

Ponderosa High School Sustainability

Design Report 2

Alexandra Miller, Project Manager

Carson Harder, CAD and Modeling Engineer

Ethan Schalnat, Manufacturing and Test Engineer

Jenna Sterry, Instructional Designer and Logistic Manager

Kaitlyn Phillips, Financial Manager

Spring 2026



Steve Sanghi College of Engineering

Project Sponsor: Ponderosa High School (PHS), Les Hauer

Sponsor Mentor: John Taylor

Instructor/Faculty Advisor: Dr. Carson Pete

Outside Advisors: Erin McAnally, Teona Miller

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

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 a potential funding of \$4000 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, five solar panels, a 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 the current battery bank.

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 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 PHS 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.

TABLE OF CONTENTS

DISCLAIMER	1
EXECUTIVE SUMMARY	2
TABLE OF CONTENTS	3
3 BACKGROUND	5
3.2 Project Description	5
3.3 Deliverables	5
3.4 Success Metrics	2
4 REQUIREMENTS	4
4.2 Customer Requirements (CRs)	4
4.2.4 Greenhouse	4
4.2.5 Bicycle	5
4.3 Engineering Requirements (ERs)	6
4.3.4 Greenhouse	6
4.3.5 Bike	7
4.4 House of Quality (HoQ)	7
4.4.4 Greenhouse	8
4.4.5 Bike	9
5 RESEARCH WITHIN YOUR DESIGN SPACE	10
5.2 Benchmarking	10
5.2.4 Greenhouse	10
5.2.5 Bike	10
5.3 Literature Review	11
5.3.4 Alexandra Miller	11
5.3.5 Carson Harder	14
5.3.6 Ethan Schalnat	15
5.3.7 Jenna Sterry	17
5.3.5 Kaitlyn Phillips	19
5.4 Mathematical Modeling	21
5.4.4 Alexandra Miller	21
5.4.5 Carson Harder	26
5.4.6 Ethan Schalnat	29
5.4.7 Jenna Sterry	31
5.4.8 Kaitlyn Phillips	34
5.4.9 Summary of Mathematical Modeling	39
6 DESIGN CONCEPTS	40
6.2 Functional Decomposition	40
6.2.4 Greenhouse	40
6.2.5 Bike	41
6.3 Concept Generation	43
6.3.4 Greenhouse	43
6.3.5 Bike	Error! Bookmark not defined.
6.4 Selection Criteria	51
6.5 Concept Selection	52
7 SCHEDULE AND BUDGET	61
7.2 Schedule	61
7.2.4 Spring Semester Gantt Chart (ME476C)	61
7.2.5 Fall Semester Gantt Chart (ME486C)	62
7.2.6 Work Breakdown Schedule	64
7.2.6.1 PHS Sustainability Capstone	64

7.2.6.2	Initiation Phase.....	65
7.2.6.3	Planning Phase	65
7.2.6.4	Execution Phase	66
7.2.6.5	Concluding Phase.....	66
7.3	Budget.....	67
7.4	Bill of Materials (BoM).....	68
7.4.4	Greenhouse	68
7.4.5	Bike.....	Error! Bookmark not defined.
7.4.6	Bike Prototype	71
8	DESIGN VALIDATION AND INITIAL PROTOTYPING	73
8.2	Failure Modes and Effects Analysis (FMEA)	73
8.3	Initial Prototyping.....	74
8.4	Other Engineering Calculations.....	79
8.4.4	Alexandra Miller.....	79
8.4.5	Carson Harder	82
8.4.6	Ethan Schalnat	85
8.4.7	Jenna Sterry.....	87
8.4.8	Kaitlyn Phillips	89
8.4.9	Summary of Other Engineering Calculations	93
8.5	Future Testing Potential.....	94
9	CONCLUSIONS	95
10	REFERENCES	96
11	APPENDICES.....	102
11.2	Appendix A: Sub-Assembly Designs	102
11.3	Appendix B: Top Level Designs.....	105
11.4	Appendix C: Solar Panel Information	107
11.5	Appendix D: FullRiver DC400-6	108
11.6	Appendix E: Prototype Bill of Materials (BOM)	110
11.7	Appendix F: Greenhouse QFD	111
11.8	Appendix G: Bike QFD.....	113

3 BACKGROUND

This section 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.

3.2 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 five 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.

After the team met with client, John Taylor and sponsor, Les Hauer, the primary goals and budget/fundraising targets were developed. The primary goals of the project are 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 assess system limitations, evaluate renewable energy generation potential, and identify opportunities for improvement and expansion. One component of this system 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.

The total budget for the PHS sustainability capstone is \$5400. An adjustable budget of \$3400 comes from the sponsor, Les Hauer, to purchase a new battery storage system for the PHS greenhouse. A set budget of \$1000 comes from NAU to fund supplies needed to improve the renewable energy system. The last \$750 is designated as the team's fundraising target to fund supplies for the human powered stationary bicycles.

This project is important because it combines technical engineering skills and analysis with meaningful impact in the Flagstaff community. The project strengthens 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.

3.3 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 PHS students

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

3.4 Success Metrics

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

Technical Perspective

Success will include:

- Completion of a validated energy audit and clearly documented assumptions and calculations.
 - Audit was created by individually adding an item into the system and reading off the power consumption in the greenhouse for accurate readings.
 - Assumptions and calculations are in the mathematical modeling sections
 - Please refer to [mathematical modeling](#) for further information
- Accurate modeling of renewable energy generation and battery system capacity
 - Referenced from other systems to be applied to our own
 - Please refer to [literature review](#) for further information
- Identification of system constraints and performance limitations
 - Battery capacity, temperature constraints, energy generated
 - Please refer to [other engineering calculations](#) for further information
- Improvement recommendations that fall within the budget
 - LED's, extra batteries, additional solar panels, creating a turtle enclosure
 - Please refer to [budget](#) for further information
- A functional and safe human-powered charging system design compatible with the existing 24V battery bank infrastructure
 - Please refer to [other engineering calculations](#) for further information

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

Education Perspective

Success will include:

- Development and engagement curriculum materials
 - Monthly lessons on individual renewable energies along with demonstrations. First semester focuses on main forms of energy, wind, and solar. Second semester will focus on electrical components and battery storage.
- Demonstration of engineering concepts in a way that enhances student engagement and encourages STEAM education

- Involves building roller coasters, creating flow drawings of energy, building wind turbines, and building a solar oven. Next semester, the team will investigate wiring and energy flow using a Makey Makey and the bikes visual display.

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

4 REQUIREMENTS

This section 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.

4.2 Customer Requirements (CRs)

The following customer requirements were identified through the project proposal and discussions with the project sponsor and client. These requirements represent the primary needs of the PHS staff and students.

4.2.4 Greenhouse

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 PHS 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. Battery Storage

The system must include sufficient battery 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.

5. Working Wind Turbine

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

6. 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.

7. Turtle Enclosure

The greenhouse contains a turtle that is unable to live in the greenhouse year-round due to the temperature being too low in the winter. The system will use 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.

8. 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.

9. 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.

4.2.5 Bicycle

1. Interactive Display

The bike's purpose is to show the students the energy output of the work they put into the bike. This will be demonstrated by lighting up LEDs in a fish tank and adding a student led competition for the led most energy generated.

2. Durability

This bike is designed to be left alone for years in an outdoor setting with minimal maintenance needed. It should be able to withstand the dry heat, additional moisture in the greenhouse, and student use for five to ten years.

3. Supplemental Energy

This bike is not intended to be a main power source, but a small supplement of energy for cloudy days or during the evening. The students should be able to charge the batteries for small uses around the greenhouse.

4. Educational Value

This bike is used as a visual and physical representation of energy. The students will have two human power bicycle generators and will feel the strength they have to apply for energy generated. This will be shown by the duration the LEDs shine for and by a virtual display that will show how much energy the students generate.

5. Safe to Use

The bike supports/truss will be made from steel to ensure stability and reduce the risk of fracture. The alternator will be protected by thick plastic box so the students cannot accidentally injure themselves.

6. Aesthetics

The bike will look safe to use and have human centric design, so it is clear how to use the bike for

its intended purpose.

7. Student Participation

The aspect of a reward, like lighting up the fish tank, will incentivize students to participate and use the bike. This also applies to making the bike easy to ride, having minimal resistance, and having a purposeful output.

8. Size

The bikes will be placed in a specific section of the greenhouse. The bike and stand must fit the allowed space from the clients.

4.3 Engineering Requirements (ERs)

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

4.3.4 Greenhouse

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
6	Battery Capacity	The maximum storage of energy in the batteries	400	Ah
7	Runtime	The time the batteries can run until they die or are less than 60% efficient	10	years

4.3.5 Bike

Table II
Engineering Requirements

ER#	Engineering Requirement	Description	Target	Units
1	Battery Performance	The efficiency and power output delivered from the battery	85	%
2	Manufacturing Cost	The cost to buy and assemble the bike stand	500	\$
3	Power Output	Power generated by the bike and converted into usable energy	100	W
4	Maintenance	The distance the motor can run until it breaks down	4000	Km
5	Structural Integrity	The weight that the bike stand can hold	800	N

4.4 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. Our project is focused on improving the greenhouse, but the bike is an integral part of our requirements. We chose to do two separate HoQ for the greenhouse and just the bike.

4.4.4 Greenhouse

Greenhouse QFD		Project: PHS Sustainability Date: 3/5/2026															
1																	
2	Wind Turbine generation		9														
3	Human-powered generation		9														
4	Solar powered generation		9														
5	Turtle habitat temperature regulation		3														
6	Greenhouse energy consumption			3	9	9	9										
7	Battery Capacity																
8	Runtime																
			Technical Requirements							Customer Opinion Survey							
			Greenhouse Energy Consumption	Turtle habitat temperature regulation	Solar Power Generation	Human Power Generation	Wind Turbine Generation	Battery Capacity	Runtime								
	Customer Needs	Customer Weights								1 Poor	2	3 Acceptable	4	5 Excellent			
1	Efficiency	4	9	3	9	1	3	9	9	-			C		B	A	
2	Student Engagement	5		3	1	9	1			-				AB		C	
3	Human Powered Bicycle Generator	4	1			9		1	1	-						C	
4	Battery Storage	2	9	1	9	1	3	9	9	-	C					AB	
5	Working Wind Turbine	5	3				9	3	3	-	C		B			A	
6	Increased Solar Power	5	9		9			9	9	-	C			B		A	
7	Turtle Enclosure	1	3	9	1		1	1		-							
8	Reliable/ Low Maintenance System	3		1	9	3	3	9	9	-			A	B		C	
9	Increased Energy Output	4	9	3	9	1	3	9		-			B	C		A	
	Technical Requirement Units		%	°F	kW	W	W	Ah	years								
	Technical Requirement Targets		4 50	7 80±10	2 3500	6 150	3 300	1 1400	5 10								
	Technical Importance		4	7	2	6	3	1	5								

Fig 1. Greenhouse QFD

For the greenhouse, increasing solar power will be the main form of energy being supplied into the greenhouse. That’s why there is a strong correlation between the energy being consumed by the greenhouse and the capacity of the batteries to store and hold energy. Without extra battery capacity, the additional solar and wind energy have nowhere to go, and without that energy, the greenhouse cannot consume as much. This played a critical role in ranking technical importance. The clients also heavily stressed the importance of student engagement, which is why it is ranked as a 5 on customer weights and a sperate HoQ was made for the bike. Zoomed in images of the greenhouse QFD can be found in [Appendix F](#).

4.4.5 Bike

HPE Bike QFD		Project: PHS Sustainability Date: 3/5/2026																								
1	Battery Performance	9																								
2	Manufacturing Cost	3	9																							
3	Power Output	3		9																						
4	Maintenance	9			9																					
5	Structural Integrity		3			9	9																			
		<table border="1"> <thead> <tr> <th colspan="3">Legend</th> </tr> </thead> <tbody> <tr> <td>A</td> <td>Waterlution</td> <td>9 strong</td> </tr> <tr> <td>B</td> <td>DIY Bike Power Output</td> <td>3 medium</td> </tr> <tr> <td>C</td> <td>HPEG system</td> <td>1 weak</td> </tr> <tr> <td>D</td> <td>BigFoot</td> <td>0 no relation</td> </tr> </tbody> </table>										Legend			A	Waterlution	9 strong	B	DIY Bike Power Output	3 medium	C	HPEG system	1 weak	D	BigFoot	0 no relation
Legend																										
A	Waterlution	9 strong																								
B	DIY Bike Power Output	3 medium																								
C	HPEG system	1 weak																								
D	BigFoot	0 no relation																								
		Technical Requirements							Customer Opinion Survey																	
		Customer Weights		Battery Performance	Manufacturing Cost	Power Output	Maintenance	Structural Integrity																		
Customer Needs																										
1	Interactive Display	3		9	9	3																				
2	Durability	5	3	1	1	9	9																			
3	Supplemental Energy	5	9	3	9																					
4	Educational Value	4			3																					
5	Safe to Use	5		3		9	9																			
6	Aesthetics	1		9																						
7	Student Participation	4			1																					
8	Size	4		3		1	3																			
Technical Requirement Units			%	\$	W	km	N																			
Technical Requirement Targets			85	500	100	4000	300																			
Technical Importance			5	3	1	4	2																			

Fig 2. Bicycle QFD

For the bike, the forefront was getting students involved while having a physical and visual representation of energy. Aesthetics were not the team’s biggest focus, instead the safety of the students as well as their engagement were the highest priorities. Durability was the central focus as the battery’s Ah capacity being higher would mean letting the system last longer. A more durable system also means the manufacturing costs will be more expensive, but with less maintenance in the future. The educational value and student participation is not high or related to the bike because this HoQ focuses on the building of the bike rather than the output of the bike. Zoomed in images of the bike QFD can be found in [Appendix G](#).

5 RESEARCH WITHIN YOUR DESIGN SPACE

This section summarizes the research that was conducted to better understand the technologies and engineering principles relevant to the PHS 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.

5.2 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.

5.2.4 Greenhouse

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

One benchmark system examined is the National Renewable Energy Laboratory (NREL) small hybrid renewable energy 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. Our system has a similar design which can be optimized based on this state-of-the-art design.

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. The goal of this benchmark is to have net zero carbon emission. These systems highlight the importance of incorporating monitoring and visualization tools so students can observe real-time energy generation and consumption. Currently the PHS greenhouse has a screen that observes real time energy generation but nothing to for energy 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 bicycle reported to have a maximum power output of 300W. 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.

5.2.5 Bike

1. Waterlution [4]

This benchmark shows a state-of-the-art pedal powered bicycle generator designed for

institutional research by Amy Darall at Waterlution. The procedure for assembling the bike is shown with the results of the design. The bike was able to power a 12-volt battery to 40% in 20 minutes of pedaling. An improvement needed in the design is a drive belt to tightly secure the bike to the DC motor.

2. DIY Bike Power Output [5]

Similarly to the benchmark above, this benchmark is a state-of-the-art pedal powered bicycle generator. However, instead of a DC motor, this benchmark utilizes an alternator. At maximum speeds, the alternator was able to produce 25 volts. This benchmark also shows different ways to maximize power such as removing resistance in certain areas and changing the circuit.

3. HPEG System [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 bicycle reported to have a maximum power output of 300W. 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.

4. BigFoot: 500 Watt Bicycle Generator and Stand [6]

This benchmark shows a state-of-the-art pedal powered bicycle generator designed for adults and students. The design utilizes a 500-watt generator to double the energy generated and an adjustable board so the stand can fit any bike. Compared to the PHS bike design, this stand is more adjustable and one-size-fits-all. This design is intended for instruction on renewable energy systems to k-12 students.

5.3 Literature Review

5.3.4 Alexandra Miller

1. Optimizing Off-grid Energy Solutions: A Hybrid Approach Leveraging Solar, Wind, and Biomass for Sustainable Development [7]

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 [8]

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 [9]

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 [10]

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 [11]

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 the team's case, the focus is specifically on the environmental benefits of the hybrid system. This is because the 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 [12]

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 [4]

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.

8. A comprehensive review of lithium-ion battery modelling research and prospects: in-depth analysis of current research and future directions [13]

This research article shows different models for lithium-ion batteries along with the advantages and disadvantages of each model. The main three models shown in this article are the equivalent circuit model (ECM), physics-based model (PBM), and data-driven models (DDM) which are further split into a traditional learning model and a deep learning model. These models analysis different components of a lithium-ion battery (ex. the physics-based model is analyzing the values form the discharge physics of a lithium-ion battery to derive their model). These models are useful to understand how to analyze a lithium-ion battery and develop a general understanding of the physics and chemistry behind discharge/charge of a lithium-ion battery.

9. Deep Gaussian process regression for lithium-ion battery health prognosis and degradation mode diagnosis [14]

This paper details the methods and results for a deep gaussian process algorithm to analyze the state of health and health degradation for a lithium-ion battery. The gaussian process depends on randomly accumulated data on voltage and temperature for a discharge profile. This allows the algorithm to map the health degradation for the corresponding layers of the lithium-ion battery. For the case of analysis at PHS, this paper shows one of the mathematical approaches for finding the health degradation of any lithium-ion battery if there is knowledge of the voltage and temperature for each discharge rate.

