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A Thermodynamics Design Project that Applies Theory, Explores Renewable Energy Topics, and Considers the Economic and Social Impacts of the Designs

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Abstract

Thermodynamics courses introduce theoretical concepts that can be applied to real-world problems using impactful project-based learning (PBL). Entrepreneurially minded learning (EML) can augment PBL by instilling an entrepreneurial mindset (EM), categorized by curiosity, making connections, and creating value, in the students. This paper describes a group project created for an introductory thermal sciences course that incorporates PBL and EML. Groups were tasked with designing a natural gas power plant using the Rankine cycle and a renewable energy portfolio, both of which were required to meet University of San Diego's energy demands. Each group had to recommend and justify one of their energy plans to the university's Board of Trustees. The project was broken into five tasks, and a technical report was due at the semester's end. In-class sessions were devoted to the project roll out, guided background research, and power plant design. Some assigned project work was aligned with lecture material (e.g., Rankine cycle) to replace the traditional homework assignment associated with that topic.

The project was designed to apply the first and second laws of thermodynamics and cycle analysis to a realistic open-ended problem, explore renewable energy topics, and to incorporate EML by posing the problem in such a way to create curiosity about the potential solutions, make connections between the technical designs and the broader impact those designs have from economic, environmental, and social points of view, and to motivate the students to create value for the university. A secondary objective was to improve the students' written communication and information literacy skills. While the project was designed to meet both skillset and mindset objectives, the inclusion and assessment of the EM component was the focus of this study.

Direct assessment of seven specific EM student outcomes was performed on the submitted group work from a section of the class taught in spring 2020. Rubrics with four performance levels for each student outcome were created. A majority of the groups were proficient or exemplary in six of the EM student outcomes assessed, and all of the groups were proficient or exemplary in two. Additionally, the project was qualitatively assessed using student feedback and instructor reflections. Preliminary results indicate the project successfully met the stated PBL and EML goals. Future work will be focused on individualizing the EM assessment process and developing a baseline for comparison to determine the effectiveness of the project at meeting the stated skillset-based course outcomes.

Introduction

In problem-based learning, students are presented with an authentic and ill-structured problem prior to learning, which then requires creative and critical thinking [1], [2]. The knowledge obtained through the authentic contexts used in problem-based learning is more meaningful and transferable, and is retained better [1]. Collaborative project-based learning (PBL) expands upon problem-based learning by requiring self-directed learning, communication, and teamwork [3], skills employers desire but that have been found to be lacking in recent graduates. A survey by the Association of American Colleges & Universities (AACU) found that employers prioritize written communication, teamwork skills, critical thinking, and information literacy [4]. Students consistently rated their preparedness in all skills much higher than employers did, with the largest gaps in critical thinking, written communication, and locating, organizing, and evaluating information (i.e., information literacy) [4]. While PBL is successful at producing the skill-based outcomes described above, it does not necessarily result in the mindset-based outcomes required of the innovative engineers of the future [5], [6]. The goal of entrepreneurially minded learning (EML) is to prepare students to identify problems and solve them in innovative ways [7]. The entrepreneurial mindset (EM) as defined by the Kern Entrepreneurship Education Network (KEEN) is categorized by curiosity (e.g., creating innovative solutions by looking at the broader world and toward the future), making connections (e.g., integrating knowledge from multiple sources), and creating value (e.g., understanding stakeholders and seeking opportunity) [8].

This paper describes a group project created for an introductory thermal sciences course taken by second-year engineering students at University of San Diego. A significant amount of theoretical content is covered in the course, and typical example and homework problems have fairly weak connections to real-world problems. Because concepts presented without contextualization or application have little meaning to students [9], the project was developed to provide a meaningful student-centered learning experience, which has been shown to better anchor knowledge and improve concept retention [1], [10]. This work was also motivated by the need to create a fully defined project package that can be used by all faculty teaching the course, including adjuncts. In this way, EM can be introduced to a significant portion of the engineering student body fairly early in their university tenure.

The course learning outcomes state that after taking the class, a student should be able to:

a. Formulate and solve thermodynamics problems using the first and second laws of thermodynamics.
b. Determine thermodynamic properties from steam tables.
c. Apply the system approach and control volume analysis to thermal science problems.
d. Solve fluid mechanics problems using the continuity, momentum, and energy equations in the control volume formulation.
e. Solve flow problems in pipes and around submerged bodies in a fluid.
f. Solve basic heat transfer problems involving conduction, convection, or radiation.
g. Approach and solve an open-ended design problem in a small group.
h. Draw connections between theoretical concepts of thermodynamics and contemporary energy issues.

