A First-Year Power Plant Design Project

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Abstract

This evidence-based practice paper discusses the development and refinement of a first-year engineering design project related to electrical power generation, including the use of renewable energy resources. An important aspect of any Introduction to Engineering course is the project or projects which are chosen for the students to work on. Since renewable energy is a relevant and multidisciplinary field, it provides a good topic for a first-year engineering design course, provided the experience is properly designed.

This paper describes a successful renewable energy project that has been used for the past seven years in an Introduction to Engineering class at a large, public, research university. Details of this project and its evolution based on the curricular needs of the university and research-based best-practices will be discussed. Some of these research-based best practices include incorporating predictive modelling, entrepreneurial mindset, and just-in-time learning. The rationale behind how this project was designed and modified will be discussed in relation to the course goals and course format and some successes will be highlighted. Finally, recommendations will be given for how this project or a similar version of this project could be implemented in different contexts.

Introduction

In recent years, first-year engineering design courses have received a lot of attention in literature as a mechanism to increase retention within engineering programs and build an identity as an engineer [1-4]. It has been considered a best practice among introductory engineering design course developers to choose projects which highlight the engineering design process (build-test-refine cycle), are "hands-on", and team based [5-7]. A wide range of course structures and project ideas have been presented in literature. Projects are usually the focus of the course and these projects range in scope from simple in-class design projects to semester-long projects [5-9]. A good project is one that offers students a chance to build upon their engineering skills while engaging them in a problem that is of interest to them. A project must be designed in a way that students with limited technical skills could complete the design but might be presented or simplified in such a way that sufficient mastery of certain technical topics could be obtained while completing the project.

The problem that is being solved also plays a role in the motivation of students to complete the project [10-13]. Projects that allow students to choose aspects that align with their interests or projects that match with the preconceived notions about the discipline they are pursuing can make the project more interesting to students [14-15]. Many first-year programs, however, are multidisciplinary and so coming up with a multidisciplinary project that has aspects of the many different disciplines can be a challenge. It has also been shown that connecting the project to a real-world scenario may also help with student motivation [16-17]. One real-world scenario that holds a lot of promise for a first-year design problem is energy harvesting. Renewable energy technology is field that is of interest to many students and has a lot of diversity in the sources of energy that can be harvested. Thus, there are many options for multidisciplinary system designs.

For these reasons, a project related to energy harvesting was developed as a part of first-year introduction to engineering design course at a large public research university. This project was originally developed seven years ago as a part of an effort to go from a discipline-specific introduction to engineering course model to a multidisciplinary course model. Over the past seven years, the project has been adapted to include renewable and nonrenewable power generating options, entrepreneurial mindset learning, just-in-time learning, and predictive modelling. This project has proven to be a scalable, robust, and adaptable project. The purpose of this paper is to describe the details of the project as well as the rationale and methodology behind the changes that were made to the project. The hope is that this will present an example of a first-year project design that can be improved incrementally. Recommendations will be made for how to implement this project in different contexts and lessons learned from the evolution of this particular project.

Background

Before discussing the project, it is important to understand the context in which the project was developed. In 2010 the first-year design courses at a large (>50,000 students) public university were being redesigned to address growing concerns about the attrition and graduation rates within engineering. A first-year faculty teaching team, composed of both tenure track and non-tenure track faculty, was established to take the current discipline-specific introduction to engineering courses that were taught by faculty in their respective departments and make a multidisciplinary version of the course that would be taught by this newly established team. Sections of this course were intentionally kept small (~40 students per section compared to their other required first-year courses which could be as large as 500 students) to increase the attention that the faculty could give to each student and give them a positive cornerstone design experience in their first year. The development of this team and the design of this course were part of a larger institutional effort to increase retention between first and second year within engineering. These combined efforts have been shown to be effective at achieving these goals [18].

