2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #51976

Project Based Learning to Teach Students About Exergy, Steam Turbines, and Modeling and Simulation in an Introductory Thermodynamics Class

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Project Based Learning (PBL) techniques are used to teach students about energy conversion techniques and modeling and simulation. Students perform exergy simulations of geothermal steam turbines and then synthesize solutions to estimate recommended geothermal steam turbine replacements for coal-fired power plants on an island with geothermal wells. PBL techniques provide the basis for introducing the Kern Entrepreneurial Engineering Network (KEEN) Entrepreneurial Mindset (EM) to students. Student outcomes such as student Curiosity, Connections, and Creating Value are part of the project. Student Curiosity and Connection is created with the context of the project. In the project scenario, student interns and are asked to perform modeling and simulation for the firm "Exergy or Lose It". Students are given geothermal conditions for six wells on the island as well as the specification sheets for real geothermal turbines and asked for a recommendation to replace 200 MW of energy. Their simulation analysis is done with a series of MATLAB® codes that help automate the analysis. Proper modeling and simulation technique are scaffolded within the project by requiring them to verify their code with a hand calculation, validate the code with output power from known steam turbines, and then do predictions for the geothermal steam turbines. The students finally Create Value in their recommendation for how to replace 200 MW of coal-fired power plants with geothermal energy.

Introduction

Project Based Learning (PBL) and Experiential Learning (EL) [1], [2] methods seem like two of the best pedagogical methods for engaging students that are learning advanced thermodynamics concepts. These methods seem easily applied to projects on power generation techniques which are part of an advanced thermodynamics course and require a complex set of steps for analysis. In this author's previous paper [3] similar techniques were used for predicting the renewable energy needs of a sustainable island as part of an engineering elective energy course. That course was almost completely project based and resulted in students indicating they "learned a great deal" in the course survey.

In other papers in the literature, various project-based techniques are used to help support students learning thermodynamics concepts. In [4], the authors show how applied learning within thermodynamics is done with a perspective on energy concepts. The course included two projects that aimed to increase the students' understanding of technical content in solar energy and energy conversion. In that paper, the projects were experimental and the students self-reported that the material was beneficial to aiding their understanding in comparing pre- and post-experiment surveys. Likewise, in [5], the authors used modeling and simulation along with team collaboration on a semester-long clean water thermodynamics project. In this study, the results revealed that students who experienced the projects, as compared to those who had not, expressed more of an affinity for the use of engineering software and for thermo-fluids courses. In [6], Python was used for a thermodynamic cycle analysis as part of a thermodynamics lab module which allowed a parametric analysis of standard Rankine, Gas Turbine, and Vapor Compression cycles. According to the authors, students acquired a working knowledge of Python programming and experienced how computational tools can be used to solve advanced engineering problems. The authors indicate that the project problems were put into an engineering context but don't describe the prompting or scenarios. The lab modules had the dual purpose of students learning Python and thermodynamics cycles. All these papers in the literature support the methods presented in this paper, but our methods are novel in that they employ both PBL and Entrepreneurial Mindset (EM) in our modeling and simulation projects.

The basis for the projects discussed in this paper grew from some initial first year PBL software explorations with a MATLAB® [7] for simulating various conventional energy and thermal systems related to objects such radiators, steam engines, gas turbines, air compressors, and steam turbines in a first course in engineering thermodynamics. For these systems, the students were provided with m-files (script files) for MATLAB® that could analyze part of the various thermal energy systems, and they were required to synthesize and adapt the parts of the code to solve their problems. The initial projects and problems used ideal gas assumptions for the analysis and used MATLAB® X Steam m-files [8] for automated water and steam table look-ups. Later in subsequent years, MATLAB Marina [9] m-files were used since these files extend beyond just steam properties. In these projects, the students were asked to analyze the systems for different input conditions (pressures, temperatures, isentropic efficiencies, etc.) and then comment on the trends for their thermal system and provide a basic design solution for their problem.

