better fit, appreciated that the “course project gave [him] a very hands-on experience with what solar design will look like in the field, which [he has] found is very rare to come by in school courses”. He also saw the course as helping him to reach his career goal:

*Photovoltaic energy is something that I have been very passionate about for a long time . . . My big picture childhood goal was always to become an electrical engineer and return to our family's construction company. We have never had an engineer on staff, and for me to be the first person to work there with a real engineering degree would be something that would enhance the company's professionalism and performance.*

The students' expressions of their personal development reflected what we observed from their deliverables and informal classroom commentary. As the students had five phases with oral presentation and report deliverables, they received five rounds of feedback and the opportunity to improve each time. Typically, an engineering course might culminate in a single report and/or one presentation; it is uncommon for students to have this many “tries” in a single course. The real-world nature of the project additionally provided opportunities to develop skills with a direct application to the workforce environment, and the students clearly saw and appreciated this opportunity.

### 3.3. Students' Self-Criticisms and Project Shortcomings

#### 3.3.1. Project Aspects Overlooked

Multiple students identified that they should have thought more deeply about the social and environmental costs of their projects. Dane noted that his team “likely spent more effort looking into the advantages than the disadvantages”; he felt their work skewed towards the technical, and regretted not diving more deeply into exploring social impact and context, including potential ties to environmental racism:

*We should have spent more time explaining the social impact and context since the aesthetic is likely the main roadblock of installing the solar PV carport . . . We could have also looked (in more detail) into the impacts that PV manufacturing sites have on residents that live near them (usually tied to environmental racism).*

Lauren similarly noted that “one of the major considerations that [her team] mostly ignored is material sourcing. It is very difficult to analyze a whole supply chain, and so while [the project] solar panels might not directly have a negative impact on the environment or society, they could in an earlier phase”. Peter agreed with the need to include more “environmental and economic considerations that may be unseen”. Lisa expressed that time limitations prevented her team from adequately analyzing the social project elements:

*The social considerations were an aspect of the project that also should have been reflected, but given the time crunch we had, we were forced to use more time to explain the technical, environmental, and economic feasibilities.*

Dalia also expressed the need for her team to delve more deeply into social analyses, and specifically identified the university neighborhood community as an important stakeholder that was left out of the conversation:

*One of the largest and most geographically relevant communities that my team left out of our feasibility conversations is the [neighborhood] community. Located right next to [the university], it would have been very beneficial for our team to work with community members directly instead of speaking on their behalf based on assumptions that we made.*

She further identified the need for community members to be directly included and partnered with, rather than spoken for:

*While we did consider the general environmental impact that our proposed system would have on the community, we didn't interview the community members to learn about their perspectives on our project . . . This is unfortunately a common occurrence in engineering projects, which makes finding ways to work with and alongside the communities most impacted by engineering projects one of the most important responsibilities of sociotechnical engineers . . . working with them to make sure that our project is implemented alongside them instead of 'for them' or 'on their behalf'.*

Madeline broadly stated that “one thing that could have been done better was the process of reaching out to people to find more specific information on our project”.

These lamentations of not focusing enough on the social and environmental aspects of their projects convey an advanced integration of the sociotechnical engineering mindset we had hoped to nurture in the students. It is interesting to note that the students were not focused on needing more technical or economic elements in their projects, which are typically the focus areas in engineering analyses.

### 3.3.2. Unsureness of Findings

The students were notably cautious about, and in some cases not confident in, the accuracy of their technical calculations, analyses, and recommendations to the university. For example, Dane reflected that they should have included “accuracy/tolerance numbers (e.g.,  $\pm 5\%$ ) on [their] calculations, a feature which would help evaluators look critically at [their] proposal”. He also conceded that, “it is likely that our estimates are very rough and could vary heavily”. Several students also expressed hesitancy about accuracy due to the assumptions they had to make. In Adam's words:

*Although we conducted a thorough societal, technical, economic, and environmental feasibility analysis, we cannot say that our calculations are completely accurate because there are many aspects of the project that required us to make assumptions due to the available information.*