The groups were tasked with designing two energy plans for the university and had to recommend and justify one of the energy plans to the university's Board of Trustees at the end of the project. The project was designed to have the groups apply the first and second laws of thermodynamics and cycle analysis to a realistic open-ended problem (course outcomes a, b, c, and g), to explore contemporary energy topics that are not contained in the textbook (course outcome h), and to incorporate EML by posing the problem in such a way to create curiosity about the potential solutions, make connections between the technical designs and the broader impact those designs have from economic, environmental, and social points of view, and to motivate the students to create value for the university. A secondary objective was to improve the students' written communication and information literacy skills, which are often overlooked in the theory-heavy second- and third-year courses. While the project was designed to meet the skillset objectives described above, course outcomes a, b, c, and h were directly assessed individually with other coursework. The inclusion and direct assessment of the EM component was the main focus of this study. Additionally, the project was qualitatively assessed using student feedback and instructor reflections.

Project Description

The context for the project was providing the energy needed by the university from traditional and renewable energy sources. One of the core values of University of San Diego is caring for the environment, and a number of sustainability initiatives have been implemented on campus in recent years. The groups were tasked with designing two very different energy plans for the university: a natural gas power plant using the Rankine cycle and a renewable energy portfolio. Both designs were required to meet the university's annual energy needs and peak power requirements. At the end of the project, the groups had to recommend one of the two energy plans to the university's Board of Trustees and justify their recommended plan by assessing both designs from technical and non-technical perspectives, taking into account economic, environmental, and social factors. The groups were told that a natural gas company would donate the natural gas power plant to the university in exchange for a named building on campus, while the university would have to pay for the renewable energy portfolio. The problem statement was worded this way to make the natural gas power plant economically appealing in the short-term, so that neither solution would seem obviously better than the other, and that there would be a variety of pros and cons to each solution.

The project was implemented in the one section of the class that was offered in spring 2020. The project was introduced one-third of the way through a 15-week semester (after the first midterm, which provided a natural break point in the lecture content) and was completed on the last day of the semester. There was a break in the project about 10 weeks into the semester to allow the students to focus on the second midterm. The overall scope of the project was fairly large, so it was broken into five discrete assignments of one to two week durations, each with their own deliverable – typically a portion of the technical report in rough draft form. Individual task descriptions, duration, and deliverables are described in Table 1. Most of the project assignments were done in parallel with typical individual class work (lectures, homework, and midterm exams). The exception to this was Task 4, designing the natural gas power plant using a Rankine cycle with irreversibilities, which was assigned the week the material was covered in class. Task 4 replaced the traditional homework assignment associated with that topic. Detailed feedback was given to the groups after each task was submitted to allow the groups time to process and incorporate the feedback before the final technical report was due. Feedback was given on both the technical content as well as the quality of the writing in the rough draft. Revising technical writing is an important facet of developing strong written communication skills [3].

Table 1. The project was broken into a number of discrete tasks, each with their own deliverable.

Task	Duration	In-class Component	Description	Deliverable
1	One week	Yes	Analyze a spreadsheet of university energy usage and cost over the past five fiscal years to determine the university's energy and peak power requirements	Short write-up summarizing findings
2	One week	Yes	Research renewable energy technology and natural gas power plants; perform stakeholder interviews to determine impact of both to the university's brand	Outline of background research (rough draft)
3	Two weeks	No	Design a renewable energy portfolio to meet the university's energy and power needs; estimate costs (short- and long-term) and environmental impact	Write-up detailing the renewable energy portfolio (rough draft)
4	One week	Yes	Design a natural gas power plant using the Rankine cycle; estimate fuel and maintenance costs and environmental impact	Write-up detailing the natural gas power plant design (rough draft)
5	One week	No	Recommend one energy plan and write the final technical report	Technical report (final draft)

Three class sessions were devoted to the project to provide support and real-time feedback to the groups. The first session was used to introduce the project and assign the first project task, which was to determine the university's annual energy and peak power requirements. To generate excitement and raise the stakes, the class met on the rooftop of a building on which solar panels were already installed. The university's Director of Sustainability was on hand to provide information about the university's energy usage and answer any student questions. One week later, a class session was used to begin the second project task, part of which was to perform background research on renewable energy and natural gas power plant technologies. The university's STEM librarian attended the lecture to demonstrate how to search academic databases to find reliable information. The STEM librarian then worked with each group to answer questions and help with their initial searches. Devoting this in-class time to background research was important for modeling the information literacy skills the groups were expected to practice. The third class session was used to begin the fourth project task, which was to design the natural gas power plant using the Rankine cycle. This session was scheduled after the more traditional lecture sessions in which the Rankine cycle was introduced and studied. In-class time was provided for this task because of its open-ended nature (i.e., groups had to choose operating pressures and temperatures to produce the net power required). This inverse problem was more challenging for students and potential solutions could be discussed with the instructor. The instructor also provided guidance and context on industry-standard power plant operating conditions.