The structure of the class is a 50 minute lecture once a week and a 2 hour and 50 minute lab time once a week. During the lab time the students would either be working through a prescribed lab designed to teach them how to use equipment or about a new topic (such as gears and motors or programming in Matlab) or working on their project. The students were a mix of Mechanical, Aerospace, Chemical, and Electrical Engineering students in their first year of study at the university. The course learning objectives (CLO) did change slightly over the 7 years that the project was used, but the 8 outcomes below reflect accurately the consistent goals of the course and form a basis for what features needed to be included in a project.

1. Students will develop problem statements and design criteria/requirements by evaluating a project scenario using design techniques (such as mind mapping or functional decomposition).
2. As a part of a design team, students will use the engineering design process to design, create, and evaluate a prototype that addresses realistic design constraints and requirements.
3. Students will self-assess, select, pursue, and demonstrate competency with a variety of tools, methods, and software as determined by their program.
4. Students will analyze engineering problems by comparing results from both application of models/physical principles and measurement data.
5. Students will apply basic teaming principles (such as the Tuckman's Model) and team effectiveness practices while working with their teams.
6. Students will write a technical report and give an oral/multimedia presentation following [course name] technical communication guidelines which include formatting, explaining and justifying aspects of the project.
7. Students will construct detailed project plans using basic project management techniques (such as scheduling and budgeting) and methods (such as Gantt charts).
8. Students will self-evaluate their prototype design decisions and reflect on the team's progress throughout the design process.

Most of these learning objectives were assessed through the project and so the project must be designed carefully to make sure that the course outcomes are satisfied. While the focus of the class is dedicated to the engineering design process, other skills such as experimental design, modelling, technical drawing, Matlab programming, basic circuits, technical communication, and basic prototyping skills were also taught in the context of the project. Reports, presentations, and other smaller deliverables would be assigned to help students document their design process. A variety of projects were designed by the instructional team, but each instructor would typically choose a single overarching design project for their course.

The renewable energy project was designed and piloted in 2011. Nine of the 15 sections used this project in the first year it was deployed. The other sections used a solar car project that had previously been developed and used. Between first deployment of the renewable energy project to the most recent offerings in 2018, the number of sections of this version of introduction to engineering increased to about 30 and anywhere between 30% to 70% of the sections would use the renewable energy project each year (over this time 6 other projects were developed by various faculty members, but the energy project was the most widely used project for those seven years). It is estimated that more than 3,500 students have completed this project over the past 7 years and was used by at least 8 different faculty members.

Project Description

Initially the project was developed to have students design and build a fully functional small-scale prototype of a renewable energy power plant (producing on the order of 1-100 mW of electrical power) for a fictional town. The stated goal was simply to generate as much energy as possible for as little cost as possible. A platform was built (seen in Figure 1) that contained two light bulbs that were pointed in different areas to simulate a variable solar intensity, a fan to simulate wind over the city, and a pump and piping system used to create a waterfall resource that could be harnessed. They were given a 1 ft x 1 ft piece of ⅝" thick plywood to build their designs on. For the initial design of the project they were constrained to put their board on a specific section of the test platform where all 3 resources would be available. They could choose to harness any combination of these three resources. For the initial design of the project the only other size constraints on the project were that it could not be more than 2 ft tall and it had to be supported completely from their plywood base. After the initial run a constraint that the design could not extend any more than 6 inches from the sides of the base was also imposed.

