Ponderosa High School Sustainability

Design Report

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EXECUTIVE SUMMARY

Ponderosa High School – Sustainability and Energy Project Description

This senior capstone project is a collaborative engineering partnership between Northern Arizona University (NAU) Mechanical Engineering Department and Ponderosa High School (PHS) in Flagstaff, Arizona. The project focuses on evaluating, analyzing, and enhancing an existing 24-volt off-grid renewable energy system that powers PHS's educational greenhouse. With up to $1,000 in NAU funding, a minimum of $750 in student fundraising, and potential additional support from PHS, the project aims to improve system performance while expanding on the greenhouse's educational value.

The greenhouse is powered by a hybrid renewable energy system consisting of a small wind turbine, four solar panels, 24-Volt battery bank, charge controllers, and inverters. The facility supports lighting, heating, fans, aquaponics pumps, and environmental controls. However, the school seeks a clearer understanding of system performance, operational limitations, and opportunities for expansion to better support greenhouse operations and sustainability education.

The project begins with a comprehensive energy audit of all electrical loads in the greenhouse. The capstone team will inventory equipment, determine rated power and duty cycles, and calculate daily, monthly, and seasonal energy consumption. This data will be synthesized into a detailed energy balance to establish current and projected energy demand.

Next, the team will analyze the existing system's capacity, including battery, peak power capability, and potential equipment constraints. This analysis will determine how much load the system can reliably support and identify any malfunctioning or outdated components, such as a potentially non-operational wind turbine.

A renewable energy resource assessment will then estimate energy production from the existing solar and wind systems using local solar and wind data, and modeled performance losses. Based on these findings, the team will propose system improvements and expansion options. Potential enhancements include increasing battery capacity, adding additional solar panels (with possible panel donations from NAU), improving load efficiency, optimizing control strategies, and implementing real-time performance monitoring for an educational display. Each recommendation will include cost estimates, technical feasibility, expected benefits, and educational value.

An innovative component of the project is the design of a human-powered charging system, such as two stationary bicycle generators, compatible with the existing 24V battery bank. This system will serve as both a supplemental charging source and an interactive teaching tool demonstrating energy conversion, human power output, and battery charging principles to the students.

Finally, the capstone team will develop STEAM-aligned educational curriculum materials for high school students. Topics will include energy fundamentals, wind and solar energy, and electricity.

Project deliverables include a detailed energy audit report, system capacity analysis, improvement recommendations, human powered charging system design and manufacturing, educational materials, and a final written report and presentation.

This collaboration provides our capstone team with real-world system analysis and design experience while strengthening sustainability education at Ponderosa High School. The project creates meaningful community impact by enhancing renewable energy infrastructure and fostering hands-on learning in clean energy technologies for future generations.

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1 BACKGROUND

This chapter provides an overview of the PHS off-grid greenhouse energy and system enhancement suggestions. This chapter will also outline the scope of work objectives, funding and importance of the work. Additionally, we will cover the expected project deliverables and establish successful criteria that will help guide our designs, analysis, and final evaluation of the project.

1.1 Project Description

This project is a collaboration between NAU and PHS. The focus is evaluating and improving an existing 24-volt off-grid renewable energy system that powers a small greenhouse. The greenhouse currently operates using a hybrid renewable energy system consisting of a set of solar panels, a wind turbine, a 24V battery bank, charge controllers, and inverters. The system supports loads required for plant growth and aquaponic operations, including lighting, pumps, fans, heating elements, and environmental monitoring to support the ecosystems in the greenhouse which also includes animals.

The primary goal of the project is to conduct a comprehensive energy audit and system capacity analysis to determine how well the current renewable energy system meets greenhouse demand. The team will access system limitations, evaluate renewable energy generation potential, and identify opportunities for improvement and expansion. One component of this expansion is the designing and eventual manufacturing of two human powered stationary bicycles that integrate with the existing battery bank and can be used not only as a supplemental method for energy production but also an interactive tool for the students.

This project is important because it combines technical engineering skills and analysis with meaningful impact in our Flagstaff community. The project strengths renewable energy infrastructure at a local high school, supports sustainability education, and provides hands-on STEAM learning opportunities. At the same time this project offers valuable real-world experience in working with a client, energy auditing, system modeling, and applied design.

1.2 Deliverables

The major project deliverables include:

- Comprehensive greenhouse energy audit
- Existing system performance analysis
- System improvement and expansion recommendations including cost estimates and feasibility
- Heat retention for animal life in the greenhouse
- Design for the human-powered energy generation system and integration
- Educational curriculum materials aligned with the above and STEAM objectives for the students

These deliverables and implementation of these objectives satisfy the clients' expectations and the course requirements for this project.

1.3 Success Metrics

Project success will be measured through both technical performance and educational impact.

From a technical perspective, success will include:

- Completion of a validated energy audit and clearly documented assumptions and calculations.

- Accurate modeling of renewable energy generation and battery system capacity
- Identification of system constraints and performance limitations
- Improvement recommendations that fall within the budget
- A functional and safe human-powered charging system design compatible with the existing 24V battery bank infrastructure

Engineering analysis will be supported through calculations, modeling, and validation.

From an education perspective, success will include:

- Development and engagement curriculum materials
- Demonstration of engineering concepts in a way that enhances student engagement and encourages STEAM education

Ultimately, the project will be considered successful if it delivers technically sound analysis, actionable system improvements, and meaningful educational value to Ponderosa High School.

2 REQUIREMENTS

This chapter defines the requirements that guide the design and evaluation of the Ponderosa High School greenhouse energy system project. Requirements are divided into two categories: Customer Requirements and Engineering Requirements. Customer Requirements represent the needs and expectations of the project stakeholder, Ponderosa High School while Engineering Requirements translate those needs into measurable and quantifiable technical specifications that can be evaluated through calculations, testing, and simulations.

2.1 Customer Requirements (CRs)

The following customer requirements were identified through the project proposal and discussions with the project sponsor. These requirements represent the primary needs of the high school teachers and students.

1. **Efficiency**

   The renewable energy system should operate efficiently by maximizing the conversion of available solar, wind, and human-generated energy into usable electrical power while minimizing energy losses in generation, storage, and distribution.

2. **Student Engagement**

   The system should be interactive and educational so that high school students can actively learn about renewable energy concepts. The project should include visual demonstrations, real-time monitoring, and hands-on learning opportunities that support STEAM education.

3. **Human Powered Bicycle Generator**

   The system should include two bicycle-powered generators that allow students to produce electricity through pedaling. The generator must be compatible with the existing 24V battery system and provide a safe, functional, and educational demonstration of human energy conversion.

4. **System Optimization**

   The existing renewable energy system should be analyzed and improved to ensure that energy generation, storage, and consumption are balanced. Optimization may include improving system efficiency, adjusting system configuration, or identifying operational changes that increase overall performance.

5. **Battery Storage**

   The system must include sufficient batter storage capacity to store renewable energy and supply power to the greenhouse loads when solar or wind generation is unavailable. The battery system should support reliable operation and maintain safe limits.

6. **Working Wind Turbine**

   The existing wind turbine should be inspected and verified to ensure it is operating correctly. The turbine will generate measurable electrical power under appropriate wind conditions and will contribute to the overall renewable energy supply.

7. **Increased Solar Power**

   The system should explore opportunities to increase solar energy generation by adding additional panels or improving the performance of the existing panels to better meet greenhouse energy demands.

8. **Tortoise Enclosure**

   The greenhouse contains a tortoise that is unable to live in the greenhouse year-round due to the temperature being too low in the winter. Using lighting, heating, a new enclosure, and water circulation to regulate this temperature. The energy system must reliably support these loads to maintain proper living conditions.

9. **Reliable/low Maintenance System**

   The renewable energy system should be designed to operate reliably with minimal maintenance requirements. Components should be durable, easy to operate, and suitable for a school environment where technical maintenance resources may be limited.

10. **Increased Energy Output**

    The system should generate enough energy to support the current greenhouse loads while allowing for some minor additional features and expansion of educational equipment. Increasing energy production from renewable sources is a key objective of the project.

2.2 Engineering Requirements (ERs)

Engineering requirements translate the customer requirements into quantifiable performance metrics that can be evaluated through calculations, simulations, or testing.

Table I

Engineering Requirements

ER#	Engineering Requirement	Description	Target	Units
1	Greenhouse Energy Consumption	Percentage of greenhouse electrical demand supplied by the renewable energy system	50	%
2	Tortoise Habitat Temperature Regulation	Maintain a stable temperature range suitable for the tortoise habitat environment	80±5	Fahrenheit
3	Solar powered generation	Total electrical power generated by the system	3500	kW
4	Human Power Generation	Electrical power produced by the bicycle(s) during operation	100	W
5	Wind Turbine Generation	Electrical power output generated by the wind turbine	300	W

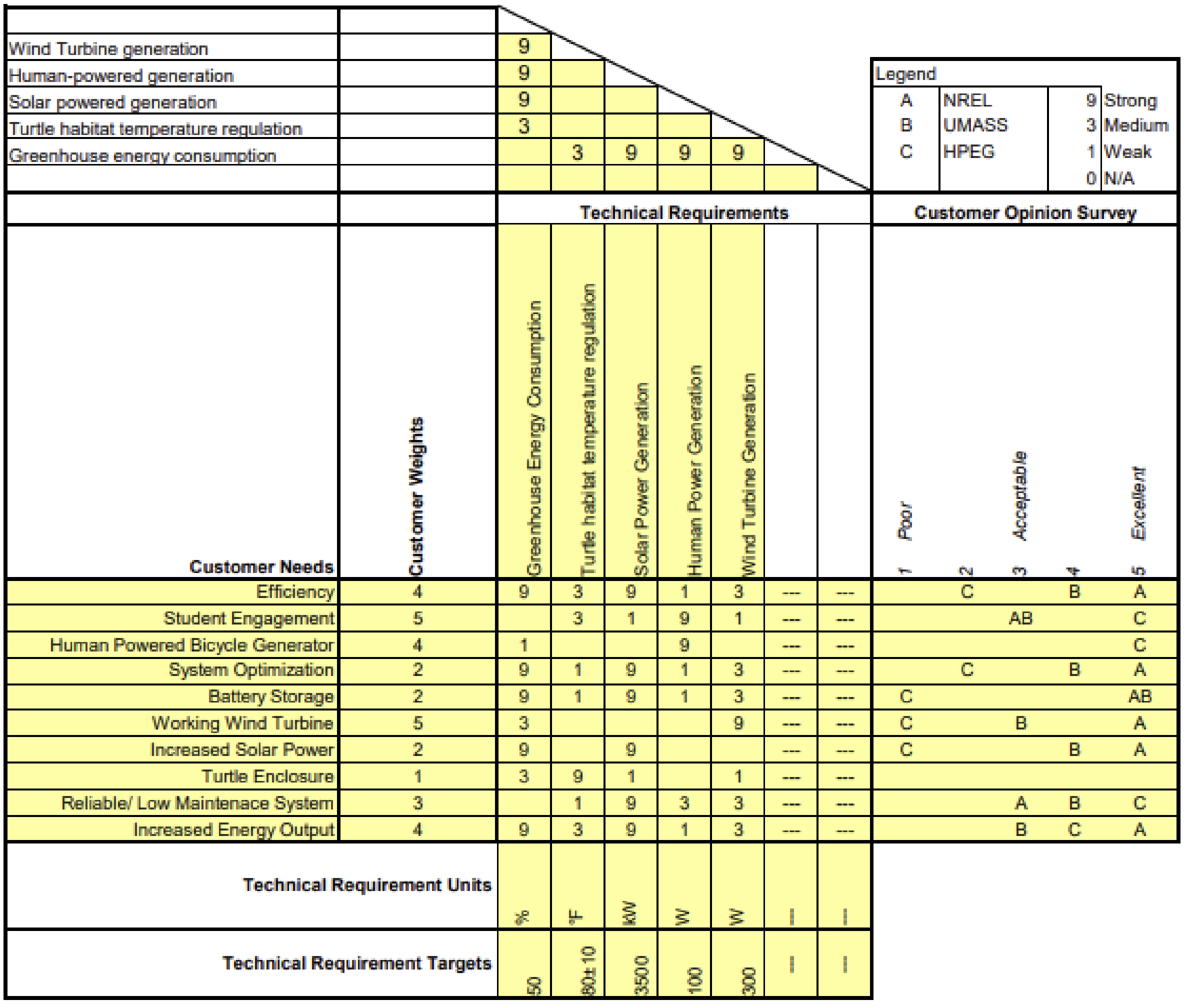
2.3 House of Quality (HoQ)

The House of Quality (HoQ) was developed to translate the customer requirements into measurable engineering requirements and guide the design decisions for the greenhouse renewable energy system.

HoQ is a key process that helps ensure that the final system design aligns with client needs while measuring technical performance targets.

The left side of the HoQ contains the customer requirements identified in the project description and provided by the sponsor. These requirements reflect the needs of Ponderosa High School. Across the top of the figure are the engineering requirements. These are measurable parameters that include a target value, allowing the team to quantitatively evaluate whether the design meets the project goals. The center of the HoQ shows the strength of the relationship between each customer requirement and each engineering requirement. Stronger relationships are indicated by larger numbers and show improvements in particular that will improve client satisfaction. The roof section of the HoQ identifies the interactions between engineering requirements. Correlations indicate that improving one parameter supports another.

Finally, the customer opinion survey values were included to ensure that the proposed design criteria are achievable within the technical constraints of the greenhouse system. The completed HoQ provides a structural framework for prioritizing design decisions and ensuring that the final system improvements meet both technical performance goals and client expectations.