10. Types of Solar Batteries: a guide to solar energy storage [15]

This online article weighs the advantages and disadvantages of commonly used battery types for solar energy storage. The types of batteries compared in this article are lead-acid based, lithium-ion, and flow batteries. Lead-acid based batteries are the current batteries being used in the PHS greenhouse (AGM batteries), so this article gave a larger understanding of the technology behind lead-acid based batteries. Additionally, the comparison between battery types showed which batteries would be most beneficial for solar energy storage (lithium-ion) but for the case of the PHS greenhouse, sticking with an AGM battery would be most beneficial for the energy storage and the clients.

11. Different Types of Battery Energy Storage Systems (BESS) [16]

Similarly to [15], this article is also looking at different types of batteries suitable for energy storage. Instead of focusing on just solar energy storage, this article focuses on battery energy storage systems (BESS) which include thermal management and control systems. The article provides pros and cons for each battery type as well as a short description of the battery type. There is a guide on features such as cost, energy loads, energy generation, and sizing to follow when choosing a new BESS. The article also discusses newer battery technology that is being analyzed and could potentially be used for energy storage in the future. This article provides a larger understanding of different battery types and a guide to follow when choosing a battery system for the PHS greenhouse.

5.3.5 Carson Harder

1. Examples and Equations for Solar Energy: Stand-Alone Photovoltaic Systems - A Handbook of Recommended Design Practices [17]

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.

2. Industry Standards for Solar Panel Installation and Energy Equations: NABCEP 2019 PV Certification Study-Guide [18]

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 [19]

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 [20]

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 [21]

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 [22]

Many factors can cause an increase or decrease in efficiency in solar panels, as the panels are exposed to the elements constantly and 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 [23]

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.

8. Most Efficient Electricity Generating Stationary Bike [24]

This website serves as a potential reference for aspects of the generator's design. The design uses springs to maintain tension on the generator to prevent the belt from slipping off it. The design also provides room for improvements for structural stability of both the bicycle and generator.

9. Engineering Mechanics Volume 2 Dynamics (Seventh Edition) [25]

This textbook will serve as both a reference and a guide for calculating the potential forces being exerted onto the bicycle stand. It provides detailed equations and potential examples that will help ensure a safe and stable stand for student and faculty use.

10. Shigley's Mechanical Engineering Design Tenth Edition [26]

This textbook serves to find the material properties of specific metals, alloys, and materials. This will be used to support calculations made during the structural analysis of the bicycle generator's stand to ensure the metal can withstand the weight of the bicycle and student as well as the dynamic forces acting upon the stand from pedaling.

5.3.6 Ethan Schalnat

1. Bicycle Power Generation and its Feasibility [27]

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 [28]

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 [29]

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 [30]

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 [31]

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 [32]

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.

8. Hands-on ESP32 with Arduino IDE [33]

This practical guide introduces the ESP32 microcontroller using the Arduino IDE development environment, targeting readers new to IoT or embedded systems development. It covers GPIO configuration, analog input reading via the onboard 12-bit ADC, PWM output, deep sleep modes for power conservation, and Wi-Fi/Bluetooth integration. The book bridges explain hardware concepts with working code examples, making it directly applicable to programming an ESP32 to log energy data and manage battery charging states in the human-powered bicycle system.

9. Kolban's Book on ESP32 [34]

This community-authored technical reference compiles detailed notes on the ESP32's hardware peripherals and firmware programming using the ESP-IDF framework. It covers every pin and function of the microcontroller, including ADC channels and attenuation settings, GPIO behavior, timers, and power management registers. For this project, it is particularly valuable for understanding how to accurately read and calibrate signals from the generator circuit, compensate for the ESP32's known ADC non-linearity, and implement efficient data logging for the interactive screen element.

10. DC-DC converters and Their Control Techniques for Renewable Energy Applications [35]

This peer-reviewed article surveys non-isolated DC-DC converters and evaluates their performance parameters using MATLAB Simulink simulation. The authors also analyze and compare control strategies such as PID, sliding mode, model predictive, state-space, and fuzzy logic control, with attention to response time and implementation complexity. The work provides a practical framework for selecting the appropriate converter topology and control method for variable-input renewable energy systems, directly applicable to regulating the fluctuating DC output of the alternator into stable voltage levels suitable for battery charging and microcontroller operation.

5.3.7 Jenna Sterry

1. Horticulture and Landscape Architecture Temperature Control in Greenhouses [36]

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 [37]

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 [38]

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 shade areas through drop cloths or plants and utilizing ventilation and fungi. This blog helps the team look at natural and cheaper ways to support the plants in the greenhouse and reduce energy loss.

4. Sustainable Agricultural Engineering Technologies and applications [39]

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 [40]

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 [41]

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 be able to calculate how much heat is needed to be supplied by the greenhouse.

7. The Energy Cost of Running reptile Enclosures [42]

This blog studies different species enclosures with the average cost per kWh and the average kW output per day. The temperature difference between the inside of the enclosure and the surroundings is about 50 degrees Fahrenheit which is what the team also expects the temperature difference to be. The wattage used is the same as the 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.

8. How to Build a Tortoise Enclosure [43]

This blog describes a simple DIY way to build a custom tortoise enclosure along with what was bought, where it was bought, and estimated costs. This blog will help the team plan on how to convert the pre-existing container into a habitable home for the tortoise.

9. What is the Best Material for a Reptile Enclosure [44]

This blog goes over the advantages and disadvantages of acrylic, glass, PVC paneling, and HDPE plastic. This will let the team decide which material is the best to use and most cost effective. The team must consider that this enclosure will be around students, will have year-round use, and kept inside a greenhouse. These factors will play a key role in determining which material to use.

10. Three-Toed Box Turtle Care Sheet [45]

This blog delves into each aspect of caring for a three-toes box tortoise. This will help the team determine what specific bulbs to buy, how to set the tank up, what foods the turtle can eat, and the tortoise's needs. This will help when building and designing the enclosure to account for the past space for a tortoise.

5.3.5 Kaitlyn Phillips

1. Wind Energy Explained: Theory, Design, and Application [46]

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 [47]

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 [48]

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 [49]

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 [50]

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 PHS greenhouse renewable energy project.

6. Wind Energy Handbook [51]

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 PHS 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 [52]

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 project because the greenhouse energy system uses 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.

8. Electrical Machinery Fundamentals [53]

This book provides the theoretical foundation used in alternator analysis for the human powered bicycle generator design. The text explains how generated voltage is proportional to rotational speed through electromagnetic induction, which directly supports the relationship between pedal speed, gear ratio, and alternator output voltage. Additionally, concepts of efficiency, power conversion, and electrical losses were applied to evaluate system performance and identify optimal operating conditions. These principles were critical in determining how to match human input to generator requirements, guiding decisions on gear ratio selection, expected voltage output, and overall system efficiency for effective integration into the greenhouse's renewable energy system.

9. Engineering Mechanics: Statics and Dynamics [54]

This book provides fundamental principles of force, motion, and rotational dynamics that support the mechanical analysis of the human-powered generator system. Concepts such as torque, angular velocity, and power relationships were directly applied in the alternator analysis to relate human pedaling input to generator rotational speed. These principles were essential in evaluating how mechanical input from the rider influences electrical output, as well as assessing system efficiency and mechanical loading on components, such as the shaft and bearings.

10. Shigley's Mechanical Engineering Design [55]

This resource provides essential methodologies for designing reliable mechanical systems under real-world loading conditions. The text was particularly relevant to the alternator analysis in evaluating component durability, including shaft loading, bearing selection, and fatigue life. Concepts such as stress analysis, factors of safety, and bearing life prediction (L10 life) were applied to ensure that the generator system can withstand the rotational speeds and loads introduced by the human-powered drivetrain.

5.4 Mathematical Modeling

5.4.4 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 the 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,

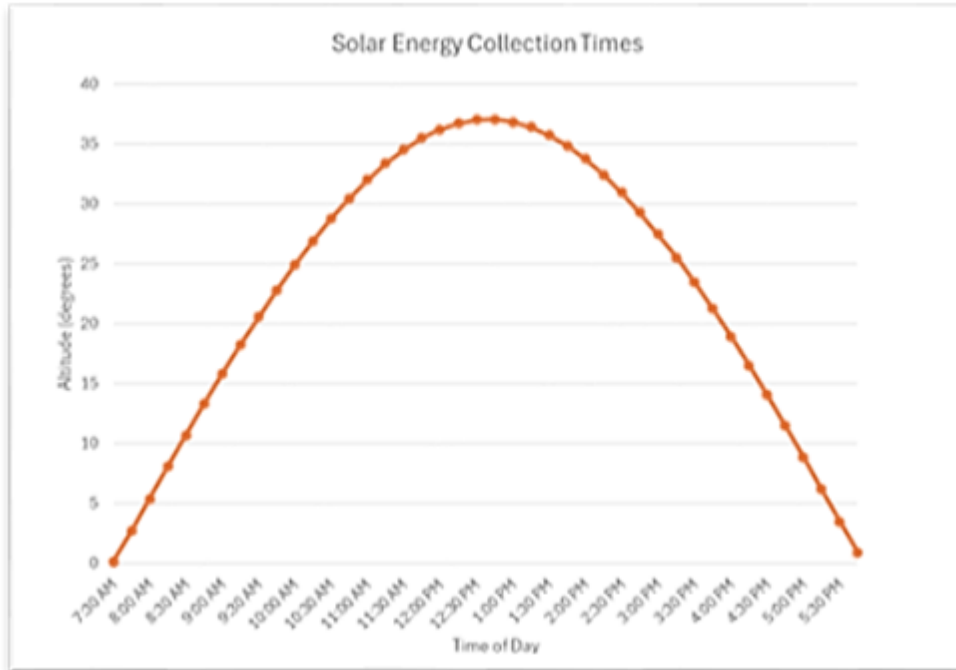


Figure 3. Solar Energy Collection Times [56]

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 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,

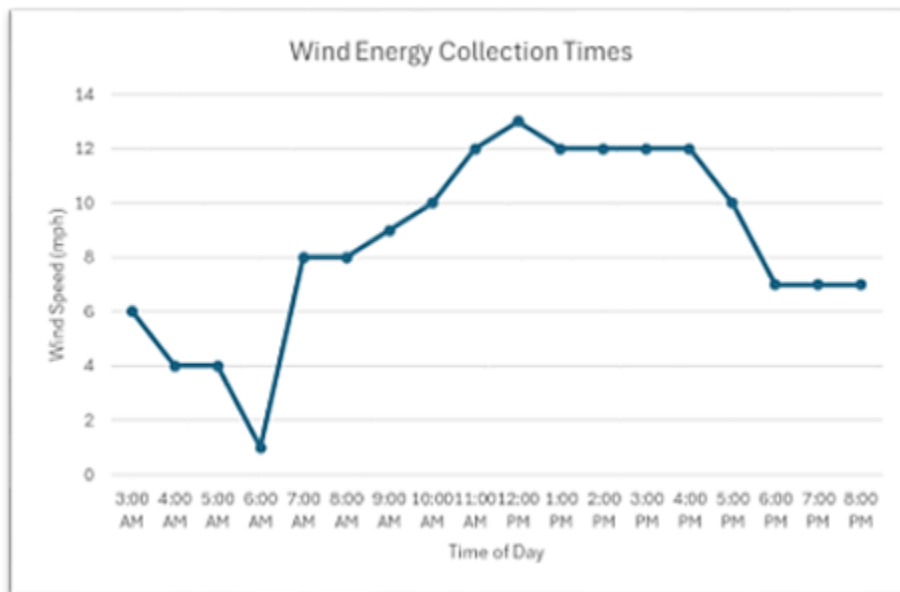


Figure 4. Wind Energy Collection Times [57]

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 PHS 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.

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 five 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") [58]
5. The allowable bending stress for the horizontal support beam is 1.5 kpsi [59]

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

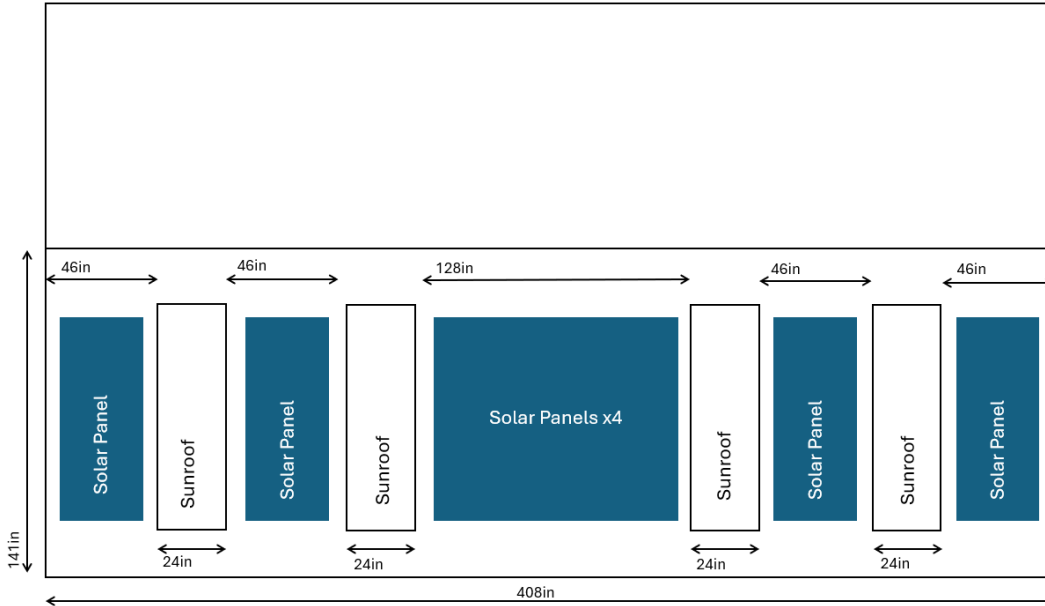


Fig 5. Schematic of the PHS Roof

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

Below is the simplified beam model of the roof,

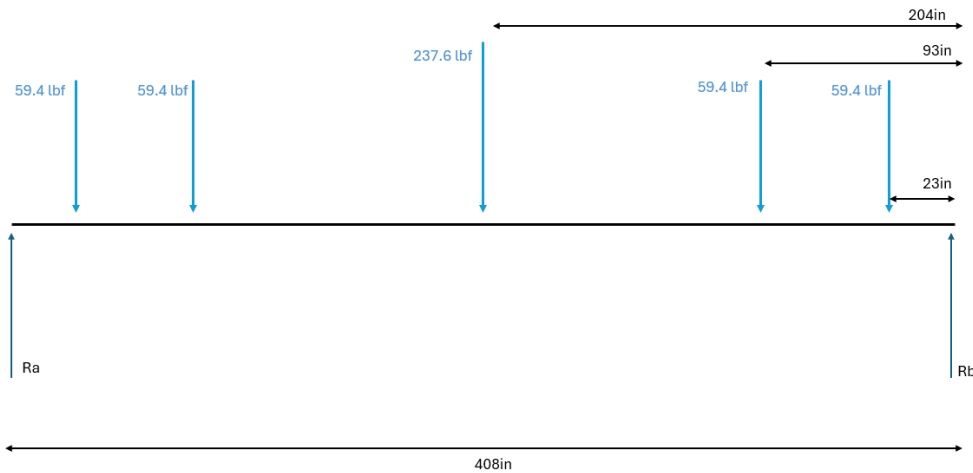


Fig 6. Simplified Beam Model

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 [60]:

$$+\uparrow \varepsilon F = 0 \quad (1)$$

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

$$R_a + R_b = 475.2 \text{ lbf}$$

Moment equilibrium [60]:

$$+\circlearrowleft M_a = 0 \quad (2)$$

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

$$R_b = 237.6 \text{ lbf}$$

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,

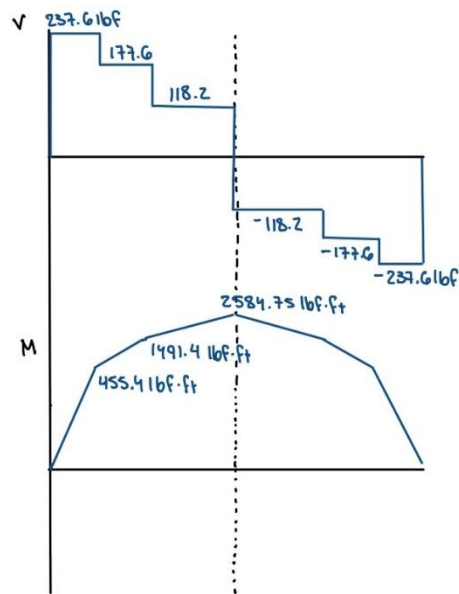


Fig 7. Shear and Moment Forces for Simplified Beam Model

From Figure 7, 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 $\leq 12"$.

The maximum bending stress [60] is described below,

$$\sigma = \frac{M_{Max} \cdot c}{I} \quad (3)$$

Where:

σ =bending stress [kpsi]

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

c = centroid of horizontal beam [ft]

I = inertia of horizontal beam [ft⁴]

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.

5.4.5 Carson Harder

Solar Energy

To elaborate further on the improvements of the solar panels attached to the PHS greenhouse, the 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 output was calculated via two methods, one accounting for energy generated based on the area of the panels and the panels' efficiencies (4) and the second one based on the panels' rated power and system efficiency (5). 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.

$$E = A \times R \times \eta \quad (4)$$

Where;

A is Area[m²]

R is Solar Radiation[kW/m²/h]

η is the efficiency of the panel(s)

$$E = \eta_s \times PSH \times \sum (N \times RP) \quad (5)$$

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 **14%** and the system efficiency is **80%**. The potential energy was compared to that of PVWatts® (Table III) and graphed in the diagram below (Fig. 8) using online data on the solar panels [61][62][63].