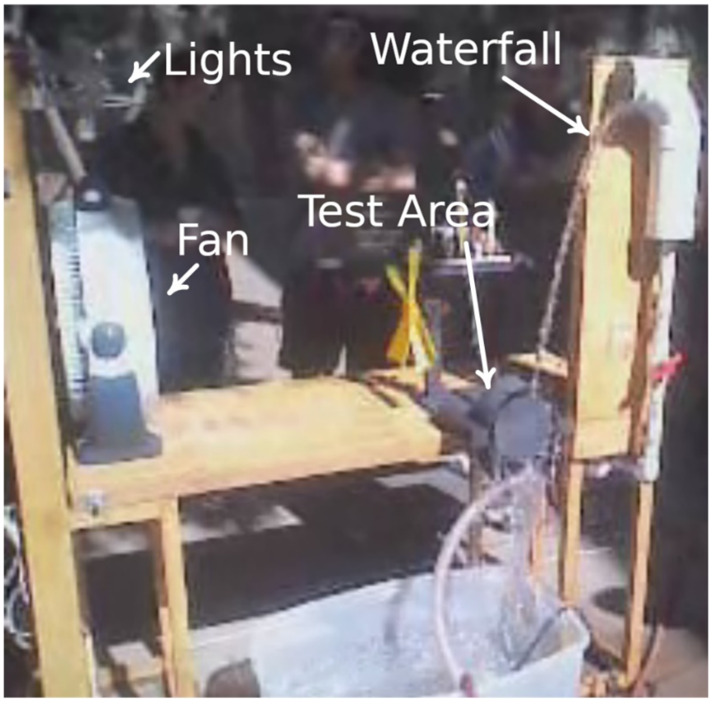

Figure 1. Photo of testing platform for power plant project

It should be noted that the testing platform was designed in such a way that any of the three available resources were viable, meaning that for a similar quality of power plant design any of the sources could produce roughly the same amount of power. This has been proved out by the wide range of successful designs over the years.

Various building materials, including small solar cells and DC motors that could be used as generators, could be "purchased" from the class storeroom. A max budget of $100 (per team of 4) was given to them (this was later reduced to $50 to force more trade-offs to be made during the design process). The funding for materials is provided via a $50 per student course fee for the class. This course fee also funds the tools and dedicated lab facilities for this course. It is also important to note that the "prices" in the storeroom may be inflated from actual purchasing costs to account for the "engineering costs" of manufactured materials. For instance, a solar cell might cost us $2 to buy but the students must count it as a $4 item in their budget. We also decrease expenses for the course by having students return any materials that have not been damaged after the course is complete. Students are also able to request or bring in materials, but they must negotiate a "price" for those materials with the instructor that will be included in their budget. Since it is undesirable to have students spend money out of their own pockets, students are encouraged to design their powerplants predominately from the materials available in the storeroom.

One important aspect of the available materials was that different options were given for the most important energy conversion components. For instance, there were two different DC motors available as generators (it was found that the Globe TRW 24V 5500 RPM motor and Johnson Electric 24V 7200 RPM motor worked well for this application) and two different solar cells (Solarbotics 24x22mm Monocrystalline Solar Cell and untabbed 3"x6" solar cells were used for this project). Each of these options intentionally have advantages and disadvantages that the students can discover through research and experimentation. This was important because it forced the students to characterize each of these elements and make a design decision which necessarily involved evaluating trade-offs. At least one lecture was devoted to learning about energy and energy conversion. Activities were designed to help them design experiments where they could find the energy conversion efficiencies by measuring power input and output under controlled conditions.

The designs were tested using a voltage probe on a SensorDAQ data logger that measured the voltage drop across a 100 Ohm resistor. The resistive load has remained the same over the life of this project and was found to be appropriate for all of the different power generating options to provide reasonable power output. A GUI was created using Labview to create an easy interface for students to see the voltage and a calculated power output plots (plotted as a function of time). They were also able to save the data to a txt file that they could then load into Matlab for post processing (and practice using Matlab for data analysis). Recently this GUI and SensorDAQ data logger were replaced with an Arduino circuit (Figure 2) and Matlab GUI (Figure 3).