Wind Turbine generation	9					
Human-powered generation	9					
Solar powered generation	9					
Turtle habitat temperature regulation	3					
Greenhouse energy consumption		3	9	9	9	

Legend			
A	NREL	9	Strong
B	UMASS	3	Medium
C	HPEG	1	Weak
		0	N/A

		Technical Requirements							Customer Opinion Survey				
Customer Needs	Customer Weights	Greenhouse Energy Consumption	Turtle habitat temperature regulation	Solar Power Generation	Human Power Generation	Wind Turbine Generation			1 Poor	2	3 Acceptable	4	5 Excellent
Efficiency	4	9	3	9	1	3	---	---		C		B	A
Student Engagement	5		3	1	9	1	---	---			AB		C
Human Powered Bicycle Generator	4	1			9		---	---					C
System Optimization	2	9	1	9	1	3	---	---		C		B	A
Battery Storage	2	9	1	9	1	3	---	---	C				AB
Working Wind Turbine	5	3				9	---	---	C		B		A
Increased Solar Power	2	9		9			---	---	C			B	A
Turtle Enclosure	1	3	9	1		1	---	---					
Reliable/ Low Maintenace System	3		1	9	3	3	---	---			A	B	C
Increased Energy Output	4	9	3	9	1	3	---	---			B	C	A
Technical Requirement Units		%	°F	kW	W	W	---	---					
Technical Requirement Targets		50	80± 10	3500	100	300	---	---					

Figure 1: QFD

3 RESEARCH WITHIN DESIGN SPACE

This chapter summarizes the research that was conducted to better understand the technologies and engineering principles relevant to the greenhouse. The research includes benchmarking of existing renewable energy systems, a literature review of technical resources, and mathematical modeling used to evaluate the system's performance. These investigations help guide design decisions and ensure that the proposed improvements are based on established engineering principles and current best practices.

3.1 Benchmarking

System-level benchmarking was conducted to understand how similar off-grid renewable energy systems operate and to identify design practices that represent current state-of-the-art solutions. These benchmarks systems include educational renewable energy installations, small hybrid renewable systems, and off-grid greenhouse energy systems. The benchmarking process evaluates system components such as solar power generation, small wind turbines, battery storage systems, and hybrid management approaches.

1. National Renewable Energy Laboratory (NREL) [1]

   One benchmark system examined is the National Renewable Energy Laboratory (NREL) small hybrid renewable system demonstration, which integrated photovoltaic panels, wind turbines, and battery storage for off-grid applications. This system demonstrates how hybrid renewable generation can improve energy reliability by combining solar and wind resources.

2. University of Massachusetts Renewable Energy Living Laboratory [2]

   This benchmark includes educational renewable energy installations designed to demonstrate solar, wind, and energy storage technologies for students. These systems highlight the importance of incorporating monitoring and visualization tools so students can observe real-time energy generation and consumption.

3. Human Powered Energy Generator System on a Bicycle [3]

   This study discusses human power energy generator system that has been designed to work with bicycles. This system demonstrates feasibility and expected power output. The reported output range establishes realistic design expectations for a human-powered charging system that could supplement the greenhouse's 24V battery bank while also servicing as a demonstration of human energy conversion.

3.2 Literature Review

3.2.1 Alexandra Miller

1. Optimizing Off-grid Energy Solutions: A Hybrid Approach Leveraging Solar, Wind, and Biomass for Sustainable Development [4]

   This paper discusses a study done in Morocco that uses different hybrid systems in rural regions to see the renewable energy potential. The hybrid systems are different in every region, so the system would be most optimal for that region. Some components found in these systems are solar generation, wind generation, hydropower, biofuel, and battery storage. The goal of this study is to find the advantages and disadvantages of a hybrid system in these rural regions. Additionally, the hybrid systems were monitored to see how much energy output was being created and how this stored energy could be preserved as a backup source for the rural towns. This paper shows the team a large-scale version of the PHS greenhouse and how different renewable energy can be an advantage or disadvantage to a specific climate.

2. Applications of Hybrid Wind Solar Battery Based Microgrid for Small-Scale Stand-Alone Systems and Grid Integration for Multi-Feeder Systems [5]

   This book discusses different applications for hybrid wind-solar energy systems (HRES). A large problem that occurs with hybrid systems is fluctuating voltages and load variation, which can affect the overall stability and efficiency of the system. Since solar and wind generation are dependent on the changing environment, there is always going to be load variation, but this can be managed through charge controllers and inverters. This book also has general knowledge about how circuits work and how they can be engineered to increase efficiency in a system. The team can learn about how charge controllers and inverters work and how essential they are to an optimized renewable energy system. This will increase the team's knowledge of the renewable energy system at the PHS greenhouse.

3. Stochastic Optimization a New Method Based on for Solving Dynamic Reactive Power Optimization Problems Involving Renewable Energy and Storage [6]

   This paper utilizes stochastic optimization to theoretically conclude what the best combination of renewable energy and battery storage would be for any hybrid system. In this paper, an approximate PSAA is used instead of SAA (the traditional mathematical approach for energy optimization). PSAA uses piecewise approximation for linear constraints instead of mixed integer linear programming (SAA). This approach to energy optimization is relatively new, and although it is used in mathematical applications right now, it gives the team a mathematical understanding of the theory behind energy generation in correspondence with battery storage.

4. Solar-Wind Hybrid Energy System Using MPPT [7]

   In this conference paper, the solar-wind hybrid energy system using the maximum point power tracking (MPPT) controller is analyzed on the stability and efficiency of the system. In this paper, solar and wind generation are specifically chosen because of how they can enhance each other's qualities. Constant voltage methods are chosen to increase stability and efficiency for the solar-wind hybrid energy system. From this conference paper, the team can look at a hybrid system that closely resembles the hybrid system at the PHS greenhouse. Additionally, this paper showcases how a solar-wind hybrid system increases the stability and efficiency of energy generation, therefore solidifying the team's choice to confirm that the wind turbine works.

5. Modeling and Optimization of Renewable Energy Systems [8]

   This book discusses a range of components for hybrid systems, different combinations of hybrid systems, and the possible energy outputs from those systems, respectively. There are case studies on hybrid systems to analyze the environmental and economic benefits for each system. This book can give the team a general overview of different hybrid systems and how each component can benefit the PHS greenhouse. In our case, we are focused specifically on the environmental benefits of the hybrid system. This is because our clients are more focused on creating a healthy environment for the animals and plants in the greenhouse than the economic benefit from the self-powering system.

6. Turn pedals into power: A practical guide to human-powered energy - The Institution of Electronics [9]

   The Institution of Electronics is dedicated to finding innovative ways to transform current mechanical devices to build electronic power. One of their areas of research is pedal power, which is specifically the type of human powered generation the team is interested in. This article discusses different ways to generate electricity using pedal power. The circuits for both DC and AC are shown in this article. This source gives the team ideas of how to set up our electrical system for the human powered bicycle generator.

7. Pedal Power: Building a bicycle-powered generator [10]

   This article showcases a step-by-step guide on how to build a human powered bicycle generator. The bike was built by Amy Darell, a big enthusiast for sustainable energy. In this article, all the materials used to build the bike are listed along with price estimates for each. The trials of building the bike are explained down to each step. Additionally, all the problems that occurred during the process are explained and the solutions to those problems. This article will help the team with concept generation, choosing materials, and building the bill of materials for the human powered bicycle generator. The solutions to common problems when building the bike will be used as a reference if the team has any problems during the manufacturing process for human powered bicycles.

3.2.2 Carson Harder

1. Examples and Equations for Solar Energy: Stand-Alone Photovoltaic Systems - A Handbook of Recommended Design Practices [11]

   This textbook shows examples of solar panel systems and energy calculations for proposed systems. This textbook provides examples of how to calculate energy consumption as well as the energy generated for off and on grid systems. Examples from the textbook can be used as a reference and can be modified to check the energy generated from the greenhouse's off

2. Industry Standards for Solar Panel Installation and Energy Equations: NABCEP 2019 PV Certification Study-Guide [12]

   The document serves as a guide for professionals learning to install solar panels for industry, as the goal is to add more solar panels, do repairs/maintenance on the current solar panels, and improve the efficiency of their current system this will serve as a reference for the team. Most of the other documents focus on equations and hypotheses while this document serves as a practical means of understanding real-world solar panel installation and safety measures.

3. Safety Regulations for electrical systems and construction: OSHA 10-hour General Industry Study Guide [13]

   The importance of this document is based off the safety measures outlined in the electrical, working surfaces and personal protective equipment. With the goal of bringing upgrades to the off-grid system and development of a bicycle powered generator, safety measures for the team, staff and students will be paramount to a safe learning environment. Providing safety measures and strategies will be implemented as hazards may occur during the project development.

4. Solar Irradiance information over the previous 30 years: PVWatts® Calculator [14]

   The information from this website serves as a datum point to verify calculations and create a range of values to compare with the team's calculations for solar energy generation. The website allows for multiple factor inputs to generate the most accurate results with a given panels area, location, angle, and efficiency.

5. Efficiency based on Temperature and Wind: Temperature and wind speed impact on the efficiency of PV installations [15]

   Other factors that may affect the efficiency of the panels are temperature and wind. Constant fluctuations in temperature over a prolonged period can decrease the efficiency of energy generation. Wind also may affect the efficiency of the cells by moving dirt onto the panels causing small scratch marks in the photovoltaic cells.

6. Effect of Humidity on the Efficiency of Solar Cell [16]

   Many factors can cause an increase or decrease in efficiency in solar panels, as the panels are exposed to the elements constantly humidity can affect the wiring and/or the cells in the panels. This article allows for a detailed review of how the change in humidity levels will affect/already affected the panels on the greenhouse.

7. Effect of tilt angles of Solar Panel in energy generation: Performance evaluation of photovoltaic modules at different tilt angles and orientations [17]

   This article provides background information on how the angle a solar panel array is set at can directly impact the total energy generated. With detailed calculations and tests, the article allows for potential optimization of the current system as well as future improvements planned for the PHS greenhouse.

3.2.3 Ethan Schalnat

1. Bicycle Power Generation and its Feasibility [18]
   This book provides a practical foundation for bicycle-based electricity generation. It catalogs real-world generator configurations rated by power output and conversion efficiency, offering a comparative analysis of alternator and DC motor-type systems. A detailed cost-benefit analysis examines the economic viability of pedal-powered generation for small-scale and off-grid systems, applicable to PHS's greenhouse.

2. Bicycling Science [19]
   This text examines the biomechanics and mechanical principles governing human cycling

performance. It quantifies human metabolic efficiency for various target groups during pedaling and derives mechanical advantage relationships across drivetrain components. These form the basis for gear ratio and torque analysis. The book dives heavily into pedaling biomechanics, including cadence, crank arm geometry, and force application, which directly informs the design of human-powered generator systems seeking to maximize power output.

3. Converting Human Power into Electricity: Current Status and Future Directions [20]
   This 2023 review surveys the current landscape of human power conversion technologies, encompassing pedal-driven, kinetic, and wearable harvesting modalities. The authors assess existing systems against efficiency benchmarks and identify critical performance gaps. The article projects future innovation trajectories, including advances in piezoelectric transduction, electromagnetic induction, and hybrid energy capture architectures. It provides a technology readiness assessment that contextualizes where bicycle generator systems sit within the broader human-powered energy domain.

4. Design and Realization of A 300 W Human Power Energy Generator System on a Bicycle [3]
   This paper presents the design, fabrication, and experimental validation of a 300 W bicycle-mounted generator system. The authors develop the governing mechanical equations relating pedaling cadence, gear ratio, and alternator angular velocity to electrical power output. System efficiency is decomposed across drivetrain, alternator, contact, and charge conversion stages, which were used to find total efficiency of the system. Empirical testing confirms the predicted power output under realistic pedaling conditions, validating design parameters for human-powered generation.

5. Human Power Production and Energy Harvesting [21]
   This encyclopedic review systematically characterizes the human body as an energy source, quantifying power output across locomotion modes including walking, running, and cycling. It surveys electromagnetic, piezoelectric, and thermoelectric transduction technologies applicable to wearable and body-worn harvesting devices. In addition, potential applications in portable electronics, medical monitoring, and military load reduction are assessed. The work provides physiological and engineering benchmarks that anchor theoretical power availability underlying human-powered generation system design.

6. Human-Powered Electricity Generation as a Renewable Resource [22]
   This paper presents a real-world example of human-powered electricity generation within a larger grid system, treating metabolic energy output from exercise as a resource. The authors conduct a feasibility analysis of gym-scale generation systems, comparing energy return on investment against solar photovoltaic benchmarks. Results indicate that while human power cannot match solar at utility scale, it holds value as a supplemental or hybrid generation source in specific high-occupancy settings.

7. Pedal Power Generation [23]
   This paper examines the practical implementation of pedal-powered generation using both dynamo and alternator conversion architectures. The authors analyze circuit-level integration of battery storage systems for load smoothing and energy buffering, addressing intermittency inherent to human power inputs. Field deployment considerations for rural and off-grid contexts are discussed, with emphasis on system reliability and cost. The work provides engineering detail on energy storage integration that is directly applicable to portable and remote-area power supply

applications.

3.2.4 Jenna Sterry

1. Horticulture and Landscape Architecture Temperature Control in Greenhouses [24]

   This paper describes the optimal temperatures for a greenhouse with different ways to cool and warm the house. The authors give pros and cons to each method with some methods like forced ventilation having numerical quantifiers. This paper helps the team consider different methods to input a temperature control system

2. Greenhouse Applications of Solar Photovoltaic Driven Heat pump in Northern Environments [25]

   This article discusses the heating requirements needed for a greenhouse along with the ideal temperatures. This article focuses more on the pump systems needed to maintain a certain temperature. This article aims to optimize heat loss which energy efficiency is a goal for this project.

3. Top 10 Greenhouse Gardening Mistakes [26]

   This blog also discusses the ideal temperatures for a greenhouse but talks about natural ways to cool down and improve the energy loss of the greenhouse. This involves creating shaded areas through drop cloths or plants and utilizing ventilation and fungi. This blog helps us look at natural and cheaper ways to support the plants in the greenhouse and reduce energy loss.

4. Sustainable Agricultural Engineering Technologies and applications [27]

   This book delves into methods to reduce heat loss, looking at thermal screens instead of drop cloths or pumps. This book also provides the team with thermal conductivity coefficients, thermal capacities, and the connectivity of dirt. This book can help the team analyze how the greenhouse is storing and releasing heat.

5. The Ideal Temperature Conditions for 3-Toed Box Tortoises [28]

   This blog educates the readers about 3-toed box tortoises which is the tortoise being housed in the greenhouse. The winters get too cold for the greenhouse to keep the tortoise, so this blog helps the team to understand the humidity, the temperature range, and the basking areas these tortoises need. This blog also helps with understanding the tortoise cycle and its brumation needs in the winter. This will help the team create a system so the tortoise can stay at the school during winter months.