He went on to reflect that “consulting with a company that would be tasked with installing and maintaining a system like the one [they] proposed” would have been helpful in checking the team's accuracy/assumptions. Lauren referenced intangibles in her reflection and recognized their importance, despite being nebulous and impossible to quantify:

*We had to make assumptions about what panels and mounting hardware would be used for the new installations, as neither piece of information was specified. Lastly, there are some intangible costs and benefits that we discussed in our economic feasibility report, but that are present throughout the project. These considerations are hard to quantify, but they are still important.*

Marco acknowledged that his team was “unfortunately not able to accurately distinguish if there will be enough space on the roof for our system to be implemented.” Tony expressed that, “We do not completely understand the technical implications of installing this solar project at [the stadium]”. Madeline noted an unfamiliarity with some characteristics of the solar panel her team recommended and thought they should have also explored the inclusion of batteries in the system. Peter also reflected on not having critical information and needing to make “rough estimates”:

*A lot of our uncertainty for the project comes from this shift to the Wellness Center. We do not have enough information on it, and we tried our best to figure out how much power would be needed. We made very rough estimates based on how much larger the pool size is and made more assumptions based on each category.*

While most of the students expressed caution about their findings with respect to the technical project aspects, Tony noted a project shortcoming in not gathering feedback on his team's proposed solar project from multiple stakeholders:

*Our proposal for the main parking structure may have missed the influence that faculty and staff can have on it, but it was because the perspective was done by students.*

We were pleased to hear the students reflect on navigating through the challenging, necessary process of making assumptions and estimates, and understood the discomfort that accompanies this process. Most often, engineering courses use theoretical problem sets, and there is a "correct"—even precise—answer to a given question. This rarely translates to real-world engineering practice, which is rife with unknowns and unwieldy projects that require a practitioner to make sound assumptions and estimates.

#### 3.4. Student Perceptions of Project Broader Impact

Students described the impacts of their projects beyond the immediate, surface-level impact of a solar energy addition to the school. They identified ripple effects: connections spanning out from the university. For example, Charles noted "the opportunity for work [the new solar project would] create outside of school". He also forecasted hidden financial costs and predicted that students would bear the brunt of these costs, stating that, "new construction will potentially charge students more on their tuition expenses". Joseph hoped that if the university invested in the proposed solar projects, there would be broader impacts:

*One of the long term ripple effects this project overall hopefully is that [the university's] administration is more open to listening to students and putting their words into action. . . . [we are a] changemaker university, and we are supposed to be leading the way in terms of social awareness and action, I think we should let students take the lead on these. Hopefully this project serves as a pathway for students to get more involved in campus's (sic) planning and projects.*

Lisa saw broader impacts of pursuing campus sustainability and solar energy in terms of university image and recruitment:

*The prestige of implementing solar energy on campus is good for the University image. We will increase the amount of students and administrators that want to work for the University by having a more sustainable campus.*

Tony thought in terms of the big picture and the university's commitment to reach carbon neutrality:

*I think the primary missed consideration is a greater understanding of how this solar project will help the university reach its Carbon Neutral goal by 2035. One of the most persuasive arguments for any solar system installation on campus will be its ability to improve the university. Whether this is by saving money, improving the school's carbon footprint, marketing the school as more green, or simply becoming a more independent and self-reliant community.*

The benefit of this project is that it was real, presenting a real opportunity to move the needle on campus sustainability. These student comments suggest that they felt this "realness" and identified a greater purpose in their project efforts beyond a grade in the course.

#### 4. Discussion

The pedagogical model we have presented in this paper can be adapted to a wide range of place-based sustainability learning contexts. The key elements of this model include:

1. Partnering with a community to co-identify a local sustainability challenge, such as those relating to waste, water, food, or energy, and a possible solution for students to explore (examples: creating a low-cost aquaponics facility in a food desert parking lot, designing water catchment systems for a water-scarce community, and so on).
2. Guiding students through a five-phase process of analyzing the potential solution through the lenses of (1) social, (2) environmental, (3) economic, and (4) technical perspectives, with the fifth phase integrating all their findings.
3. Facilitating students in presenting their findings to community partners.
4. Prompting students to engage in reflective practices, such as journaling with prompts, as they navigate through the project phases.