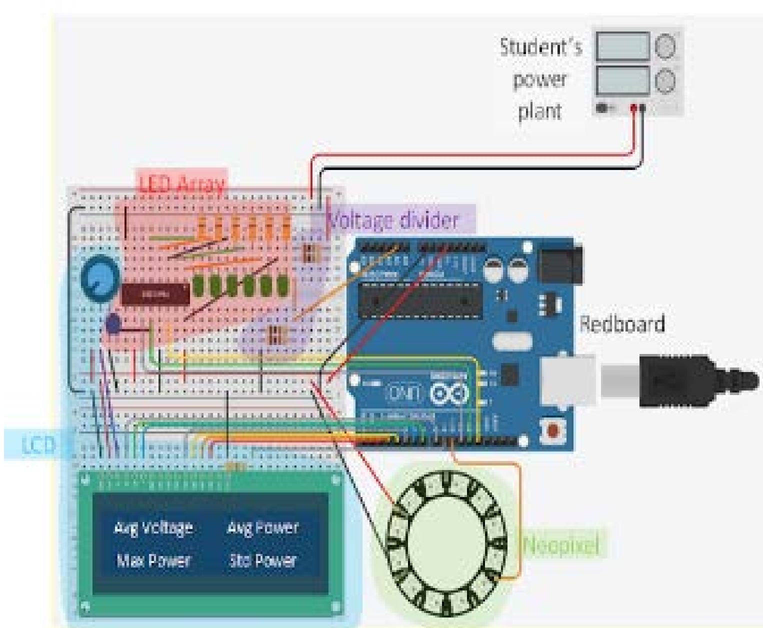

Figure 2. Schematic of Arduino circuit used to measure power

One early insight that students were able to gain from the GUI is that there are fluctuations in power even for dc power sources due to noise. This actually helped address the difference between energy and power and what are appropriate values to report (for instance, is the max power a useful quantity or is a mean value more appropriate). The consistency of the power produced, as quantified by the standard deviation of the power, would become a criterion for evaluating the designs in the future based on these early results. After the first run of the project, there was also impetus to assess more than just power output and cost and so criteria of aesthetics, craftsmanship, and creativity/innovation we also implemented into the grading for the prototypes. These last three criteria have always been evaluated based on peer feedback as well as instructor evaluation and were weighted fairly equally with power output and cost. When this set of criteria was first established, the rubric which showed that they were of equal importance was given to the students (this would change in later years and this shift will be discussed further in the next section). However, it was often the case that design fixation [19] would drive the engineering decisions more than the rubric until the very end of the term when many would realize there is more than just power that needed to be considered when designing a power plant.