Table III
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

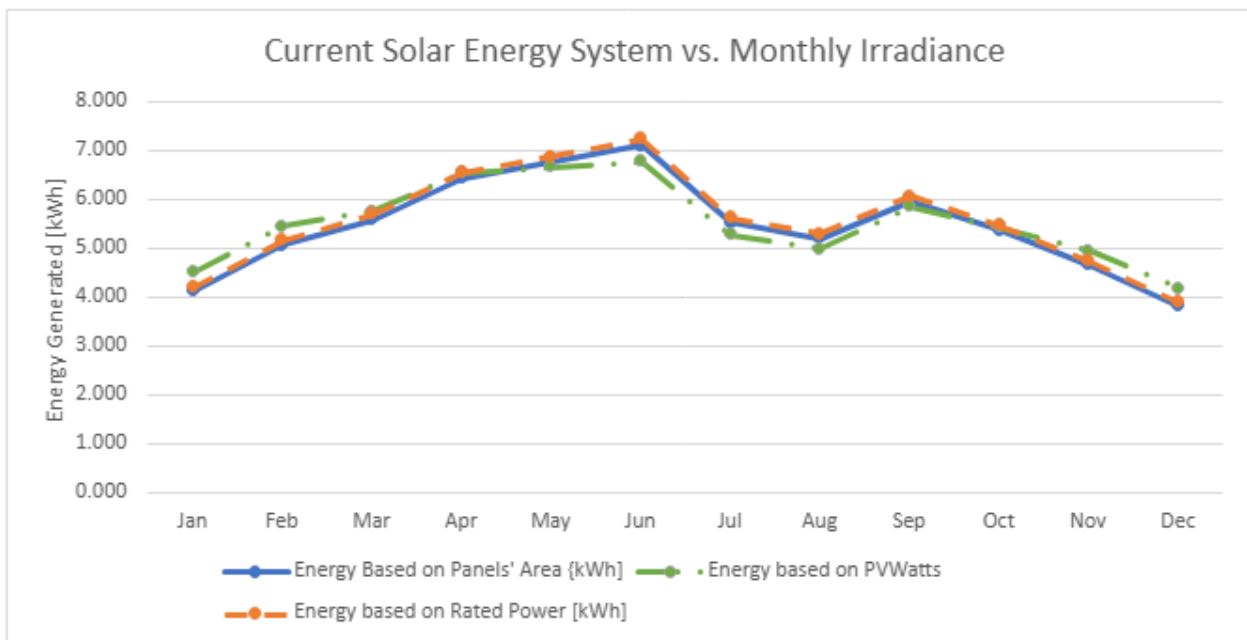


Fig 8. Current Solar Energy System Estimations vs Average Monthly Irradiance

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 in [Appendix C](#) and adding that information into the calculations the team 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 rated power (5) increased from **80%** to **85%** due to the new introduced panels being new compared to the current greenhouse's solar array.

Table IV
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

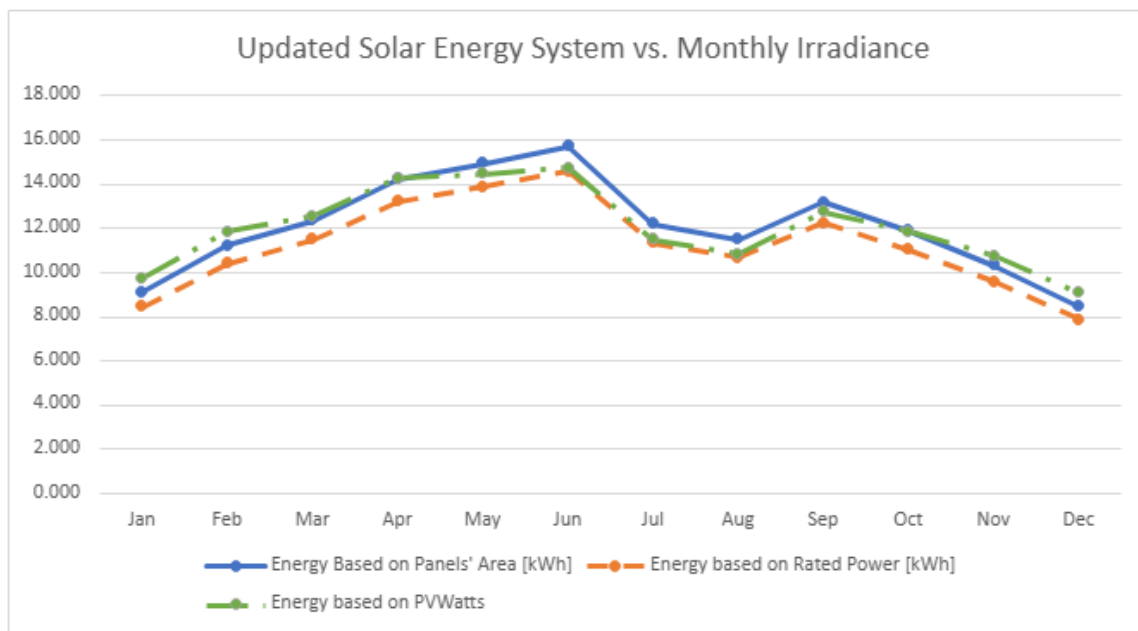


Fig 9. Updated Solar Energy System Estimations vs Average Monthly Irradiance

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.

5.4.6 Ethan Schalnath

Human Powered Bicycle Energy Output

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.45), 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 V.

Table V
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* [28] 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 (7). The resulting alternator shaft speed is then calculated using Eq. 8.

$$G_{bike} = \frac{N}{n} \quad (6)$$

$$G_{alt} = \frac{r}{r_{alt}} \quad (7)$$

$$\omega_{alt} = \omega G_{bike} G_{alt} \quad (8)$$

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 in Equations (11) and (12).

$$\tau [N * m] = Fr \quad (9)$$

$$P_{mech} [W] = \tau \omega \quad (10)$$

$$\eta_{sys} = \eta_{alt} \eta_{drive} \eta_{contact} \eta_{charge} \quad (11)$$

$$P [W] = P_{mech} \eta_{sys} \quad (12)$$

Rather than assuming a fixed cadence and pedal force, the model applies a linear force-cadence tradeoff across the cassette, as shown in Table VI. 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 10.

Table VI
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

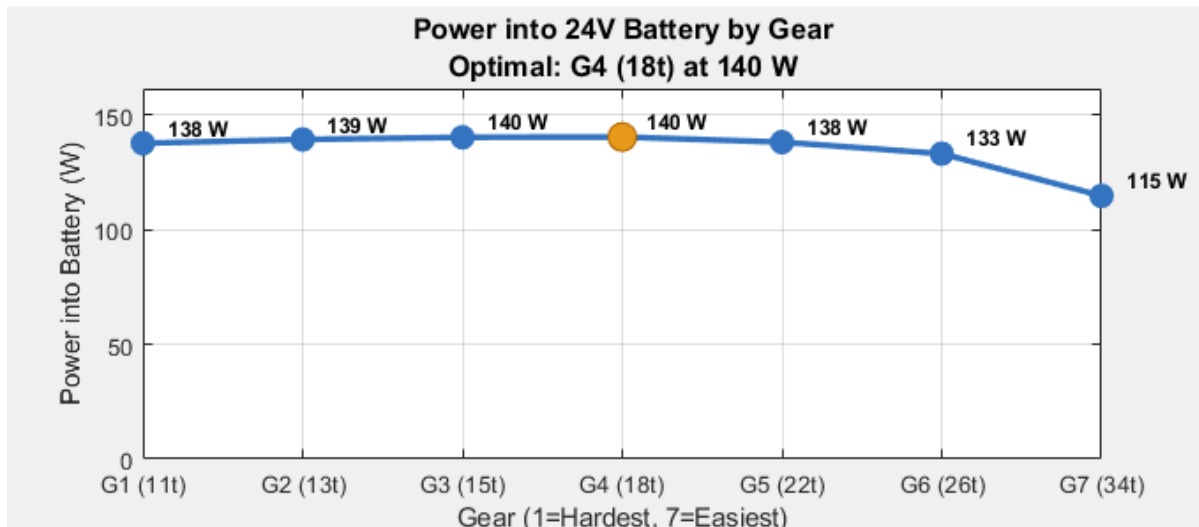


Fig 10. Gear Analysis Results

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** [28], and the result that peak output occurs at moderate resistance is consistent with literature showing maximum sustained power at intermediate loads [28].

5.4.7 Jenna Sterry

Tortoise Habitat

The tortoise that lives in the greenhouse has been a missing animal in their system. The tortoise gets too cold in the winter to survive and must 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/m²** and the size of the tank will have an area of **4.96 m²** and a volume of **59568 in³**.

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 referenced together since their temperatures average the same. The high and low temperatures are calculated for the most extreme conditions.

Table VII
Temperature Over 5 Years

Temperature (K)	Winter	Spring/Fall	Summer
Average	273.17	281.4	292.19
High	292.04	299.63	272.22
Low	252.59	264.08	307.41

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

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

Steady State

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

Power

$$\dot{Q} = UA\Delta T \quad (15)$$

kWh Conversion

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

E basking

$$E_{bask} = lamp(kW) \cdot time(hr/day) \times 365 \text{ day/year} \quad (17)$$

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

Table VIII
Power Consumption

Power (W)	Winter	Spring/Fall	Summer
Average	79.34	54.84	22.72
High	23.16	0.57	-22.60=0
Low	140.61	106.42	82.17

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

Table IX
Yearly Energy Consumption No Water or Lamp

Energy (kWh)	Winter	Spring/Fall	Summer	Total (kWh/yr)
Average	174.53	240.36	49.78	464.65
High	50.76	2.48	-49.51=0	53.24
Low	308.15	466.42	180.07	954.64

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 X
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	$1229.6 + \sum_{i=1}^{12} \frac{\dot{Q}_{evap,i} \cdot t_i}{1000}$
-----	--

This power consumption allows the team to evaluate and plan for how much energy will be needed from the batteries and what to expect as the weather continues to hit record highs.

5.4.8 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 ratio 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 [46]:

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

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 [46]:

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

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]

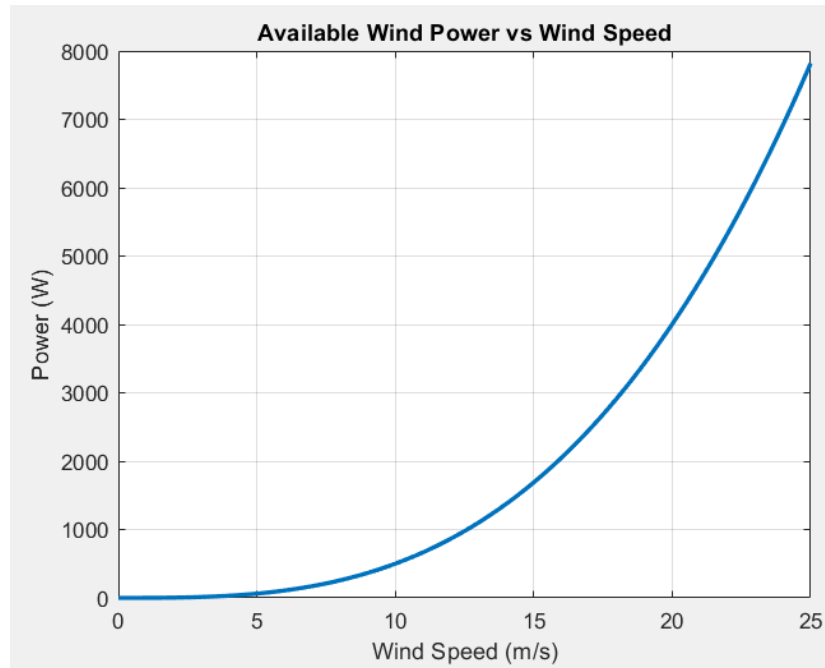


Fig 11. Available Wind Power related to wind speed

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 [46]:

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

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.

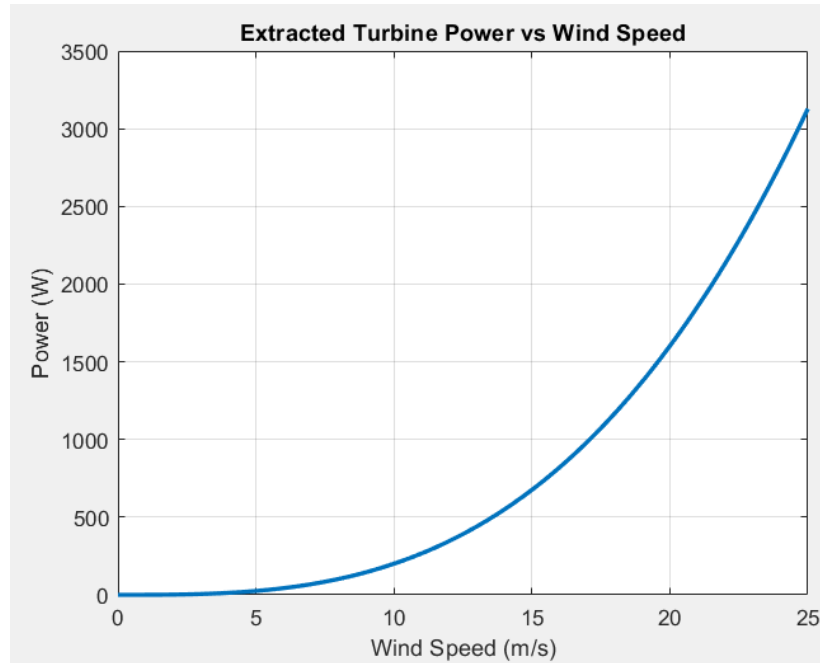


Fig 12. Extracted Turbine Power related to Wind Speed

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 [46]:

$$\lambda = \frac{\omega R}{v} \quad (21)$$

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:

$$\lambda = 2.55W$$

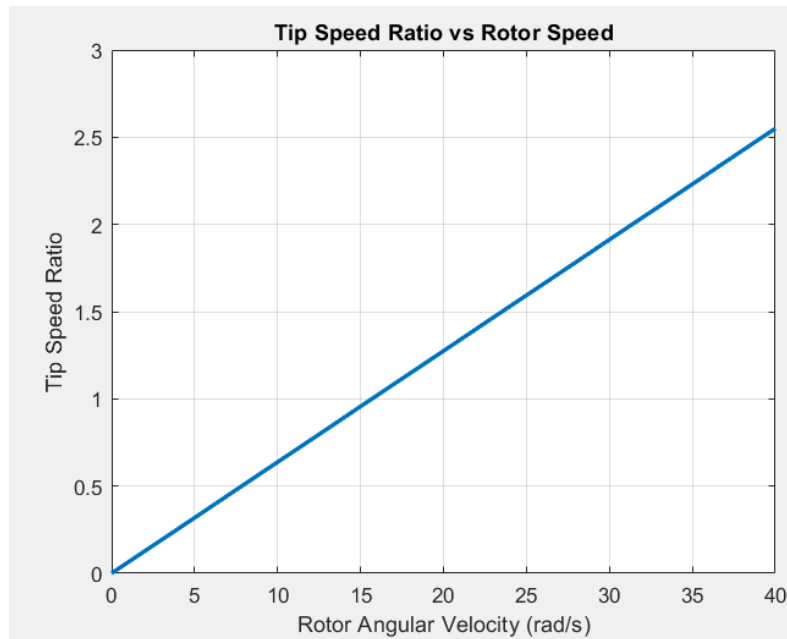


Fig 13. Tip Speed Ratio related to rotor speed

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 [46]:

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

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.