These foundational elements can be adapted to fit with a broad range of topics or disciplines and can be scaled in increased or decreased complexity to be appropriate for learners of any age. Additionally, although we implemented this project model over the course of a 14-week semester, it could also be adapted into a much shorter module or a longer multi-course sequence. This model resonates with the call by Nelson and colleagues to achieve the potential of PV technology to help motivate students and to use innovative pedagogies to help students see the relevance of the curriculum [26]. This model is complementary to the model proposed by Gelles and Lord for integrating sociotechnical modules into materials science classes [9] and adds to the literature on sociotechnical integration in engineering curricula [45,55–60].

Overall, the students reflected favorably on this place- and sustainability-based photovoltaic solar energy course and project. They welcomed its sociotechnical structure and, if anything, craved more opportunities to work on social and environmental project components. We were encouraged to see the students reflect on needing more depth in their social and environmental analyses and find it suggestive of an advanced integration of the sociotechnical engineering mindset we had hoped to nurture in the students: a valuing of the “socio”. This contrasts with our findings in previous work with students earlier in the curriculum, in which students focused on the technical and economic rather than the social or environmental [9,47,54].

The students also expressed perceived self-growth in personal development across skills and abilities that would be difficult to cultivate in a traditional classroom setting with only hypothetical, single-answer problem sets. As an example, the students were required to make many assumptions and estimates in order to complete their analyses. They were uncomfortable with the process and unsure of their findings; this is not a skill commonly practiced in the classroom. However, the ability to make sound assumptions and estimates is critical in an engineering practice, which regularly deals with unknowns, intangibles, and unquantifiable aspects that must still be considered in order to create effective, responsible, ethical, and sustainable engineering designs. The importance of these professional skills have been emphasized in the literature [61]. Developing comfort with ambiguity is also one of the important aspects of design thinking and user-centered design [62], which is increasingly critical in modern engineering practice.

The solar projects the students were required to explore for the course were complex, layered, and multidimensional: there was no “right” answer for how the university should proceed with the projects. As instructors, we purposely defined the projects in an open-ended way and did not know ahead of time what the students would come up with at the end. Ultimately, they recommended that the university move forward in investing in each of the solar upgrades/investments that they explored, and they made their case to do so to the university leaders. We hope that the student voices will be considered as the university works to achieve carbon neutrality by 2035 and that this process sets a precedent for student collaboration with sustainability-oriented campus decision making in the future.

## 5. Limitations

This study was limited by the small class size, which was based on a single offering of the course. The small sample size prevented us from being able to consider the impact of demographic factors on the students' perceptions and experiences. Additionally, we taught the course to students who had already chosen an integrated, sociotechnical pathway through engineering and who have had multiple experiences with non-traditional engineering courses. We suspect that piloting the same course and project with students accustomed to traditional, techno-centric, and lecture-heavy engineering courses might garner some student pushback.

## 6. Conclusions

To help educate engineering students to be ethical and effective practitioners, we developed and offered a new upper-division elective on photovoltaic solar energy. Informed by place-based pedagogies and culturally sustaining pedagogies, we designed the course to be relevant to the students' lived experiences by coupling the learning about the technical elements of solar energy with a focus on solar energy projects and sustainability on campus. Prior to running the course, we identified four potential new solar investment/upgrade projects for the university. We divided the class into four teams, with each team assigned to assess the feasibility of a solar project through (1) social, (2) technical, (3) economic, and (4) environmental analyses. Finally, the students integrated their findings and made recommendations to key university stakeholders about how to proceed with solar energy investments on campus. In their reflections, the students commented on the course structure, including valuing the sociotechnical nature. They described takeaways and provided examples of personal development. The students recognized areas in which they and/or the project could be improved. They appreciated the potential broader impact of the projects. This course design could serve as a model for other courses that embrace a place-based mindset.

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