6. Understanding U-Value of Windows [29]

   This website gives information on the conductive, convective, and radiative coefficients of glass. It provides the rate of heat transfer, U (W/m^2), of single, double, and triple pane windows. This gives the team a good idea of the heat loss through a standard piece of glass and to be able to calculate how much heat is needed to be supplied by the greenhouse.

7. The Energy Cost of Running reptile Enclosures [30]

   This blog studies different species enclosures with the average cost per kWh and the average kilowatt output per day. The temperature difference between the inside of the enclosure and the surroundings is about 50 degrees Fahrenheit which is what our team also expects the temperature difference to be. The wattage used is the same as our team expects to use, but the enclosure is about 2.5 times smaller than the one in the greenhouse. This gives the team a good base to understand the heat loss they should expect when designing the enclosure.

3.2.5 Kaitlyn Phillips

1. Wind Energy Explained: Theory, Design, and Application [31]

   This book provides a comprehensive overview of wind energy systems, including wind resources assessment, turbine aerodynamics, and power production modeling. The text explains how wind turbine power output depends on air density, rotor swept area, wind speed, and turbine efficiency. It also introduces statistical wind modeling using the Weibull distribution. This reference supports the wind resources assessment and power modeling components of the capstone project.

2. Aerodynamics of Wind Turbines: A Physical Basis for Analysis and Design [32]

   This book focuses on the aerodynamic principles governing wind turbine performance. It describes blade element momentum theory and explains how blade geometry and tip speed ratio influence turbine efficiency. The material is useful for understanding how small wind turbines convert kinetic wind energy into mechanical power, which supports modeling the expected output of the greenhouse wind turbine.

3. Analysis of Wind Turbine Usage in Greenhouses: Wind Resources Assessment, Distributed Generation of Electricity and Environmental Protection [33]

   This article examines the use of small wind turbines to power greenhouse operations. The study analyzes wind resource availability, power generation potential, and environmental benefits of integrating wind energy into greenhouse systems. The research demonstrates how distributed renewable energy systems can reduce reliance on conventional electricity sources while supporting agricultural applications.

4. Design and Optimization of a Hybrid Solar-Wind Power Generation System for Greenhouses [34]

   This paper investigates hybrid renewable energy systems designed specifically for greenhouse environments. The authors analyze the performance of combined solar and wind systems and demonstrate how hybrid systems improve energy reliability compared to single source renewable generation. This research informs the hybrid modeling and system optimization aspects of the capstone project.

5. Space, Time, and Size Dependencies of Greenhouse Gas Payback Times of Wind Turbines in Northwestern Europe [35]

   This article evaluates the environmental impact of wind turbine installations, focusing on the greenhouse gas emissions associated with turbine manufacturing and operation. The study analyzes how turbine size, location, and operational lifespan influence environmental payback time. The findings support the sustainability goals of the greenhouse renewable energy project.

6. Wind Energy Handbook [36]

   This book is a comprehensive reference on the design, analysis, and operation of modern wind turbine systems. It covers topics including wind resource assessment, turbine aerodynamics, electrical power generation, and control systems used in wind turbines. The text also discusses system-level integration of wind turbines with electrical grids and off-grid systems. For the greenhouse renewable energy project, this resource provides important background on estimating wind energy production, evaluating turbine efficiency, and understanding the operational limits of small wind turbines used in hybrid renewable energy systems.

7. Small Wind Turbines for Electricity Generation [37]

   This book focuses specifically on small-scale wind turbines designed for residential, agricultural, and off-grid energy systems. It discusses turbine sizing, installation considerations, wind resource evaluation, and performance expectations for small wind energy systems. This book also evaluates the economic and practical considerations involved in implementing small wind turbine systems. This reference is directly relevant to the capstone project because the greenhouse energy system used a small wind turbine. The information can help guide evaluation of turbine performance, expected power output, and how the turbine integrates with the other existing battery and solar systems.

3.3 Mathematical Modeling

Mathematical modeling is used to estimate the performance of renewable energy systems powering the greenhouse. These models allow the team to analyze energy generation, system capacity, and expected performance under different environmental conditions.

3.3.1 Alexandra Miller – Wind-Solar Collection Times

One of the largest benefits to a hybrid system is that the collection times for each component in the hybrid system are different. The off-grid renewable energy system at Ponderosa High School (PHS) currently has two components for energy generation, solar and wind generation. During this project, the team will be adding an additional human powered generation component to energy system. To showcase how a hybrid system can result in longer collection times, data from Flagstaff weather and sun angle calculations are used to model the collection times for the solar and wind generation.

Below is a graph of the solar energy collection times based off the sun’s angle at PHS,

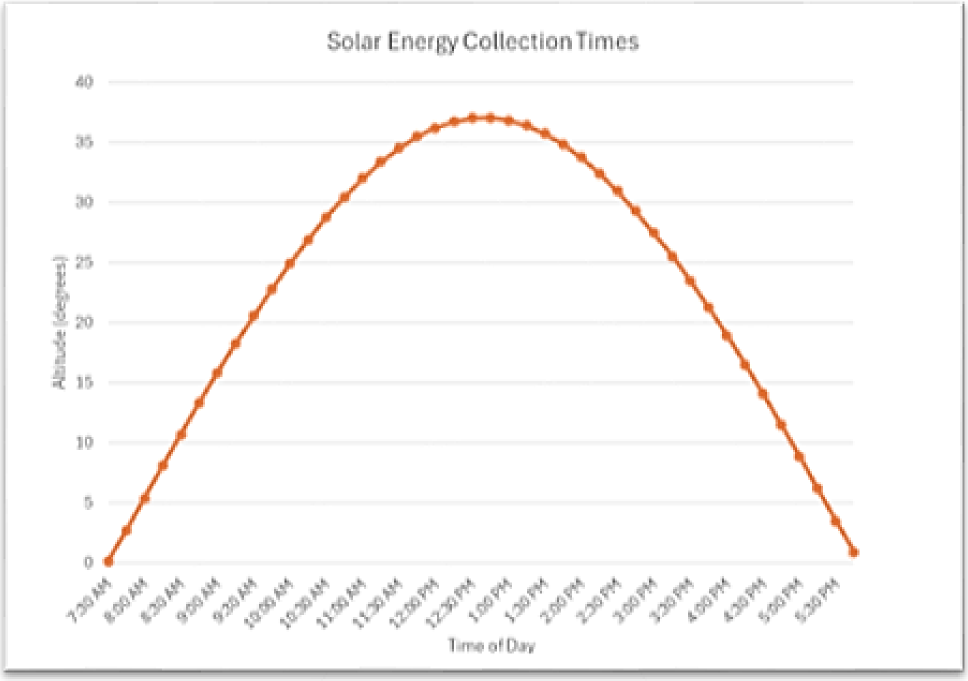


Figure 2. Solar Energy Collection Times [38]

From the graph, the sunlight will be most direct on the solar panels around midday from around 11:30 am to 1:30 pm. When the sun is at the highest peak and most direct on the sunlight is when the solar panels can absorb the most photovoltaic rays. The full collection time for the solar panels is between 7:30 am to 5:30 pm.

Below is a graph of the wind energy collection times based off wind speed in Flagstaff,

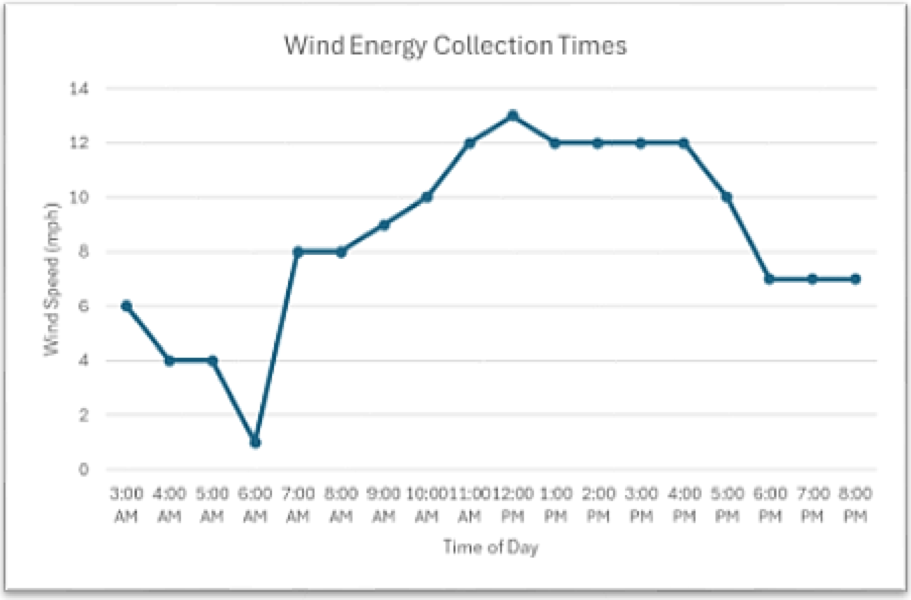


Figure 3. Wind Energy Collection Times [39]

From the graph, the highest wind speeds also occur around the afternoon from 11:00 am to 4:00 pm. In contrast to the solar energy collection times, the wind turbine at the PHS greenhouse continues to collect energy overnight. Although wind speeds tend to drop during the night, there is still additional wind energy that can be collected. The most prominent collection times are between 3:00 am to 8:00 pm for wind energy.

The human powered generation for Ponderosa High School will be dependent on when students will be using the bikes to generate power. Based on the school's schedule, the collection times for the human powered generation will be between 8:00am to 2:00pm. The most prominent hours for collection will be 8:00-9:30am (greenhouse is open to the students) and 11:00am to 12:30pm (break period).

The modeling of collection times for wind and solar generation along with general knowledge of the collection times for the human powered generation showcase how a hybrid system not only increases energy generation but also the times for energy generation. Therefore, the hybrid system is optimal for the off-grid renewable energy system at PHS, and it should be a priority for the team to confirm that all components of the system (solar, wind, and human energy generation) will be working and efficiently generating energy.

3.3.2 **Alexandra Miller – Static Loading of Solar Panels**

One of the client tasks for PHS sustainability capstone is to increase energy generation for the off-grid renewable energy system in the Ponderosa High School. One way the team can increase energy generation is by adding solar panels to the roof of the greenhouse. Currently the greenhouse has 4 solar panels on their roof with space for at least 4-5 more solar panels. Since the team is planning on increasing the battery capacity of the system, adding solar panels to the roof is an effective way to fill up that new space.

Since the team wants to add a new load to the roof, it is important to confirm that the roof will be able to structurally hold this. From schematics and information from the clients, mathematical modeling can be used to create an accurate estimation for how much weight the roof can hold.

Assumptions for modeling:

1. All solar panels have a similar weight (27kg ~59.4lbf)
2. There are two vertical support beams alongside the length of the greenhouse (one on each end of the greenhouse)
3. The team is adding one solar panel in between each sunroof (the team still needs to confirm dimensions for the new solar panels)
4. For the horizontal support beam, the material is wood and the dimensions are (4x12”) [40]
5. The allowable bending stress for the horizontal support beam is 1.5 kpsi [41]

Below is a top view schematic of the PHS roof with the added solar panels,

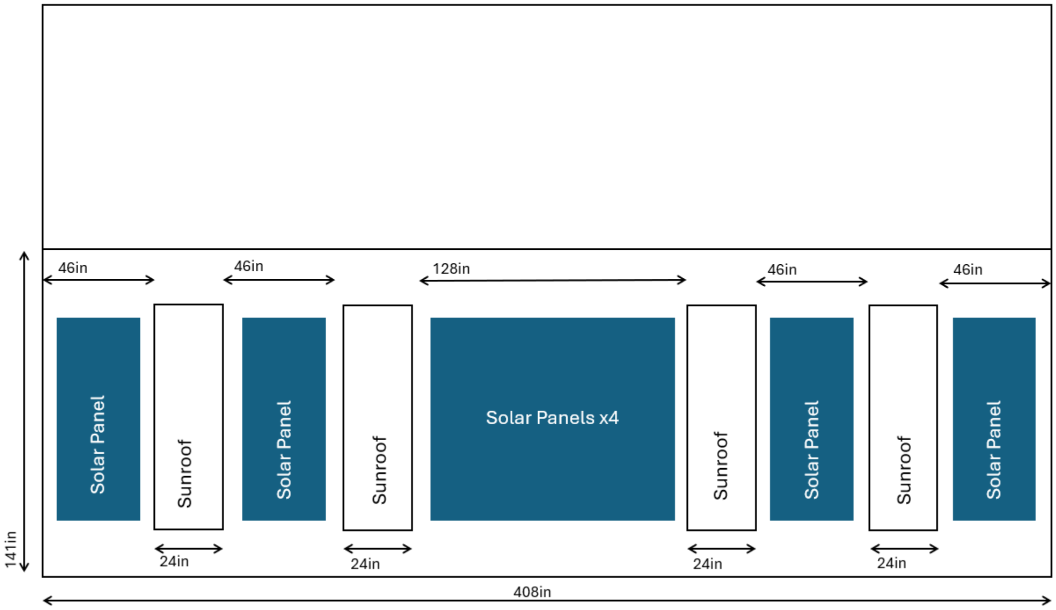


Figure 4. Schematic of the PHS Roof

To simplify calculations for mathematical modeling, we will be using point loads for the solar panels and a beam model of the roof system.