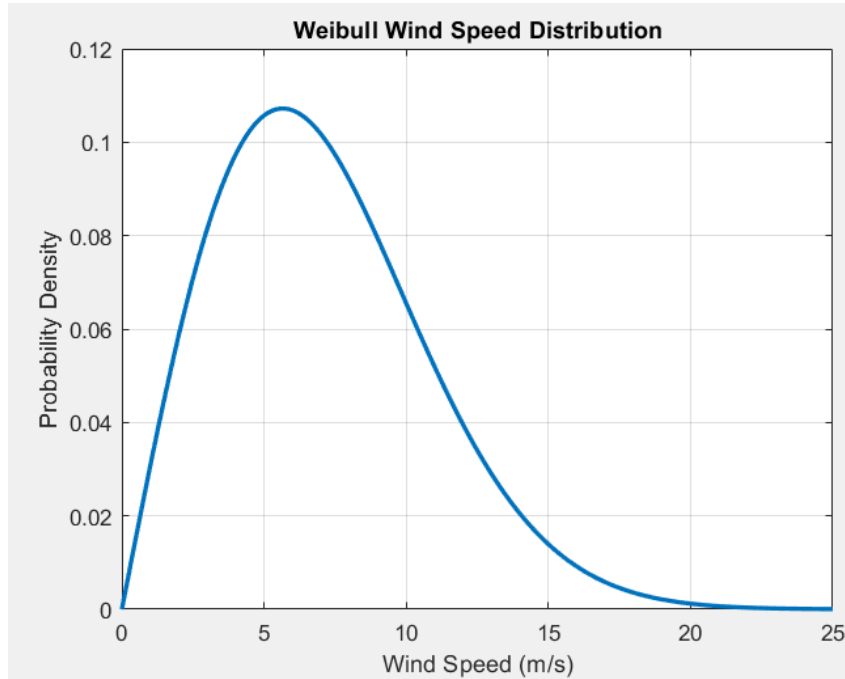


Fig 14. Wind Turbine Weibull Wind Speed Distribution Curve

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 [46]:

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

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:

$$E[P] = 136.05 \text{ W}$$

5.4.9 Summary of Mathematical Modeling

Table XI
Summary of Mathematical Modeling

Analysis Conducted	Team Member Responsible	ER validated	Results/Next Steps
Wind/Solar Collection Times	Alexandra Miller	Multiple sources for energy generation	Graphs show different collection times. 20% increase in energy generation with multiple sources. Confirm wind and solar power generation next.
Static Loading Analysis	Alexandra Miller	Additional solar power generation	Adding 5 more solar panels to the roof will be structurally stable. Conduct a wind and snow dynamic analysis next.
Solar Energy Generation	Carson Harder	Solar power generation	Calculating the potential energy generation from additional solar panels. Determine what efficiency all panels are running to improve performance.
Bicycle Energy Generation	Ethan Schalnat	Power output of HPE	Ideal force-cadence analysis shows that gears 3 and 4 on the donated bike generate an optimal 140 W through the alternator. Next, obtain real force-cadence data and calculate net power with interactive display.
Turtle Habitat Heat Loss	Jenna Sterry	Turtle habitat temperature regulation	Calculations showed an average battery usage of 739.675 kWh per year. Re-evaluate the materials, the structure, and a cost analysis next.
Wind Energy Analysis	Kaitlyn Phillips	Wind energy generation	Expected power output is 136.05W. Confirmation of wind turbine operation was done. Next steps would be to determine how best to utilize wind turbine power in the greenhouse system.

6 DESIGN CONCEPTS

This section 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. However, there is black box modeling and design generation created for the PHS greenhouse. All design decisions documented in this chapter reflect the team's effort to maximize energy output, usability, and educational value.

6.2 Functional Decomposition

6.2.4 Greenhouse

After evaluating and decomposing the bicycle generator, the team then made another black box model of the current greenhouse's systems as shown in Fig. 15. This model establishes the current boundaries of the system before adding the bicycle generator and clarifies PHS current inputs and outputs of their systems.

Black Box Model for Greenhouse

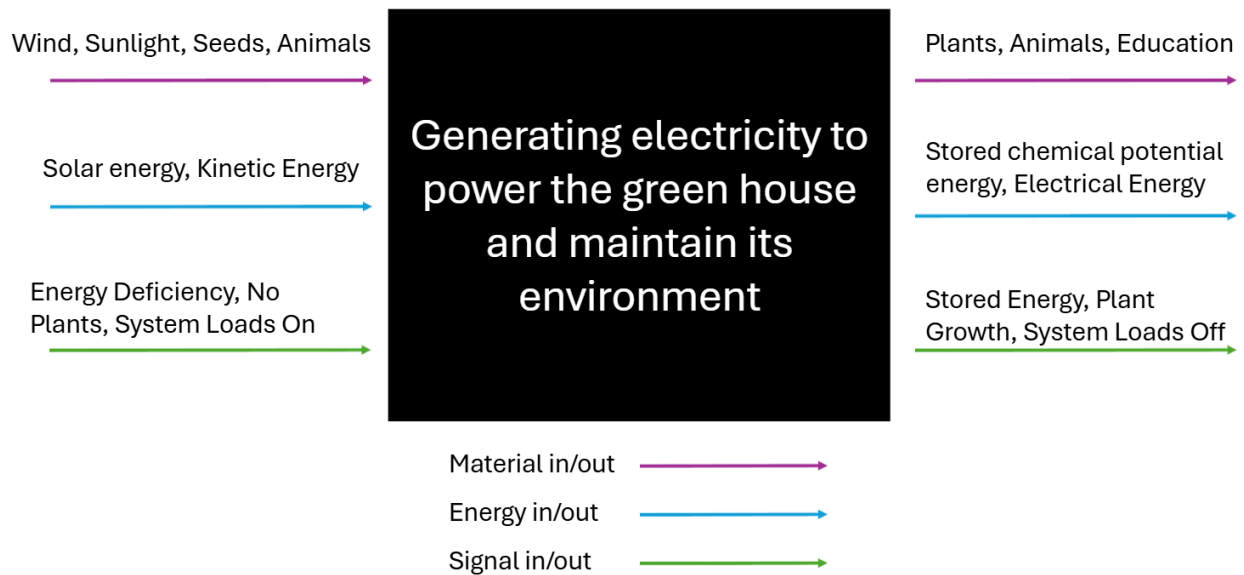


Fig 15. Black Box Model of the PHS Greenhouse

The model focuses on how the greenhouse maintains itself as an off-grid system. The material going into the system is sunlight, wind, and seeds. The material does change through the system as the sunlight and wind are converted into energy and the seeds sprout into plants, with the only material remaining the same being the animals as they serve as a method of maintaining the greenhouse's environment. Energy entering the system is a mix of solar and kinetic energy that is converted to stored chemical energy in the battery system and mechanical energy that goes and powers the greenhouse's loads. The signals that cause

the system to function are the loads being active, battery storage being low on power and if no plants are growing. The systems turn off if the plants are growing, the battery storage is full, and the active loads are no longer active.

Similar to the generator, the team created a decomposition model to have a better grasp of how the system works as seen in Fig 16.

Functional Decomposition Model for Greenhouse

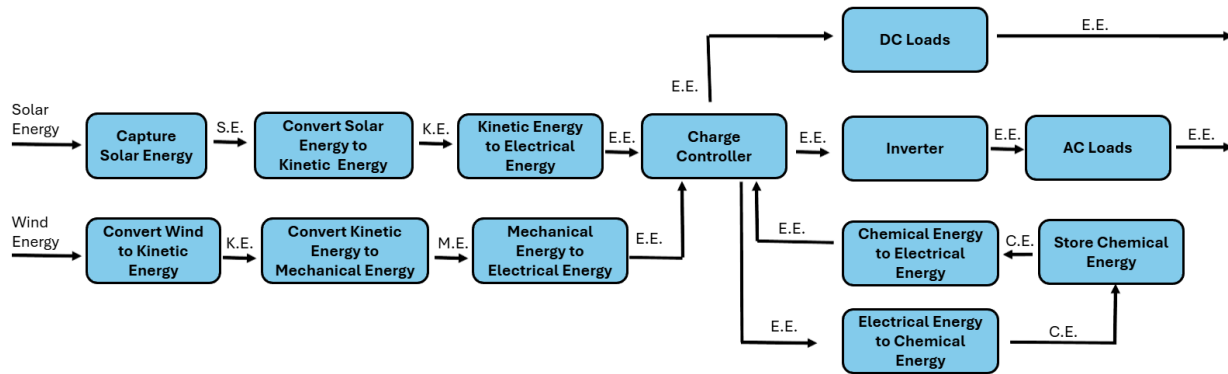


Fig 16. Decomposition Model of the Greenhouse Electrical Systems

This model starts with both solar and wind energy, being the two sources of energy for PHS greenhouse systems. Their energies are then converted from mechanical and kinetic energy, respectively and then to electrical energy. This is then put through a charge controller that distributes the energy to the battery storage by converting the electrical energy to chemical energy, DC loads, and AC loads via an inverter. It's important to note that the chemical energy can go back into the charge controller by being converted back into electrical energy.

The decomposition of the greenhouse’s energy system is important, so the team can connect the bicycle generator to the system and complete the energy audit. The team needs to understand how their system works and how each component works in maintaining the greenhouse’s off-grid system. This will serve as a guide for the energy audit and clearly defining each individual component of the grid.

6.2.5 Bike

The team began the functional decomposition by developing a black box model of the bicycle generator, shown in Fig. 17. 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.

Black Box Model for Bike

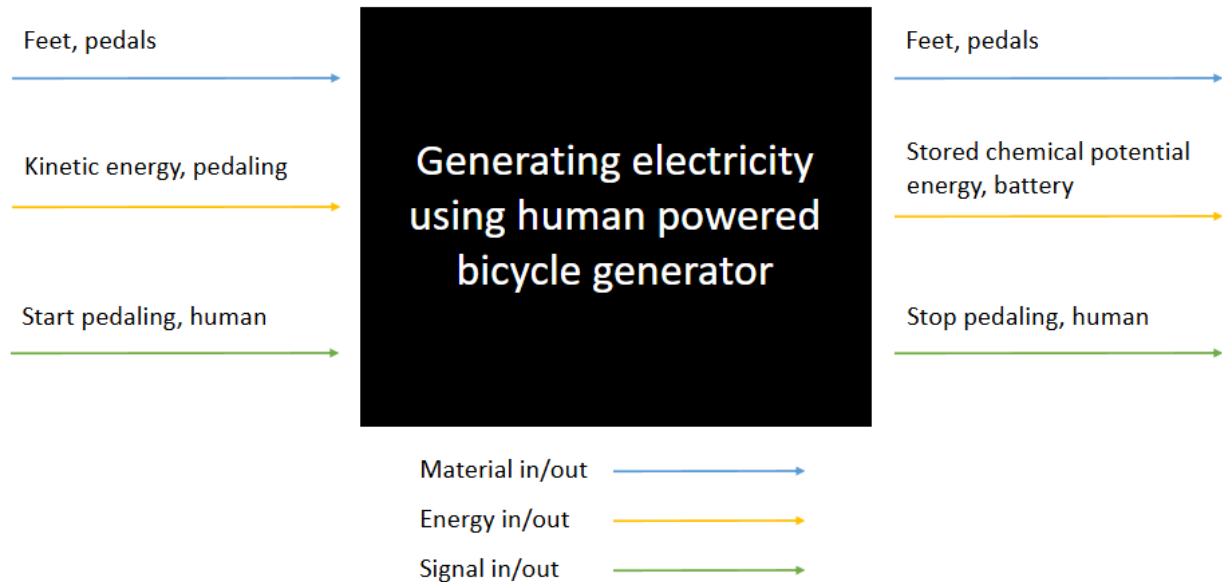


Fig 17. Black Box Model of the Bicycle Generator

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.

Functional Decomposition Model of Bike

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

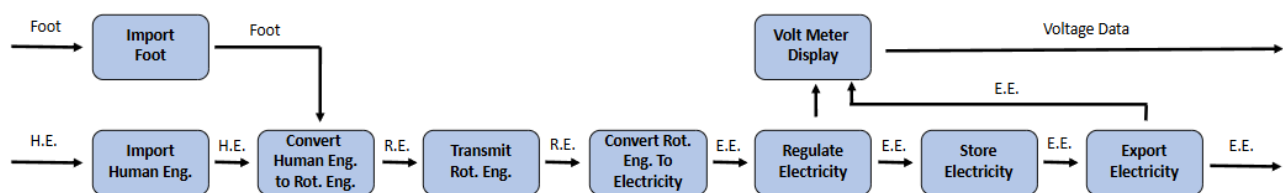


Fig 18. Decomposition Model of the Bicycle Generator

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 necessary components for the team's concept

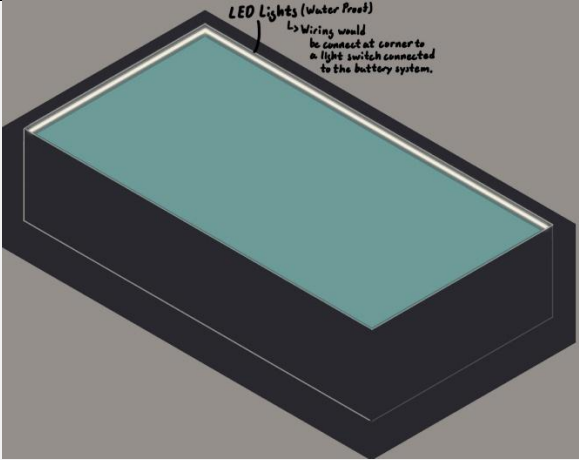
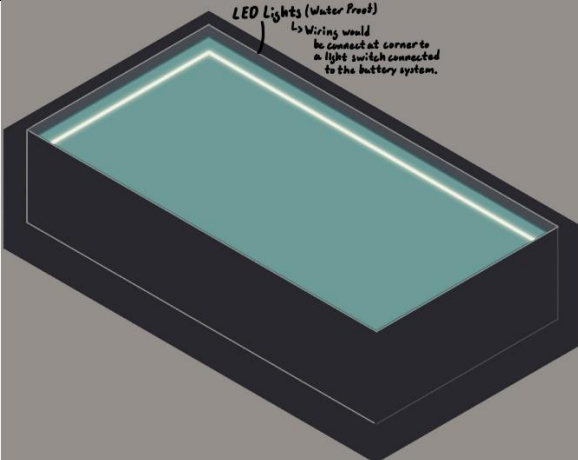
generation. Three main components needed are: a way of generating human energy (pedals, bike, etc.), a device to convert human energy into rotational energy (motor), and a display of that energy (screen, light, etc.). The components identified in the decomposition model are used to generate concepts.

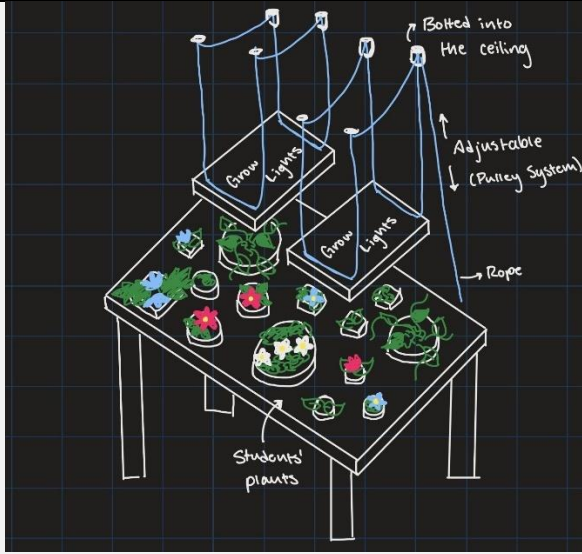
6.3 Concept Generation

6.3.4 Greenhouse

Below are designs for different components of the PHS greenhouse. The components of the greenhouse are detailed below table XII.

Table XII
Greenhouse Designs

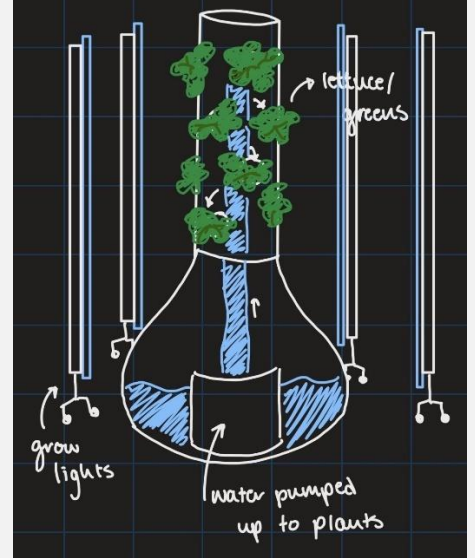
1	2
Fish Tank Lights (A)	
 <p data-bbox="578 1247 613 1276" style="text-align: center;">A1</p> <p data-bbox="488 1297 708 1329" style="text-align: center;">“LED lights (top)”</p> <p data-bbox="480 1350 716 1381" style="text-align: center;">Fig 19. LED lights (top)</p>	 <p data-bbox="1295 1247 1331 1276" style="text-align: center;">A2</p> <p data-bbox="1182 1297 1450 1329" style="text-align: center;">“LED lights (bottom)”</p> <p data-bbox="1182 1350 1450 1381" style="text-align: center;">Fig 20. LED lights (bottom)</p>
Grow Lights (B)	



B1

“Pulley system”

Fig 21. Pulley system

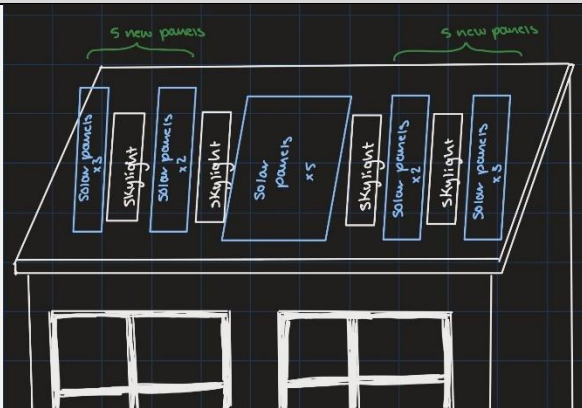


B2

“Dome shaped”

Fig 22. Dome shaped

Solar Panel Placement (C)

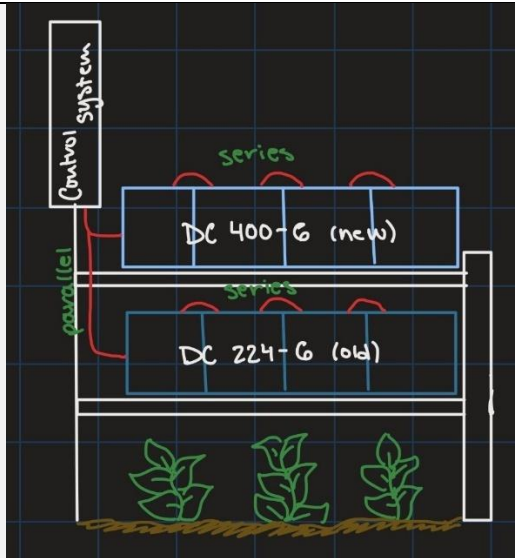


C1

“Symmetric”

