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Case Report

An Introductory Energy Course to Promote Broad Energy Education for Undergraduate Engineering Students

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Abstract: Engineering graduates must be prepared to support our world's need for a clean and sustainable energy future. Complex problems related to energy and sustainability require engineers to consider the broad spectrum of interrelated consequences including human and environmental health, sociopolitical, and economic factors. Teaching engineering students about energy within a societal context, simultaneous with developing technical knowledge and skills, will better prepare them to solve real-world problems. Yet few energy courses that approach energy topics from a human-centered perspective exist within engineering programs. Engineering students enrolled in energy programs often take such courses as supplemental to their course of study. This paper presents an engineering course that approaches energy education from a socio-technical perspective, emphasizing the complex interactions of energy technologies with sustainability dimensions. Course content and learning activities are structured around learning outcomes that require students to gain technical knowledge as well as an understanding of broader energy-related impacts. The course attracts students from a variety of majors and grade levels. A mixed quantitative/qualitative assessment conducted from 2019–2021 indicates successful achievement of course learning outcomes. Students demonstrated significant gains in technical content knowledge as well as the ability to critically address complex sociotechnical issues related to current and future energy systems.

Keywords: education; energy; engineering; socio-technical; sustainability

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1. Introduction

Energy is inarguably one of the most pressing issues faced by humanity in the 21st century, and a reliable and sustainable global energy system will be key to a sustainable future. Worldwide energy consumption is expected to nearly double by 2050, with most of that growth in countries outside of the Organization for Economic Co-operation and Development (OECD) [1] as efforts progress to reduce global disparities in energy access, particularly among the world's most vulnerable populations. Sustainable development requires consistent access to clean, affordable energy to support economic activity, improve national development, and improve human wellbeing [2]. In addition, there is the undeniable link between the energy sector and global climate change—energy-related carbon emissions hit an historic high in 2018, mainly from the carbon-rich fossil fuels that generated nearly 85% of the world's energy [3]. According to a recent report by the International Energy Agency, a key response to global climate change will require drastic changes in the way we produce and consume energy [4]. This includes, among other actions, a massive scale-up of renewable resource technologies to replace fossil fuels. In a letter to The Guardian in 2020 [5], a group of over 100 well known economists urged governments, industries, and institutions of financial power around the world to actively phase out the fossil fuel industry and put an end to the 'carbon economy' within decades. The authors noted that this period in time "creates an opportunity to bring about a better future for ourselves and our children". At the same time, efforts to increase the use of renewable energy resources are impaired by pre-existing and widespread fossil infrastructure, geopolitical factors, and lack of public understanding. This is demonstrated, for example, by the fact that in the last 10 years the U.S. dependency on fossil fuels has dropped just five percentage points, from 83% in 2010 to 78% in 2020 [6]. Research suggests that the relatively slow pace of developing and adopting renewable resource technologies is due less to technical factors than to widespread lack of public support stemming from a combination of social and educational barriers. Such barriers include, for example, the public's inadequate access to appropriate information, general apathy, misunderstanding of external costs associated with fossil fuel resources, and psychological factors such as a general tendency to resist behavioral change [7,8].

These widespread findings pose a call to action for educational institutions at every level to better prepare graduates to tackle the wicked problems related to global energy and climate issues. Energy education crosses many traditional academic boundaries [9], and sustainability requires the development of clean, renewable energy resources with full consideration of economic, social, and environmental limitations [2,9]. Efforts to encourage widespread energy literacy will help students in a range of disciplines engage in decisions and actions that promote a sustainable energy and climate future. We view this opportunity as a chance to develop and promote energy education programs that provide engineering students with a solid technical foundation while also challenging them to explore broader socio-technical issues surrounding our energy systems, including environmental, economic, and socio-political factors.

This paper is part of a special issue entitled "Engineering Education for a Sustainable Energy Future". As described in an earlier paper in this special issue, Hoople and co-authors [10] note that engineering students often struggle to find relevance in the energy-content of their engineering courses, which typically focus on basic fundamentals and curricular-specific aspects of energy extraction, conversion, transmission, and distribution, with little connection to the students' lived experiences. Several energy engineering degrees exist at graduate and undergraduate levels (see [11] for a thorough review), yet most of these programs—especially at the undergraduate level—require students to take basic engineering foundation courses while the broader, contextualized energy content is provided in classes taken from across disciplines. In this paper, we describe and assess an engineering course that introduces students to energy issues from a socio-technical perspective, framing the technical content within a societal context that includes environmental, economic, and socio-political aspects related to energy generation and consumption. The course was developed to complement a minor in Sustainable Energy Systems Engineering. The minor is described to contextualize the course, which is then presented in greater detail. Course learning objectives, content, and pedagogical strategies are described, highlighting a few key teaching and learning activities that are not typical for an engineering course. Results of an assessment to determine student outcomes and overall responsiveness to the course over the last three years, from 2019 through 2021, are presented. The findings illustrate gains that can be achieved in terms of students' technical content knowledge as well as their capacity to address energy issues from a broader, socio-technical perspective.

2. Background

Global energy challenges intersect with several of the 14 Engineering Grand Challenges identified by the National Academy of Engineering [12] as well as the 17 United Nations Sustainable Development Goals established in 2015 [13]. Identifying these goals or challenges, as such, is a way of calling out the need for attention and resources to tackle the world's most significant problems. More than two decades ago, a joint conference on engineering education and training for sustainable development was held by the United Nations Environment Program (UNEP), World Federation of Engineering Organizations (WFEO), World Business Council for Sustainable Development (WBCSD), and the Ecole de

Pont Paris Tech (ENPC). One key outcome of the conference was the acknowledgement that engineering education plays a primary role in equipping engineering graduates with knowledge, competencies, and skills necessary to solve the world's challenges of the 21st century [14].

The WFEO Engineering 2030 Plan [15] further recognizes the critical role of engineers for promoting sustainable development. They include 'Capacity Building for Engineering Education' projects that address the need to develop better standards for engineering education that will support their commitment to advance the UN Sustainable Development Goals, including the need for affordable and clean energy. These best practices include a response to future needs of industry and society as well as appropriate teaching approaches (pedagogies).

The WFEO recently signed an agreement with the International Engineering Alliance (IEA) to work together to promote accreditation and competence assessment in engineering [16]. Engineering graduates from all programs accredited under the IEA Washington Accord are expected to have an understanding of sustainability in the context of engineering practice in their field [17]. In the United States, the Accreditation Board for Engineering and Technology (ABET) recently revised the list of student outcomes to include two criteria that incorporate engineering solutions within a societal/environmental context [18]. ABET Criterion 3.2 requires engineers to be able to "apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors"; and according to ABET Criterion 3.4, they must "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". The incorporation of engineering for sustainable development (ESD) concepts in engineering education is also supported by discipline specific documents such as the American Society of Civil Engineers' code of ethics statements, which include sustainability in the tenets of practice [19].