Below is the simplified beam model of the roof,

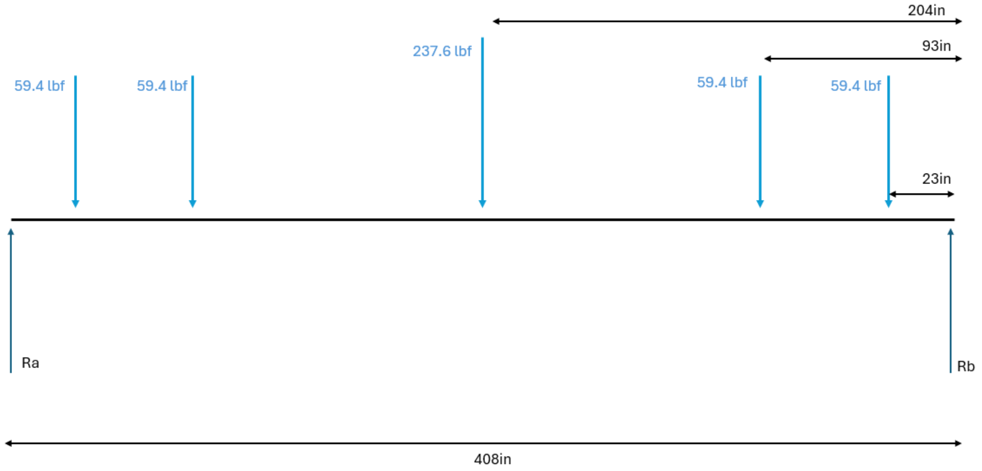


Figure 5. Simplified Beam Model

Note that loads and reaction forces are symmetrically with respect to the central axis. From here, the reaction forces in R_a and R_b can be found using force and moment equilibrium [42]. Below are the force and momentum equilibrium for the simplified beam model,

Force equilibrium [42]:

$$+\uparrow \varepsilon F = 0 \tag{1}$$

$$R_a + R_b - 4(59.4\ lbf) - 237.6\ lbf = 0$$

$$R_a + R_b = 475.2 lbf$$

Moment equilibrium [42]:

$$+\circlearrowleft M_a = 0 \tag{2}$$

$$(-113.85 - 460.35 - 4039.2 - 1559.25 - 1905.75) lbf \cdot ft + 34 R_b = 0$$

$$R_b = 237.6\ lbf$$

From the force and moment equilibrium equation, both R_a and R_b are **237.6 lbf**. This is congruent with the couple moment concept for static loading, The shear force and moment force can then be shown in the figures below,

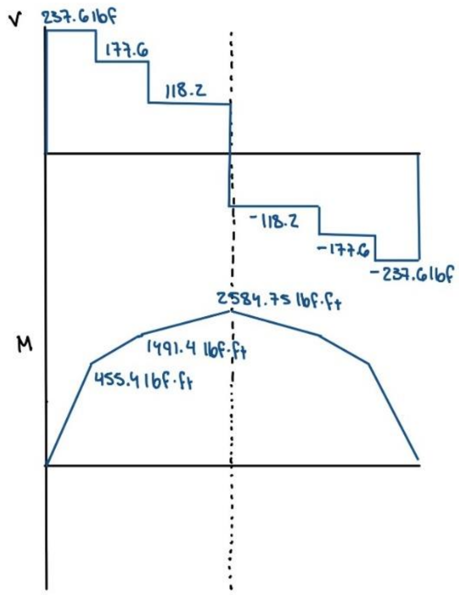


Figure 6. Shear and Moment Forces for Simplified Beam Model

From Figure 6, the largest moment will occur at the center of the beam at **2.5847 kip·ft**. This is where the roof is most likely to cave in from the additional solar panels. To confirm that the roof will be structurally secure, the minimum dimensions of the horizontal support beam must be smaller than or equal to the dimensions of the calculated dimensions. For analysis, the height is going to be set at the estimated dimension of 4" and the mathematical calculations will determine the width to be **≤ 12"**.

The maximum bending stress [42] is described below,

$$\sigma = \frac{M_{Max} \cdot c}{I} \tag{3}$$

Where:

σ =bending stress [kpsi]

M_{Max} =maximum bending moment [kip·ft]

c = centroid of horizontal beam [ft]

I = inertia of horizontal beam [ft^4]

Using this equation, the resulting width of the horizontal beam to keep the roof in static equilibrium is **10.34 in**. Therefore, initial calculations show that the vertical and horizontal support beams will be able to support four additional solar panels on top the PHS greenhouse. To solidify this initial calculation, 3D analysis and snow load will be analyzed in future calculations.

3.3.3 Carson Harder – Solar Energy

To elaborate further on the improvements of the solar panels attached to the PHS greenhouse, our team needed to calculate the current energy generation of their system. As the team wants to upgrade their battery system, they will need to account for the current and future energy produced by the system for storage as on average the range for peak sunlight hours is from 4 to 6 hours per day depending on the day of the year. For the initial calculation the expected power, out was calculated via two methods, one accounting for energy generated based on the area of the panels and the panels' efficiencies (Eq. 4) and the second one based on the panels' rated power and system efficiency (Eq. 5) [11]. To keep the calculations, uniform the total amount of solar irradiance will be based off the data provided by PVWatts® due to its extensive 30 years of data in the flagstaff area.

Original System

Using data from PVWatts® to get the average solar radiation each month for the past 30 years, the potential energy generated of the current system was calculated based off the system's area as well as the rated power of each panel, demonstrated in the equations below.

$$E = A \times R \times \eta \tag{4}$$

Where;

A is Area[m^2]

R is Solar Radiation[kW/m^2/h]

η is the efficiency of the panel(s)

$$E = \eta_s \times PSH \times \sum (N \times RP) \tag{5}$$

Where;

η_s is the system efficiency

PSH is the Peak Sunlight Hours[h]

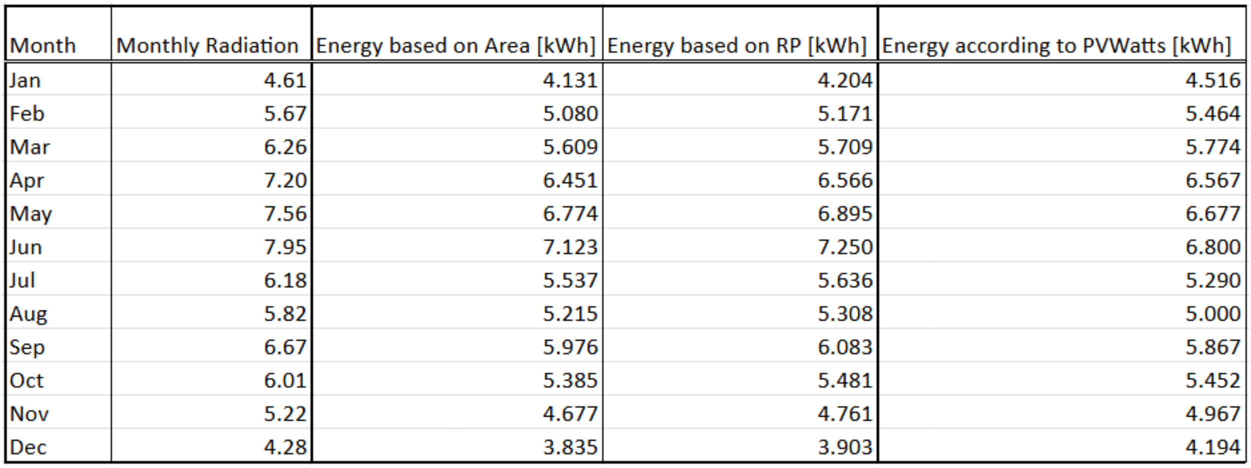
N is the number of Panels

RP is the Rated Power[kW].

Using the data given from the equations and operating under the assumptions that the panel efficiency is all 14% and the system efficiency is 80%. The potential energy was compared to that of PVWatts® (Table 2) and graphed in the diagram below (Fig. 7) using online data on the solar panels [43][44].

Table II

Average Energy Generation based on Area, Rated Power, and PVWatts®



Month	Monthly Radiation	Energy based on Area [kWh]	Energy based on RP [kWh]	Energy according to PVWatts [kWh]
Jan	4.61	4.131	4.204	4.516
Feb	5.67	5.080	5.171	5.464
Mar	6.26	5.609	5.709	5.774
Apr	7.20	6.451	6.566	6.567
May	7.56	6.774	6.895	6.677
Jun	7.95	7.123	7.250	6.800
Jul	6.18	5.537	5.636	5.290
Aug	5.82	5.215	5.308	5.000
Sep	6.67	5.976	6.083	5.867
Oct	6.01	5.385	5.481	5.452
Nov	5.22	4.677	4.761	4.967
Dec	4.28	3.835	3.903	4.194

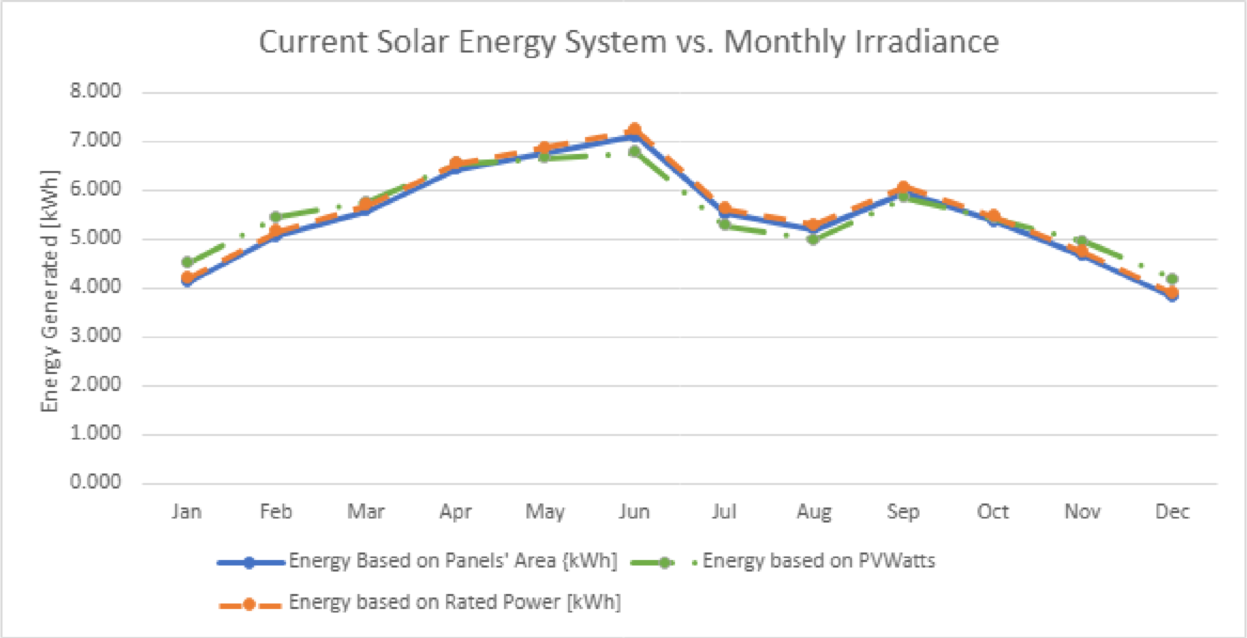


Figure 7. Current Solar Energy System Estimations vs Average Monthly Irradiance

Updated System

With the goal being to improve the systems efficiency and energy generation, Solar Panels will be donated from Northern Arizona University via Professor Carson Pete, who will also serve as a guide on installing and connecting these solar panels to the Ponderosa Greenhouse. Using the information provided by the new solar panels provided [45][Appendix C.1] and adding that information into the calculations we can predict how much energy the new system will generate. It is important to note that the system efficiency for the energy generated based on the Rated Power (Eq. 5) was increased from 80% to 85% due to the new introduced panels being new compared to the current greenhouse's solar array.

Table III

Improved Energy Generation based on Area, Rated Power, and PVWatts®

Month	Monthly Irradance	Energy based on Area	Energy based on RP	Energy according to PVWatts
Jan	4.61	9.113	8.464	9.742
Feb	5.67	11.208	10.410	11.857
Mar	6.26	12.375	11.493	12.548
Apr	7.20	14.233	13.219	14.267
May	7.56	14.945	13.880	14.452
Jun	7.95	15.716	14.596	14.733
Jul	6.18	12.217	11.346	11.484
Aug	5.82	11.505	10.686	10.839
Sep	6.67	13.185	12.246	12.733
Oct	6.01	11.881	11.034	11.839
Nov	5.22	10.319	9.584	10.767
Dec	4.28	8.461	7.858	9.097

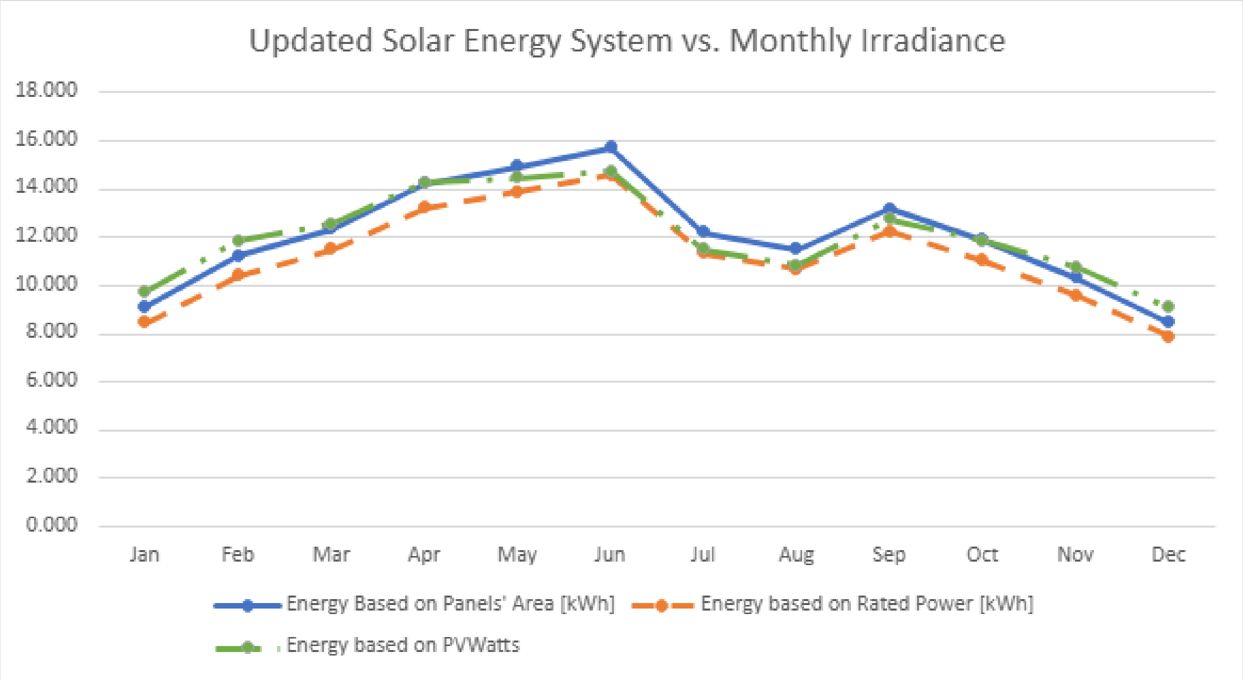


Figure 8. Updated Solar Energy System Estimations vs Average Monthly Irradiance

Using this information the team can determine how much energy the upgraded battery system will need to store the energy for around 3 days and use it for additional features inside the greenhouse as well as work in tandem with the wind turbine and the proposed bicycle generators.

