Student Development of a Five kW Solar Furnace for Solar Thermal Chemistry Research

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Abstract

Numerous publications have described positive student outcomes when undergraduate engineering students participate in meaningful, real-world projects. Moreover, even students not directly involved in the real-world projects benefit through formal classroom interactions and informal social interactions with those students that are participating in the projects. Recently, students at Valparaiso University completed a massive, interdisciplinary project to design, manufacture, assemble, and test a half-million dollar, five kW solar furnace. Because of the scope of the project, 50 students spanning seven years of graduating classes and two engineering departments were involved. The avenues of student participation included summer internships, independent project work, and Capstone Senior Design projects. By working on the solar furnace project, students developed a myriad of valuable skills in such areas as project management, technical writing, communication, design, manufacturing, mechatronics, finite element analysis, circuit analysis, programming, and instrumentation. Additionally, 40 percent of the students who participated in the project chose to continue their engineering studies in graduate schools around the country.

1. Introduction

Multiple studies\textsuperscript{1-3} have shown the benefits of project-based learning. Students who participate in complex engineering projects develop a myriad of valuable skills. They develop the ability to solve large complex problems\textsuperscript{4}, they gain an appreciation of the entire engineering process, and they develop creative thinking skills\textsuperscript{5}. Moreover, their performance in the classroom improves\textsuperscript{6} as they see the connection between real-world problems and the fundamentals they are learning. Additionally, students learn how to work in teams and their communication skills improve\textsuperscript{7}. Finally, they are more prepared for graduate school or industry whose work environment focuses on projects and teams.

In 2006, a unique opportunity presented itself to mechanical engineering faculty at Valparaiso University. Professor Robert Palumbo had a history of including undergraduate engineering students in his research. Some of the research was completed during the school year; however, Professor Palumbo would also take three students with him to perform research in the solar furnace located at the Paul Scherrer Institute\textsuperscript{8} in Villigen, Switzerland. In 2006, funds became available from the Department of Energy and donations to build a five kW solar furnace at Valparaiso University. It would be the fifth large scale solar furnace in the United States.

The faculty had the option of outsourcing the design and construction of the solar furnace to professional engineering firms or providing undergraduate engineering students the opportunity to complete the majority of work. The disadvantage of using students was the increase in the time to completion and the increased level of faculty involvement. However, based on the project-based learning advantages outlined above, the decision was made to involve students in the design, manufacturing, assembly, and testing of the solar furnace. Fifty undergraduate engineering students in the mechanical and electrical engineering departments participated in the development of the solar furnace which was completed in 2013 and is now operational.
This paper describes the myriad contributions of the students to the solar furnace and the resulting positive student outcomes. An overview of the solar furnace is first presented to provide context for the discussion of student participation. The avenues in which students participated are then presented. We suggest that these avenues form a model for other universities interested in engaging students in a multi-year, interdisciplinary project spanning multiple generations of students. Specific student contributions are described in tandem with the major components of the furnace. Next, the relevant Accreditation Board for Engineering and Technology (ABET) student outcomes are associated with specific, supporting project examples, and additional positive outcomes are described. Finally, the lessons learned from the project are explained, and the paper ends with conclusions.

2. Solar furnace overview

The five kW solar furnace is depicted in Figs. 1 and 2. It is an instrument used to test technology that uses highly concentrated solar radiation as a source of process heat at temperatures in excess of 900 °C. The major components of the solar furnace are a heliostat, louvers, concentrator, reactor table, and associated controls and instrumentation. The heliostat, which holds 36 m² of solar mirrors, is located in front of the main building. It rotates on two axes to track the sun, reflecting sunlight into the building which houses the remaining furnace components. Note that the glass door, shown extended in Fig. 1, is lifted out of the path of the reflected beam during furnace operation. The louvers, an assembly of rotatable panels comparable to venetian blinds, regulate the furnace power level by attenuating some of the light reflected from the heliostat. The concentrator focuses the admitted light to a spot in front of the mirrors. An adjustable table assembly (i.e., reactor table) positions the aperture of a receiver into the concentrator’s focal point. A data acquisition system and measurement instrumentation monitor critical input and output variables such as in-plane solar radiative flux at the aperture and process temperature. The electrical and control system are used to locate the heliostat, louvers, and reactor in desired positions, enter control parameters, display outputs, and monitor the safety components.