Fig 23. Symmetric

Battery Placement (D)

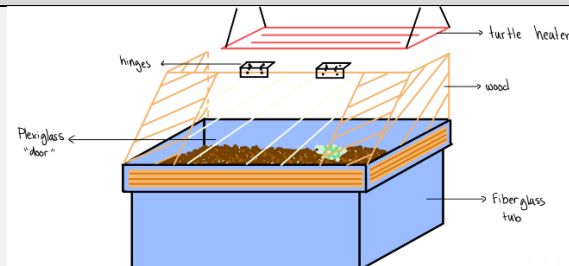


D1

“Series/parallel placement”

Fig 24. Series/parallel placement

The Turtle Habitat (E)

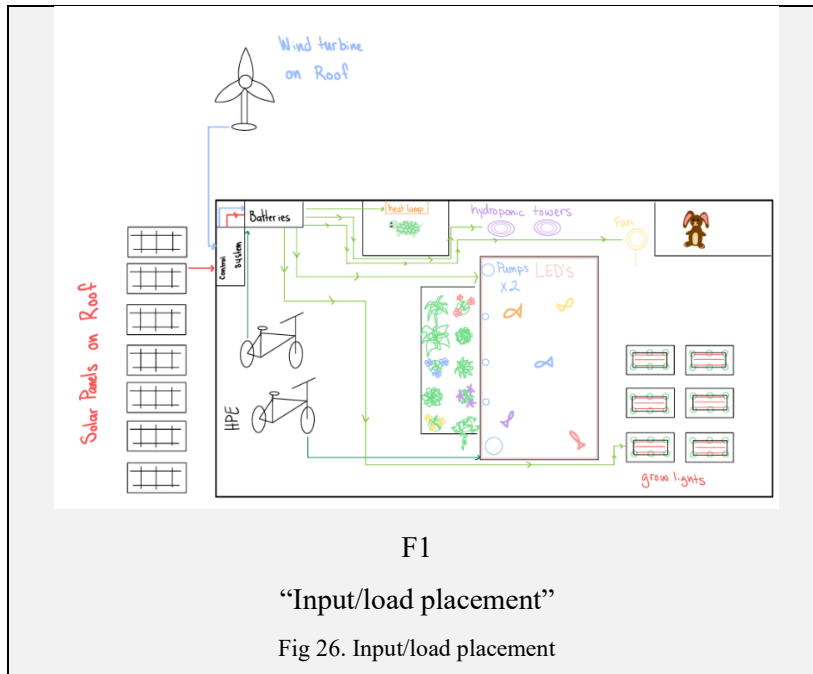


E1

“Wood and plexiglass”

Fig 25. Wood and plexiglass

Placement for Input and Loads (F)



- **Fish tank lights (A)**

- “LED lights (top)” (A1): LED lights will be added to the top of wall along the perimeter of the tank.
- “LED lights (bottom)” (A2): LED lights will be added to the bottom of wall along the perimeter of the tank.

- **Grow lights (B)**

- “Pulley system” (B1): Rectangular grow light boxes will be attached to the ceiling with rope and a pulley system to adjust height of the grow light boxes.
- “Dome shaped” (B2): Using the cylindrical dome grow container, a water pump will be added to the bottom of the cone and cycle water to lettuce/mixed greens growing in the holes. Vertical grow lights will be placed in a circle around the cylindrical dome.

- **Solar panel placement (C)**

- “Symmetric” (C1): 10 additional solar panels will be added to the roof, symmetrically placed on the south side of the PHS greenhouse roof.

- **Battery placement (D)**

- “Series/parallel placement” (D1): The new batteries will be placed in series and then in parallel with the old batteries. There will be two shelves for these batteries with plant space below.

- **The turtle habitat (E)**

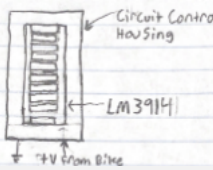
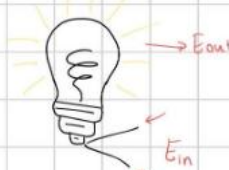

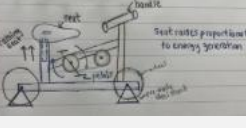
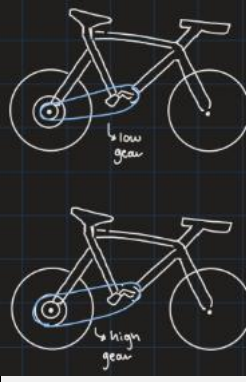
- “Wood and plexiglass” (E1): the turtle habitat will be made from wood with a plexiglass window that can be opened. This structure will be added on top of the current turtle habitat.
- **Placement for inputs and loads (F)**
 - “Input/load placement” (F1): this diagram shows where energy inputs will be in the greenhouse and the distribution of loads.

6.3.5 HPE Bicycle

Sub-assembly designs

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](#). Below table XIII are descriptions of each component.

Table XIII
Morphological Matrix

1	2	3	4	5
Competition/Energy Display (A)				
				
<p>A1 “Energy bar” Fig 27. Energy Bar</p>	<p>A2 “Lightbulb” Fig 28. Lightbulb</p>	<p>A3 “High score” Fig 29. High score</p>	<p>A4 “Raised seats” Fig 30. Raised seats</p>	<p>A5 “High vs. Low gear” Fig 31. High vs. Low gear</p>
Motors (B)				

<p>B1</p> <p>“DC motor”</p> <p>Fig 32. DC motor</p>	<p>B2</p> <p>“Alternator”</p> <p>Fig 33. Alternator</p>			
Material/Design of Stand (C)				
<p>C1</p> <p>“Removable”</p> <p>Fig 34. Removable</p>	<p>C2</p> <p>“Steel”</p> <p>Fig 35. Steel</p>	<p>C3</p> <p>“Premade”</p> <p>Fig 36. Premade</p>	<p>C4</p> <p>“Wood”</p> <p>Fig 37. Wood</p>	
Point of Connection (D)				
<p>D1</p> <p>“Direct Connection”</p> <p>Fig 38. Direct Connection</p>	<p>D2</p> <p>“Drive belt”</p> <p>Fig 39. Drive Belt</p>			

Descriptions for each category in the sub-assembly concept generations are provided below,

- **Competition/Energy Display (A)**

The competition/energy display is how the component that will show the results of power generation to students. This component must have some way to conceptually show how energy is being generated and encourage a “competition” between students to generate more energy. The team and clients decided to add a competitive component so there will be larger student interest.

- “Energy Display Bar” (A1): a bar will increase in height with energy being generated.
- “Lightbulb” (A2): a lightbulb will generate lights as energy is being generated.
- “High score” (A3): a display will show the energy being generated by different students and create a scoreboard.
- “Raised seats” (A4): the seat of bicycle will raise as energy is generated
- “High vs. Low gear” (A5): two bikes will be set to different gear ratios to demonstrate resistance.

▪ **Motors (B)**

The motors component is referring to which motor will be used to generate energy on the human power bicycle design.

- “DC motor” (B1): a DC motor will be used to generate energy.
- “Alternator” (B2): an alternator will be used to generate energy.

▪ **Material/Design of Stand (C)**

The material/design of stand component is to decide which materials and stand design will benefit the human power bicycle the most. This component shows wood and steel for possible materials and different shaped designs for the stand.

- “Removable” (C1): this design allows for bikes to be swapped in and out of the stand.
- “Steel” (C2): steel is used to build the design of the stand.
- “Premade” (C3): an exercise bike stand is purchase online.
- “Wood” (C4): wood is used to build the design of the stand.

▪ **Point of Connection (D)**

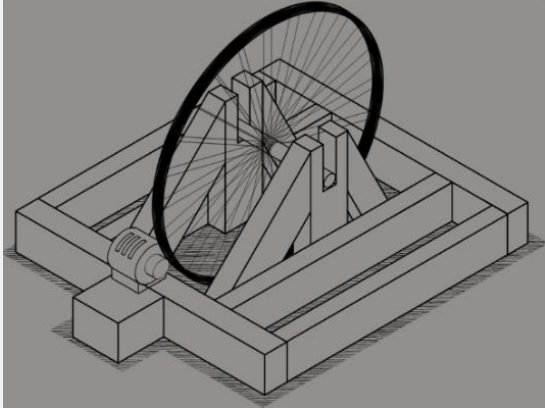
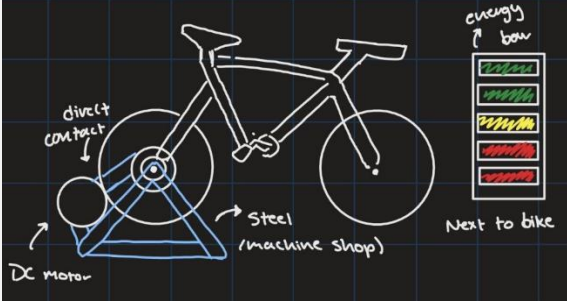
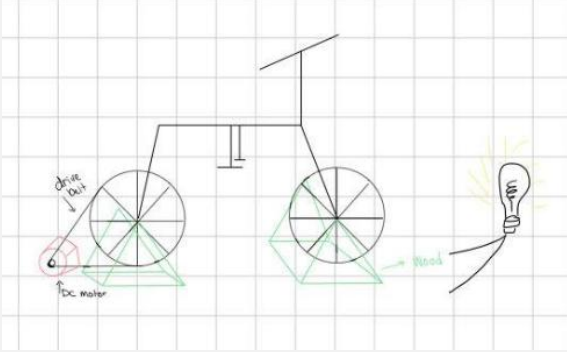
The point of connection is referring to how the bike will be connected to the motor to generate power.

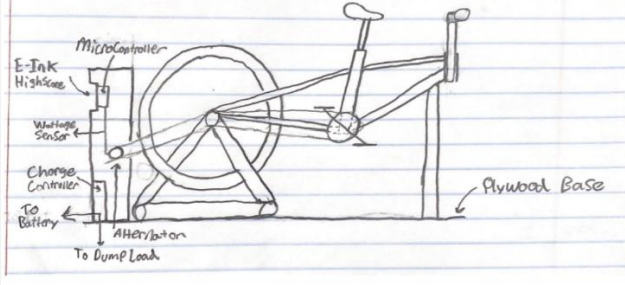
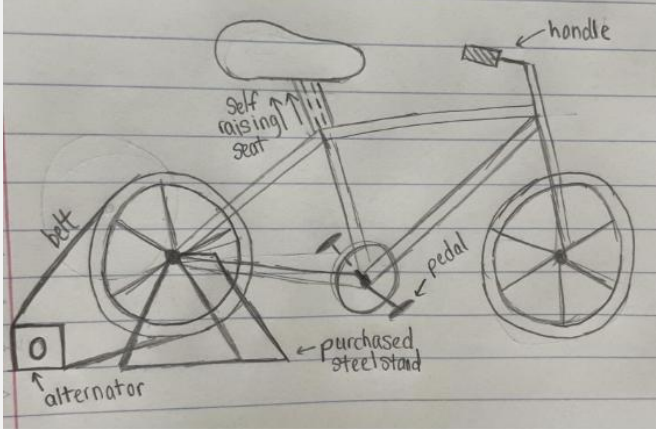
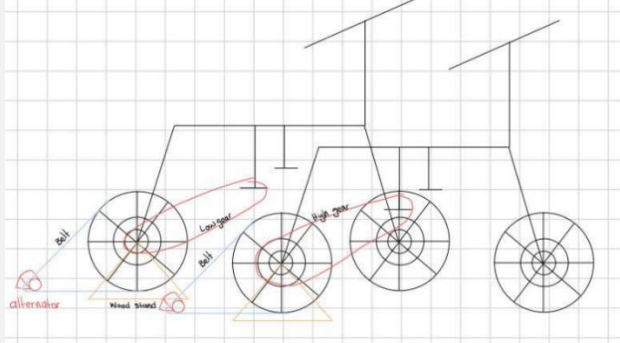
- “Direct connection” (D1): the rear bike wheel is directly connected to the motor.
- “Drive belt” (D2): a drive belt connects the rear bike wheel and motor.

Top-level designs

The top-level designs for the human powered bicycle generator are shown below. Further descriptions and larger images of the top-level designs can be found in [Appendix B](#).

Table XIV
Top-level Assemblies with Advantages/Disadvantages

Design #	Figure	Sub Assem. Used	Advantages/Disadvantages
#1	 <p>Figure 40. Design 1</p>	<p>A5 B1 C1 D1</p>	<p>Advantages: easy maintenance, cheap</p> <p>Disadvantages: weak energy display and aesthetics</p>
#2	 <p>Figure 41. Design 2</p>	<p>A1 B2 C2 D1</p>	<p>Advantages: strong energy display, strong durability</p> <p>Disadvantages: expensive stand and motor</p>
#3	 <p>Figure 42. Design 3</p>	<p>A2 B2 C4 D2</p>	<p>Advantages: strong energy display, cheap stand</p> <p>Disadvantages: weak durability, weak ease of maintenance</p>

<p>#4</p>		<p>A3 B1 C4 D2</p>	<p>Advantages: strong energy display, cheap motor Disadvantages: difficult maintenance</p>
<p>#5</p>		<p>A4 B1 C3 D2</p>	<p>Advantages: easy maintenance, easiest stand to get Disadvantages: expensive stand, medium energy display</p>
<p>#6</p>		<p>A5 B1 C4 D2</p>	<p>Advantages: cheap stand, cheap motor Disadvantages: weak durability, weak energy display</p>

6.4 Selection Criteria

The selection criteria used for the human powered bicycle generator are listed in table 15 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 XV
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 (~\$30) Motors: Alternator (~\$100*donated), DC Brushless (~\$50)	Designs using wood and self-built or locally built stands will 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

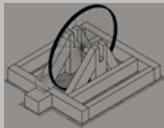


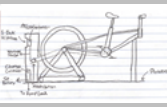

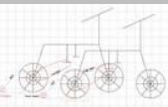
6.5 Concept Selection

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.

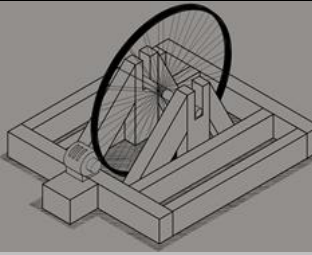
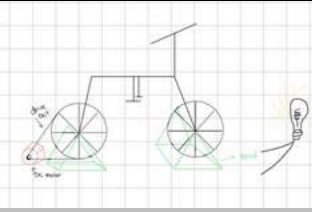
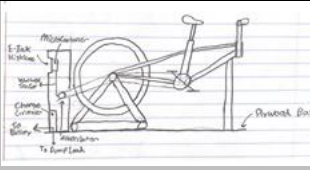
Table XVI
Pugh Chart

Design Criteria	#1  Figure 40	#2  Figure 41	#3  Figure 42	#4  Figure 43	#5  Figure 44	#6  Figure 45 (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 PHS 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 XVII
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 the clients' needs along with the feasibility and decided to go with design one. This final idea included the high score bar

system showing the voltage the students generated. The team 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 brushless DC 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.

CAD Assembly

Using all 3 designs as a basis, the team has started work on a finalized CAD Model. The model below is a representation of the teams' plan for a belt driven generator using an alternator. The design uses a wooden platform for structural stability on the gravel floor of the PHS greenhouse, but also utilizes metal supports for the main stand.



Fig 46. CAD Model of Bicycle Generator using a DC motor and belt

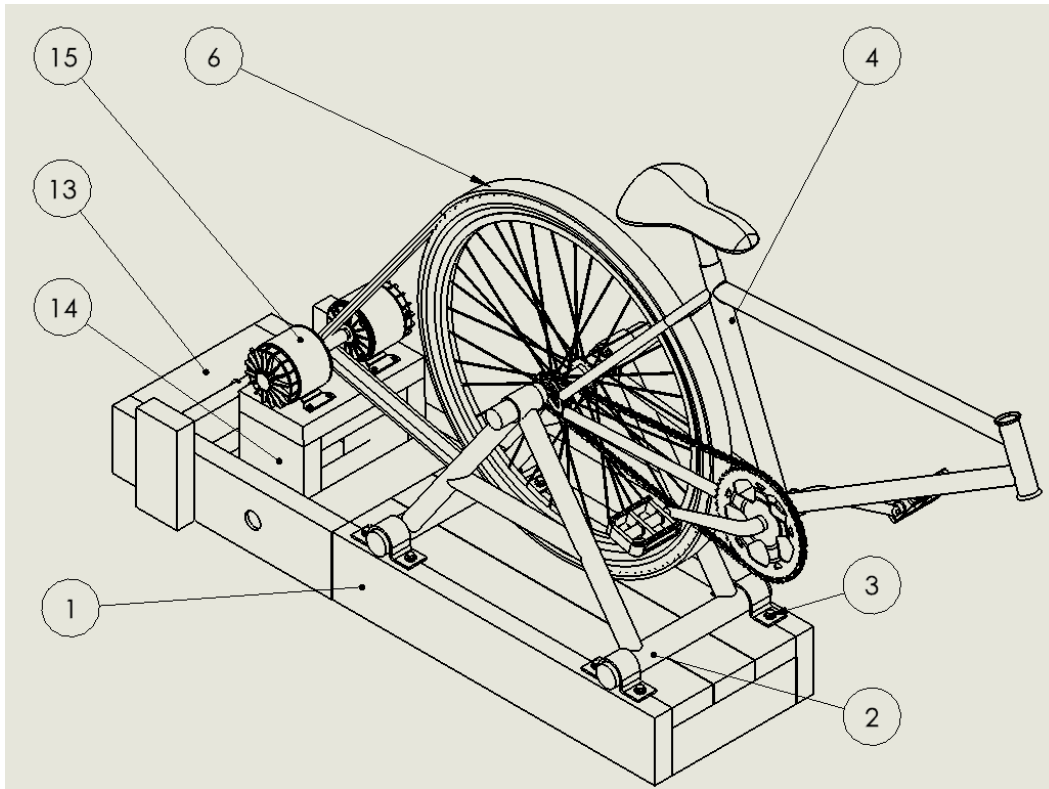


Fig 47. Drawing of CAD Model with listed components

To go more in depth on the model Fig 47, is a drawing of the generator with each component listed.