3.3.4 Ethan Schalnat – Human Powered Energy Generation

To integrate the human-powered bicycle generator into the broader energy system, it was necessary to calculate the expected electrical power output under realistic riding conditions. The power a cyclist delivers to the drivetrain is governed by two competing quantities: the tangential force applied to the pedals and the cadence at which they can sustain that effort. As gear selection shifts, so does the balance between these two, as harder gears demand greater force at lower cadence, while easier gears allow higher cadence at reduced force. Since power is the product of torque and angular velocity, neither extreme is optimal, and the relationship between force and speed becomes the central design consideration. As shown in Design 6 (Fig.21), every bicycle design incorporates variable resistance between two bikes, intentionally exposing students to this tradeoff as a hands-on learning opportunity.

To identify the gear that maximizes power delivered to the battery, a force-cadence tradeoff model was applied across all seven gears of the donated mountain bike cassette. The bicycle drivetrain connects a 34-tooth chainring to the cassette, with the rear wheel making direct contact with a small roller on the alternator shaft. This contact drive provides a mechanical gear-up that keeps the alternator above its minimum operating speed across all gears. Output from the alternator passes through an MPPT charge controller before reaching the 24V battery bank. The model accounts for losses at each stage of this system, from drivetrain friction through to controller efficiency. The constants used in this analysis are provided in Table 4.

Table IV

System Constants Used in Gear Selection Analysis.

Symbol	Description	Value
R	Wheel radius	0.356 m
r	Crank arm length	0.19 m
r_{alt}	Alternator roller radius	0.025 m
N	Chainring teeth	34
n	Cassette sprocket teeth	11, 13, 15, 18, 22, 26, 34
ω	Sustainable pedaling cadence	45–75 RPM
F	Sustainable tangential pedal force	125–250 N
η_{alt}	Alternator efficiency	70%
η_{drive}	Drivetrain efficiency	96%
$\eta_{contact}$	Wheel-roller contact efficiency	96%
η_{charge}	MPPT controller efficiency	95%
ω_{min}	Alternator minimum cut-in speed	1000 RPM

Using equations from Bicycling Science [19] we first calculate mechanical advantage. The gear ratio between the chainring and the selected sprocket is given by Eq. 6, and the gear-up from the wheel to the alternator roller is given by Eq. 7. The resulting alternator shaft speed is then calculated using Eq. 8.

$$G_{bike} = \frac{N}{n} \tag{6}$$

$$G_{alt} = \frac{r}{r_{alt}} \tag{7}$$

$$\omega_{alt} = \omega G_{bike} G_{alt} \tag{8}$$

Rider mechanical power is calculated from the torque applied at the crank and the pedaling cadence, shown in Eq. 9 and Eq. 10 respectively. The power delivered to the battery accounts for all system losses via the overall efficiency term (Eq. 11 and Eq. 12).

$$\tau\,[N * m] = Fr \tag{9}$$

$$P_{mech}\,[W] = \tau\omega \tag{10}$$

$$\eta_{sys} = \eta_{alt}\eta_{drive}\eta_{contact}\eta_{charge} \tag{11}$$

$$P\,[W] = P_{mech}\,\eta_{sys} \tag{12}$$

Rather than assuming a fixed cadence and pedal force, the model applies a linear force-cadence tradeoff across the cassette, as shown in Table 5. A maximum force of 250 N at 45 RPM was assigned to G1 (11t) and a minimum force of 125 N at 75 RPM to G7 (34t), with intermediate gears interpolated between these values. Using a MATLAB script, the calculated power curve for the cassette is shown in Figure 9.

Table V

Gear Analysis Results

Gear	Teeth	ω (RPM)	F (N)	ω_alt (RPM)	P (W)
G1	11	45	250	1978	137.5
G2	13	48	239	1771	139.2
G3	15	50	228	1619	140.1
G4	18	54	212	1454	140.3
G5	22	60	190	1305	138.0
G6	26	65	168	1201	133.0
G7	34	75	125	1067	114.6

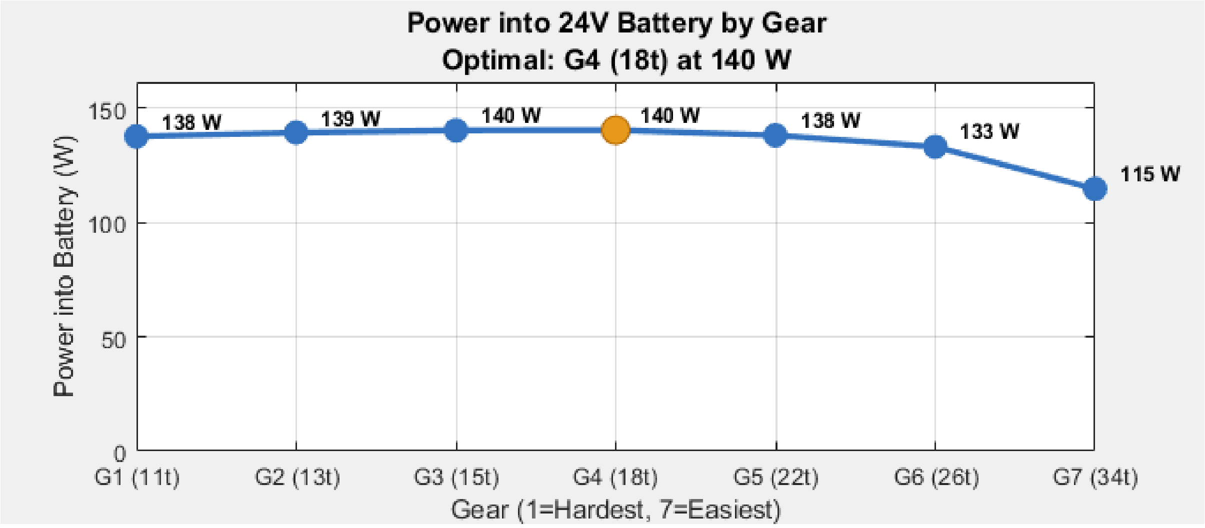


Figure 9. Gear Analysis Results

G4 (18t) produces the highest power output at 140.3 W into the 24V battery, with G3 (15t) essentially equivalent at 140.1 W. The power curve across gears G1 through G5 is notably flat, spanning only approximately 3 W. This is a direct result of the linear tradeoff assumption, in which force and cadence change in near-equal proportion such that their product remains nearly constant. Only at G6 and G7 does output decline more meaningfully. In practice, the force-cadence relationship is nonlinear and subject to rider fatigue and biomechanical limitations, which would produce a more pronounced curve with a clearer optimal gear. Additionally, alternator efficiency varies with shaft speed in ways not captured by the constant efficiency assumption, particularly near the cut-in threshold. Physical testing will be required to validate and refine the model once our team completes a prototype later in the semester.

All seven gears remain above the 1000 RPM cut-in threshold, confirming that the wheel-roller contact geometry provides sufficient mechanical advantage to keep the alternator operational across the full cassette. The 140 W peak output is consistent with the established recreational cyclist sustained power range of 75–150 W [19], and the result that peak output occurs at moderate resistance is consistent with literature showing maximum sustained power at intermediate loads [19].

3.3.5 Jenna Sterry – Tortoise Habitat

The tortoise that lives in the greenhouse has been a missed animal in their system. The tortoise gets too cold in the winter to survive and has to be transported down to Phoenix. The clients would like the tortoise to remain in the greenhouse for the students to learn and take care of their pet. Creating an enclosure for the tortoise will draw energy to heat up the space. Mathematical modeling will determine the energy lost by the system and help the team understand how much energy needs to be supplied. These calculations were created by assuming the temperature inside the enclosure is 80 degrees Fahrenheit, the U heat transfer rate for one paned glass is .6 w/m^2 and the size of the tank will have an area of 4.96 m^2 and a volume of 59568 in^3.

Temperature

Using temperature data collected over 5 years in flagstaff the average, high and low temperatures for each season were gathered. Winter is December to February, Spring is March to May, Summer is June to August, and Fall is September to November. Fall and Spring months were referneced together since their temperatures average the same. The high and low temperatures are calculated for the most extreme conditions

Table VI

Temperature Over 5 Years

Temperature	Winter	Spring/Fall	Summer
Average	273.17 K	281.4 K	292.19K
High	292.04K	299.63K	272.22K
Low	252.59K	264.076K	307.409K

Heat Loss

Using the first law of thermodynamics, heat loss was calculated by assuming steady state conditions and taking in to affect the evaporation and heat lamps effect. Below are the equations used in calculations:

First Law of Thermodynamics

$$\dot{Q}_{net} - \dot{W}_{net} = \frac{dE_{cv}}{dt} \tag{13}$$

Steady State

$$\dot{Q}_{loss} = \dot{Q}_{heater} = UA\left(T_{in} - T_g\right) + \dot{Q}_{evap} + \dot{Q}_{vent} \tag{14}$$

Power

$$\dot{Q} = UA\Delta T \tag{15}$$

kWh Conversion

$$E = \frac{\dot{Q}(W) \cdot t(hr)}{1000} \tag{16}$$

E basking

$$E_{bask} = lamp(kW) \cdot time({}^{hr}/_{day}) \times 365\, {}^{day}/_{year} \tag{17}$$

The power needed to keep the enclosure warm is listed in the table below,

Table VII

Power Consumption

Power (W)	**Winter**	**Spring/Fall**	**Summer**
Average	79.341	54.839	22.716
High	23.162	.566	-22.594=0
Low	140.611	106.415	82.169

That power was converted to energy by estimating the total hours for that season range.

Table VIII

Yearly Energy Consumption No Water Or Lamp

Energy (kWh)	**Winter**	**Spring/Fall**	**Summer**	**Total (kWh/yr)**
Average	174.534	240.36	49.781	464.645
High	50.7602	2.479	-49.514=0	53.2392
Low	308.149	466.419	180.074	954.642

Assuming a heat lamp is added, it would be 100 W running for about 10 hours every day but would not be running in the summer months. This estimates the energy used by the lamp for a full year would be about 275 kWh. Adding that to the energy calculated above and assuming there will be energy usage from a pond being in the tank we get the following yearly energy:

Table IX

Yearly Energy Consumption

Power (kWh)	Yearly Total
Average	$739.675 + \sum_{i=1}^{12} \frac{\dot{Q}_{evap,i} \cdot t_i}{1000}$
High	$328.24 + \sum_{i=1}^{12} \frac{\dot{Q}_{evap,i} \cdot t_i}{1000}$
Low	$1229.6 + \sum_{i=1}^{12} \frac{\dot{Q}_{evap,i} \cdot t_i}{1000}$

3.3.6 Kaitlyn Phillips – Wind Energy Modeling

The wind energy subsystem of the greenhouse power system consists of a small wind turbine used to supplement solar generation and charge the 24V battery bank. Mathematical modeling of the wind turbine system was conducted to estimate the potential electrical power production based on local wind conditions. The modeling process includes calculations of the rotor swept area, available wind power, turbine power extraction, tip speed ration relationships, and expected power output using a wind speed probability distribution.

Rotor Swept Area

The amount of wind energy captured by a turbine depends on the rotor swept area. This area represents the circular region covered by the rotating blades and determines how much air mass passes through the turbine.

The rotor swept area is calculated as [31]:

$$A = \pi R^2 \tag{18}$$

Where:

A = rotor swept area $[m^2]$

R = rotor radius [m]

Rotor swept area:

A = $0.82m^2$

Available Wind Power

The theoretical power available in the wind flowing through the rotor area is determined from the kinetic energy of moving air.

The available wind power is calculated as [31]:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{19}$$

Where:

P_{wind} = total power available in the wind [W]

ρ = air density [kg/m^3]

A = rotor swept area $[m^2]$

v = wind speed [m/s]

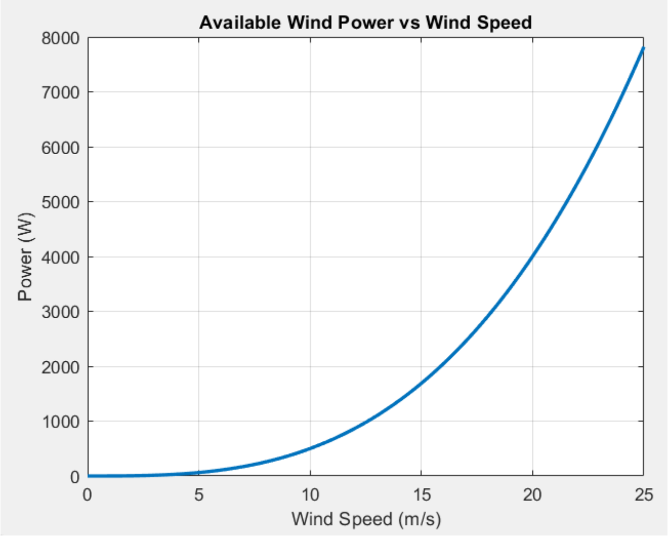


Figure 10. Available Wind Power related to wind speed

Available Wind Power:

P_{wind} = $0.50V^3$

Extracted Turbine Power

A wind turbine cannot capture all the power contained in the wind. According to Betz's law, the maximum theoretical efficiency of a wind turbine is 59.3%. In practice, turbines operate at lower efficiencies due to aerodynamic, mechanical, and electrical losses.

The actual power extracted by the turbine is given by [31]:

$$P_{turbine} = \frac{1}{2} C_p \rho A V^3 \tag{20}$$

Where:

$P_{turbine}$ = power output [W]

C_p = power coefficient [turbine efficiency]

ρ = air density [kg/m^3]

A = rotor swept area [m^2]

V = wind speed [m/s]

The power coefficient represents the efficiency of the turbine in converting wind energy into mechanical energy. Small turbines typically operate with C_p values between 0.25 and 0.45 depending on blade design and operating conditions.