Then, the University of Denver became part of The Kern Entrepreneurial Engineering Network (KEEN) in 2018. That summer our faculty started attending the KEEN Integrating Curriculum with Entrepreneurial (ICE) Mindset workshops. ICE workshops connected problem-based and active and collaborative learning techniques to the development of the KEEN Entrepreneurial Mindset (EM) [10]. Part of the Entrepreneurial Mindset (EM) skillset is to have Curiosity, Connections, and Creating Value (3 C's) [10]. Using techniques from these workshops, our faculty worked on improving the PBL in many of their courses to include EM. Though the initial thermodynamics projects had PBL and were well received by students, the PBL was made more impactful by providing similar projects but injecting more of the 3 C's.

The revamped KEEN projects used story and role-playing to excite the students about determining energy conversion needs from both a societal and technical viewpoint and used actual specification sheets for turbine manufacturers, technical reports and scientific literature. The next section describes this basic pedagogical methodology including the project specifications along with some typical results. In addition, some general comments on the course are included. The project described in this paper has been implemented in a "Thermodynamics II" course from Fall 2019 through Fall 2025 and the next sections describe the KEEN ICE PBL implementation during Fall 2025.

Methods

The students were first introduced to using the MATLAB® methods and MATLAB® Marina (automated property lookups) in their problem sets in their homework as an initial type of scaffolding. At the same time the students started the quarter with a "Thermodynamics I" review and then moved on to their first new topic, exergy, in which they worked hand problems to gain this new skillset along with some MATLAB® problems. Shortly after completing this section, a project problem on exergy was introduced that required modeling and simulation. The following prompt was presented to the students about five weeks into the quarter after they had some general scaffolding with Thermodynamic concepts and MATLAB® code:

> You have been employed by "Exergy or Lose It" to look at the efficiency of installed and planned energy systems. Your company's mission is to find cost effective energy solutions by providing exergy analysis of planned energy systems using a variety of analysis tools that can look at predicting the performance of individual components that might be installed in existing energy systems. Your company has most recently been contracted to look at steam turbines used in small power plants. In fact, you were hired in anticipation that this branch of the company would take off, creating new work for all the new hires. Your future employment may depend on successfully completing this steam turbine analysis efficiently. No worries, your manager expects that you can write, verify and validate MATLAB® code to analyze steam turbines and then efficiently analyze the various steam turbines being considered for future power plants by your client.

A major fundamental of modern modeling and simulation is to verify and validate a code before making predictions with that code. In this project, students are introduced to those concepts through project related tasks. The students are typically given two to two and a half weeks to complete this project. It is one of two projects assigned during the quarter. Students work in teams of two to four students and are allowed to assemble their own teams. Each student is required to fill out an open survey on the learning management platform with their team member names shortly after the project is assigned. The finished project includes a technical report with their verification, validation, and predictions for their power plants as well as recommendations. The students project management their own timeline for the tasks, but the project statement guides them first through verification, then validation, and then prediction. A grading rubric is provided to the students when the project is handed out. The rubric is used to evaluate if the appropriate content is in each of the technical sections, about 60% of the grade, and then the final 40% of the grade comes from whether the verification, validation, and predictions along with recommendations are correct and reasonable.

Verification

The first student requirement was to verify that their code worked on a fundamental textbook exergy problem for a steam turbine. The required verification is provided in the project scope. The students use verification to ensure that their computer model correctly implements the conceptual exergy model. They should be asking "Did I build the code correctly to solve this problem?". Here is the prompt for this part of the problem:

> Develop your MATLAB® code to evaluate the following problem in SI units as verification of your code. Steam enters the steam turbine at 1.5 MPa and 600.0 °C and leaves the turbine at 8.0 kPa with a quality of 96%. If the flow rate is 10.0 kg/s, what is the maximum amount of power that could be produced by this turbine in kW. Hint: You are looking for the change in the exergy rate between the two states. MATLAB® Marina uses Moran and Shapiro Tables (provided), verify that you get the same result with those tables by doing a hand calculation (answer = 12,383.8 kW).

Once the students are able verify that their code, they are ready to move on to validating their code.