Assessment of EM

While it is difficult to assess mindset, the expanded KEEN student outcomes (eKSOs) developed by Ohio Northern University identify approximately ten specific and measurable student outcomes within each EM category [11]. In this work, several student outcomes from each of the three mindset categories were used to assess EM in the project reports, and are shown in Table 2.

Table 2. EM student outcomes used for the project, taken from the list of eKSOs [11].

Mindset	**Student Outcome**
Curiosity	Recognize and explore knowledge gaps
	Collect feedback from many stakeholders
	Explore multiple solution paths
Connections	Understand ramifications (technical and non-technical) of design decisions
	Persuade why a discovery adds value from multiple perspectives (technological, societal, financial, environmental, etc.)
Creating value	Create solutions that meet customer needs
	Engage with actions with the understanding that they have the potential to lead to both gains and losses

Direct assessment of student outcomes can be performed using rubrics, which can help objectify the assessment [12], [13]. For each of the eKSOs used to assess EM in this project, a rubric with four performance levels was used. The performance levels were "does not meet expectations," "developing," "proficient," or "exemplary." The rubrics for each student outcome are shown in Table 3. Some rubric content was adapted from 2011 rubrics created to assess a previous version of the KEEN learning outcomes, which have since been modified [12]. Assessment results of all seven student outcomes addressed by the project are shown in Figure 1. The class was taken by 32 students and they were asked to organize into groups of four. Because the assessments were made on work submitted by the eight groups (there were no individual student project artifacts), the results presented here provide very preliminary and general trends.

Table 3. Rubrics for each of the EM student outcomes assessed.

Student Outcome	**Does not meet Expectations**	**Developing**	**Proficient**	**Exemplary**
(1) Recognize and explore knowledge gaps	Minimal search, selection, or source evaluation skills	Adequate search and selection of information sources, but evaluation of sources is not adequate	Adequate search, selection, and evaluation of information sources	Proficient + Ability to identify uniquely salient information sources
(2) Collect feedback from many stakeholders	Fails to collect stakeholder feedback	Collects minimal stakeholder feedback	Collects adequate stakeholder feedback	Collects detailed feedback from all stakeholders
(3) Explore multiple solution paths	Does not come up with feasible solutions	Effort to minimally explore solutions	Explores several solutions	Explores many solutions, and produces original and relevant solutions
(4) Understand ramifications of design decisions	No ramifications addressed	Minimal ramifications addressed	Several ramifications addressed, but missing key areas	Majority of the ramifications addressed
(5) Persuade why a discovery adds value from multiple perspectives	No persuasion evident	Persuade from one perspective	Persuade from several perspectives	Persuade from majority of perspectives
(6) Create solutions that meet customer needs	Customer needs not identified	Customer needs are identified but not met	Customer needs are identified and met	Solution exceeds customer needs
(7) Engage with actions with the understanding that they have the potential to lead to both gains and losses	No discussion of solutions' potential gains and losses	Minimal discussion of solutions' potential gains and losses	Discusses solutions' potential gains and losses, may miss some points or have shallow reasoning	Thoroughly discusses potential solutions' gains and losses