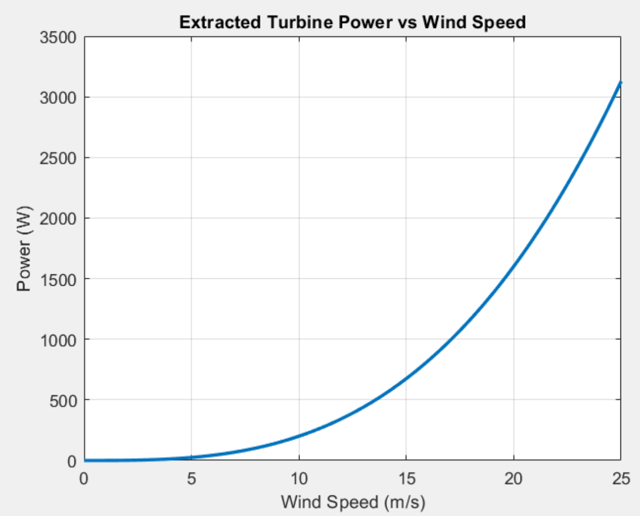


Figure 11. Extracted Turbine Power related to Wind Speed

Extracted Turbine power:

$P_{turbine} = 0.20V^3$

Tip Speed Ratio

Wind turbine performance is strongly influenced by the tip speed ratio, which describes the relationship between the blade tip velocity and the wind velocity.

The tip speed ratio is defined as [31]:

$$\lambda = \frac{\omega R}{v} \tag{21}$$

Where:

λ = tip speed ratio

ω = angular velocity of the rotor [rad/s]

R = rotor radius [m]

v = wind speed [m/s]

Each turbine design has an optimal tip speed ratio where the power coefficient reaches its maximum value. Operating near this optimal value maximizes energy capture.

Tip Speed Ratio:

λ = 2.55W

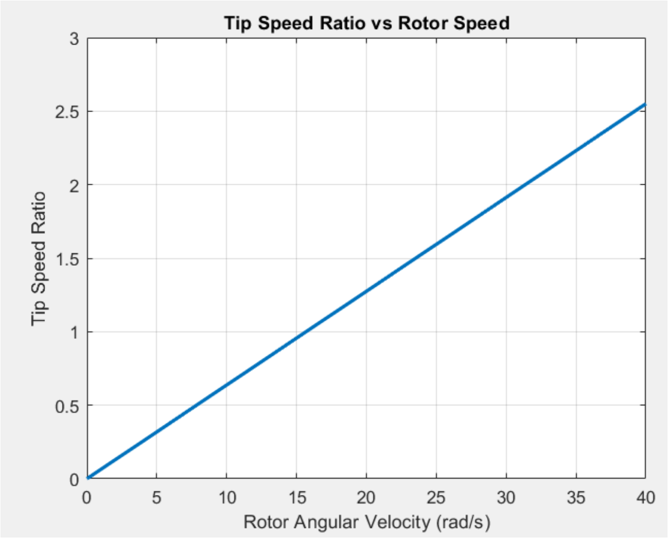


Figure 12. Tip Speed Ratio related to rotor speed

Weibull Distribution

Wind speed varies continuously over time, so estimating turbine power production requires a statistical representation of wind speed frequency. The Weibull distribution is commonly used model wind speed probability at a given location.

The Weibull probability density function is [31]:

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1}e^{-(\frac{v}{c})^k} \tag{22}$$

Where:

$f(v)$ = probability density of wind speed

v = wind speed [m/s]

k = shape parameter

c = scale parameter

The shape parameter determines the distribution spread, while the scale parameter is related to the average wind speed at the site.

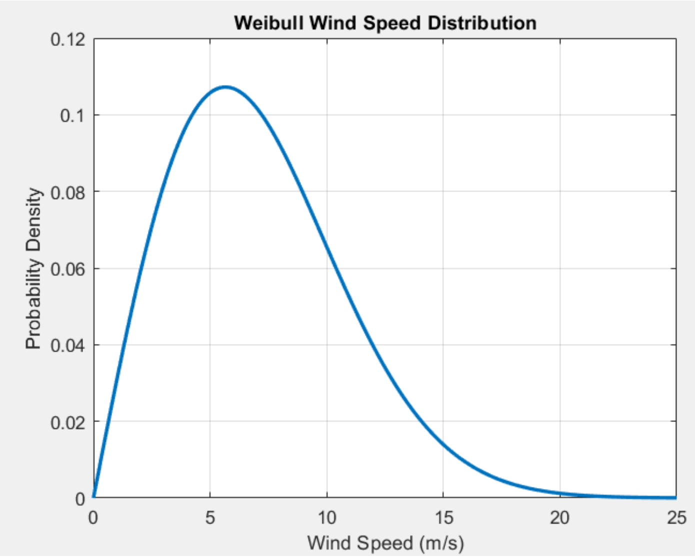


Figure 13. Wind Turbine Weibull Wind Speed Distribution Curve

Expected Power Output

To estimate the average turbine power output, the turbine power curve is combined with the wind speed probability distribution. The expected power output is obtained by integrating the product of the turbine power and wind speed probability density across all wind speed [31]:

$$E[P] = \int_0^\infty P(v)f(v)dv \tag{23}$$

Where:

E[P]= expected turbine power output [W]

$P(v)$ = turbine power as a function of wind speed

$f(v)$ = wind speed probability density function

In numerical modeling, integral is typically solved using numerical integration methods.

These wind energy equations were implemented in MATLAB to simulate turbine performance under varying wind speeds.

Expected Power Output:

E[P] = 136.05 W

4 DESIGN CONCEPTS

This chapter summarizes the functional decomposition, concept generation, selection criteria, and concept selection process for the PHS sustainability capstone project. Because the project largely works within existing greenhouse infrastructure, focusing on analysis, optimization, and integration of new components, the primary design component is the human-powered bicycle generator. As a result, all concept generation and evaluation was centered around the bicycle, and the design decisions documented in this chapter reflect the team's effort to maximize its energy output, usability, and educational value within the broader system.

4.1 Functional Decomposition

The team began the functional decomposition by developing a black box model of the bicycle generator, shown in Fig. 14. This model establishes the boundaries of the bicycle and clarifies what the design must accept as inputs and reliably deliver as outputs before moving into more detailed functional analysis. It showcases the materials, energies, and signals coming in and out of the system.

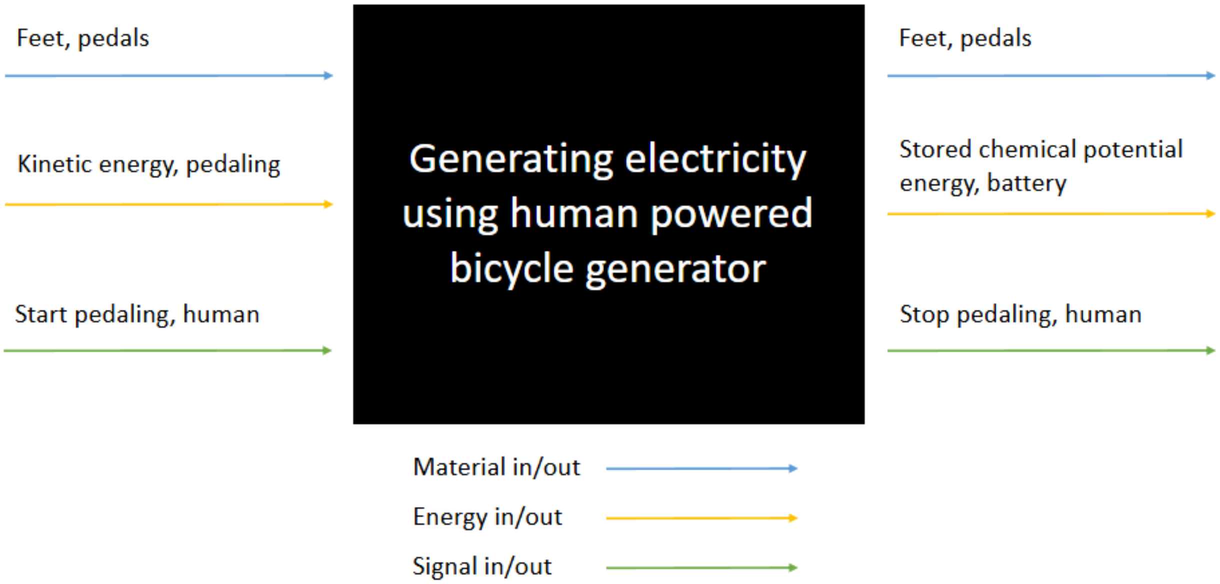


Figure 14. Black Box Model

This model focuses on the function of generating electricity using the bicycle generator. The material going in/out of the bike is the pedals and the feet rotating the pedals. The material does not change during the function. The energy going into the bike is the kinetic energy from pedaling which is then transformed into stored chemical potential energy in the PHS battery system. The signal going in/out of the bike is to start/stop pedaling.

Using the black box model, the components of material, energy, and signals were then expanded out into a decomposition model.

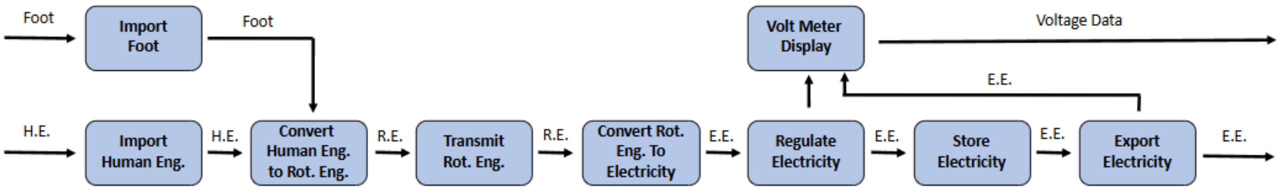


Fig 15. Decomposition Model

The decomposition model starts the human energy from beginning to pedal. This energy is converted to rotational energy which is then transmitted into electricity. To regulate and export electricity, a voltmeter display is used which will capture voltage data. The rest of the electricity generated is stored in the battery system.

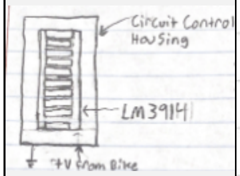
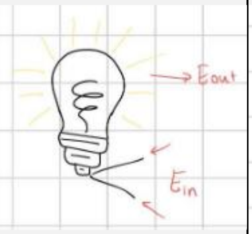
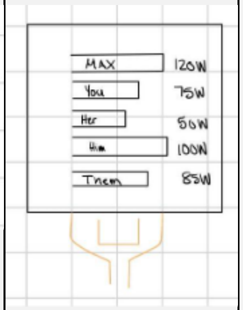
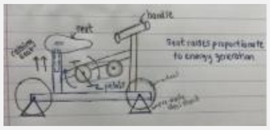
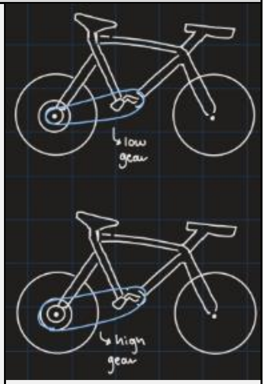
The decomposition model is important at showcasing important components for the team's concept generation. Three main components needed are: a way of generating human energy (pedals, bike, etc.), a device to convert human energy into rotational energy (motor), and a display of that energy (screen, light, etc.). The components identified in the decomposition model are used to generate concepts in the concept generation.

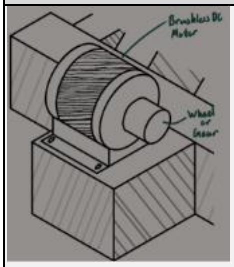
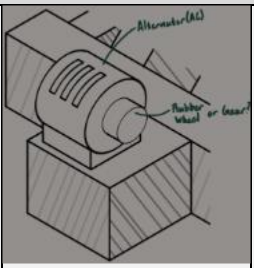
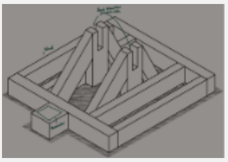
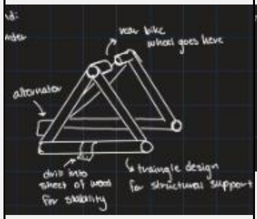
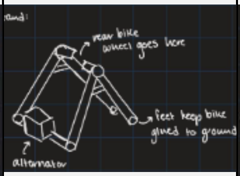
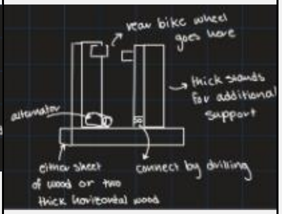
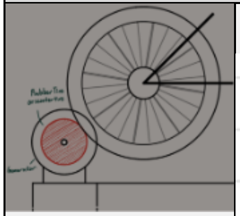
4.2 Concept Generation

Below are the sub-assembly concept generations for the human powered bicycle generator design. The morphological matrix categories include competition/energy display (A), motors (B), materials/design of stand (C), and point of connection (D). Figures illustrating each concept, along with descriptions and the advantages and disadvantages of each design, are provided in Appendix A.