Validation

The second requirement was to validate their code by providing real-world exergy estimates for real steam turbines. In this case, the students are asked to produce estimates of exergy for three steam turbines that were measured for power plant output and reported in an Environmental Protection Agency (EPA) technical report [11]. There are enough technical specifications for the steam turbine power plant in the technical report that the student can estimate the exergy and compare it to the actual power plant output. The expectation is that the exergy estimates should exceed the actual power plant output. The students can then estimate a type of 2nd law efficiency for the power plants. The students use validation to ensure the model accurately represents the real-world system for its intended purpose. The students ask, "Did I build a code with models that represent this type of problem?". Here is the prompt for this part of the problem:

> As a case study, use your new code to evaluate the three turbines in Table 1 that were characterized by the EPA. These types of turbines are known as non-condensing back-turbines (meaning that the discharge of steam out of the turbine is above atmospheric conditions, i.e., 50 psig for System 1). Through monitoring and measuring, the EPA found the values in Table 1. Assume that the steam quality is typically 98% at the exit. Use the mass flow rates provided to estimate the power potential of these turbines (don't forget to work in the correct SI units accounting for gauge pressures). How does the power potential compare with the value reported/measured? Assuming that the electrical generator efficiency is that given in Table 1 calculate the 2nd Law efficiency for these three steam turbines. Indicate what 2nd Law Efficiency tells us about our ability to improve the performance and how likely the nominal power was reported correctly. Use the cases in Table 1 as a baseline and as additional data for making recommendations in the next section.

Table 1. Backpressure steam turbines cost and performance characteristics [11]

Steam Turbine Parameters[67]	System		
	1	2	3
Nominal Electricity Capacity (kW)	500	3,000	15,000
Typical Application	Industrial, PRV application	Industrial, universities, hospitals	Industrial, universities, hospitals
Equipment Cost ($/kW)[68]	$668	$401	$392
Total Installed Cost ($/kW)[69]	$1,136	$682	$666
O&M Costs ($/kW)[70]	$0.010	$0.009	$0.006
Turbine Isentropic Efficiency (%)[71]	52.5%	61.2%	78.0%
Generator/Gearbox Efficiency (%)	94%	94%	96%
Steam Flow (lbs/hr)	20,050	152,600	494,464
Inlet Pressure (psig)	500	600	700
Inlet Temperature (° Fahrenheit)	550	575	650
Outlet Pressure (psig)	50	150	150
Outlet Temperature (° Fahrenheit)	298	373	379.7

Curiosity and Connections to how modeling and simulation may be used to analyze real systems is made through introducing a real engineering technical report for real steam turbines as this work on exergy is extended beyond just textbook problems. Through this validation analysis the students should begin to understand the efficacy and limitations of the exergy analysis and should feel confident using the code to move on to the prediction phase of the project.

Prediction

A definition of prediction is the outcomes of the simulation, which forecasts future states, performance, or results, extending beyond observed data by using fundamental laws or complex data. The students then are asked to predict the exergy of geothermal steam turbines to replace existing coal-fired power plants on a fictional island. The prompt for this part of the project is the following:

> The client is interested in developing a geothermal steam power plant and they are considering Siemens steam turbines such as that shown in Figure 1. Siemens has developed turbines specifically for geothermal applications known as models SST-400 GEO (Sizes 1 – 4) and SST-500 GEO (Sizes 5 – 6) which are given in the pamphlet provided [12]. This type of geothermal plant is known as a flashing steam power plant. Flash steam power plants are the most common and use geothermal reservoirs of water with temperatures typically greater than 182 °C. This very hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam and the maximum pressure is controlled coming out of the well with a pressure relief valve. The steam is separated from the water and used to power a turbine/generator. Any leftover water and condensed steam are

injected back into the reservoir, making this a sustainable resource. At the proposed site there are five wells with steam properties as shown in Table 2. These are the values after flashing and are the entry conditions into the turbines.

Figure 1. Siemens Turbine for the geothermal power plant [8].

Table 2. Temperatures, pressures and flow rates of steam coming from the six deep geothermal wells marked by a red dot on the map. Readings are at the top of the well after flashing.