A strong connection to sustainability is critical for any effective energy education program [20–22], and the inclusion of sustainability-related content in engineering education has occurred over the past decade with a growing number of institutions starting to address shifting needs and expectations of engineering graduates [23–28]. Census data collected in 2012 and 2016 by the National Council for Science and the Environment (NCSE) show a 15% increase over this time period in the number of interdisciplinary environmental, science, and energy (IESE) degrees offered, and a 40% increase in the number of units (departments, divisions, schools, colleges, institutes, or centers) that offer IESE degrees, among the 2327 institutions of higher education (baccalaureate and graduate degree-granting and specialty institutions) in the U.S. [29]. However, only 3% of these interdisciplinary environmental/energy degrees are offered in programs categorized as engineering/technology and environmental sciences. Yet the inclusion of ESD content within existing engineering degree programs is much higher. In a study to benchmark sustainable engineering course activity in the U.S., Murphy et al. found that teaching and research in sustainable engineering are part of the activities of most of the country's top 100 engineering programs [24]. Incorporating ESD content in engineering programs is also becoming more prevalent internationally, although the growth is somewhat slow and fragmented [28,30,31].

While there has been progress to incorporate general sustainability-related content in engineering education, there is less evidence that courses are being developed for engineers that specifically address energy topics in a broader sense. A comprehensive report from the NCSE used the previously mentioned census data to assess trends in energy education programs, specifically, throughout the U.S. [32]. The study considered non-traditional broad energy (NTBE) programs in all disciplines that focused on energy sources other than fossil fuels, hydropower, and nuclear energy, and investigated the extent to which the various programs align with two different learning pathways. Elaborating on the work of Daniel Sarawitz [33], the authors categorized the NTBE programs as either:

- Path 1, focused on science and technology, developing knowledge and skills that lead to technological innovation and advancement; or
- Path 2, focused on critical thinking and decision making, encouraging students to consider ethical, social, political, and economic dimensions of energy issues, to better inform and facilitate energy-related decisions.

Among the broader IESE courses described above [29], the study found that energy-oriented degree programs are the second fastest growing type of program, increasing by 48% and comprising 62% of the IESE growth overall. However, all of that growth was in Path 2 programs, and was primarily in non-technically oriented units. The number of Path 1 programs, which predominate in engineering and technology (76 out of 91 total), was relatively stable from 2012 to 2016. In a review of energy engineering education programs worldwide, Ruiz-Rivas and co-authors found an increasing number of universities offering energy degrees, yet few programs were oriented toward sustainability or aligned with the NTBE characteristics described above [32].

Tramontin and Moodley [22] cite a growing recognition of the need for sustainable development education [34], noting the specific need for a human-centered approach to energy education in higher education, particularly for technical students such as those involved in the construction industry [22,35]. In terms of the NCSE categories, there is a need for broad technology-based energy education programs that incorporate a mix of knowledge development pathways to help prepare engineering professionals for their role in a clean and sustainable energy future. Modern, networked technological systems are inextricably linked with human and natural systems, and their complex problems cannot be addressed in isolation. Likewise, complex problems such as those related to energy and sustainability require students to consider the broad spectrum of interrelated consequences including human and environmental health, sociopolitical, and economic factors [9,36–38]. Teaching engineering students about energy issues in a societal context, simultaneous with developing the depth of their technical knowledge and skills, will better prepare them for engaging in real world problem solving. To that end we can look to effective ESD education, which uses a systems-based approach to integrate multiple perspectives from a socio-technical frame of reference, contextualizing the technical issues within the larger, more complex societal, economic, and environmental challenges [27,39–42].

In addition to approaching energy from a socio-technical standpoint, preparing engineering students to engage in the solution of ESD and energy problems requires a paradigm shift that is also characterized by immersive, collaborative educational strategies that use democratized decision making, creative inquiry, reflection, and iterative learning [26,38,43–47]. These strategies support and engage different types of learners and are widely shown to develop critical thinking, communication, and problem-solving skills, extending beyond knowledge formation to challenge students' values (e.g., through ethical considerations) and behaviors [43,48]. Connecting course content to changing societal situations and allowing for self-selected project topics leverages the interests of each student [47]. Kandpal and Garg, early proponents of energy education in India [38,49], maintained that university-level energy education programs should provide a balance between theory and practical aspects, to develop skills that meet the specific needs of the students. Solutions to the world's energy problems will require engineers who are prepared to collaborate with others and address broader impacts from multiple perspectives, including ethical implications, of technological development.

In summary, there is a growing need for engineering curricula that better prepare engineering students to develop and use their technical expertise within the complex sociotechnical systems of today's world. Education that improves students' energy literacy, in a broader sense, will help them develop an empathetic perspective and the broad skills necessary for tackling energy issues and moving us toward a sustainable energy future.

3. Institutional Context—Sustainable Energy Systems Engineering Minor

It is clear that engineers are among the many types of professionals that need to understand the limits of our present energy systems and lead us to a future in which we can continue to provide reasonable energy resources to maintain or improve human quality of life. Two critical areas in which engineers must contribute to sustainable energy systems include:

(1) Increasing the efficiency of engineered systems so that fewer energy resources are consumed for the same productivity;
(2) Development and sustainable use of alternative energy resources.

Engineers from all disciplines are necessary to develop the technologies for these advances as well as understanding the broader environmental and economic impacts associated with the transitions to a more sustainable energy paradigm.

Given this need for all types of engineers to consider energy systems within the context of their own disciplines, Clarkson University created a minor in Sustainable Energy Systems Engineering (SESE) in 2009 to meet the needs of students from all undergraduate engineering majors. A review paper at that time indicated both the need for this type of program and the scarcity of academic programs covering this challenge [50]. The overall learning outcomes are described below.

Bachelor of Science (BS) graduates with a minor in SESE will be able to:

1. Design sustainable energy systems to meet both supply and demand requirements and constraints
2. Integrate social, environmental, and policy constraints and tradeoffs in engineering systems
3. Analyze and improve energy systems
4. Assess the impact of energy systems on human and natural environments
5. Quantify and interpret the energy flow throughout an entire system
6. Integrate energy constraints into any and all engineering decisions
7. Recognize and determine solutions to energy problems be it technical, social, or political

Based on these learning objectives and a clear need to integrate technical and non-technical aspects of energy systems, a set of courses totaling 21 credits was defined for the minor.

- Thermodynamics (required already for most majors)
- An energy systems class (new)
- An environmental impacts class (Industrial Ecology or Climate Change)
- Energy content within the capstone design class in each major
- A policy-oriented course
- Two energy-related technical electives, at least one of which must include aspects of design of energy systems

The Introduction to Energy Systems class described here was developed to meet the needs of this minor.

4. The Course: Introduction to Energy Systems

Introduction to Energy Systems (ES238) is a sophomore-level survey course that provides students with a broad and general understanding of our energy systems. The course was piloted in 2010 and has been taught as a one-semester course each year since 2011. In addition to being required for students in the SESE minor, ES238 also fulfills specific, defined outcomes associated with the university's "Common Experience" curriculum. The Common Experience curriculum is designed in part to develop students' communication, problem solving, and critical-thinking skills, and for engineering students, an understanding of the social, ethical, and economic implications of an engineer's work. As such, all undergraduate majors of the university are required to complete one technology course as well a range of elective courses with content that intersects with a variety of topics within the Humanities and Social Sciences. ES238 carries the designation of both a Technology and a Science-Technology-Society (S-T-S) course. S-T-S perspectives recognize that technologies are comprised of technical as well as sociocultural and political dimensions.