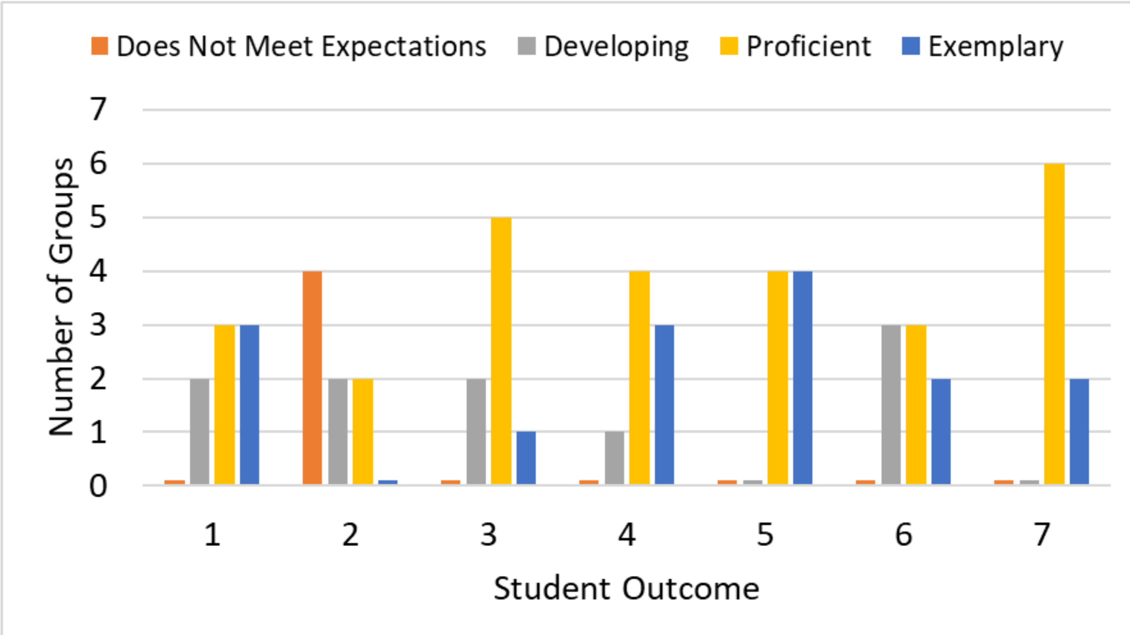

Figure 1. Assessment of EM student outcomes from the project. Total number of groups was eight.

Performance levels of proficient and exemplary represent satisfactory achievement of the specific EM student outcome. All groups achieved student outcomes 5 and 7, and this is likely because they were explicitly directed to do work very similar to these stated outcomes at different points in the project. Outcome 7 (engage with actions with the understanding that they have the potential to lead to both gains and losses) was captured in Task 2, in which groups were asked to research economic costs, environmental issues, and social impacts of all potential energy sources, and reinforced in Tasks 3 and 4, when groups had to come up with detailed quantitative estimates for those topics for their chosen designs. Outcome 5 (persuade why a discovery adds value from multiple perspectives) was captured in Task 5, in which the groups had to recommend and justify one of their two energy plans to the customer (the university's Board of Trustees) at the end of the project. Interestingly, more groups were able to reach the exemplary performance level for this outcome, perhaps because the justification was tailored to the customer after all technical work had been completed. Outcome 4 (understand ramifications of design decisions) was achieved by all but one group. Again, this was explicitly asked for in Tasks 3-5, and the one group that did not achieve the outcome discussed the ramifications but not in enough depth to be classified as proficient.

The remaining four student outcomes were met with varying levels of success. Both Outcome 1 (recognize and explore knowledge gaps) and Outcome 3 (explore multiple solution paths) were achieved by 75% of the groups, but the distribution indicates that Outcome 1 was achieved slightly more successfully as three groups met the exemplary standard for the outcome. This is likely because Task 2 of the project explicitly directed the students to produce work consistent with Outcome 1. In both cases, however, 25% of the groups only achieved the developing performance level. Outcome 6 (create solutions that meet customer needs) was achieved by 62.5% of the groups, however no group fell below the developing performance level. For this outcome, group work was classified as developing if there were significant design flaws (e.g., the final design did not produce enough energy for the university or the final design was technically or physically infeasible). All groups were able to properly identify the customer needs even if their technical designs did not meet those needs, again likely because this was explicitly asked of them in Task 1 of the project. Finally, only 25% of the groups met Outcome 2 (collect feedback from many stakeholders), and half did not meet expectations (i.e., collected no stakeholder feedback). This was surprising, as stakeholder feedback was included as a required item during Task 2 of the project. However, guidance was not provided outside of the Task 2 handout and the exact expectations may not have been clear to the groups.

Qualitative Project Assessment

The overall quality and success of the project was qualitatively assessed through student and instructor reflections provided at the end of the course.

Student reflections

Positive comments about the project typically reflected the real-world, applied nature of the project. As this is one of the benefits of PBL, these comments indicate the project worked as intended.

- This class felt very abstract to me. It helped to have the project where we can apply what we learned to a more realistic goal.
- I really enjoyed the project as I had prior interest in alternative energy sources.
- I did enjoy learning more about renewable energy because there ended up being a lot of things I did not know about them that surprised me. I also enjoyed the project as a whole. I thought that this was a very relevant project to the class and I appreciated how it was a true professional report. I think this experience will help me in future endeavors where I will have to create a proper report for recommendations.
- I enjoyed working together to understand what it takes to find a proper energy solution in the real world.

Critical comments about the project reflected students' frustrations with the scope and organization of the project, and issues with communication that arose out of the unexpected transition to remote learning. While the former can be addressed in future iterations of the project, the latter may be naturally resolved after a return to in-person instruction.