Site	Temperature (°C)	Pressure (bar)	Flow Rate (ton/hr)
PC43	190.0	10.0	360
PC46	205.0	9.0	450
PC47	204.0	8.0	220
PC48	200.0	6.0	180
PC44	203.0	11.0	150
PC45	204.0	10.0	250

Assume that the turbines will be installed in the geothermal power plant in exhaust condensing mode, and that the steam quality is typically 92% at the exit of the turbine. The client is hoping to replace 200 MW of electrical generating capacity that is done with a coal-fired power plant and would like any advice you have on using the SST-400 GEO and SST-500 GEO turbines (all sizes). They would like to know how all six types of turbines would perform at each well (the max power potential possible). For each turbine size, you cannot exceed its maximum input temperature, pressure or the maximum power rating given in the brochure, but you are limited by the values given in Table 2. The electrical generator is 95% efficient. Remember that Max Power Potential (exergy) is an idealization when making these recommendations. For instance, the real turbines have a second law efficiency and will not attain the max power potential. Siemens indicates these are modular units, and it would be possible to purchase multiple units to reach the desired power output capacity. Give your recommendations to your manager based on your exergy calculations. The client is open to any reasonable solution that has been documented well with calculations and logic.

Curiosity about geothermal power is used in this part of the project as well as students become curious about a new application for steam turbines other than coal-fired power plants. Connections to real-world steam turbine manufacturers and performance specification are made by connecting their recommendations to actual Siemens turbines by consulting manufacturer pamphlets. And again, this work on exergy is extended beyond just textbook problems. The students demonstrate the third “EM C” by Creating Value in their recommendation for how to replace 200 MW of coal-fired power plants with geothermal energy. Also, they circle back to their validation to give a sense of what is realistic for an exergy prediction.

Results and Assessment

In this section, typical student results are presented for the three project tasks, verification, validation, and prediction.

Verification

For the verification, nearly 100% of student groups were able to verify the result. The students provided a hand calculation that predicts the same result as their code for the change in exergy which equates to the maximum amount of power output possible from the steam turbine. When the hand calculation is done with the Moran and Shapiro Tables [13], they should agree well their maximum power output. The code predicts 12,383.82088 kW and with the tables, they typically calculated 12,383.8 kW.

Typical student results:

Student MATLAB Code Output:

```
Power =

   1.2384e+04
```

Power = 12383.82088 kW

Student Sample Hand Calculation:

$P_1 = 1.5\ MPa = 1500\ kPa$

$T_1 = 600^\circ C = 873\ K$

$P_2 = 8.0\ kPa$

$x = 96\% = 0.96$

$\dot{m} = 10.0\ kg/s$

$\dot{W}_{rev} = ?$

Dead State Properties

$T_0 = 25^\circ C = 298\ K$

$P_0 = 101\ kPa$

State 1 Properties

Table A-4:

$h_1 = 3694.0\ kJ/kg$

$s_1 = 7.8385\ kJ/kg \cdot k$

State 2 Properties

Table A-3:

$h_{2f} = 173.88\ kJ/kg$

$h_{2fg} = 2403.1\ kJ/kg$

$s_{2f} = 0.5926\ kJ/kg \cdot k$

$s_{2g} = 8.2287\ kJ/kg \cdot k$

$$h_2 = h_{2f} + x h_{2fg}$$
$$h_2 = 173.88\ kJ/kg + 0.96(2403.1\ kJ/kg)$$
$$h_2 = 2480.9\ kJ/kg$$

$$s_2 = s_{2f} + x(s_{2g} - s_{2f})$$
$$s_2 = 0.5926\ kJ/kg \cdot k + 0.96(8.2287\ kJ/kg \cdot k - 0.5926\ kJ/kg \cdot k)$$
$$s_2 = 7.923\ kJ/kg \cdot k$$

$$\Delta\psi = h_2 - h_1 - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$
$$\Delta\psi = h_2 - h_1 - T_0(s_2 - s_1) + 0 + 0$$
$$\Delta\psi = 2480.9\ kJ/kg - 3694.0\ kJ/kg - 298\ K(7.923\ kJ/kg \cdot k - 7.8385\ kJ/kg \cdot k)$$
$$\Delta\psi = -1238.3\ kJ/kg$$

$$\dot{W}_{rev} = \dot{m}\Delta\psi$$
$$\dot{W}_{rev} = 10\ kg/s(-1238.3\ kJ/kg)$$
$$\dot{W}_{rev} = -12383\ kW$$

The maximum amount of power that could be produced by this turbine is -12383 kW.