Figure 1. The James S. Markiewicz Solar Energy Research Facility (Outside View)
3. Avenues of student participation

There were three avenues through which students could participate in the development of the solar furnace: 1) summer internships, 2) senior design projects, and 3) independent project work for credit. In regards to summer internships, students were selected in January based upon their academic performance and interest in the project. The students were offered a minimum stipend of 4,800 dollars for a 12 week internship. Additionally, Valparaiso University offers free summer dormitory housing for summer interns, allowing the students to live on campus without housing costs. Thirty-five students received summer internships during the development of the solar furnace, and the solar concentrator, louvers, and electrical and control systems were designed, manufactured, assembled, and tested during these internships. The summer interns worked under the supervision of four mechanical engineering faculty members.

A second avenue of student participation was senior design projects. The Capstone Senior Design course at Valparaiso University is a two course sequence: a three credit course in the fall semester and a three credit course in the spring semester. Both courses are required for all electrical engineering, computer engineering, and mechanical engineering students. The first course focuses on the definition, design, and analysis of the system and the second course focuses on the manufacture and testing of the system. Two multi-disciplinary senior design teams of mechanical and electrical engineering students participated in the development of the solar furnace. One team developed the reactor table, and the second team completed a solar
thermal electrochemical reactor. Each team had project budgets of approximately 20,000 dollars.

The final avenue of student participation was independent project credit. Mechanical engineering students at Valparaiso University can receive up to three credits towards their degree by working on a project under the supervision of a faculty member. Fifteen students used this avenue to participate in the development of the solar furnace, focusing on the conceptualization and design of the heliostat.

4.0 Solar furnace description and student contributions

In this section, student contributions to the solar furnace will be explained. Faculty supported, reviewed and validated all student work.

4.1 Concentrator

The concentrator (Fig. 2) is approximately 18 foot in diameter and consists of 305 adjustable hexagon-shape solar mirrors. They are supported by one nylon and two fiberglass brackets and are constrained within a slot machined in the brackets (Fig. 3). The fiberglass brackets are rigid and are used to support the mirror from below. The rigidity of the fiberglass eliminates creep of the mirror location with time enabling the mirrors to remain in focus. The flexible nylon bracket at the top of the mirror allows the placement and removal of the mirror in the assembly without removing fasteners. The rod end and clevis connection (Fig. 3) along with the threaded connection to the support plate allow the mirrors to be rotated to the desired angles. By adjusting these components, the mirrors are coarsely focused. Fine adjustment of the focus is accomplished at the back of the subassembly via the threaded rods. The mirror adjustment subassemblies are supported by a structure (Fig. 2) consisting of welded steel tubular sections that are bolted together and the entire structure is attached to the floor with concrete anchors.

The students developed the concentrator. Initially, the students designed the mirror adjustment subassemblies in SolidWorks\textsuperscript{10} and manufactured and mounted 12 units for prototype purposes. Using SolidWorks, each of the mirrors locations in the final array was then determined, which affected the length of the individual mirror subassemblies. Next, the students designed the concentrator frame and analyzed the frame using SolidWorks Simulation finite element software to check for static failure. The concrete mounting anchors were also specified to carry the appropriate loads. Once the design was complete, the students manufactured over 3000 parts in the machine shop and interacted with vendors to specify and purchase the remaining components. Additionally, students created manufacturing prints and worked with a certified welding shop to specify and purchase all welded components. After all parts were available, the students assembled each mirror subassembly. Finally, the students received lift safety training, assembled the concentrator frame, installed the mirror subassemblies, and spent two weeks focusing the mirrors. Fig. 4 shows a student mounting a mirror and preparing for the focusing operation.
4.2 Reactor table