4.1. Course Design: Learning Outcomes

The Introduction to Energy Systems course enhances the SESE minor by inviting students to take a step back from their keenly technical interests and aspirations, to approach the study of energy systems within a broader context. ES238 introduces students to fundamental energy principles and strives to help students develop an understanding of the U.S. and global energy system, including trends in primary energy resources, conversion, use, and impacts. Ultimately, the students are required to critically analyze sustainability dimensions and goals of energy resources and energy systems to gain a comprehensive understanding of the role of energy in our current and future society. The course was designed around specific course learning outcomes (LO), listed below.

Students who complete the course are expected to develop skills that will enable them to:

LO1. Demonstrate an understanding of the concepts of energy, power and work

LO2. Describe the relative availability, consumption rates and end-uses of various energy resources

LO3. Describe the environmental impacts related to various energy systems

LO4. Perform simplified analysis of renewable and non-renewable energy systems

LO5. Critically analyze issues surrounding energy (consumption, resources, systems) and its impact on our society

LO6. Effectively communicate their analysis of at least one energy system or energy topic in written and oral formats to a range of audiences

LO7. Work effectively with an interdisciplinary, multi-age team to investigate and report on multiple aspects related to an energy topic

The course-level learning outcomes and specific course activities align with a number of the student outcomes included in the ABET accreditation Criterion 3, for preparing graduates of baccalaureate level engineering programs to enter the professional practice of engineering [18]. Specific and relevant ABET outcomes include:

3.3 an ability to communicate effectively with a range of audiences (LO4, LO5, LO6)

3.4 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 (LO3, LO5)

3.5 an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives (LO4, LO7)

3.7 an ability to acquire and apply new knowledge as needed, using appropriate learning strategies. (LO3, LO4, LO5, LO6, LO7)

4.2. Course Structure: Content and Pedagogy

Course topics and activities have varied somewhat over the years, in order to maintain current content in a changing field and in response to student interests and learning styles. Topics generally comprise a mix of basic energy concepts, energy efficiency, conservation, systems analysis, and life cycle analysis, followed by a closer examination of a range of various energy systems. Table 1 provides an example course schedule for a 15-week semester. Additional content and pedagogy-related details, which are provided in the sections that follow, demonstrate our approach for contextualizing the energy content within a socio-technical framework, and our focus on developing skills for understanding how today's energy-related decisions and actions will impact a sustainable energy future.

Table 1. Summary of course topics.

Week	Topic
1	Introduction: Perspectives for a Sustainable Energy Future
2–3	Energy Basics and Energy Systems
4–5	Energy Resources, Energy Consumption
6	Electricity
7–8	Fossil Fuels
9–15	Student-selected topics, which may include: Energy Storage, Solar Energy, Nuclear Power, Wind Energy, Energy from Water, Transportation Energy Technologies, Biological Energy Resources

The first half of the semester (roughly through week 8) focuses on the first three course learning outcomes. Classes are taught mainly by the instructor and are intended to develop a baseline of energy-related knowledge and an understanding of key energy topics. This is important given the diverse background of students enrolled in the course (see below, Section 4.4). The second half, which is organized around a series of topics selected by the students, uses a class format that incorporates a mix of student presentations, site visits, and lectures by visiting professionals as well as the instructor, to address the remaining course learning outcomes. We generally host several guest speakers, both from the faculty at Clarkson as well as from industry, to share their current research interests and technical expertise in related energy topics. We also take advantage of field trip opportunities. In the past, we have visited both large and small hydropower plants, a nearby solar array and wind turbine test site operated by the university (Figure 1), a full-scale wind farm, a wood chip production facility, and a bioenergy plant that combusts wood chips in a cogeneration facility to produce electricity and heat.

Figure 1. Students visit Clarkson University's wind turbine test site in Potsdam, NY.

4.2.1. Establishing a Baseline of Energy Knowledge

The class starts out with an exploration into some of the critical factors that may shape future energy systems, along with an assignment requiring students to reflect on their own energy-related beliefs and priorities. This reflection sets the stage for engaging and thought-provoking classroom discussion, and plants the seed for deeper analyses later in the course when we investigate global energy consumption patterns and the relationships between energy consumption, economic growth, and overall quality of life. Students revisit this written assignment at the end of the course as a way to further reflect on what they have learned throughout the semester. An introductory reading excerpted from energy systems textbooks [51,52] provides background for the assignment and discussion. The reading offers three basic options for transitioning from current to future energy systems, including the *growthist* who assumes a strong relationship between economic growth and energy consumption ("business as usual"); the *peakist* who tempers energy growth because of limited fossil fuel reserves; and the *environmentalist* who maintains that ultimately the environmental impacts (namely climate change) will dictate the need for us to curb global energy consumption behaviors. In simpler terms, these perspectives can all align with a *mainstream* perspective, which seeks to satisfy our growing energy demand with low carbon energy resources, vs. a *deep ecologic* perspective that invites us to consider efforts to reduce overall energy consumption patterns. Although different, each of these approaches intends to bring us toward a sustainable, carbon free energy system, representing examples of weak vs. strong sustainability, respectively.

Following this introspective course introduction, students spend the next two weeks learning about basic energy fundamentals. We start with an electric hot water kettle to model a simple energy system (Figure 2), and to explore energy vs. power concepts and units, the first and second laws of thermodynamics, efficiency calculations, primary vs. secondary energy resources, and ultimately, systems analysis—including the importance of defining the system boundary, inputs, outputs, and energy services.

Figure 2. The electric water kettle—a simple energy system that uses electric energy to provide hot water.

By expanding the boundary of our simple electric hot water kettle energy system beyond the electric outlet to include the primary energy resources and conversion systems that are used to produce the electricity, students learn the importance of considering the full life cycle when analyzing an energy system. We compare the energy flow through a system that heats water with an electric kettle vs. a system that uses natural gas, to demonstrate the loss of energy as it is converted from one form to another and that 'appliance efficiency' can be very different from 'life cycle efficiency' (Figure 3). In addition to energy consumption, a simplified (qualitative) life cycle assessment guides students to explore how environmental and social impacts associated with an energy system are very different when we look beyond the appliance that provides our energy services. A classic example is the comparison of an electric vehicle (EV) with a hydrogen fuel cell vehicle (HFC), whose environmental impacts vary greatly when the system boundaries are expanded beyond the cars themselves to include the source of electricity or hydrogen used to fuel each car [53].