Validation

The students were relatively successful in taking the input conditions for the three turbines reported in the technical report and making an estimate of the maximum electric power output that was possible. Most student groups came up with reasonable results despite some minor errors.

Example student results for the validation are shown in this excerpt from a student report .

System	Actual Electric Power Output (kW)	Maximum Electric Power Output(kW)	Second Law Efficiency
1	500	838.05	59.7%
2	3,000	4,541.7	66.05%
3	15,000	18,906.24	79.34%

To obtain these results the students needed to use their verified code. Using their code required them to convert English units to SI units correctly, understand gauge versus absolute pressure, correctly apply the generator efficiency and then compare either actual electric power to maximum potential electrical power or compare actual mechanical power to maximum potential mechanical power to get an estimate of the 2nd law efficiency. Likewise, they should note that the plant is producing less power than the exergy calculation which would be expected since exergy represents the maximum power potential. In the end, the exergy calculation is a reasonable estimation of the power potential, so it can be used for further analysis and predictions.

Prediction

Using the Siemens geothermal steam turbine pamphlet specifications and the provided geothermal well information, the student groups were able to make some reasonable predictions and determine if the existing wells would be able to provide replacement energy for the conventional coal-fired power plant.

An example student results for the predictions are shown in this excerpt from the student report.

Sites	Turbine	Power (MW)
1	5	49.0105
2	5	59.413
3	3	28.158
4	3	21.299
5	3	20.5105
6	4	33.6775
Total	**212.069 MW**	

The above numbers are close to what was expected; the maximum amount estimated by the professor was about 205.0 MW. The students are limited to inputting the given temperatures, pressures, and flow rate from the well. Effectively, this meant that there were only six inputs and six possible results for power production. All the outputs from the turbine were the same for condensing mode which was prescribed in the project description. Some flow rates produce more power than the turbine can produce. The students typically optimized their designs by choosing turbines that were not oversized as those would have cost more money. Lastly, the best student results were ones that noted that the maximum amount of power could not be produced if one considers the validation data from the second part of the project. Realistically, they would only capture 60% to 80% of the energy based on the 2nd law efficiencies in the validation. Thus, as given, the wells are likely to produce about 120 to 160 MW which will not necessarily replace the 200 MW. A major recommendation by most students was to consider drilling additional geothermal wells for additional turbines to get to the 200.0 MW level.

Discussions

The above results are simply highlights of some of the results students can obtain by learning through PBL in "Thermodynamics II".

By incorporating the KEEN EM skillset through these types of projects the students develop Curiosity about different aspects of exergy and energy systems as presented in their PBL scenarios. Through exploring different energy conversion methods such as geothermal steam turbines in this project, the students develop curiosity about all the different ways that energy conversion can be done and what conversion methods might be done in the future.

The KEEN EM skillset of Connections is used by integrating information from many sources to gain insight and assess and manage risk. As can be seen in these scenarios, the students connect real technical reports, turbine pamphlets, and real-world data for assessing real engineering scenarios.

The students exhibit the KEEN EM skillset of Creating Value. The project gives the students the opportunity to create value by going beyond the status quo and each team can provide a unique insight into what they think will work best for replacing the coal-fired power plants with geothermal energy. Each student group came up with a unique and valuable solution or insight. Lastly, the students learned about aspects of modeling and simulation such as verification, validation, and prediction and how that could create value for engineering solutions.

This version of the project was given to 60 students who were Juniors in this required course. This course had the largest number of students that were ever taught in "Thermodynamics II". However, these projects were engaging for students and kept them interested in the course through the 3 C's. The course evaluations had a 92% response rate (55/60). Three metrics used for yearly teaching evaluation from the course questionnaire are the following: (1) I learned a great deal in the class, (2) Overall, this is an excellent course, and (3) Overall this is an Effective Instructor. The student evaluation results for this course are given below and compared to the results compiled for other courses in the Engineering College and the Mechanical Engineering

Department (ME). The Thermodynamics II course with the EM projects is a significant 0.5 to 0.7 point higher than the rest of the college and department in the various categories. Likewise, a comparison between the Fall 2025 survey for Thermodynamics II to the Fall 2015 results for Thermodynamics II, where projects had limited EM content but the same instructor, show that they are now 0.3 to 0.4 points higher in these categories.