The reactor table (Fig. 5) is used to accurately locate solar thermal reactors, high-temperature receivers, or measurement sensors at the focal point of the furnace. The reactor table is constructed of Bosch\textsuperscript{11} extrusion and capable of supporting a variety of reactors and receivers up to 110 kg. A three-axis linear drive system composed of linear ball bearings with associated tracks, ball-screws, and drive nuts moves the table. The accuracy of the motion is 0.12 mm in each direction. The ball screws are driven by 24 VDC motors with incremental encoder feedback. The motor used to lift the table in the vertical direction includes a brake to prevent the table from falling in the event of a power failure.

Students, working as part of a Senior Design team, designed the reactor table in SolidWorks. During the design process, students had to work closely with Thomson Industries\textsuperscript{12} to specify and integrate the linear components. Students also had to perform analysis and work with Groschopp Motors\textsuperscript{13} to specify the motors and feedback sensors. Finally, with the exception of the purchased parts and vertical support column, the students machined all remaining parts and assembled and tested the final system.
4.3 Reactor

The students developed a reactor for the electrothermal dissociation of zinc oxide. It is depicted in Fig. 6. Here we provide a brief summary. Concentrated sunlight enters the reactor through the aperture, which is constructed from zirconia felt, and heats a silicon carbide cavity to 1300–1500 K. The heat is conducted to a crucible that contains a zinc oxide-molten salt mixture. Electricity is supplied to the mixture through a platinum anode and molybdenum cathode causing the zinc oxide to dissociate with the oxygen forming on the anode and zinc vapor forming on the cathode. The gas migrates out of the molten salt mixture and flows out of the reactor through chimneys where the zinc condenses at cooling coils. The reactor is insulated and contained in a stainless steel shell.

The students performed multiple tasks to complete the reactor. They used SolidWorks to design the reactor assembly and components such that the reactor could be easily assembled for experimental runs (e.g., placement of the electrolyte and metal oxide, locating of the electrodes, etc.). Also, they completed a one-dimensional heat transfer analysis to predict temperature throughout the body, assuring the reactor was adequately insulated so that the stainless steel shell was within temperature specifications, and the electrolyte and metal oxide mixture would reach the specified temperature. Additionally, the students interfaced with outside suppliers to order a variety of specialized materials including the silicon carbide crucible and core and an alumina aperture and board insulation. The students also worked with a sheet metal supplier to produce the stainless steel shell, and some parts, such as the top plate, were machined by the students. Finally, the students assembled the reactor and mounted it on the reactor table.

4.4 Louvers

The louvers (Fig. 7) regulate the amount of solar energy concentrated into the solar furnace. They are composed of eight .724 m wide, 5.46 m tall, and 3.18 mm thick aluminum panels. These panels are connected to flanged roller bearings which allow the panels to rotate. As shown in Fig. 8, one panel is connected to a 24 VDC motor with a 124 to 1 planetary gearbox through a
Students used SolidWorks to design the louver assembly and components. As part of the design process, students worked with a sheet metal shop to specify the louver panels, performed analysis and worked with Groschopp Motors to specify the motor and feedback sensors, and interfaced with Motion Industries to purchase the drive belt and pulleys. Additionally, students machined all of the linkages and panel interface components. Finally, students assembled and tested the louver assembly.