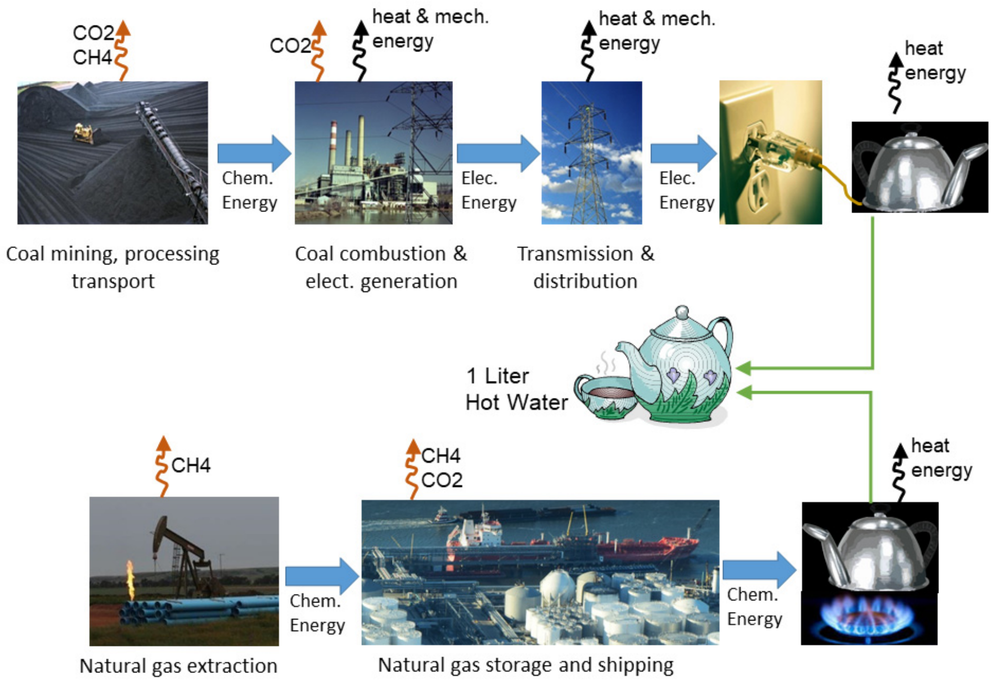

Figure 3. Comparing the life-cycle flow of energy from primary resource to energy service for two different energy systems—one that uses an electric appliance and another that uses a natural gas flame. Although the electric appliance is more efficient than the natural gas stove top (~85% vs. ~35%), the efficiency of natural gas extraction, processing, and transportation is much greater than thermal electric power generation (~91% vs. ~35%), resulting in a much greater lifecycle efficiency for the natural gas system. If our goal is to select the most efficient system for heating water, expanding the system boundary to include the entire life cycle will impact our decision.

The main goal for the unit on energy resources and energy consumption is for students to understand our energy system (i.e., what resources do we use, and what do we use them for?). Important concepts include energy density, energy return on energy investment (EROI), and the applicability of various resources for specific end use applications. Students compare and contrast current, historic trends, and future projections in energy consumption—total and by source—in the U.S. and globally. This provides an opportunity to connect back to their earlier reflections about different approaches for moving into a sustainable energy future and what that might look like for people in different areas of the world.

A key instructional tool used to analyze U.S. energy consumption and to initiate the exploration of linking energy resources to energy consumption is the compilation of U.S. energy flow charts produced by Lawrence Livermore National Laboratory, LLNL [54]. Based on the 'Sankey diagram' first produced by Captain Matthew H.R. Sankey to illustrate the flow of energy through a steam engine [55], these diagrams effectively visualize the flow of any material through a process. The energy flow charts have been produced by LLNL since the mid-1970s to graphically depict quantitative information about energy consumption, tracing the flow of energy from each primary resource to its end use application. Figure 4 shows the Sankey diagram for U.S. energy consumption in 2020. Energy resources are represented with boxes on the left, while the boxes on the right represent end use sectors, and the width of each line is proportional to the amount of energy flowing from each respective resource to end use sector. Students use Sankey diagrams to evaluate the relative amount and type of energy used by each of our end use sectors, which leads to an exploration of how energy is used in the average U.S. household and the growing importance of electricity over time. The other key information shown by the Sankey diagram is the overall efficiency of our U.S. energy system, as demonstrated by the large amounts of rejected, or wasted energy from each sector including electricity generation.

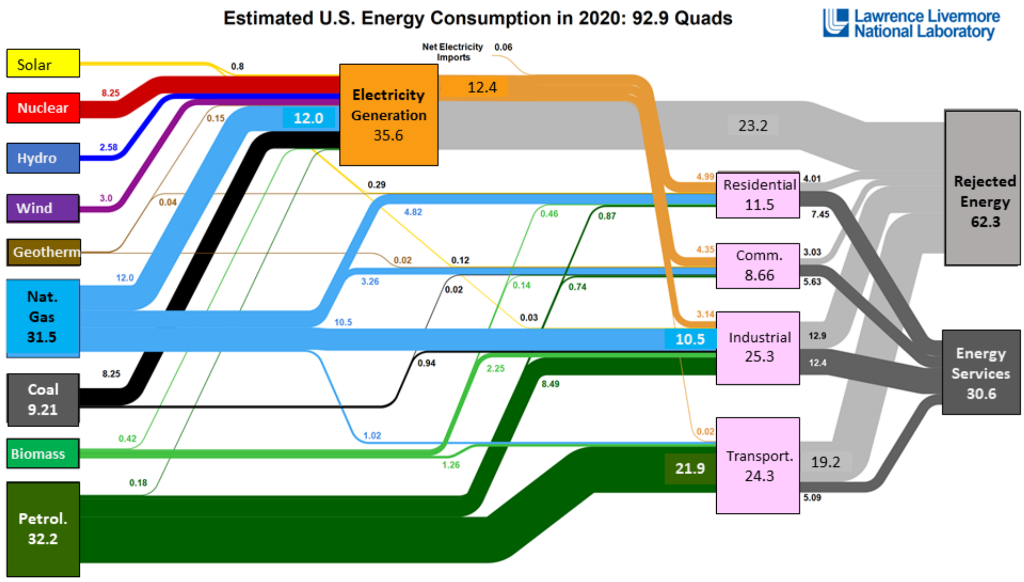

Figure 4. Energy flow chart for the U.S.A. in 2020 [54].

The Sankey diagram provides a convenient segue into the electricity topic. Students trace the flow of energy through a range of power generation facilities, starting with the primary resource and ending with electricity. With the exception of solar PV, the importance of the turbine is evident, as are the similarities among the various steam generating systems and the prevalence of energy loss. Students then assume the role of 'energy analyst' and work through a case study to compare a few different options for a given sized community that needs an electric generating facility. They apply foundational energy knowledge to determine the average electricity demand, required power plant size based on an average capacity factor, and total amount of primary energy resources consumed on an annual basis. A comparison of levelized costs vs. the 'true costs' of each facility requires them to apply what they learned about life cycle assessment and external costs, in a very simplified descriptive analysis. The goal is to critically evaluate various energy resources, looking beyond technical aspects such as size and direct costs and consider social, environmental, and economic factors.

The Sankey diagram also demonstrates the current significant role that fossil fuels play in our energy economy, both in the U.S. and globally. Examining the reserves-to-production ratios helps to emphasize that the timeline for these finite resources is running out. At the same time, the large amount of petroleum used by the transportation sector is supported with growth in nonconventional resources such as oil sands and shale oil. Besides data exploration and discussion, we use a variety of interactive strategies to help students further explore conventional and unconventional fossil fuel resources. For example, students have been assigned to research and prepare brief descriptions about unconventional fossil fuel resources and share this information in a class-wide speed-dating scenario. The activity wraps up with a discussion about tradeoffs in terms of convenience and continued use of existing infrastructure vs. decreased EROI and huge environmental and social costs.