Component 1 is the main wooden bicycle stand that will hold the metal portion of the generator, so it remains level in the greenhouse. **Component 2** is the metal bicycle stand that will hold the rear wheel of a bicycle utilizing stunt pegs for extra stability on the stand. **Component 3** are metal brackets that will hold the metal stand in place. **Component 4** is the bicycle itself, for this drawing of the halfway model it only depicts the rear portion of the bicycle. **Component 5** is the drive belt the bicycle uses to rotate the alternator. **Component 13** is the secondary base that supports the tension bar used to maintain tension in the belt. **Component 14** is the moving bases that is supported by the belt and springs to maintain tension. **Component 15** is the alternator itself sitting on top of component 14.

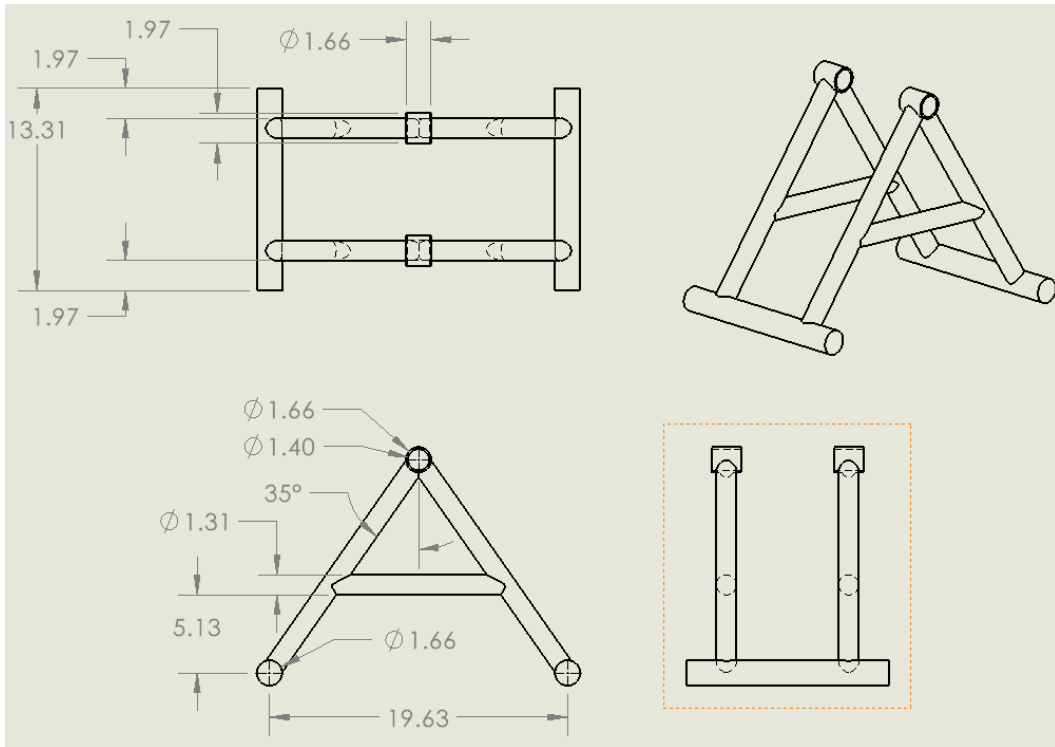


Fig 48. Drawing of CAD Model with listed components

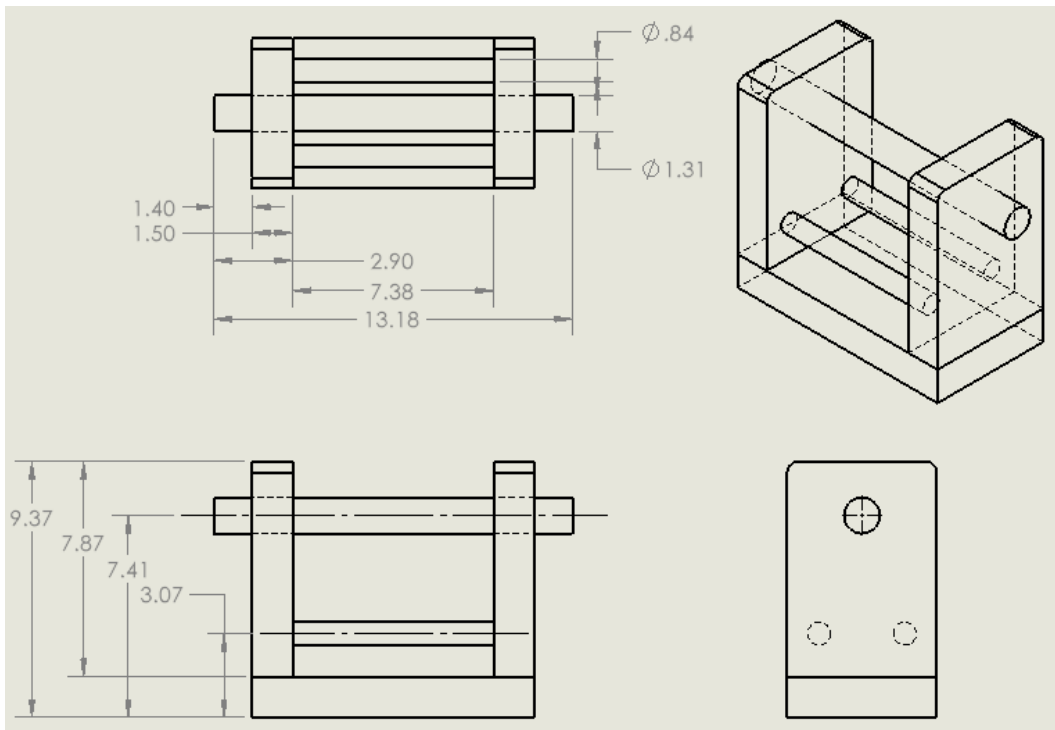


Fig 49. Drawing of CAD Model with listed components

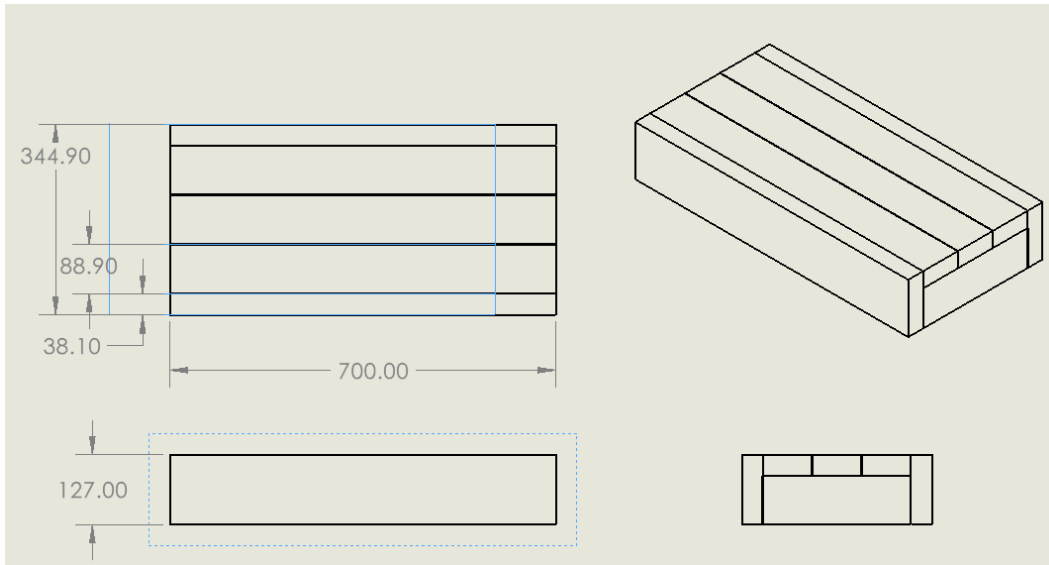


Fig 50. Drawing of CAD Model with listed components

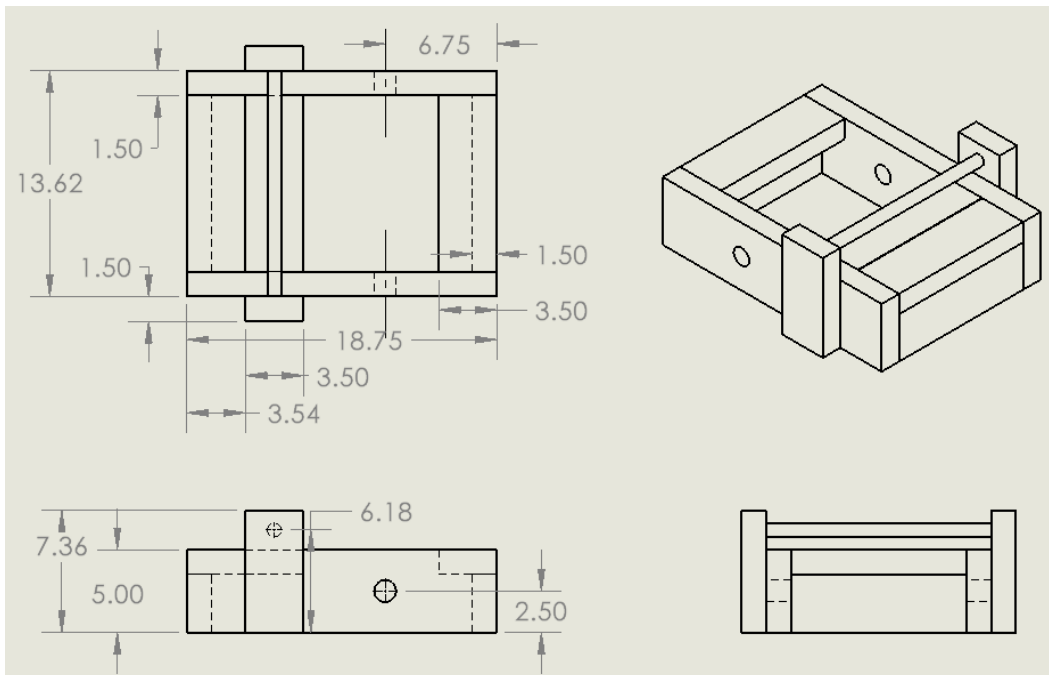


Fig 51. Drawing of CAD Model with listed components

To give emphasis on the importance of the bases, stand and tension support components, drawings of each component are shown in Fig. 48-51. Each component uses industry standard components such as 2x4s and 2x6s for wooden pieces and 42.2[mm] and 33.4[mm] steel pipes. The reason for the mix of both metric and imperial systems is due to the US utilizing imperial standards for construction materials such as wooden planks and the pipe measurements typically being in the metric system.

In regard to a finalized CAD model, work is still being done and will have the front section of the bicycle, the “score board” display, as well as two different models utilizing the belt contact method and direct contact method using a similar design to the current model.

Energy Flow Diagram

Figure 52 illustrates the complete electrical system architecture for the greenhouse, integrating three renewable energy sources into a unified 24V DC power system.

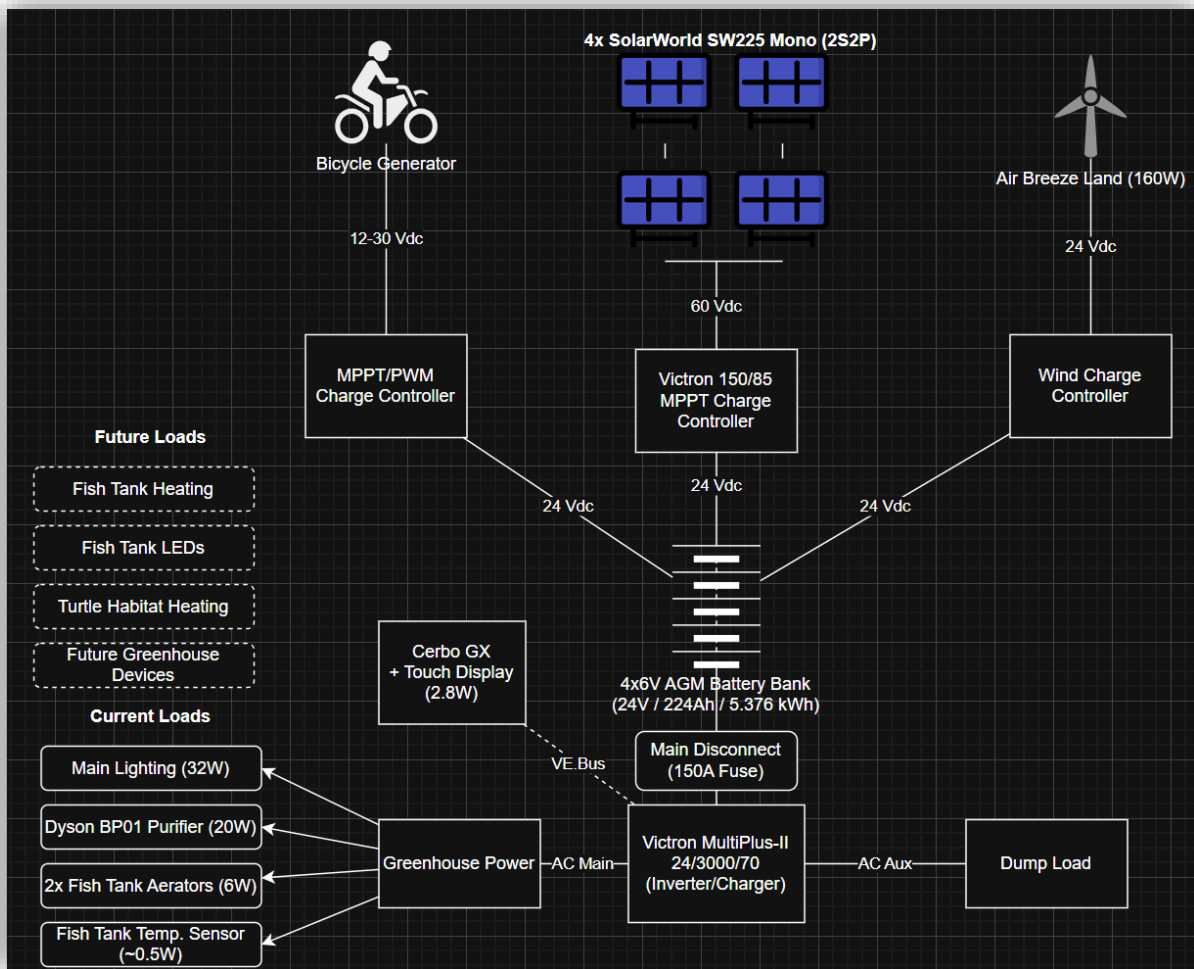


Fig 52. Energy flow diagram of PHS greenhouse

Solar energy is harvested through four SolarWorld SW225 Mono panels arranged in a 2 series, 2 parallel configuration, delivering 60 Vdc to a Victron 150/85 MPPT charge controller. Supplementing solar generation are a 160W Air Breeze Land wind turbine, managed by a dedicated wind charge controller, and this project’s bicycle generator producing 12–30 Vdc, routed through an additional MPPT/PWM charge controller. All three sources converge on a 4x6V AGM Battery Bank (24V / 224Ah / 5.376 kWh), which serves as the system's primary energy storage.

From the battery bank, power flows through a 150A Main Disconnect fuse to a Victron MultiPlus-II 24/3000/70 Inverter/Charger, which supplies AC power to the greenhouse loads and routes excess energy to a dump load via an AC auxiliary output. Current loads include main lighting (34W), a Dyson BP01 air purifier (20W), two fish tank aerators (6W), and a fish tank temperature sensor (~0.5W). System monitoring and control is handled by a Cerbo GX with Touch Display (2.8W), connected via VE.Bus. Several future loads will be added, including fish tank heating and LEDs, turtle habitat heating, and other additional greenhouse devices, reflecting the system's design for scalability as energy needs increase.