Figure 7. Louver Assembly

Figure 8. Louver Drive Assembly

4.5 Heliostat

The heliostat (Fig. 9) consists of a vertical support, a drivetrain, a mirror support structure, and 42 mirror subassemblies arranged in a 7 by 7 array. Structural support is provided by a 16 inch diameter alloy steel tube embedded in a concrete footer (vertical support). A Winsmith DST-100 gearbox with an 18200 to 1 reduction in both the azimuth and elevation directions is located on the top of the vertical support. This gearbox, which is the heart of the drivetrain (Fig. 10), was provided by Sandia National Laboratories and was refurbished for use in our facility. Two 24 VDC, 126 W Groschopp motors with a 5 to 1 planetary gear reduction drive the azimuth and elevation motion to position the heliostat on-sun with the calculated sun position. The motors incorporate incremental, rather than absolute, encoders for positional accuracy. The heliostat must therefore be homed to a reference position. The reference position is located when homing flags on the underside of the mirrors activate plunge action limit switches. For safety and equipment protection, redundant limit switches are used to limit the motion of the heliostat in the azimuth and elevation directions. These sensors bypass the controller and shut-off the power to the motors if engaged.

The mirrors of the heliostat are supported with steel tubing and T components. A 25.4 cm diameter torque tube is attached to the gearbox and supports the structure to which the mirrors are attached. Bolted to the torque tube are 4 structural tubes connected by structural T components. The mirror subassemblies are bolted to the structural T components. To prevent excessive torque loads on the gearbox, the mirror support structure and subassemblies were located as close to the gearbox center of rotation as possible.
The mirror subassemblies were provided by PanelTec and the 3 mm solar mirrors were provided by Flabeg. The mirrors are supported by a light-weight aluminum panel structure constructed from 19 mm thick aluminum honeycomb sandwiched between two pieces of .81 mm aluminum sheet. Square aluminum tubing 19 mm on a side frames the four outer edges of the panel and all of the pieces are epoxied together. Double-sided 3M VHB tape covers the entire surface between the mirrors and the panel to secure the mirrors.

The students developed the initial heliostat concept and performed a finite element analysis using SolidWorks Simulation to analyze the structure for stresses due to wind and snow loading. Additionally, the students worked with PanelTec to specify the mirror subassemblies, manufactured mounting brackets, and mounted and wired all homing and limit switches. Due to safety concerns, Larson Danielson Construction Company was hired to finalize the design concept, manufacture the structural components, and install the heliostat.

![Figure 9. Final Assembly of Reactor Table](image)

![Figure 10. Heliostat Drive Assembly](image)

### 4.6 Electrical and controls

The electrical and control system is located in two separate UL listed cabinets, one located inside the building and the second located at the heliostat. The electrical cabinet in the building is shown in Fig. 11. The main controller is a National Instruments CompactRIO incorporating four motor drive modules (one motor for the louvers and three motors for the reactor table), digital I/O modules, and analog I/O modules. The cabinet also includes SICK safety relays, a 24 VDC power supply, and terminal blocks. The heliostat electrical cabinet is similar to the cabinet in the building but also includes relays to switch between normal heliostat operation and back-up power operation and two amplifiers to drive the larger motors on the heliostat.

The controllers are connected through a local network to a computer located in the control room. The LabVIEW graphical user interface (GUI), depicted in Fig. 12, is executed from this computer. From the GUI, the user can enable the drive systems for the heliostat and reactor table, initialize the heliostat in its reference position, set the drive systems for manual or automatic operation, and record measurements from the host computer. The GUI displays communication status with the controllers and it also displays outputs from sensors such as the heliostat azimuth and elevation angles, limit switch status, the temperature in the electrical cabinets, electric currents drawn by the heliostat drive, x-y-z coordinates of the reactor table, and percent opening of the louvers.
Students contributed to the development of the electrical and control system in multiple ways. They created electrical prints and panel prototypes (Fig. 13) for both panels. Additionally, students reviewed final design drawings, answered questions, and validated the final electrical panels which were supplied by Mega Design, L.L.C, an electrical engineering design and fabrication firm. Students installed both panels and wired remote components. Finally, students worked on the development of the LabVIEW GUI and assisted in the software programming of the control system.