4.2.2. Student-Selected Topics—The Debate Project

An instructor-facilitated debate about the positives and negatives surrounding the use of unconventional fossil fuels provides a model to prepare students for their major class project, referred to as the "Debate Project," which comprises a significant portion of scheduled class time and weighs heavily in the student grade calculations (Section 4.3). This project has been adapted from the Taking Sides® collection developed by what was formerly the Contemporary Learning Series group within the McGraw-Hill Higher Education division, now referred to as "McGraw-Hill Create". The title "Clashing Views in Energy and Society" [56], published in 2009 and currently out of print, was used to establish the framework for the ES238 Debate Project. The present version of the Debate Project ensures that materials and topics are current by requiring students to find appropriate articles from the literature on their topic. Students work in teams to (1) research, (2) teach a class, with a facilitated discussion/debate, and (3) write a paper, all focused on an energy topic that they select. They are required to investigate technical aspects as well as to critically examine the pros/cons related to environmental impacts and economic/social/political issues.

Each team identifies a broad controversial issue related to their topic and selects two reading assignments for the rest of the class (the participants) to prepare them for a class discussion/debate. Participants complete brief summaries of the readings and compile a list of pro/con debate points. Following a presentation by the lead team, students are divided into smaller groups for a discussion/debate facilitated by one lead team member. Significant peer-peer learning occurs, not just between the lead team and the participants but also among the members of the lead team, as each must prepare the rest of their team to facilitate the discussion/debate about the unique aspects of their research.

Student-led classes are scheduled weekly for most of the second half of the semester. For a class that meets bi-weekly (twice/week), this arrangement allows us to focus on one topic per week and use the second class for a field trip, guest speaker, or an additional related activity to round out the learning experience. Generally speaking, the Debate Project, combined with real-life exposure through site visits and guest speakers, provides the most memorable and noteworthy learning experiences for students.

4.3. Course Support Materials and Grading Criteria

Readings assigned from literature and web-based resources from key energy information organizations such as the International Energy Agency (IEA), Energy Information Administration (EIA), U.S. Department of Energy, and the National Renewable Energy Laboratory (NREL) help ensure that students have access to up-to-date information in the rapidly changing world of energy technologies. Nevertheless, we have found that a textbook anchors the course and provides a framework for organizing topics. A number of texts have been used. Most recently, we have used a text published by Imperial College Press called "Energy Studies" [57], which was selected because it includes straightforward introductory chapters about energy fundamentals, resources, and use, and also covers the range of energy resources and conversion systems that we discuss in class, in a comprehensive yet fairly elementary manner. Students are expected to read chapters that correspond to course topics, and to use the text as a resource in preparation for the class discussions/debates. Although students indicated in course evaluations a general dissatisfaction with the text (Section 5.2.1), several students did report that they appreciate it for gaining an overview of the various energy systems and especially for getting a start on their research project.

Student grades are assigned using the grading scheme in Table 2. In addition to the Debate Project work, homework assignments are designed to reinforce key concepts from the readings and class lectures, and to help students prepare for two hour-long exams. The exam questions are based directly on homework assignments and class discussions.

Table 2. Student grade composition.

Activity	Percent of Final Grade
Team-taught Class/Discussion/Debate	35
Participation in Class Discussion/Debate	25
Homework Assignments	10
Exams (2)	30
Total	100

4.4. Course Enrollment

Since it was first piloted in 2010, ES238 has attracted an increasingly diverse group of students beyond those needing it for their minor. Enrolled students range from first year to fourth year (senior) students and come from a variety of engineering and engineering-related disciplines, as shown in the three-year cumulative summary in Figure 5. A total of 102 students enrolled over the three-year period from 2019 to 2021. While enrollment was dominated by mechanical engineering majors (30), a full range of other engineering disciplines was represented. Three students were enrolled in Clarkson's interdisciplinary Engineering and Management program, and five were from majors other than engineering (environmental science and policy, physics, and undeclared majors). Approximately 25% of the total students (24) enrolled over these three semesters were registered for the SESE minor; the remaining students took the class as an elective to fulfill requirements of the university's common curriculum. The grade level distribution was fairly even, over the three-year period as well as for each individual year, allowing for the formation of student teams that were both interdisciplinary and multi-grade-level.

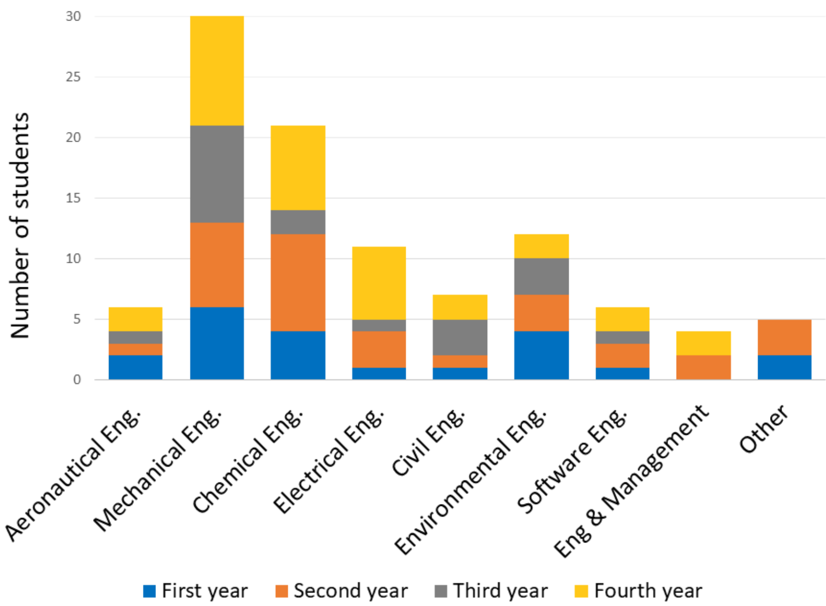

Figure 5. Student enrollment data 2019–2021, by major and grade level.

5. Course Outcomes and Assessment

5.1. Assessment Procedure

We used a combination of quantitative and qualitative approaches to assess the course's impact on student learning and their general responsiveness to the course content and pedagogical approach. University-administered course evaluations provide quantitative feedback and anecdotal comments from students regarding their satisfaction with course content and instructional procedures. The form includes four Likert-type questions directly related to the course content and pedagogy, that use a five-point scale with responses ranging from strongly disagree (1) to strongly agree (5), and one open-ended question soliciting general comments about the course. Another source of feedback consists of informal, anonymous questionnaires created and administered by the instructor toward the end of the course. Students enrolled in 2019 and 2021 were asked to respond to a number of formative questions about the course. (This assessment was not completed during 2020 due to the emergency shift to online teaching in March because of the COVID-19 pandemic.) These questionnaires use a combination of Likert-type and open-ended questions to gather information from the students' point of view about their own learning, the utility of course readings and assignments, and their responsiveness to course projects and other pedagogical approaches. In addition, all 102 students were asked to reflect on the Debate Project by answering two open-ended questions after finishing the project, which provided important insight regarding how the project and course materials helped students achieve the broader course learning outcomes regarding energy issues situated within a socio-technical frame of reference (LO3, LO4, LO5).