Quarter	**My Scores versus Engineering and ME:** (1) (2), (3)
Thermo II, Fall 2025 w/Project Thermo II, Fall 2024 w/Project	5.64/6.0, 5.70/6.0, 5.82/6.0, 92% response 5.60/6.0, 5.78/6.0, 5.86/6.0, 89% response
Engineering College	5.12/6.0, 5.02/6.0, 5.21/6.0 Spring 2024 4.99/6.0, 4.90/6.0, 5.07/6.0 Fall 2024 4.97/6.0, 4.86/6.0, 5.02/6.0 Winter 2025
Mechanical Engineering (ME) Courses	4.94/6.0, 4.97/6.0, 5.25/6.0 Spring 2024 5.12/6.0, 5.07/6.0, 5.17/6.0 Fall 2024 5.00/6.0, 4.87/6.0, 4.98/6.0 Winter 2025
Thermo II, Fall 2015 Project (limited EM content)	5.37/6.0, 5.30/6.0, 5.41/6.0, 85% response

Some additional anonymous feedback from the students through student course questionnaires (faculty course evaluations) are the following:

Prompt: What were the strengths of the course?

> "Information coverage and explanation, homework problems and projects related directly to course work" --Student, Fall 2025
>
> "The material was interesting and the projects were fun to work on." --Student, Fall 2025
>
> "Providing project code let us focus on the thermodynamics aspect instead of the MATLAB aspect." --Student, Fall 2025
>
> "The first project connected fully with what we were doing in class and helped us expand what we were doing to the everyday connection of what we were doing. I think that the first project helped me connect what we were learning in class to how it can be implemented outside of class." --Student, Fall 2025
>
> "I really liked the group projects; I think they made me realize how the workforce will be when I am trying to incorporate thermodynamics. I enjoy that we had to work in a group setting, and we were still having fun while struggling through it." --Student, Fall 2025
>
> "I appreciated the real life examples, especially the projects.." --Student, Fall 2025

The above comments focus on the PBL and EM methods and exhibit that the students are enjoying the EM skillset development as well as the technical skillset development.

Negative comments were more about the length of the projects, the spacing between projects, and the time of the quarter the projects were due. Some students didn't like MATLAB®. Some students felt the projects were "confusing". However, as first quarter junior engineering students they have not had as many opportunities to synthesize complex material for actual applications, and thus the material may have felt "confusing". Some students would like step-by-step instructions on how to complete the project, but the project has some open-ended aspects. Some comments that are related to the above summary comments are the following given below.

Prompt: What three things could you suggest that would most improve the quality of this course?

> "The projects felt sort of ambiguous at times, they could have been slightly more detailed in their instructions." --Student, Fall 2025

> "The projects were a little confusing when trying to understand the deliverables." --Student, Fall 2025

> "Reduce the matlab in homework keep it for the project." --Student, Fall 2025

> "Give out better explanations for the project, especially the handout. I had to read it a couple of times before fully understanding what we had to do." --Student, Fall 2025

> "One thing I would suggest is doing one MATLAB project, then doing one small project like we did in thermo one." --Student, Fall 2025

Conclusions

Through incorporating PBL and EM methods, a project was created to provide a "real-world" scenario. In this project on exergy, geothermal energy, and modeling and simulation, students synthesized concepts on renewable energy conversion through using MATLAB® scripts to simulate and predict geothermal energy conversion scenarios to replace existing conventional energy power plants. This analysis furthered their understanding of how exergy could be used to estimate the potential power production. In addition, they learned about some of the tenants of modeling and simulation like verification, validation, and prediction and its limitations.

Lastly, the EM prompt of providing renewable energy replacement for conventional energy provided the framework for the students to first become curious about how energy is provided and how much energy might be needed. Through the prompts, students began to see the connections between actual steam turbine specifications, geothermal energy wells, and the actual amounts of energy that could be produced. Finally, by role playing that this analysis was for conventional energy replacements, the students could see that they were creating value by providing "better" solutions. In this way, the PBL projects provide a means by which to produce both a technical and EM skillset. Student course questionnaires indicated that they appreciated this mode of learning and this course received some of the highest course ratings from students in the engineering college.

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