![Figure 11. Electrical Cabinet](image1)

![Figure 12. Control Interface](image2)

![Figure 13. Students Assembling Prototype Panel](image3)

5. **Student Outcomes: ABET Criteria**

Students working on the solar furnace project developed multiple abilities and understandings as defined in the student outcomes section of the “Criteria for Accrediting Engineering Programs” by ABET. Each relevant student outcome along with specific project examples are provided below. The solar furnace is now operational to specification; therefore, as a group, the students developed the requisite abilities and understandings. In other words, the solar furnace would have not been completed or functional if the students had not developed the abilities and understandings defined by the ABET student outcomes.

5.1 **Outcome A: An Ability to Apply Knowledge of Mathematics, Science, and Engineering**

Students who worked on the solar furnace had a unique opportunity to apply their knowledge of engineering to a real-world engineering problem. For example, students created specifications and then designed the concentrator, louvers, reactor table, and reactors in SolidWorks CAD software. The designs were then analyzed using statics or finite element analysis software to assure that the associated loads could safely be supported or in the case of the reactor that the temperature on the reactor surface remained within specification. Once the designs were complete, reviewed, and revised, manufacturing prints were created and the students either worked with vendors contracted to produce the parts or manufactured the parts themselves in the
machine shop. A second example is the electrical and control system where students specified components, created electrical prints, designed and prototyped the electrical panels, worked with the supplier to produce the final electrical panels and cabinets, and programmed the system controller.

5.2 Outcome B: An Ability to Design and Conduct Experiments, as Well as Analyze and Interpret Data

The participating students developed an ability to design and conduct experiments, as well as analyze and interpret data. One example of the development of this ability was the testing of the operational solar furnace to determine the power output based on the sun’s irradiance. An off-the-shelf instrument was not available for this testing; therefore, the students first had to conceptualize, design, manufacture, and calibrate a custom calorimeter. This calorimeter approximates a black body and was placed at the focal point of the concentrated sunlight. The sunlight entered the device and heated flowing water. Knowing the inlet and outlet temperatures of the water along with the flow rate, the students could determine the sun’s energy entering the calorimeter. Once the calorimeter was developed, students used a pyrheliometer to measure the sun’s irradiance and correlate it to the calorimeter power readings. The final analysis included an uncertainty analysis which incorporated both biased and random uncertainty contributions.

5.3 Outcome C: An Ability to Design a System, Component, or Process to Meet Desired Needs Within Realistic Constraints Such as Economic, Environmental, Social, Political, Ethical, and Health and Safety

Student participants in the solar furnace project developed an ability to design a system to meet desired needs within realistic constraints. Three examples will be used to illustrate this point. First, the overall budget for the solar furnace was 500 thousand dollars and this budget was subdivided into smaller budget requirements for each system (i.e., concentrator, heliostat, etc.). So every student working on the project had to design within a specified economic constraint. Second, the students had to design a system that could be operated under OSHA safety requirements. In this respect, students developed hazardous energy control procedures for locking out hazardous energy, created job safety analysis procedures for the operation of the facility, and guarded all moving equipment to zero access guarding requirements. University safety personnel signed off on all of these procedures. Finally, the students had to design within the aesthetic requirements of the university and the donor, both who were integrally involved in the appearance of the solar furnace.

5.4 Outcome D: An Ability to Function on Multi-Disciplinary Teams

All students who worked on the solar furnace project participated as a member of a multi-disciplinary team consisting of mechanical engineering, electrical engineering, and computer engineering students and faculty. By participating as a member of a multi-disciplinary team, students were able to develop knowledge in areas beyond their specific field of study and gain teamwork skills that are much sought after by industry and graduate programs. As an example of a multi-disciplinary team effort, consider the reactor table which was produced by a multi-disciplinary senior design team. The team members had to work together to create a design
The students then had to work together to produce a design that incorporated both mechanical and electrical components such as bearings, motors, sensors, controllers, etc. Finally, the team members had to manufacture or order the components, assemble them, program the controller, and test the entire system for functionality.