Table X

Morphological Matrix

1	2	3	4	5
Competition/Energy Display (A)				
	 A2	 A3		 A5

A1			A4	
Motors (B)				
 B1	 B2			
Material/Design of Stand (C)				
 C1	 C2	 C3	 C4	
Point of Connection (D)				
 D1	 D2			

The top-level designs for the human powered bicycle generator are shown below,

Table XI

Top-level Assemblies with Advantages/Disadvantages

Design #	Figure	Sub Assem.	Advantages/

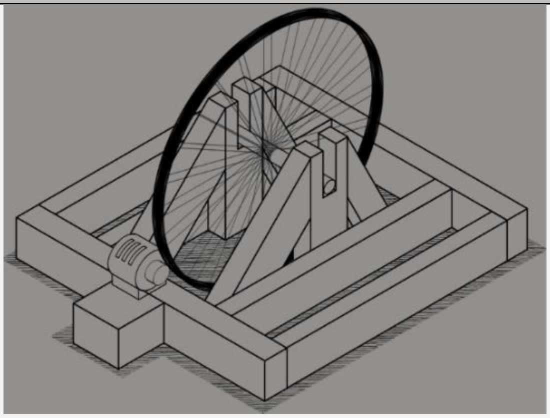
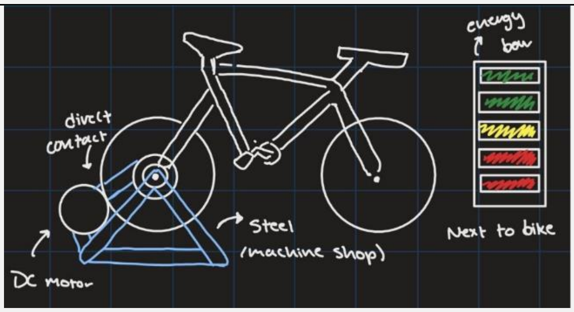
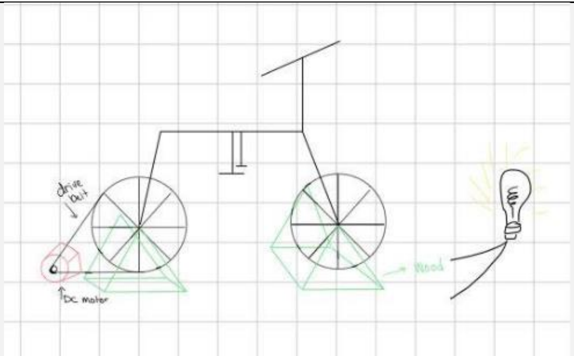
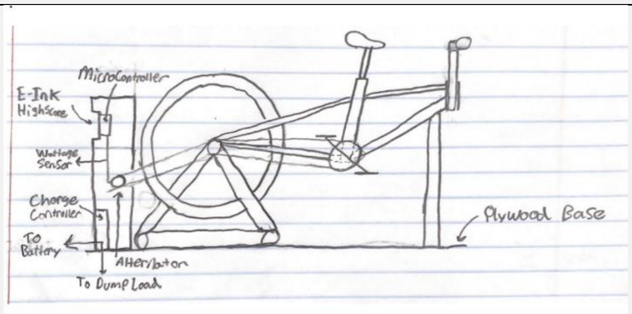
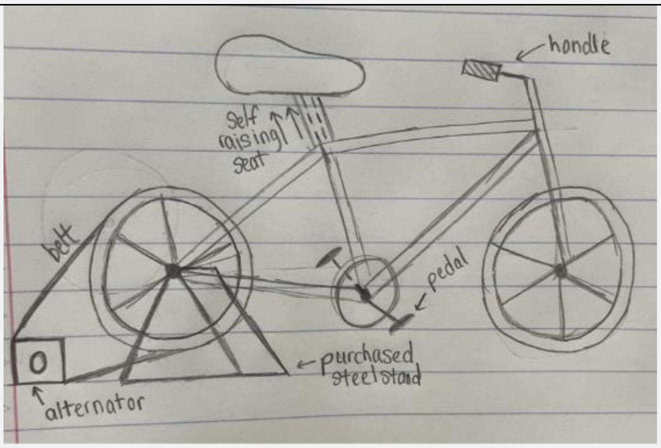
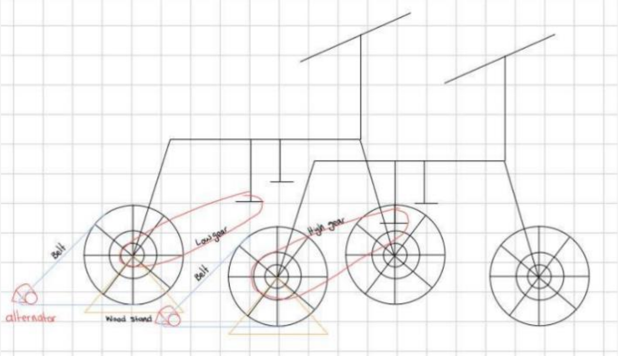
		Used	Disadvantages
#1	 Figure 16. Design 1	A5 B1 C1 D1	Advantages: easy maintenance, cheap Disadvantages: weak energy display and aesthetics
#2	 Figure 17. Design 2	A1 B2 C2 D1	Advantages: strong energy display, strong durability Disadvantages: expensive stand and motor
#3	 Figure 18. Design 3	A2 B2 C4 D2	Advantages: strong energy display, cheap stand Disadvantages: weak durability, weak ease of maintenance
#4		A3 B1 C4 D2	Advantages: strong energy display, cheap motor Disadvantages: difficult maintenance

	Figure 19. Design 4		
#5	 Figure 20. Design 5	A4 B1 C3 D2	Advantages: easy maintenance, easiest stand to get Disadvantages: expensive stand, medium energy display
#6	 Figure 21. Design 6	A5 B1 C4 D2	Advantages: cheap stand, cheap motor Disadvantages: weak durability, weak energy display

4.3 Selection Criteria

The selection criteria used for the human powered bicycle generator are listed in table 12 below. Because this design is a component of the PHS sustainability project, all concepts considered in the selection process were required to meet the minimum requirements of generating 100W of power through human input. For each criterion, the team conducted research and performed engineering calculations to ensure an accurate and objective evaluation of each concept during the selection process.

Table XII

Quantitative Selection Criteria

Criteria	Research/Calculations	Results
Competition	Two bikes Measurable power output	Designs that show progress and physical readings of power will create more competition with high school students
Cost	Stand: Pre-made (~$150), Wood	Designs using wood and self-built or locally built stands will

	(~$30) Motors: Alternator (~$100*donated), DC Brushless (~$50)	be cheaper. Designs using an alternator will be cheaper
Net Power	Alternator: $P = I \cdot V \cdot PF$ DC motor: $P = I \cdot V$	Designs with an alternator and direct connection will have a large output of power Designs that do not use an energy display will have larger net power
Educational Value	Hands on learning Quantifying power output	Designs using high vs. low gear will have higher educational value. Designs powering a light/display will have higher educational value. Designs that show power output will have higher educational value.
Maintenance	Physical items in way of maintenance Wear Rate= Mass loss/Distance	Designs that the bike can be removed from will have better maintenance.
Aesthetics	Display and lights "eye catching" Slim, clean looks "modern"	Designs with a display, light and a slim design will have better aesthetics

4.4 Concept Selection

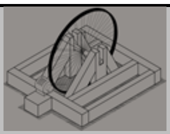
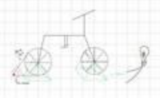
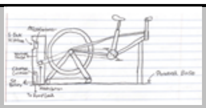
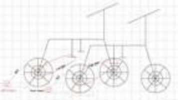
From the morphological matrix, each team member designed at least one bicycle generator concept. Designs 1,5, and 6 feature a high and low gear configuration to adjust pedaling resistance and energy output. Design 2 features a high score bar to display the amount of energy generated by the used. Design 3 demonstrated energy generation by illuminating a light bulb, while design 4 raises the seat height proportionally to the energy output produced by the student.

Among the concepts, design 1 is the only configuration that includes a removable stand, allowing for easier transport, storage, and maintenance. In contrast, designs 3, 4, and 6 utilize a static wooden frame.

Table XIII

Pugh Chart

Design Criteria	#1	#2	#3	#4	#5	#6

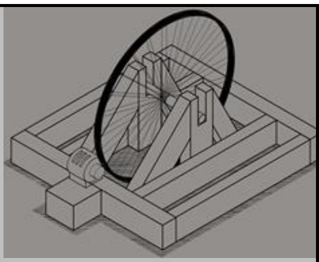
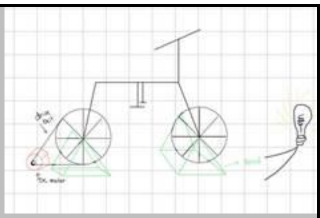
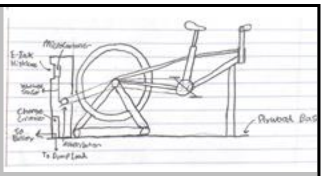
	 Figure 16	 Figure 17	 Figure 18	 Figure 19	 Figure 20	 Figure 21 (datum)
Competition	S	+ Bar	S	+ High Score	S	Datum
Cost	+ Direct Contact	- Steel	+ DC motor	- High Score	- Steel	Datum
Net Power	+ Direct Contact	- DC Motor and bar	- Lightbulb and DC	- Electronics	S	Datum
Educational Value	S	+ Bar Visual	+ Light Visual	+ Screen	+ Raised Seat	Datum
Maintenance	+ removable	S	S	S	S	Datum
Aesthetics	S	+ Visual	+ Visual	+ Visual	S	Datum
Total ‘+’	3	3	3	3	1	Datum
Total ‘-‘	0	2	1	2	1	Datum
Total ‘S’	3	1	2	1	4	Datum

After comparing all concepts to the datum design, the three highest-performing concepts were further evaluated based on the customer requirements. Educational value and net power output were weighted the highest, as the primary purpose of the bicycle generators is to provide an engaging educational tool for students while demonstrating renewable energy generation.

Because the bicycles are intended to remain at the school for long-term use, maintenance requirements were also given significant weight. The system should allow students and staff to perform simple repairs and basic maintenance as needed. Additionally, the clients emphasized the importance of including a competitive element to further motivate student participation. Cost was considered a lower priority since many of the components used in the design are expected to be donated to the team or can be purchased at a low cost.

Table XIV

Decision Matrix

		 Design #1		 Design #3		 Design #4	
Criterion	**Weight**	**Unweighted Scores**	**Weighted Scores**	**Unweighted Scores**	**Weighted Scores**	**Unweighted Scores**	**Weighted Scores**
Competition	0.15	5	0.75	8.5	1.275	10	1.5
Cost	0.10	10	1	9	0.9	8	0.8
Net Power	0.25	10	2.5	9	2.25	8	2
Edu. Value	0.25	6.5	1.625	7.5	1.875	10	2.5
Maintenance	0.20	10	2	7.5	1.5	5	1
Aesthetics	0.05	7	0.35	8	0.4	10	0.5
Total	1	**Sum:**	8.125	**Sum:**	8.2	**Sum:**	8.3

After ranking all the designs, the scores were very close to each other. We re-evaluated our clients' needs along with our feasibility and decided to go with design one. This final idea included the high score bar system showing the voltage the students generated. We liked the visual aspect of competition and the game-like feel it has. This bike also has a direct contact system for an alternator to reduce any wasted energy from a drive belt. The alternator is also more efficient than a dc brushless motor. This design will be a two-bike system with one high gear and one low gear for the students to compare how much extra energy they need to reach the same voltage output.

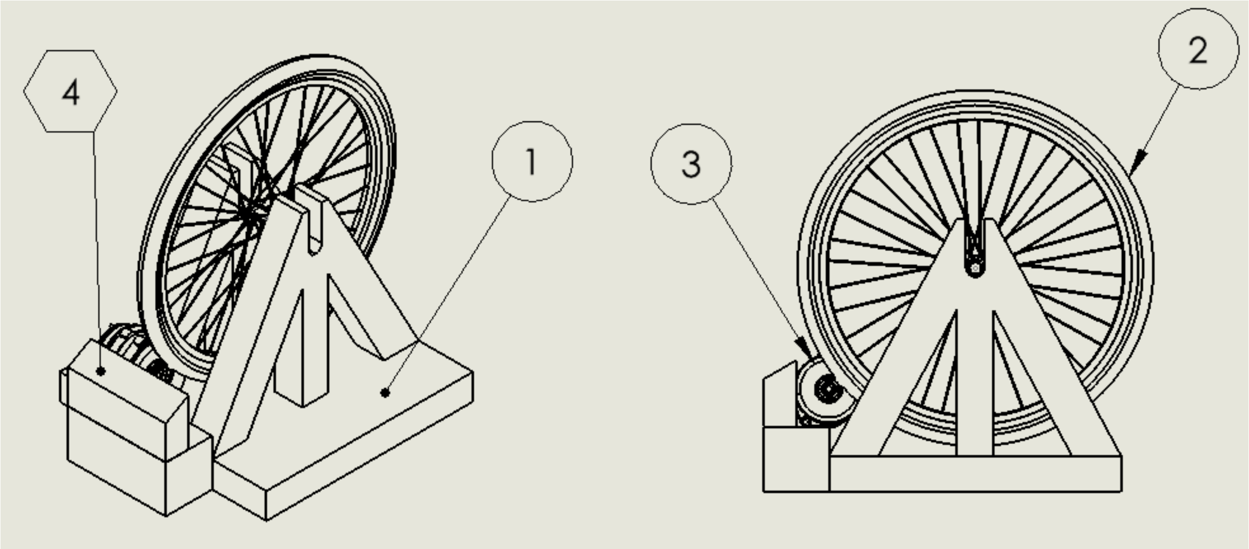


Fig 16. Drawing of CAD Model with listed components

Component 1 is the bicycle stand that will hold the back wheel of a bicycle to allow for different bicycles to be used as a generator. Component 2 is a bicycle wheel which will be held against an alternator. Component 3 is an alternator; this will be used as the generator and connected to the electrical system. Component 4 is a safety guard for component 3, as due to the electrical generation and moving components it’s to protect the team and students from potential shocks or mechanical failure.

5 CONCLUSION

This report summarizes the initial design and analysis for the Ponderosa High School (PHS) greenhouse improvement and outreach project. The tasks for this project are to evaluate and enhance the overarching performance of the off-grid system that utilizes a hybrid system of solar panels and a wind turbine to power the greenhouse. In addition to improving the performance of their systems, the team is conducting an energy audit of their current systems to not only clarify how their systems currently operate, but also expand the educational value provided by the greenhouse systems. This will be achieved through STEAM orientated lessons, interactive renewable energy technology in the form of bicycle powered generators, and classroom participation through art and classroom opportunities.

The report lays the foundation for the project by outlining the customer requirements sent by the clientele which guide the design process for the team. These metrics are emphasized by an increase in energy generation by renewable means, an emphasis on education engagement for and by the students of PHS, and improved system efficiency via an energy audit. A House of Quality was developed to communicate the clients' requirements into engineering metrics that are measurable. A list of these targets includes an upgraded energy production, improved battery storage capabilities, bicycle-powered generators, and improved temperature regulation for the tortoise habitats during the frigid months.

Going into research and benchmarking, the team needed to understand the current practices concerning hybrid energy systems, small-scale wind energy systems, household and/or small-scale solar energy systems, and human-powered generators. Each member was responsible for a comprehensive literature review of each background to take background information and equations and turn them into comprehensive engineering references to elaborate on system analyses and design concepts. Once done, mathematical models were then created to estimate the energy generated by the solar panels, wind turbine and human-powered generator. The models were also used to evaluate the structural stability and feasibility of additional photovoltaic panels as well as the thermal energy needed to maintain a stable and healthy temperature for the tortoise enclosure.