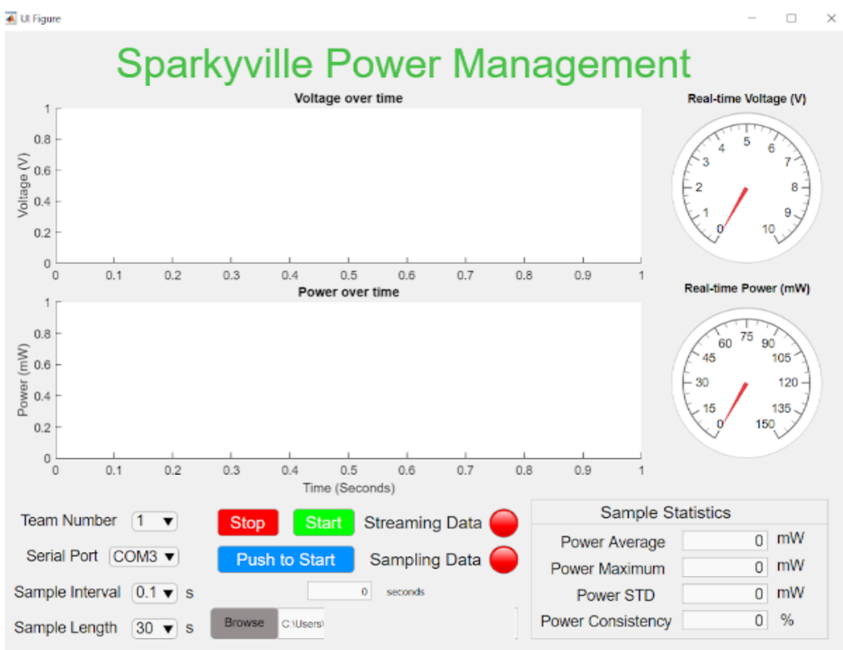

Figure 3. Matlab Power Measurement GUI

Project Evolution

One of the strengths of this particular project design was the ways that the constraints and goals could be adapted to achieve different learning objectives or prevent a single superior design from emerging over the years. One example of this that has already been mentioned is decreasing the maximum budget from $100 to $50. This forced students to pay more attention to budgeting (CLO 7) and provided a more meaningful constraint to the project. There were two other changes made to the project that would significantly impact student design decisions: 1) we started modelling the variability in the wind and solar resource by making the wind speed and the number of lights that were turned on based on the roll of a dice on demonstration day, and 2) we added the constraint that the water could not splash out of the bucket placed below the setup which modelled environmental impact that a hydroelectric plant might have. This was part of an effort to better fulfill CLO 2 (making the constraints more realistic). The impact that these two changes had was to bias designs towards hydroelectric plants because of the variability in the other sources caused by change 1 and the downplaying of the impact of change 2. While it is not desirable to skew designs in a single direction, it has been a good learning experience for students to run into issues satisfying a requirement that they initially did not think was going to be a problem and also see how the “non-obvious” solutions can outperform their more “obvious” design.

In 2013 a requirement was added to the proposal to calculate a predicted power output of their design as a means of helping justify their design decisions. In their final report, they would then have to compare their predicted value with their actual power output. This allowed for direct assessment of CLOs 3 and 4. To prepare the students for this, a lab related to Matlab programming was developed to walk students through the creation of a computer program that calculated power available in each of the three renewable power sources as a function of parameters they could measure from the testing platform. A follow-up lab was also designed where students would measure the efficiency of a dc motor and solar cell. Even though some of these students had not had physics, the labs scaffolded the calculations enough that they could gain insight to the efficiency of energy conversions and all of the different energy conversions involved in a power plant. This was found to be a good, tractable way of incorporating modelling into the design process.

In 2015 a significant redesign of the course structure turned this project from a half-semester long project to a full semester project. This was done for a number of different reasons. First, materials had been developed that allowed for the implementation of a flipped-classroom model of instruction. Students would now be required to watch videos before coming to lecture. Lecture would be spent on in-class directed activities to review the lecture topics in a controlled, in-class activity. They would then apply these concepts directly to the project right when they needed them. This just-in-time learning strategy was proven effective in literature at helping students develop self-directed learning skills and make connections to how topics in class are applied in the real world [20-21]. This change in course structure was also evaluated directly in a paper that studied how this just-in-time learning approach affected students’ ability to identify key steps in the design process [22]. This was also done to allow more opportunities for CLO 3 by taking out step-by-step lab procedures and putting in more labs where they were forced to apply concepts in new situations by themselves. Non-renewable options, such as battery or pressure vessel-based projects were also included as potential options to consider for energy capture. These options have never been particularly popular with students and most of the designs still focused on the three renewable options offered to the students. However, this was an important addition to the project to provide options for students who were really interested in chemical engineering. It did allow students to break from more traditional designs that had previously dominated the project and allowed for creativity and innovation (which was encouraged in the class).