Student learning outcomes were also evaluated with items selected from course assessment materials, including student exams and debate project deliverables, as well as a pre/post quantitative questionnaire that included a series of both knowledge-based and attitudinal questions administered in 2020 and 2021. The questionnaire contains 19 energy-knowledge questions adapted from a previous questionnaire developed by the authors [58,59] and described more fully in [10]. Topics include energy fundamentals (six questions), electricity generation (four questions), and energy policy (eight questions). Each knowledge question uses a five-option multiple-choice format with one correct answer. Eight questions about the importance of professional engineering skills, adapted from [60], use a seven-point Likert-type scale ranging from very unimportant (1) to very important (7). Skills addressed include fundamental, technical, business, and professional skills, as well as cultural, ethical, and sociotechnical. The full questionnaire is available by request from the authors. Survey responses were analyzed using the software package R. Average student scores were calculated for each item and by subscale (knowledge, skills), as well as for each of the three knowledge topics. Knowledge scores are reported as the percent correct out of 100; responses to the engineering skills questions are reported as the overall mean value, ranging from 1 to 7. Pre-post mean scores were compared using a paired *t*-test, again by question, topic, and overall subscale.

5.2. Results and Discussion

5.2.1. Student Responsiveness to the Course

Because of the important role that motivation and engagement play in the extent and success of student learning [61], our assessment includes an evaluation of students' overall responsiveness as a measure of their engagement with the material. Students provided feedback on their overall satisfaction with the course content and pedagogy through two types of anonymous surveys: the university-wide course evaluation form and an informal feedback questionnaire administered by the instructor. Despite numerous concerns regarding the effectiveness and utility of formal course evaluations (see for example [62,63]), we chose to include them as one component of the overall assessment plan, and to use the questions that related to the course rather than those related to the instructor. There has been evidence that students' ratings of their instructor on these course evaluation forms are sometimes correlated to the instructor's grading policies (i.e., easy graders get higher ratings), and worse, that students may report false information as a way of retaliating for a bad personal experience they may have had [63]. Still, students do tend to use course evaluations to express their feelings and reactions to their learning experiences, and although they should not be the only form of evaluation, course evaluations can contribute to our understanding of the students' overall impression of the course. In all, 62 students (response rate of 61%) completed the online course evaluations over the three-year period. Responses (Table 3) indicate that overall students were most satisfied with the degree to which participation (93% of students responded that they agreed or strongly agreed) and questions (88% responded that they agreed or strongly agreed) were encouraged by the format of the class. Students expressed less satisfaction with some of the learning aids: 68% responded that they agreed or strongly agreed that the text/course materials, and 69% that the assignments/homework, were useful.

Comments related to the overall quality of the course were generally positive (22 out of 28 in all). Sixteen comments specifically referred to the interesting content and breadth of material, often responding positively to the socio-technical context, though not in those exact words. For example: "The course was very good at covering a lot of different systems and information in such a short amount of time . . . " and "This course is a very good introduction to the various processes that power not only our country but our world.

It manages to cover energy predicaments from many scales, from single digesters and combustion systems to the generation of power for the United States' entire grid". Students expressed positive feedback about the engaging debate format, field trips, and guest speakers. There was also some degree of frustration, however. Among the six negative comments were complaints about too much work (2), frustration about learning from other students instead of the instructor (4), as well as gaining superficial knowledge about a range of topics but true depth of knowledge in only the topic their group studied (2).

Table 3. Selected Items from Course Evaluations.

Item [1]	Overall Mean Score [2]
The instructor makes students feel free to ask questions.	4.4
The instructor encourages class participation.	4.4
The text and course materials were useful learning aids.	3.7
The assignments and homework were useful learning aids.	3.9

[1] Out of 14 questions in all, these four most directly related to the course content, learning supports, and pedagogy (inferred by instructor's encouragement to participate and ask questions). [2] Mean scores are calculated based on a range of 1 (strongly disagree) to 5 (strongly agree), for a total of 62 student responses. Descriptive statistics are not reported because raw data are not available.

The informal, anonymous instructor-prepared questionnaires provide a more in-depth look at student reactions to course content and pedagogy and corroborate, to some extent, the course evaluations as well as the degree to which students are achieving broader course learning outcomes. These were administered in 2019 and 2021 (not administered 2020 due to the COVID-19 pandemic), with a total of 57 respondents over the two semesters. Although there was a similarly negative reaction to the usefulness of the textbook (70% agreed or strongly agreed that it was useful), 96% of the students surveyed agreed or strongly agreed that they learned a lot from the readings that were assigned prior to the debates, a question that was not well articulated in the university-wide course evaluation form. Students also valued exposure to professionals and nearby energy facilities, with 95% agreeing or strongly agreeing that these were a valuable component to the course. In response to an open-ended question asking what students 'liked best' about the course, guest speakers and/or field trips were most frequently indicated (22 out of 55). This aligns with previous findings; studies have found these opportunities for first-hand exposure to not only be enjoyable, but also effective learning experiences that enhance interest and motivation toward lifelong learning (e.g., [64–66]). The second most frequent 'liked best' response was student presentations and debates (18), with the remaining responses (15) related more generally to overall structure/pace of the class and the breadth of content, similar to what was found in the course evaluation comments and indicating an appreciation for the socio-technical approach. For example, "I really enjoyed learning about different types of energy production and how they are utilized in today's world".

Student receptiveness to the Debate Project was gauged with two reflection questions administered to all students after finishing the project, shedding light on specific positive ("What did you like best about the project?") and negative aspects ("How do you think this project could be improved?"). Among the 84 forms received, students overwhelmingly mentioned the positive experience of learning more in depth about a topic they were able to select; others mentioned that they enjoyed the process of working with a group and putting together the entire presentation and class. Other students reflected on the project overall, noting that they found the format of debates/discussions an engaging way to learn. Most relevant to the goals of this paper are the comments that indicated an appreciation of the socio-technical approach—23% (19 students) mentioned that they appreciated learning about a broad range of energy systems, and 26% (22 students) wrote that they appreciated hearing different perspectives and being forced to consider both the positive and negative sides to different systems. In terms of opportunities to improve the project, aside from the inevitable complaints about group structure and workload, the large majority of comments focused on the overall organization of the project. Many students had difficulty managing their time and keeping track of deliverables, a finding not uncommon for project-based learning or learner-led education efforts. According to Iversen et al. [67], a key difference among student responses and capabilities of maximizing the learning opportunities afforded by active learning approaches is their self-efficacy, or sense of confidence in being able to accomplish the task. Students with lower self-effiacy need more support and pushes from the facilitator/instructor to guide them to a successful completion without feeling as many time management stresses. In response to this issue, attempts are made each year to simplify the project, and changes over time in student survey responses give some evidence for improvement. When asked to complete this statement: "This is how I feel about the debate project:" students' responses in 2019 were a blend of positive (9), negative (11, mostly concerned with overall structure and organization), and mixed comments (8, e.g., a lot of work but overall helpful). In 2021, however, most comments were positive (19), with still some mixed (6), and no negative responses. Several of the mixed comments referred to issues with group dynamics, a problem exacerbated by the fact that some students were attending the course online, as demonstrated by the following comment: "I would have liked the Debate project better if it was in person and if I had more of an open line of communication with my team".