- The hardest thing for me was the project, specifically communication with my group after switching to remote learning.
- Group project was challenging given the not streamlined nature of the assignment.
- Maybe provide an example project from a past year (maybe with different numbers, I am not sure) or explain some of the tasks a little bit more clearly. But overall it was very well designed.
- I feel like some things were unclear? I found all the tasks to be clear, however, my teammates would be confused about what to do for the tasks assigned. Therefore, most of the meetings we had to do the tasks involved me explaining and re-explaining the task,

> and ultimately doing most of the work since I was the only one who understood the tasks. I feel like most of the misunderstanding was not the professor's fault, but rather the students not paying attention or not understanding the material being covered in class and not seeking out help outside of class. So, this problem isn't necessarily the professor's fault, but rather the students for not reaching out and asking questions covered in class or about the task itself.

Instructor reflections and recommendations

Using this project to inject EML in a second-year thermal sciences course went better than I anticipated. The students got to apply theory to a real-world problem and create solutions for a customer they were familiar with – their own university. In a way, asking them to create value for their university was asking them to create value for themselves. Many of the students come to University of San Diego because they feel a connection with its mission and values, one of which is a commitment to sustainability and caring for our common home. Exploring potential renewable energy sources allowed them to tap into a fundamental motivation that many of them have in becoming engineers: to design and create in ways that improve the world around them.

The students were very engaged in the project and produced detailed and lengthy technical reports despite not being required to meet a minimum word or page requirement. The support provided by our STEM librarian was critical for getting the groups to perform quality background research. While the technical achievement varied between the groups, all of them put in significant effort and learned information and practiced skills not normally covered in the course in the process. Task 5 was originally designed to use a fourth class session for technical presentations, but we lost a week of classes because of the pivot to remote learning, and this was cut to preserve the required content coverage. The inclusion of oral presentations would have been ideal so students could both practice and improve their oral communication skills and to see the work of the other groups. Because some groups recommended the university should invest in renewable energy sources while some recommended the university should accept the donation of the natural gas power plant, I expected the presentations to result in lively discussions.

I would recommend reducing the scope of the project. It was difficult to implement on top of the required course material (course outcomes require coverage of thermodynamics, heat transfer, and fluid mechanics). The design of the natural gas power plant using the Rankine cycle was assigned in parallel with lecture material, but because it was a group assignment, some students did not get the same exposure to the calculations, and this was evident in the final exam scores. Additionally, the project spanned the final two-thirds of the semester. I suspect this had a big influence on the frustrations expressed by the students. Additionally, even with a fully developed project package (i.e., project schedule, task assignments, report templates, and grading rubrics), it would require significant work from adjunct faculty, therefore project implementation across all sections may be limited. Based on the EM assessment, many of the student outcomes could still be met by a project with a reduced scope. In fact, EM outcomes may be improved by focusing on fewer outcomes and improving how explicitly they are addressed in the project material.

Conclusions

The student comments and the groups' overall achievement of the EM student outcomes indicate that this project successfully met the stated PBL and EML goals. The fact that a majority of the groups satisfactorily achieved six out of the seven EM student outcomes that were assessed lends confidence to the use of this project to promote EM in a second-year thermal sciences class that traditionally focuses on skillset-based outcomes. Additionally, for all but one EM student outcome, all group work was assessed at the developing performance level or higher. As this may have been the first time many students were asked to use EM skills in a project, it is understandable that some groups performed at a developing level. Projects and assignments with an EML focus in upper-division courses would allow students to further improve their EM skillset before graduation.

Several modifications to the project will be made to address student frustrations and to encourage the implementation by adjunct faculty. First, the natural gas power plant design using the Rankine cycle will be removed. This allows the scope of the project to be reduced while maintaining the renewable energy topics and information literacy session, both of which were found to be critical for the EML component of the project. Second, a standalone task to collect stakeholder feedback will be created, as this was the only EM student outcome that was not achieved by a majority of the groups. Finally, to continue to facilitate quality background research and information literacy, an instructional video and a how-to document that can be used by all course instructors will be created.

The quantitative EM assessment of the project in this study provided promising but preliminary results; assessments were made on group work with a small sample size. While EM student outcomes will still be assessed using submitted group artifacts, future work will be focused on refining and individualizing the EM assessment process as well as determining the overall effectiveness of the project at meeting specific course outcomes. A post-project individual reflection assignment will be used to gather students' attitudes and perceptions about EM, and survey instruments will be developed to perform indirect assessment of EM. Finally, to determine the effectiveness of the project at meeting skillset-based course outcomes (course outcomes a, b, c, and h), individual performance on those outcomes by students that complete the project will be compared to the performance of students who do not.

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