The semester long project provided the larger context for learning that made this approach successful. It also opened the opportunity to address concerns that were identified from the previously cited paper. Specifically, students seemed to have a hard time articulating the importance of defining the problem based on customer wants and needs [22], a common problem for novice designers [23]. So, in 2016 effort was made to incorporate a strong emphasis on creating value for customers through the inclusion of entrepreneurially minded learning (EML). In 2017, four stakeholders were introduced into the project. These stakeholders included the Mayor, City Engineer, President of prominent HOA, and the president of an environmental action group. Each of these fictional stakeholders had pre-described concerns with a power plant design as well as opinions about what a good power plant might do. These stakeholders were designed to have some points of commonality, but also points of disagreement on their wants/needs for the power plant. Once the stakeholders were introduced to the project, documentation that described the requirements and criteria of the project were reduced substantially. The information they needed would now be determined by "interviewing" the stakeholders in a Q&A online forum. The instructional staff role-played as the appropriate stakeholder to create a typed response to the students' questions. One practical concern related to adding fictional clients is the need to clearly define the information that each stakeholder has so that TAs or other instructors will give the same information when responding as the same person. The first attempt at adding clients did have some issues where the information given by an individual stakeholder would be inconsistent when two different people played that role. This was corrected using stakeholder bios that were given to the instructional staff ahead of time but were not provided to the students. It also helps if the instructional staff can add in "personality" rather than just giving raw information. Some TAs were found to be better at this than others.

In a work-in-progress paper, preliminary results showed that this approach increased student awareness of the role of clients in defining problems and was similar to the effects of having real clients used for the project [24]. More options were also given for where the design could be "built" and there were advantages and disadvantages of each site, both in terms of available resources and public opinion. This again added another layer of realism to the project, but also allowed for more design trade-offs (such as cost, availability of resources, and environmental impact). Work still needs to be done to determine exactly what the differences are in student perception of fictional clients versus real clients and the learning benefits that can be expected for each, but it does seem that adding clients to a project has had a positive impact on students' understanding of the important role of clients in the design process.

Impact on Learning

In the seven years of running this project, the impact on student learning has been assessed from a variety of different perspectives. The purposes of these previous studies were to assess the impact of the class and project aspects of the class, not on assessing this particular project. However, by looking at the data from these previous studies, some insights into the effectiveness of this project can be ascertained. For instance, in 2016 a study was done to understand the impact of transitioning the project from a half-semester project to a full semester project (the experimental data in this paper includes data from the project described in this paper as well as a different project) on students' ability to critique an engineering design process Gantt chart [22]. No direct comparison can be made between the different projects that were a part of the experimental group, but the data does show an improvement in the understanding of the engineering design process as indicated by an increase in mean critique assessment scores from 5.83 at the beginning of the project to 11.52 at the end of the project (out of a possible 16) [22]. There was also shown to be a significant increase (more than double the scores) in identifying the importance of "idea generation" and the "building ant testing" parts of the engineering design process over a control section (different project) [22].

A direct comparison between projects was made in a 2017 study where the levels of EML was assessed based on final project reports [24]. The two projects that were compared that did not have real clients had similar effects on students' articulation of EML concepts. The few differences were that after this project 90 % of the teams in the study were able to articulate specific ways that they were able to create value for their stakeholders. While 42 % of the teams completing a different comparable project articulated value creation [24]. The energy project was not as effective as this other project in helping students identify the importance of the customer in a different design context (mean scores of 82 % and 89 %, respectively on the assessment item), although both scores were high [24].

Finally, in 2014 a supplemental course evaluation survey was administered to students. This survey asked questions related to the course structure and the course material. Students were asked to rate on a 5-point Likert scale their level of agreement with the statements "The instructor presents material that enhances my perception of engineering" and "The instructor presents material that gets me excited about engineering", among other questions. While it is difficult to isolate the effect of the project verses the other material presented in the course, the project plays a large role in directing the course material that is presented in this class. On these two questions mean scores of 4.245 and 3.98, respectively, were reported by the 74 students (~50 % response rate) who filled out the survey. These relatively high scores do indicate that the project topic is one that stimulates interest in the students, although this survey is far from definitive. More work would need to be done to assess the impact of this particular project on students' perceptions of the engineering discipline.

While there are other opportunities to assess student learning by coding successful completion of outcomes from final reports and digital design notebooks, these must be left for future work since we do not currently have IRB approval for such a study. Overall, the course has been received positively by students and faculty, which is demonstrated by the longevity and breadth of use within this university.

Recommendations

There were five main lessons from the refinement process of this project that may be useful to others when designing projects for first-year students.