In summary, students' responses to the course were generally positive: they found the pedagogical format engaging and appreciated the range of content covered and the socio-technical context. Most valuable to them were the guest speakers and field trips, and the interactive nature of the debate project, as indicated by the following comments:

> *I feel that this was the most productive section of the course for me. I think this is true primarily because I felt a strong sense of accountability to someone other than myself.*
>
> *I really liked the debate project. It definitely helped that I as already interested in my topic but I still learned way more than I originally anticipated.*
>
> *I enjoyed having to research the positives and negatives associated with an energy resource since it is a pivotal time in our lives that we need to lean off Fossil Fuels. There is not 1 key solution but understanding all the major energy sources can help people create informed decisions.*

5.2.2. Student Learning Outcomes, Technical Content

Active learning pedagogies such as those employed in this class have been widely shown to improve students' engagement, knowledge retention, critical thinking, and problem-solving skills, commonly referred to as '21st Century Skills' [68]. Mills and Treagust [69] cite a number of studies that show the overall benefits of using class projects in engineering education that also align with 21st century skills, including the development of autonomy, adaptability, and time management, teamwork, and communication skills. According to Chickering and Gamson, learning is enhanced when students have the opportunity to "talk about what they are learning, write about it, relate it to past experiences, apply it to their daily lives, and make what they learn part of themselves" [70] (p. 5). Nevertheless, this style of teaching and learning takes time, and comes at the expense of 'covering more' in terms of content [71]. Furthermore, approaching energy topics from a broad perspective that incorporates sociopolitical and environmental aspects can exacerbate those challenges, particularly with respect to developing technical content knowledge. Despite these challenges, our results indicate that students did, overall, learn technical content, as demonstrated by the significant pre/post increase in their scores on the energy knowledge questionnaire (Figure 6 and Table 4).

Student scores increased on average by eight percentage points ($\sigma = 11$), determined to be significant using a paired t-test ($t = 5.4$, $p < 0.001$, 95% confidence interval on the difference of means [4.9–10.6]). Scores were analyzed for the three separate categories of questions described earlier, with details shown in Table 4. Post-scores were highest in the energy fundamentals and energy generation topics, although student scores increased significantly across all three topics. Student gains were highest on questions related to the energy resource mix, for the U.S. and for New York State. For example, by the end of the course, 86% of students identified wind as the most prevalent renewable resource used to produce electricity in the U.S. (up from 61% on the pre-test) and 56% identified petroleum as the resource that provided most of the energy used in the U.S. (up from 36% on the pre-test).

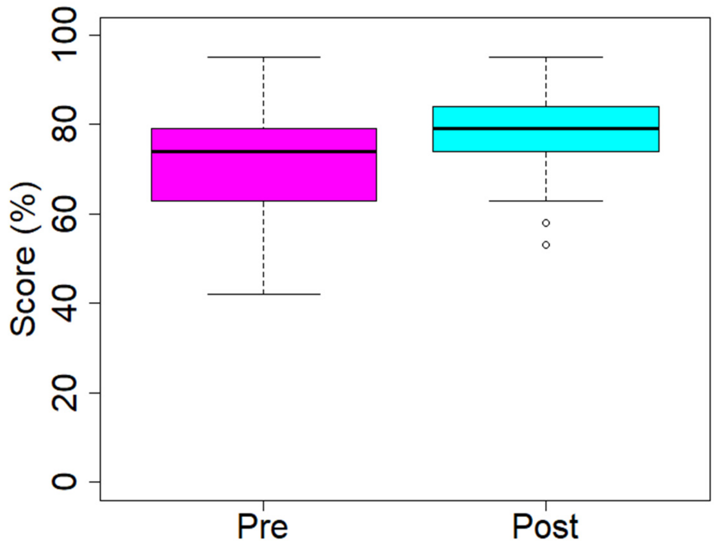

Figure 6. A box and whisker plot showing student improvement on the knowledge questions in the pre/post energy questionnaire for 2020 and 2021. Student scores increased eight percentage points, from a pre-mean of 71% (median 75%) to a post-mean-score of 79% (median 84%).

Table 4. Summary of pre-post results, Energy Knowledge Questionnaire.

Questionnaire Category	Score (%)		Gain	*p*-Value [1]
	Pre	Post		
Overall Score	71	79	8 ± 11	< 0.001
Energy Fundamentals	83	89	6	0.02
Energy Generation	69	79	10	0.05
Policy	63	70	7	0.007

[1] Matched *t*-test, n = 57 (questionnaire was administered 2020 and 2021).

Technical content knowledge was also assessed with the midterm exam, administered roughly halfway through the semester. Student grades on the midterm exam were quite high, with an average of 80.4% (n = 96, standard deviation = 14.9) over the three-year period. Although the use of students' course grades to assess course learning outcomes can be controversial because of variable standards [72,73], there is general agreement among the educational research community that student grades are an adequate reflection of their knowledge, skills, and competencies [74], at least with respect to the instruments' assessment criteria. The midterm exam contains a combination of discussion questions and calculation problems designed to assess the first three course learning outcomes. Qualitative discussion questions, which are typically about 20% of the total exam grade, require students to describe and discuss in general terms such energy topics as trends in energy consumption patterns, microgrid and smart grid technologies, and the overall procedure for sizing and conducting a life cycle analysis to determine the best choice of an electric generating facility for a particular community among a list of alternatives. The remaining 80% of the exam is comprised of quantitative calculation problems that cover such topics as efficiency, energy density, energy return on energy investment (EROI), and relating primary energy consumption to a particular end use application. Specific exam problems can be requested from the authors.

5.2.3. Student Learning Outcomes, Broad Socio-Technical Issues

The course learning outcomes reflect a broad range of knowledge and skills that we have argued are necessary for preparing students to adequately tackle global energy challenges. The broader outcomes (LO3 through LO7) align with the 21st century skills described earlier [66]. Our additional focus on energy and sustainability reflects the need to develop students' skills to critically analyze energy resources in the context of socio-political, economic, and environmental parameters. These broader outcomes are assessed with the following measures:

- Selected questions from the final exam
- Student grades on the Debate Project
- Selected questions from the pre/post energy questionnaire
- Student feedback on instructor-prepared questionnaires

Comprehensive final exams administered at the end of the course were largely focused on broader student outcomes. Because the exams were optional, we were not able to capture data from all students. Two types of questions are especially helpful for providing more specific insight into student learning and skill development. One type of question, utilized in 2020 and 2021 (n = 46), required students to read and interpret graphical data and explain socio-technical factors impacting the observed trends in energy production over time. For example, students were asked to describe the underlying reasons for and socioeconomic impacts related to the rise in natural gas production in the U.S. in the 1990's (development of hydraulic fracturing). They were similarly asked to respond to a graph showing the recent upward trend in petroleum production in Canada and Venezuela (oil sands development in ~2003 and ~2010, respectively). The second type of question asked students to compare and contrast various energy resource systems, using a socio-technical perspective that considered environmental, socio-political, and economic factors. This category of questions was used in all three years (n = 79). Results, shown in Table 5, indicate that students performed well on the exam overall as well as on each of the specific critical-thinking question categories. Students did exceptionally well in comparing and contrasting various energy resource systems, with an overall average of 83.9%. This is likely due to the extensive practice they gained preparing for and arguing the positive and negative aspects of various topics in the class debates. Student grades on the graph interpretation questions were lower, but still quite high at an average of 80.9%.