Moving into the design phase, as the greenhouse is already an established building and the plan is to make improvements to the current system, the primary focus was on the construction of a human-powered bicycle generator that can be integrated into the existing 24V battery system as well as an upgraded battery system. For concept generation a full decomposition of already pre-established bicycle generators was conducted to pinpoint where aspects of the design may fluctuate and identify potential sub-systems for the assembly. Design concepts from each team member were evaluated using the engineering selection criteria generated from the customer's requirements. The selected criteria consisted of the competition aspect of the design, the cost of manufacturing, the potential net power, the educational value of the generator, the maintenance and upkeep, and the aesthetics of the design. Once determining what designs and aspects of the designs were most important, a weighted decision matrix was made to compare those lead concepts and select which were the most suitable design for further development. When going through the weighted matrix the team determined that the lead designs had close rated scores which enlightened the team to which aspects of the design were important for future development.

The analysis conducted during the initial phase of the project has shown considerable improvements to the greenhouse off-grid system and are not only technically feasible but also beneficial to the current system. The preliminary modeling indicates that the addition of a human-powered generator and improved solar, wind and battery systems can increase the greenhouse's overall energy output for additional systems as well as expanding upon its educational capabilities.

Plans for the next phase of the project are currently underway, with the team continuing to further refine the system's potential efficiency and associated equations. Plans for fabrication and testing of a bicycle generator prototype as well as a handheld prototype are currently underway, with further work consisting of a full comprehensive energy audit, development of a STEAM orientated curriculum, and implementation of a heating and cooling system for the greenhouse. The completion of this project will provide Ponderosa High School with an improved renewable energy system while encouraging and promoting students to explore the STEAM field via hands-on engagement through a sustainable and clean energy education.

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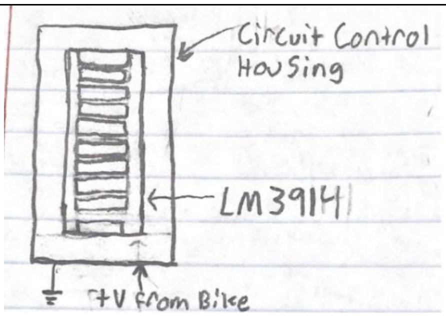
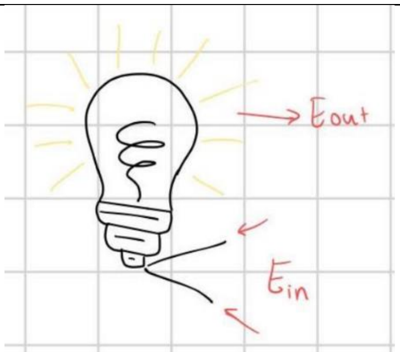
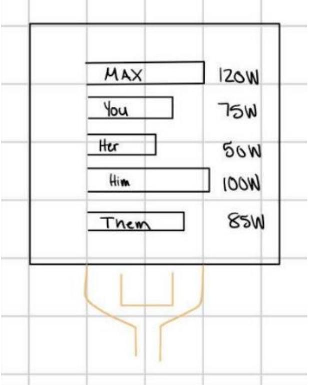
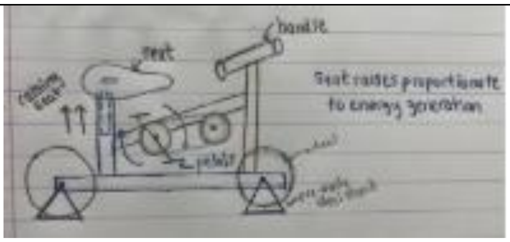
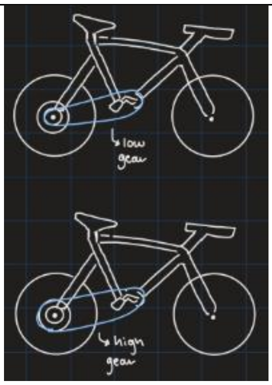
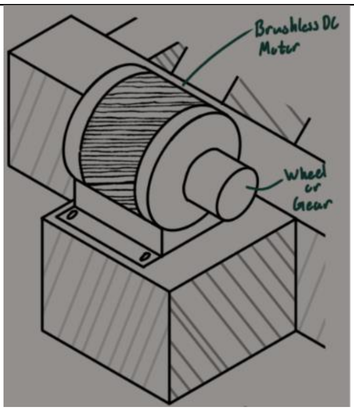
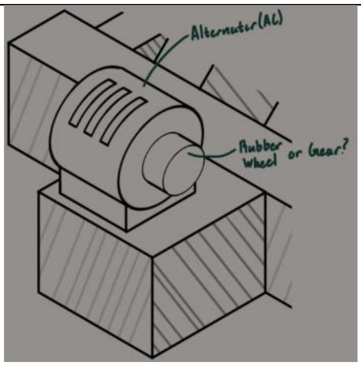
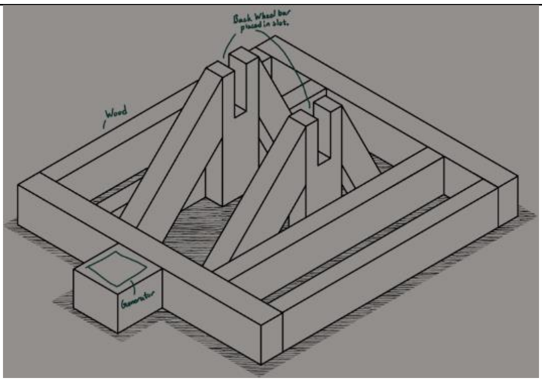
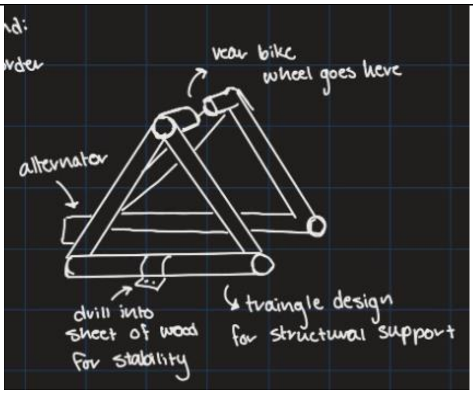
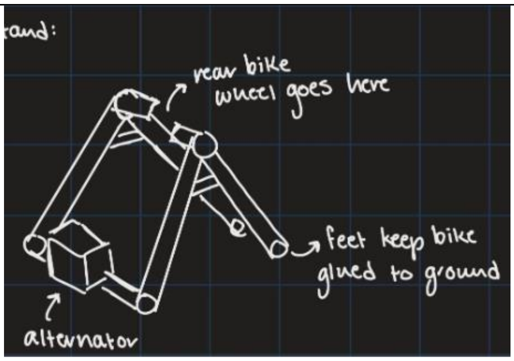
[45] “Buy Solar Module Suntech STP270-24/Vd | pvXchange.com,” *Buy Solar Module Suntech STP270-24/Vd | pvXchange.com*, 2017. https://www.pvxchange.com/Solar-Modules/Suntech/STP270-24-Vd_1-992500169 (accessed Mar. 08, 2026).

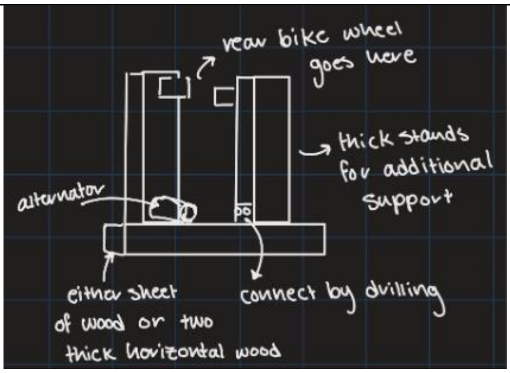
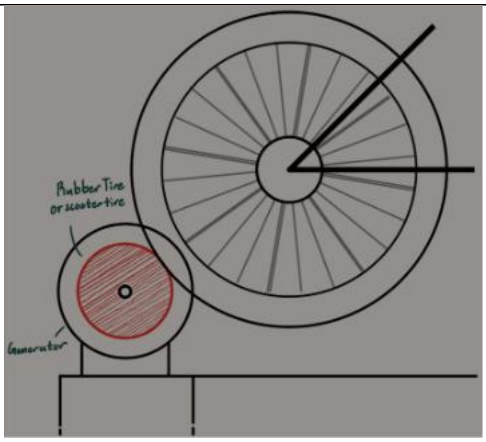
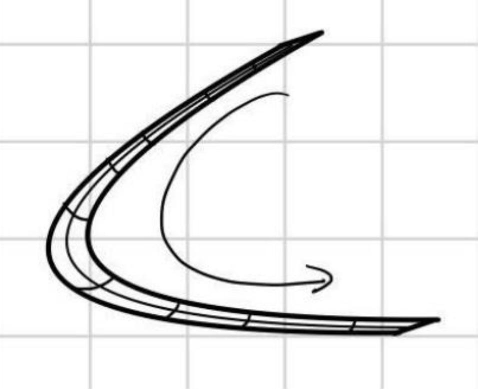
7 APPENDICES

7.1 Appendix A: Sub-Assembly Concepts

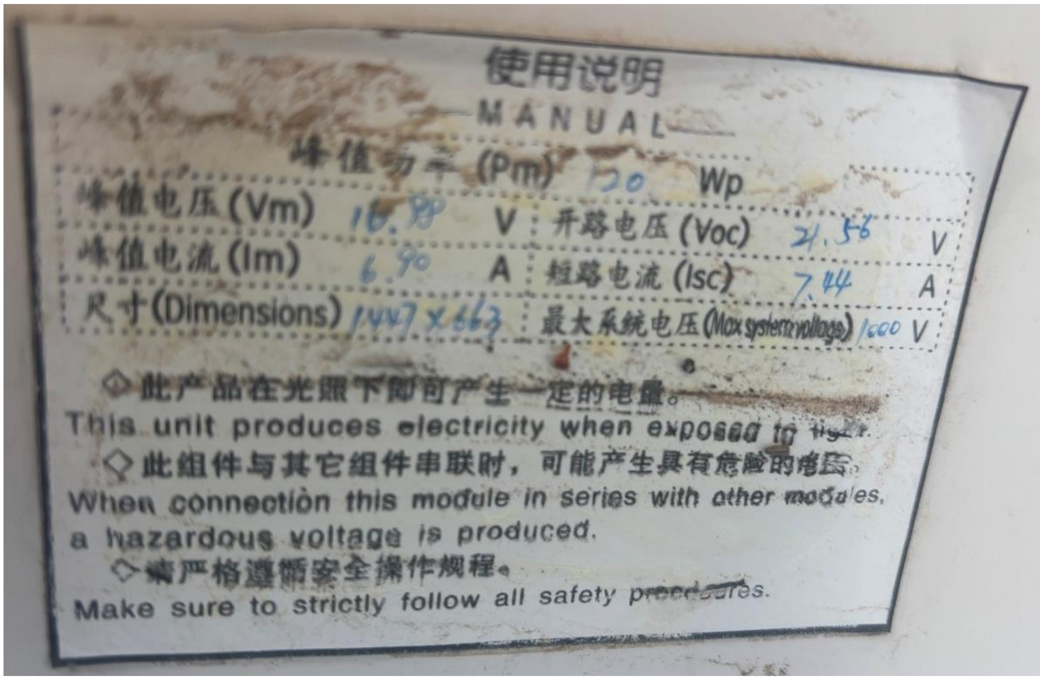
 Appendix A1. Sub Assembly A1	Description: Energy display bar Advantages: - High Educational Value Disadvantages: - Uses a large amount of energy generated from bicycle - Complex Voltmeter
 Appendix A1. Sub Assembly A2	Description: light bulb displaying energy input Advantages: - Some Educational Value - Uses very little energy Disadvantages: - Uses energy generated from bicycle - Hard to translate to a value
 Appendix A1. Sub Assembly A3	Description: high score display screen Advantages: - Encourages Student Competition Disadvantages: - Uses a large amount of energy
	Description: raised seat with power input Advantages: - High Educational Value Disadvantages: - Difficult to Maintain

Appendix A1. Sub Assembly A4	- Complex machinery
 Appendix A1. Sub Assembly A5	Description: high gear vs low gear power generation Advantages: - High Education Value - Makes use of Gear Ratios Disadvantages: - Maintenance
 Appendix A1. Sub Assembly B1	Description: brushless DC motor Advantages: - DC Energy Generation - Cost Effective Disadvantages: - Low Energy Generation
 Appendix A1. Sub Assembly B2	Description: Alternator Advantages: - High Energy Generation Disadvantages: - Expensive Pricing

 Appendix A1. Sub Assembly C1	Description: removable bike stand Advantages: - Cost Effective - Easily buildable - Stable Disadvantages: - Environmental Decay - Human Error
 Appendix A1. Sub Assembly C2	Description: steel stand (machine shop) Advantages: - Structurally Strong - Long term maintenance Disadvantages: - Expensive pricing - Human Error
 Appendix A1. Sub Assembly C3	Description: pre-made exercise stand Advantages: - Factory Made - Easy Assembly Disadvantages: - Expensive pricing

 Appendix A1. Sub Assembly C4	Description: self-made wooden stand Advantages: - Cost Effective Disadvantages: - Low Durability - Hard to Maintain over time
 Appendix A1. Sub Assembly D1	Description: direct contact Advantages: - Direct power transfer; increase efficiency - Less maintenance Disadvantages: - Potential Slippage - Degradation of wheels due to friction
 Appendix A1. Sub Assembly D2	Description: drive belt between rear wheel and motor Advantages: - Quiet, minimal vibration - Cheap Disadvantages: - Limited life span - Risk of Failure

7.2 Appendix B: Solar Panel Information



使用说明

MANUAL

峰值功率 (Pm) 120 Wp

峰值电压(Vm)	16.88	V	开路电压(Voc)	21.56	V
峰值电流(Im)	6.90	A	短路电流(Isc)	7.44	A
尺寸(Dimensions)	1447×663		最大系统电压(Max system voltage)	1000	V

◇此产品在光照下即可产生一定的电量。

This unit produces electricity when exposed to light.

◇此组件与其它组件串联时，可能产生具有危险的电压。

When connection this module in series with other modules, a hazardous voltage is produced.

◇请严格遵循安全操作规程。

Make sure to strictly follow all safety procedures.

Appendix B1. Small, 120W Rated Power Solar Panel