5.5 **Outcome E: An Ability to Identify, Formulate, and Solve Engineering Problems**

The students working on the solar furnace project had multiple opportunities to develop an ability to identify, formulate, and solve engineering problems. For example, one engineering problem associated with the concentrator was that a system and method was required to focus each mirror. To accomplish the focusing, the system requirements including the ability to rotate each mirror around three orthogonal axis and translate the mirror in the direction of one axis. Additionally, the mirror focus had to be accurate to within 0.5 degrees. The students formulated and executed the solution shown in Fig. 3 which used a threaded rod and a rod a clevis assembly to rough focus the mirrors and threaded rods at the end of the subassembly to fine focus the mirrors. In addition to the design, the students developed a system to correctly locate each mirror subassembly in the mirror array, designed and produced a fixture for focusing each individual mirror, and spent two weeks performing the actual focusing of the 305 mirrors.

5.6 **Outcome J: A Knowledge of Contemporary Issues**

Students who worked on the solar furnace project gained expansive knowledge in a current area of great importance, the ability to generate and store clean energy. By interacting with project associated faculty, students learned about the importance of reducing emissions, especially greenhouse gas emissions, and the challenge of reducing these emissions in a cost competitive manner. Additionally, students working during summer internships participated in a university wide research support program where they were required to present their work to faculty and students from diverse backgrounds, including non-technical fields. Following these presentations, student and faculty discussions took place, providing another opportunity for students working on the solar furnace to receive a diverse range of suggestions and opinions.

5.7 **Outcome K: An Ability to Use the Techniques, Skills, and Modern Engineering Tools Necessary for Engineering Practice**

The solar furnace project students developed many skills necessary for engineering practice. They improved their computer aided design abilities by producing designs of the heliostat, concentrator, louvers, reactor, and reactor table in SolidWorks. By creating manufacturing prints and working with suppliers, they increased their drawing skills. Additionally, the students performed analysis of the concentrator and heliostat structures, developing skills in the area of finite element analysis software. By producing parts in the manufacturing laboratory for all major solar furnace systems, they learned computer aided manufacturing programming skills along with manual and computer numerical control machining skills. The students developed LabVIEW skills by programming the controller and creating a human-machine interface, and finally, students developed MATLAB programming skills by using ray tracing techniques to predict the solar energy entering the reactor.
6. **Additional Outcomes**

6.1 **Availability of Unique Instrument**

The student’s participation is the solar furnace project led to the development of a unique instrument as there are only four other large-scale solar furnaces in the United States. Having access to the solar furnace has already been instrumental in Valparaiso University receiving a 2.3 million dollar grant from the Department of Energy ARPA-E program to study the production of magnesium using sunlight and a National Science Foundation grant to study the production of hydrogen using sunlight. It is unusual for an undergraduate only engineering program to receive grants of this nature. These grants will provide a multitude of researchers and students the opportunity to use the solar furnace to develop and test high-temperature solar technologies. Additionally, students and faculty will have the ability to perform research in other areas that require high temperatures (e.g., materials science, chemistry, physics, etc.). Finally, Valparaiso University and the College of Engineering will gain recognition by having a world-class research facility located on the campus. This recognition will attract additional, talented students who are interested in engineering and the sciences along with solar energy. Fig. 14 shows the furnace in operation with the sunlight concentrated on a water-cooled target.

![Figure 14. Solar Furnace in Operation](image)

6.2 **Job Placement and Graduate School**

Twenty students who worked on the project continued their education in graduate school, and the remaining 30 students progressed to industry with a 100 percent placement rate. Student team members are currently employed or received offers of employment by such reputable companies as Honeywell, Navistar, John Deer, and Caterpillar. Multiple student team members have received fully-funded fellowships to continue their engineering studies in graduate school at prestigious universities such as Georgia Tech, the University of Minnesota, the University of Florida, the University of Illinois-Urbana Champagne, the University of Michigan, and Vanderbilt University.