7 SCHEDULE AND BUDGET

7.2 Schedule

7.2.4 Spring Semester Gantt Chart (ME476C)

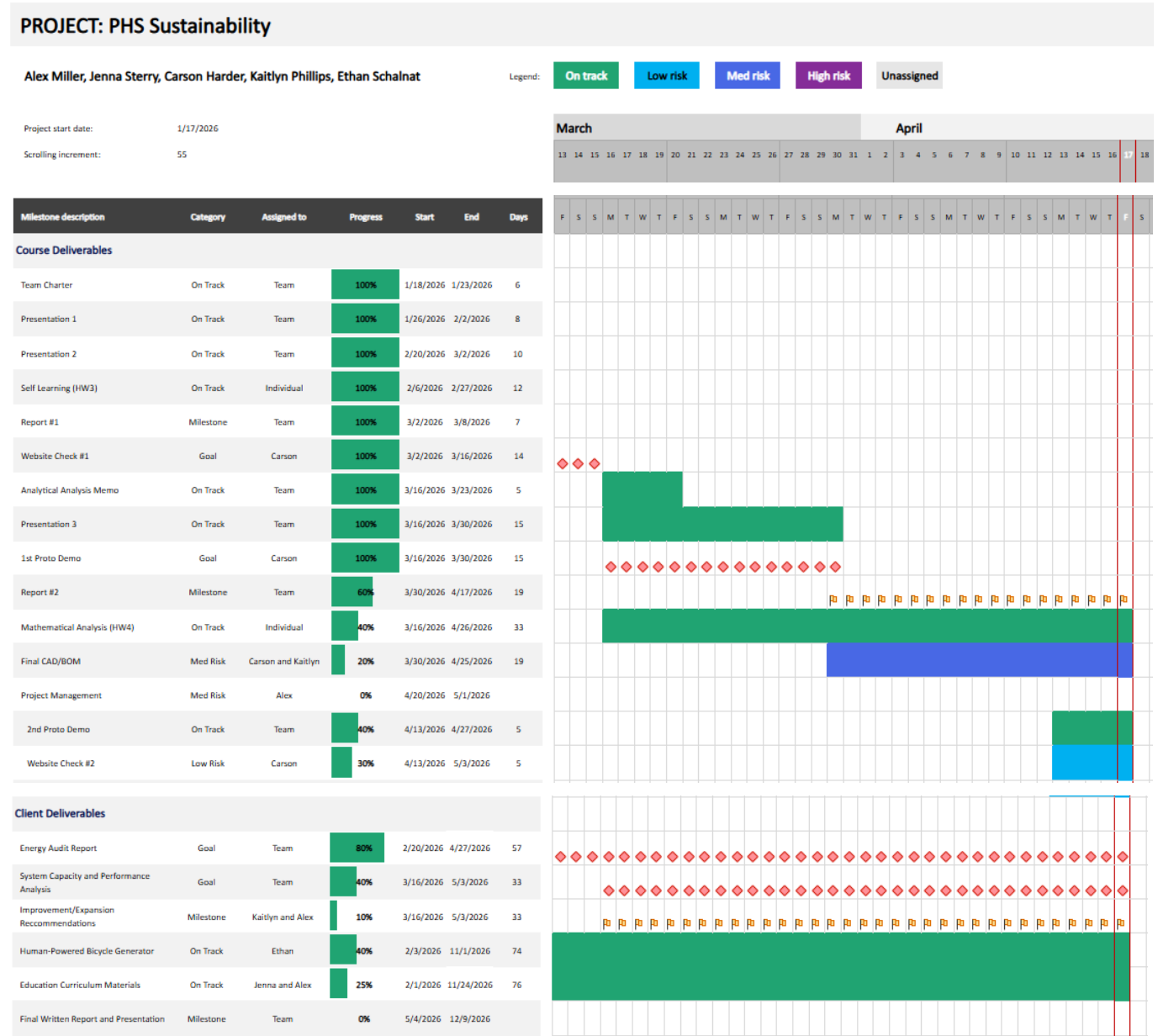
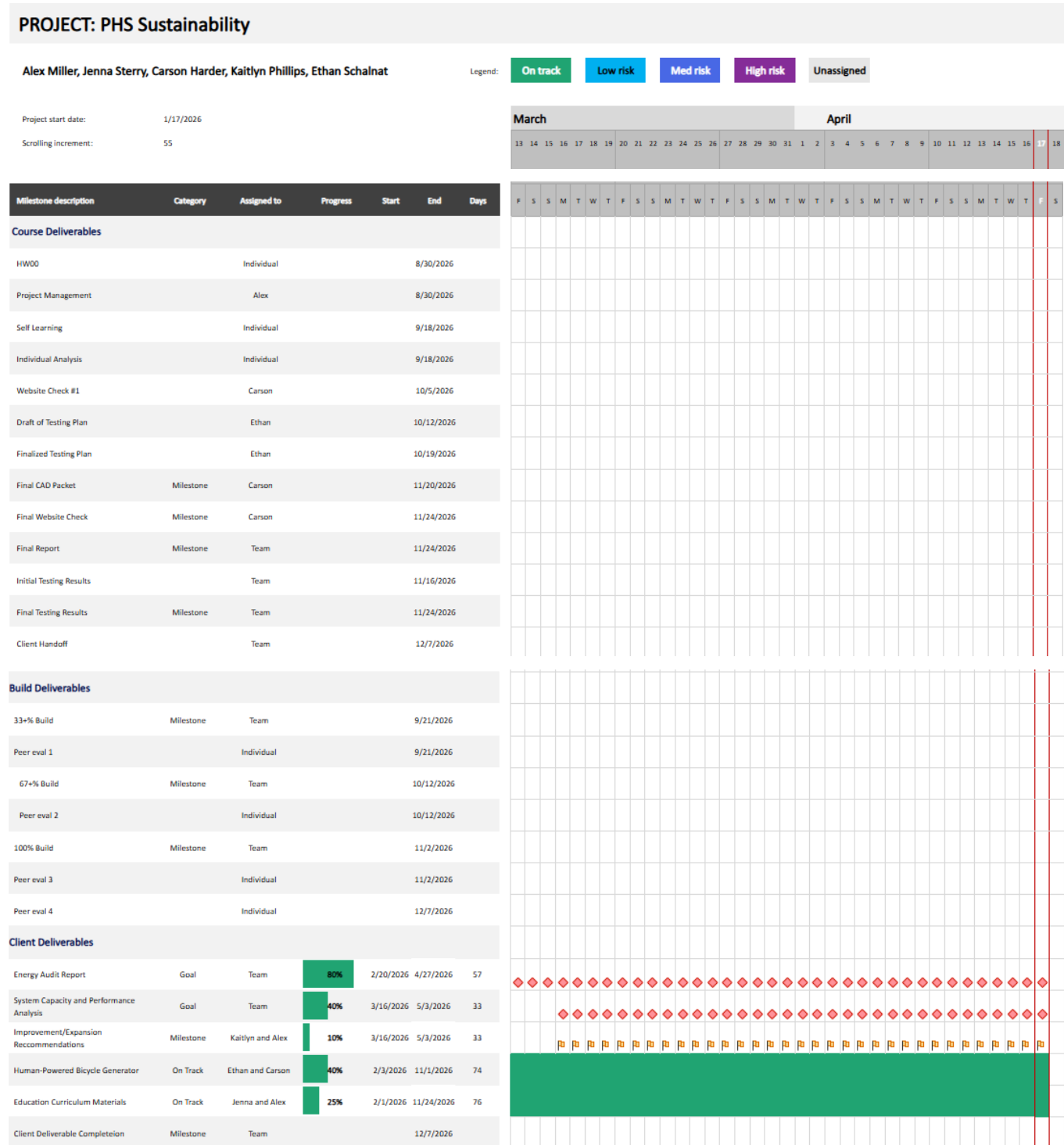


Fig 53. ME476C Gantt Chart

7.2.5 Fall Semester Gantt Chart (ME486C)



Ugrad/Efest deliverables

Ugrad/Efest registration	Alex	10/19/2026
Draft of Poster	Team	10/26/2026
Final Poster	Milestone Team	11/9/2026
Final Presentation	Milestone Team	11/9/2026
Efest Practice (Demo and Presentation)	Team	11/30/2026
Efest	Milestone Team	12/5/2026



Education Curriculum Deliverables

Lesson Plan draft	On Track	Jenna and Alex	100%	2/1/2026	2/16/2026	16
February Lesson	On Track	Jenna and Alex	100%	2/20/2026	2/26/2026	7
March Lesson	On Track	Jenna and Kaitlyn	100%	3/17/2026	3/24/2026	8
KidWind participation	On Track	Team	100%	4/1/2026	4/2/2026	2
April/May Lesson	On Track	Jenna and Alex	30%	4/13/2026	4/21/2026	5
August/September Lesson		TBD				
October Lesson		TBD				
November Lesson		TBD				
Cummulative Education Report	Milestone	Team			11/24/2026	
Community Impact Presentation		Jenna			11/24/2026	

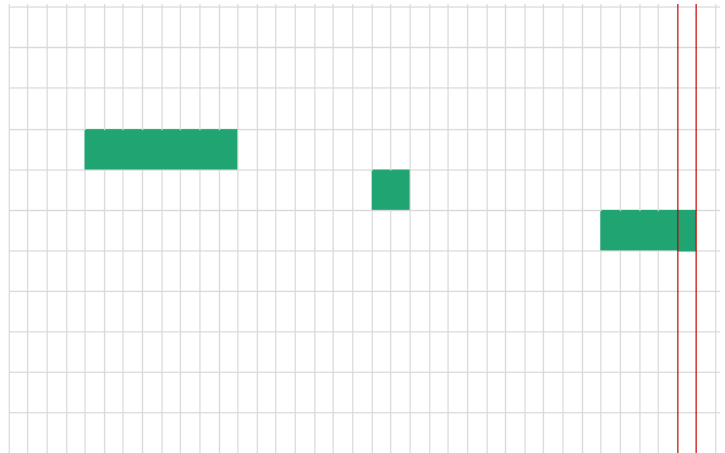


Fig 54. ME486C Gantt Chart Draft

Note about the draft for the ME486C Gantt Chart: current due dates are based off the tentative schedule provided to the team. Additionally, Efest may be moved two to three weeks earlier than proposed in this drafted Gantt chart. All dates are subject to change.

7.2.6 Work Breakdown Schedule

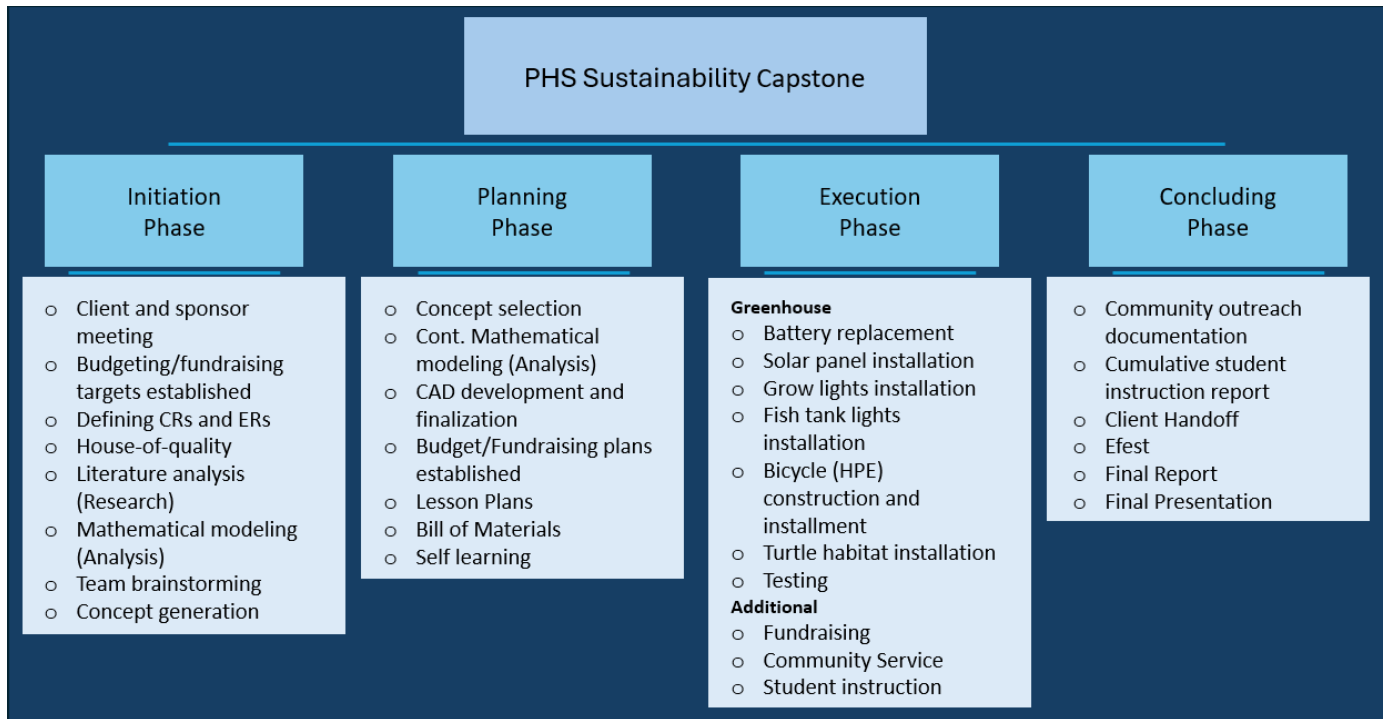


Fig 55. Work Breakdown Schedule

7.2.6.1 PHS Sustainability Capstone

- **Initiation Phase**

The initiation phase includes conceptualizing the project, exploring background research and initial mathematical modeling. The team works closely to brainstorm and develop ideas for solutions to pieces of the PHS sustainability capstone.
- **Planning Phase**

After defining the goals for this project and developing solutions, the team develops a plan of attack in the planning phase. Concepts and CAD models are finalized; additional mathematical modeling is conducted. Plans for the budget and fundraising are established. The team also creates lesson plans to begin student instruction.
- **Execution Phase**

The execution phase is when all construction and installation occur. Components of the greenhouse are being installed and manufactured. The team can begin testing to ensure the results concluded in mathematical modeling are correct. Additionally, the team will hold student instruction, fundraisers, and community service to continue outreach to PHS and NAU.
- **Concluding Phase**

Results and completion of the greenhouse manufacture and installation are shown in the

concluding phase. Documentation is gathered to show and analyze results. Presentations and reports are made to show the community outreach with the PHS sustainability capstone. All final reports and presentations will be in this phase, including the final Efest presentation.

7.2.6.2 Initiation Phase

- **Client and sponsor meetings:** team meets with clients and sponsors for introductions, updates, and establishing goals.
- **Budgeting/Fundraising targets established:** confirm budget and fundraising goals for the capstone. Start development plans and budget making.
- **Defining CRs and ERs:** from client and sponsor meetings, team establishes all CRs and transitions them in ERs.
- **House-of-Quality:** QFD developed by team is used to establish quantitative goals for all ERs. State-of-the-art research is explored at this step.
- **Literature analysis (research):** all team members conduct a literature analysis to develop an understanding in different physical concepts of this project.
- **Mathematical modeling (analysis):** all team members conduct mathematical modeling to further research physical concepts, validated with examples of traditional results.
- **Team brainstorming:** the team comes up with possible solutions to components of the project.
- **Concept generation:** the ideas are developed further into concept generation. Designs generated are validated with mathematical modeling.

7.2.6.3 Planning Phase

- **Concept selection:** designs made in concept generation are compared against each other and selected for their strengths.
- **Cont. Mathematical modeling (analysis):** all team members continue their mathematical modeling to confirm the new designs selected before continuing.
- **CAD development and finalization:** CAD models are generated to virtually analyze and model concept selection. These designs will be finalized for manufacturing.
- **Budgeting/Fundraising plans established:** plans to achieve budgeting/fundraising goals are established.
- **Lesson plans:** team generates schedule for student instruction along with lesson plans that showcase the goals and objectives for each student instruction.
- **Bill of materials (BOM):** table with detailed item and cost information generated to keep updates on all purchases and future purchases.
- **Self-learning:** all team members perform self-learning to prepare their skill set for future assignments, manufacturing, testing, etc.

7.2.6.4 Execution Phase

- **Battery replacement:** battery storage system in greenhouse is replaced with new battery storage.
- **Solar panel installation:** 10 additional solar panels are added to greenhouse roof.
- **Grow lights installation:** Grow lights placed on pulley system above PHS students' plants.
- **Fish tank lights installation:** lights installed in the roof of fish tank.
- **Bicycle (HPE) construction and installment:** human powered bicycle generator manufactured and installed in greenhouse by the team.
- **Turtle habitat installation:** glass paneling placed around turtle enclosure to improve temperature regulation.
- **Testing:** testing is conducted to ensure all pieces of greenhouse are working appropriately.
- **Fundraising:** fundraising events are carried out. All money is moved to appropriate spots.
- **Community service:** team (partnered with energy club) carries out community service events for NAU and PHS.
- **Student instruction:** students at PHS are instructed and exposed to renewable energy concepts with the PHS team (partnered with energy club).

7.2.6.5 Concluding Phase

- **Community outreach documentation:** documentation of students' responses, digital media, and physical demonstration are compiled to showcase results of community outreach. Additional community service will also be documented here.
- **Cumulative student instruction report:** a report will be generated by the team showing the goals and results of student instruction at PHS. Goals defined by the EIA literature guide will be checked off here.
- **Client handoff:** documentation, models, analysis, and improvements/recommendations are handed off to the clients here. The team will ensure that the clients have all the information they need to upkeep this project after completion.
- **Efest:** the team will present the PHS sustainability capstone. The process of completing this project will be shown here.
- **Final report:** a final report showcasing the full process of this project will be documented here.
- **Final presentation:** a final presentation showing the results of this project will be shown here. This is when the team will demonstrate their learning and reflection of this project.