1. The choice of project should be impacted by topics that are broadly relatable and hopefully adaptable enough for students to explore different aspects that are of interest to them personally. The more a student can relate to the project, the more they will be willing to put into it and the more they will learn in the process.
2. When designing the project carefully consider the constraints that are given and design in the ability to change constraints in ways to vary the student experience. An adaptable project will have a much longer lifespan and will inhibit a preferred solution from developing over time.
3. Build in opportunities for just-in-time learning. Having students research what they don't know or letting their questions dictate the topics you teach enhances the learning experience and makes the class more fun.
4. Pay attention to the CLOs of your particular course and make sure that they are supported by your project. If new CLOs are added to your course, the project should change to allow you to meet them. It should be the CLOs that guide the development of the project, not the other way around.
5. Stakeholders or clients should drive the design. Consider adding opportunities for students to get needed information from clients (even if they are fictional clients) rather than from the instructor. Creating competing viewpoints is both realistic and helpful for creating a diversity in the solutions.

While these are all generalized recommendations for any first-year engineering project there are a few things that someone trying to run this project should know before implementing it in their class. Getting the platform together is the largest initial cost of implementing this project. We have found that a dedicated setup worked well for our purposes, but if you had a fan, some lights, and a way of creating a waterfall, this could be set up on a standard lab bench. We had the ability to have the setup placed outside in a patio near our lab space and this helped minimize the mess with the water (there will be a lot of splashing during initial testing). When choosing a fan, you want one that is at least 22 in in diameter, but something greater than 24 in creates a large region of wind to harness. You will also want to provide students with a wind anemometer (it does not have to be fancy) and just make sure that the wind speeds are between 4.5 m/s and 5.2 m/s at the high speed. This provides enough energy to be competitive.

One of the secrets that students do not often realize until the end is that because our setup is placed outside, most of the light energy does come from the sun (even though we place the setup in the shade). If you are going to be doing this inside, it is recommended to use higher wattage incandescent or sunlight bulbs with some way of focusing the light into a smaller region. One important thing that we were trying to model with using two different bulbs focused in different areas of the platform (and then telling students that there is a possibility that one or the other light would be off) was to model the variability of the solar resource. A flood lamp makes everything too uniform and so spot lamps were used instead. If the sun is not increasing the light intensity on the platform, you may want to use more bulbs or allow larger areas for solar cells to make solar a more viable option. This may require some testing to see what it would take to get between 100 mW and 300 mW in a best-case scenario.

For the waterfall, you want to make the source at least 30 in high off the platform so that the students cannot connect directly to it. This also provides an appropriate amount of gravity head. It is also recommended to have a settling chamber before the water comes out and a ball valve to control the flow rate. If you are doing this outside, a common factor that students overlook is the effect of the natural wind on the falling water. In strong gusts the water may blow out of its intended location and cause it to miss their waterwheel.

The final recommendation is to remind students that there is more to a successful design than power output. As the project has progressed, and specifically when there are multiple competeting stakeholder views, I simply ask them to justify how they created value for their stakeholders. They could do this through making efforts to minimize environmental impact, decreasing cost, having a low standard deviation, by creating large amounts of power, or maybe in some other way. The goal of the course is to better understand the engineering design process and to apply a rigorous process to solving a problem. The project is simply a vehicle to assess and teach these skills.

Summary

An energy project was developed that incorporates real-world concerns in a manageable first-year project. By changing constraints and using research-guided approaches to improve the project over time, this particular project has become an example of applying incremental improvements to meet the changing needs of an evolving introduction to engineering design class. The project itself has many advantages in that it provides opportunities for predictive modelling that is still tractable at a first-year level, it is adaptable through the changing of customer-generated constraints, and the topic itself is broad enough to cover a lot of different disciplines and interests. Recommendations based on lessons learned were given for any first-year project that may be developed and for specific concerns related to this project if this project were to be implemented in another setting.

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