Table 5. Student scores on graded material—final exam and Debate Project.

Graded Material	Mean Score ± Stand. Dev.
Final Exam, overall	81.7 ± 11.4
Data/Graph interpretation—Socio-technical factors related to energy production	80.9 ± 19.9
Compare/contrast energy systems	85.4 ± 14.2
Debate Project—Group project	88.1 ± 6.9
Individual debate preparation/participation/reflection	90.8 ± 12.1

Although student exam scores are helpful, the primary evidence for broader student learning outcomes is provided by student performance evaluations from the Debate Project, which requires students to critically examine the benefits and drawbacks of various energy systems from a socio-technical frame of reference and then to communicate their findings, both orally and in writing. Student grades on the Debate Project (Table 5) were higher than exam grades, with an overall average of 88.1% and 90.8% for the group project and individual debate preparation/participation/reflections, respectively. Student work was evaluated with a variety of rubrics adapted for each project component, with a focus on the degree to which students have (1) incorporated sound, literature-based information, and (2) addressed social, economic, political, and environmental factors related to the energy topic or energy system in question. The individual debate participation assignments require students to extract critical information from assigned readings in preparation for an oral debate, and then to reflect in writing on how the class conversation and debate impacted their understanding of and views regarding the energy topic or energy system in question. The major components of the group project include the class presentation and written technical report. Both must contain a technical overview of their topic as well as a description of the relevant environmental and social/economic/political aspects, and both are evaluated in terms of the degree to which (1) the content is complete and supported with literature and (2) the information is clearly communicated –the oral presentation as well as the written report. These relatively high grades indicate that, overall, the Debate Project is achieving the desired results, in terms of students' broader learning outcomes.

Two questions from the pre/post energy questionnaire corroborate these positive findings. Student scores on a knowledge question requiring them to recognize that "living in a country with large amounts of fossil fuel resources does not equate directly with having a high standard of living" increased 10 percentage points, from 42% (pre) to 53% (post), a substantial change but not statistically significant ($t = 1.4$, $p = 0.16$). The skills portion of the pre/post energy questionnaire required students to assess the importance of eight professional engineering skills including fundamental, technical, business, and professional skills, as well as cultural awareness, ethics, societal context, and volunteerism. Students showed a measurable increase in their appreciation for the importance of only one: societal context skills, i.e., how the engineers' work connects to society and vice versa, with the average mean response increasing from 5.7, pre, to 6.2, post, on a scale ranging from 1 (very unimportant) to 7 (very important) ($t = 2.7$, $p = 0.01$, 95% confidence interval on the difference). There was no significant change in students' appreciation of any of the other engineering skills listed. This suggests that teaching technical energy content within a broader socio-technical context helps students recognize the importance of considering engineering solutions within this broader context.

In addition to these quantitative measures, one of the open-ended reflection questions administered to students after finishing the project provides anecdotal data supporting the degree to which the project in particular helped students achieve the broader course learning outcomes and appreciation for learning about energy issues situated in a socio-technical context. Students were asked to describe the most valuable aspect of the project. The vast majority of students expressed the value of learning in depth the positive and negative aspects associated with an energy topic that they were interested in, as well as learning to critically analyze and discuss a range of energy issues in general. For example, one student noted that he " ... liked diving deep into the controversies surrounding ethanol as an energy source". Another student, whose group investigated hydropower, described the value of learning about the socio-political implications of the Grand Ethiopian Renaissance Dam [75]: "I was very intrigued by the political tensions caused across borders regarding water". This additional quote further emphasizes the project's positive impacts:

> *This project helped me to understand the processes that come with the retrieval, processing, combustion, and emissions of various fossil fuels. I really had to do some critical thinking about how the future of energy looks and learned a lot along the way about not only fossil fuels but also all kinds of renewable sources and their relative usefulness in the future.*

Taken as a whole, results from the combination of assessment strategies indicate that students are, by and large, achieving the goals established by the course learning outcomes. These include technical content knowledge (LO1, LO2, and LO3) and a broader understanding of the complex socio-technical issues related to energy systems (LO3, LO4, and LO5), as well as communication (LO6) and teamwork (LO7) skills. The active learning pedagogies and group projects employed in this course are known to enhance student learning and retention, critical thinking, real-world problem abilities, and other important 21st century skills [68,69,76–78], all of which are important for preparing students to collaborate with others in careers where they can help solve global problems. In addition, the course has modeled effective practices for ESD education, using a systems-based approach and contextualizing technical issues within larger, more complex societal, economic, and environmental challenges [40–42]. Like the integrated engineering course presented by Hoople et al. [10], this broad energy course is preparing engineering students to tackle complex challenges related to energy and sustainability. These findings indicate that a course such as the one presented here can offer an effective response to the need for improved energy engineering curricula for a sustainable energy future (e.g., [11,22,35]).

6. Conclusions

In this paper we have presented a broad energy course for engineering students that is required for students minoring in Sustainable Energy Systems Engineering. The course approaches energy topics from a socio-technical perspective, incorporating a mix of knowledge development pathways that include both a strong technical component as well as interactive pedagogies that encourage students to engage in discourse and require them to critically analyze sustainability dimensions and goals of energy resources and energy systems. Results collected over three years using a mixed-methods assessment plan show positive findings, in terms of broad student learning outcomes and their general receptiveness to the course. Students especially appreciate the active teaching and learning style afforded by the structured class debates, the opportunities to visit energy facilities and hear from energy professionals, and the broad range of course content. Students are required to explore energy issues in a broad socio-technical context, focusing not just on the technical aspects but also taking a wider perspective in order to discuss and reflect on the pros and cons related to various energy resources in terms of real-world situations. A combination of student grades, responses to open-ended reflection questions, and questionnaire responses indicate that students have gained an understanding of the complex ways in which our energy systems, and sustainable solutions to our energy problems, intersect with environmental, economic, and socio-political factors.

Issues related to energy, the environment, and climate change are among the most pressing problems that will be faced by our engineering graduates. Preparing students to successfully contribute toward solving such wicked problems will require more than a strong foundation of technical knowledge. Equally importantly, they will need to develop skills that enable them to collaborate with others and critically analyze the complex interactions of technology with the natural and social systems in which they are used. Our findings have shown that technical students are receptive to a course that approaches the study of technology from a socio-technical perspective. Students appreciate the need for engineers to consider socio-political, economic, and environmental dimensions as they develop solutions to complex technical problems, and appear to be gaining the skills to do so.

It should be noted that the findings presented here are limited to this one case study: one energy course taught to engineering students at one university over a three-year period. As such, the results are not generalizable. The course, however, is ongoing. Future work will probe the course's impact on students' perceptions of their future role as an engineering professional, and their ability to contribute toward developing a sustainable energy future.

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