6.3 **Student Financial Support**

Student team members received over 100,000 dollars of internship pay for their contributions to the project. In addition, summer internship students received free housing in dormitories. Finally, the completed solar furnace enabled grants that will provide future funding for 25 additional students.
6.4 Faculty Benefits

By participating with students on the solar furnace project, faculty were able to improve their own skills and develop knowledge and skills in such areas as mentorship, project management, design, analysis, and programming and remain current in their fields. The faculty now transfer this new knowledge to all engineering students through such mediums as the classroom, laboratory, and senior design projects. As one example, participating faculty had not previously used or programmed the National Instruments CompactRIO controller, but by working with students on the project, they have been able to master the controller and transfer their newfound skills to other students now using the controller on various senior design project unrelated to the solar furnace project.

6.5 Community Benefits

By developing the solar furnace, the students have also created an instrument that benefits the university community, the Northwest Indiana community, and society in general. The facility that houses the solar furnaces is open for tours to campus group, community groups, and local school groups and many of these groups have already visited. During the visits, the guests learn about engineering and science through an exciting medium while also learning about the potential and challenges of solar energy as a clean energy resource.

7. Lessons Learned

The faculty who participated in the development of the solar furnace project learned many lessons that could be applied to future projects of this magnitude. The first lesson that was learned is that it is important to meet with the project stakeholders before the project begins to determine their requirements and expectations. For example, donors have expectations in regard to aesthetics, student participation, and project timelines. The university administration has expectations in regard to budgetary constraints, aesthetics, safety, and timelines. Finally, different faculty have varying expectations on participation level and time commitments.

The second lesson that was learned is that communication is critical to the success of the project. It is important to hold weekly update meetings with the participating faculty and students to prioritize work, review designs, and transfer knowledge. Bi-yearly meetings with all stakeholders including donors and university administration are also critical to assure that all important expectations are being met.

The third lesson that was learned is that a documentation procedure must be created before the project begins and rigorously followed during the course of the project. Unlike a graduate student program where the associated students remain with the project for years, the solar furnace project, being exclusively undergraduate, had students participate for approximately one year in length. To assure the success of the project and an acceptable hand-off of information, documentation is critical. Specific computer folders and project binders were created for the solar furnace project and updated and assessed on a regular basis.
Finally, having multiple students contribute in multiple ways to a large project is very different than having students work on separate projects. A large project has multiple advantages. The students are excited about participating in something large and unique that has the potential to contribute to an interesting field of study, clean energy. The student experience is also diverse as they participate within a multi-disciplinary group and learn about all aspects of the project, even the areas that are not their direct responsibility. The students also get to interact with donors, university administration, faculty from across campus, community groups, and school groups. Through this interaction, the students practice and hone their communications and interpersonal skills. A large project also has disadvantages. The logistics of completing a multi-year project with multiple students are challenging and although the students get to experience the satisfaction of completing their small area of the project, they don’t see the entire completed project until they return to campus after graduation.

8. Conclusions

The incorporation of project-based learning in an undergraduate engineering education generates countless opportunities for students to develop and gain practical engineering skills. The mechanical engineering faculty at Valparaiso University believe one approach to completing large-scale projects with undergraduates is to offer a variety of avenues of participation including summer internships, independent project work, and Capstone Senior Design projects. This approach was incorporated during the development of a half million dollar, five kWatt solar furnace where 50 undergraduate students participated in the project. The project was successful as the solar furnace is now operational and multiple positive student outcomes were produced. These outcomes include multiple student outcomes identified in the ABET criteria, the creation of a unique instrument, 100 percent placement in graduate school or industry, a high percentage of student participants proceeding to graduate studies, student financial support, the development of faculty skills and knowledge, and community benefits.

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