7.3 Budget

The total project budget was developed to support the design, prototyping, and implementation of the Ponderosa High School greenhouse sustainability improvements. Funding was obtained through a combination of university support, fundraising efforts, and financial contributions from Ponderosa High School. The budget accounts for materials, prototyping costs, educational components, and system upgrades including the human-powered generator.

Revenue

The total estimated project revenue was \$5,400.00 with an actual received amount of \$5,292.00. Funding sources include:

- Northern Arizona University: \$1,000.00
- Fundraising: \$1,000.00
- Ponderosa High School: \$3,292.00 (slightly below the estimated \$3,400.00)

Fundraising

Fundraising efforts were successfully achieved through two primary events:

- Chipotle fundraiser: Estimation of \$500.00 raised
- Plant Sale: Total amount raised was \$1,440. The Energy Club has agreed to give our project \$500.00 toward our fundraising goal

These events met the fundraising target and demonstrated strong community engagement and support for the project.

Revenue	Estimated	Actual
NAU	\$1,000.00	\$1,000.00
Fundraising	\$1,000.00	\$1,000.00
Ponderosa High School	\$3,400.00	\$3,292.00
	\$5,400.00	\$5,292.00

Expense Type	Budget	Expense	Remaining
Tools	\$250.00	\$60.14	\$189.86
Batteries	\$3,400.00	\$0.00	\$3,400.00
Solar Panel	\$505.00	\$0.00	\$505.00
LED Lights	\$75.00	\$0.00	\$75.00
Human Powered Energy Bike	\$500.00	\$18.96	\$481.04
Animal Insulation	\$262.00	\$0.00	\$262.00
Curriculum	\$300.00	\$13.00	\$287.00
Total Expenses:	\$5,292.00	\$92.10	\$5,199.90
		Total Revenue:	\$5,292.00
		Total Balance:	\$5,199.90

Fig 56. Budget

Expenses

At the current stage of the project, total expenditures amount to \$92.10 leaving a remaining balance of \$5,199.90 for next semester for the implementation of the completed design. Early expenses primarily

reflect initial prototyping and curriculum development activities.

Most major cost categories include batteries, solar panels, and insulation, which have not yet been utilized, as these components are planned in next semester project phases.

The project is currently under budget and financially stable, with sufficient funds available to support upcoming phases. Successful fundraising efforts and careful budget allocation have positioned the team to complete system upgrades, including battery storage and the human-powered generator, while maintaining cost efficiency and project goals.

7.4 Bill of Materials (BoM)

A comprehensive Bill of Materials (BoM) was developed for Ponderosa High School greenhouse improvement project, including the greenhouse system upgrades, the human-powered bicycle generator, and the prototype systems. The BoM provides a detailed breakdown of all components required for one complete unit of the final design, supporting cost estimation, procurement planning, and fabrication.

Each BoM includes critical information such as material name, description, cost, quantity, and vendor. This level of detail enables efficient sourcing and reduces risk during the build phase. The BoM for the prototype can be found in [Appendix E](#).

7.4.4 Greenhouse

The greenhouse BoM focuses on components required to improve energy generation, storage, and environmental control within the system.

Key Components

- Battery storage system
- Solar Panel racking and wires
- LED lighting system
- Insulation materials for temperature regulation

The battery system represents the largest cost component, totaling approximately \$3,400 and is critical for maintaining reliable energy storage in the off-grid system. Solar panels support energy generation and efficiency improvements while insulation materials are essential for maintaining stable temperatures within the turtle habitat.

Most greenhouse components are purchased off the shelf to ensure reliability and reduce fabrication complexity lead times for these components are moderate and were considered in project scheduling to ensure timely system integration.

Table XVIII
Greenhouse Bill of Materials

PART NAME	DESCRIPTION	VENDOR	UNITS	UNIT COST	AMOUNT
Pulley System	M25 Stainless Steel Pulley System Kit	Walmart	1	\$ 22.25	\$ 22.25
Solar panel MC4 cables	MC4 Connector Solar Panel Cable Kit	Harbor Freight	3	\$ 17.99	\$ 53.97
Solar panels racks	30 in Aluminum Rails, 4 end clamps, and 2 mild clamps	Home Depot	3	\$ 35.90	\$ 107.70
Batteries	Fullriver Battery DC400-6 Sealed AGM Deep Cycle 6 Volt	NAZ Solar Electric	4	\$ 823.13	\$ 3,292.52
Wood	2in x 4in x 96in Premium Grade KD-HT Stud	Home Depot	4	\$ 3.85	\$ 15.40
Plexiglass	Optix 18in x 24in x 0.093 (3/32) in clear acrylic sheet	Donated	1	\$ -	\$ -
LED Light strands	Waterproof LED Neon Rope Light Multi-Color App RF Remote	The DIY Outlet	2	\$ 129.79	\$ 259.58
TOTAL PARTS:			18	TOTAL COST:	\$ 3,751.42

7.4.5 HPE Bicycle

The bicycle generator BoM includes all components required to construct a fully functional human-powered energy system.

Electrical Components

- Generator/alternator
- Wiring and connectors
- Rectifier and voltage regulation
- Battery connections

Mechanical Components

- Bicycle frame and stationary stand
- Shaft and coupling components
- Bearings
- Mounting brackets and structural supports

The bicycle BoM consists of a combination of purchased and manufactured components. Standard mechanical and electrical components are purchased, while custom components such as the mounting stand, alternator housing, and support brackets will be manufactured to ensure proper alignment and size.

Cost distribution within this BoM is relatively balanced, with major expenses associated with the generator and structural materials. Lead times are generally short for standard components, allowing flexibility during assembly and testing.

Table XIX
Bike Bill of Materials

PART NAME	DESCRIPTION	VENDOR	UNITS	UNIT COST	AMOUNT
Bicycles	2 mountain bike with gears donated to use to create the human powered energy generation stationary bike	Donated	2	\$ -	\$ -
Alternator	Converts mechanical energy into electrical energy	Donated	2	\$ -	\$ -
Wood 2 X 4	To build a wooden frame to fix the back tire of the bicycles and hold them in place	Home Depot	6	\$ 3.85	\$ 23.10
Plywood Sheet	Flat plywood surface to be place under the frame and secured	Home Depot	2	\$ 21.48	\$ 42.96
Prime-Line carriage nuts and bolts	1/4 inch-20 teeth per inch (TPI) measuring 1/4 inch diameter x 1-7/8 inch length.	Home Depot	10	\$ 3.30	\$ 33.00
Metal Rod	Zinc plated steel rod	Home Depot	2	\$ 10.53	\$ 21.06
LED Display	Display screen that provides a visual that supports student engagement	Amazon	2	\$ 80.00	\$ 160.00
TOTAL PARTS:			26	TOTAL COST:	\$ 280.12

7.4.6 Bike Prototype

A detailed BoM was developed for initial prototyping to enable testing and iteration of design concepts.

Key Prototype Components

- Low-cost generator components
- Temporary mounting hardware
- Basic structural materials
- Simplified wiring and electrical connections

Prototype components were intentionally selected to be low cost and easily replaceable, allowing the team to test system functionality without committing to final design materials. Final prototype will be used to

validate:

- Generator performance
- Basic electrical output
- Strength/sturdiness of materials

Cost and Lead Time Considerations

The BoM analysis highlights several key cost and procurement considerations:

- The battery system dominates overall cost, making it a critical financial component
- Most bicycle generator components are relatively low cost but require fabrication effort
- Lead times for standard components are minimal, while specialized components may require advance ordering

These considerations were incorporated into project planning to ensure that all materials can be acquired and assembled within the project timeline.

The BoMs provide a detailed and structured breakdown of all components required for the greenhouse improvements, bicycle generator, and prototype systems. By including cost, sourcing, and manufacturing details, the BoM supports informed decision-making, efficient procurement, and successful system integration. The inclusion of a prototype BoM further strengthens the design process by enabling early validation before final implementation.

8 DESIGN VALIDATION AND INITIAL PROTOTYPING

A Failure Modes and Effects Analysis (FMEA) was conducted to systematically identify potential failure modes within the bicycle generator system and evaluate their impact on system performance, safety, and reliability.

8.2 Failure Modes and Effects Analysis (FMEA)

Table XX
FMEA

Part	Potential Failure Mode	Potential Failure Effect	SEV	Potential Causes of Failure	OOB	Detection Method	DET	RPN	Action Plan
Stand	Force-Induced Deformation High-Cycle Fatigue	Structural Collapse, Vehicle Instability, Rider Injury	8	Overstressing, Cyclic Failure, Tangential Stress	5	Visual inspection load cycle testing	5	200	Add Reinforcement, Locking Fasteners, Load Testing
Bike Assembly	Force-Induced Deformation, High-Cycle Fatigue	Rider Injury, Damage to Alternator, Generator Assembly Failure	9	Overstressing, Cyclic Failure, Tangential Stress	4	Visual inspection, strain gauge monitoring, fatigue testing	5	180	Consistent Inspection, Reinforce Joints
Interactive Display Circuit	Abrasive Wear, Circuit Overloading	Damage to Battery, Fire Hazard, Power Loss	8	Faulty Wiring, Component Failure, Cyclic Failure	5	Electrical bench test, overcurrent trigger test	7	280	Overcurrent Protection (dump load), Clean Circuit Wiring
Electrical Housing	Force-Induced Deformation	Live Electrical Exposure, Moisture Ingress, Power Loss	7	High-Impact Loads	3	Ingress test, impact testing with visual inspection	5	105	Strong Polymer, Rounded Corners
Alternator Contact	Force-Induced Deformation, High-Cycle Fatigue	Power Loss, Battery Drain	7	Cyclic Failure	5	Vibration analysis, bearing wear, voltage monitoring	7	245	Integrate ventilation, Alignment Verification

The FMEA identified several high-risk components requiring targeted design analysis and improvements. The interactive display circuit exhibited the highest RPN value (280), primarily due to the risk of circuit overloading and potential fire hazards. This risk is driven by faulty wiring and component failure under repeated use. To mitigate this, the design incorporates overcurrent protection mechanisms, such as a dump load, and emphasizes proper circuit layout and wiring practices to reduce electrical faults.

The alternator contact system also presented a high RPN (245), associated with power loss and battery drain due to misalignment and cyclic loading. This is particularly critical given the rotational nature of the system. Mitigation strategies include alignment verification during assembly and monitoring through vibration and voltage analysis to detect early signs of failure.

The stand and bike assembly components showed moderate-to-high risk due to potential structural deformation and fatigue failure. These failures could result in instability or rider injury. To address these, the design includes reinforcement of structure, potential use of locking fasteners, and validation through load cycle and fatigue testing. These measures ensure the system can withstand repeated loading from human operation.

Electrical housing presented a lower relative risk (RPN = 105) but still requires attention due to the possibility of electrical exposure and moisture ingress. Mitigation strategies include the use of durable, impact-resistant materials, such as strong polymers, along with rounded geometries to reduce stress concentration and improve safety.

The FMEA process enabled the team to identify and prioritize critical failure modes and implement targeted mitigation strategies to improve system safety and reliability. High-risk areas, particularly in the electrical and alternator subsystems, were addressed through design improvements such as overcurrent protection, alignment verification, and structural reinforcement. The analysis ensures that performance enhancements are balanced with mechanical durability and user safety. These considerations will guide further refinement and validation of the system in the next phase of the project.

8.3 Initial Prototyping

8.3.1 3D Printed Proof of Concept

Question: Can a small DC motor generate usable electrical output when driven by a friction wheel in contact with it?

A miniature 3D-printed chassis was constructed to mount a small DC motor to make direct contact with a spinning tire surface. The assembly was designed to replicate, at reduced scale, the fundamental operating principle of the full system, transferring rotational energy from the tire to a generator through frictional contact rather than a belt or drivetrain connection. This approach was chosen for its simplicity and reliability, both of which are desirable properties for the bicycle.

Testing confirmed that the contact-drive mechanism functions as intended. Current was produced across the motor terminals under load, and the friction wheel maintained consistent contact with the motor surface throughout operation. This was visually confirmed using a red LED connected to each terminal of the motor. Additionally, no clamping force was needed beyond the weight of the assembly itself. The prototype therefore validated the core generation concept and demonstrated that no fundamental physical barrier exists to scaling the approach.

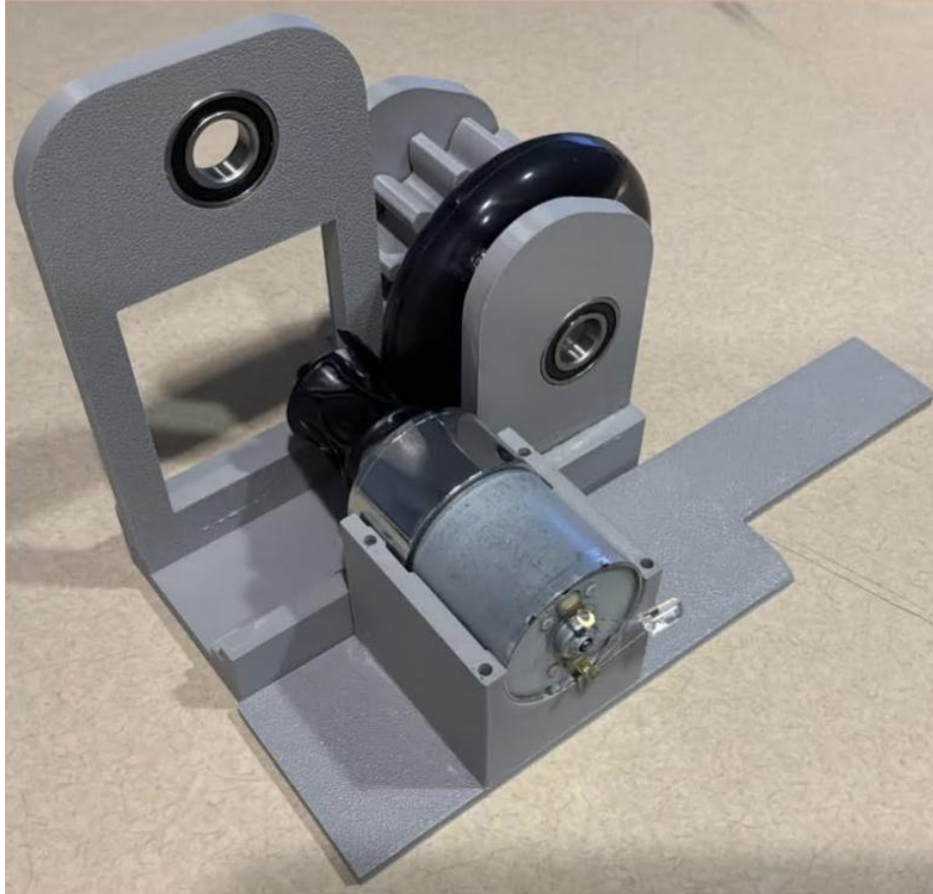


Fig 57. Proof of Concept Assembly

Moving forward, the primary design questions raised by this prototype concern material selection and geometric optimization at full scale. As shown in Figure 57, this design did not utilize bike tires, reflecting the scale constraints of the prototype. The friction wheel's surface material informs both the efficiency of pedaling torque transfer, due to slipping, and the rate of tire wear, that will require further testing on a full-scale model. Motor selection similarly needs to be revisited, as the characteristics of a standard bicycle wheel differ substantially from those of the scaled-down configuration, which will significantly impact generator choice. Taken together, these findings directly motivate the full-scale physical prototype described in the following section.

8.3.2 Physical Bicycle Stand

Question: Will a direct-contact generator mounting system maintain stable, consistent contact with a

bicycle tire under realistic loading conditions, and what structural and data collection opportunities does a full-scale prototype enable?

A full-scale structural prototype was constructed to hold a bicycle in a fixed stationary position while a generator assembly was pressed against the rear tire under conditions approximating real use in the PHS greenhouse. The fixture was designed with rigidity as a primary concern, as flex or vibration in the mount would introduce variability in contact force and degrade energy transfer consistency. The assembly allowed the alternator pulley to be held at a controlled angle against the tire, simulating the contact geometry intended for the final design.



Fig 58. Physical Bicycle Stand



Fig 59. Physical Bicycle Stand, Direct Contact

Testing confirmed that direct contact between the drive wheel and tire is mechanically stable across a range of simulated pedaling intensities. No significant slippage or loss of contact was observed during sustained operation, and the structural members of the fixture showed no significant deflection under load. One limiting factor was identified: the prototype bicycle's deformed rear rim prevented full tire contact throughout rotation, and this bicycle will therefore not be used for power generation testing going forward. Despite this constraint, the fixture demonstrated considerable value as a platform for continued development. Because the bicycle is held in a repeatable, controlled position, the setup is well-suited for data collection, including RPM measurement at the tire surface, contact force quantification, and electrical output logging. These results can also be compared against a belt-drive configuration to further inform the contact method selection.

8.3.3 Interactive Display Circuit

Question: How much power does the user-facing display circuit consume across operating conditions, and does that parasitic draw meaningfully reduce the net power available to the load?

A circuit was developed to drive an interactive display providing the user with real-time feedback on system performance, including instantaneous power output and cumulative energy generated. Providing this feedback to fuel competition is a core feature of the intended student experience. However, any power consumed by the display and its supporting circuitry is necessarily subtracted from the net output delivered elsewhere in the system. Although calculations can assume this to be negligible compared to generation, quantifying this overhead precisely is still a direct input to the system's power budget. Figures #60 and #61 below show the full diagram and current prototype, respectively.

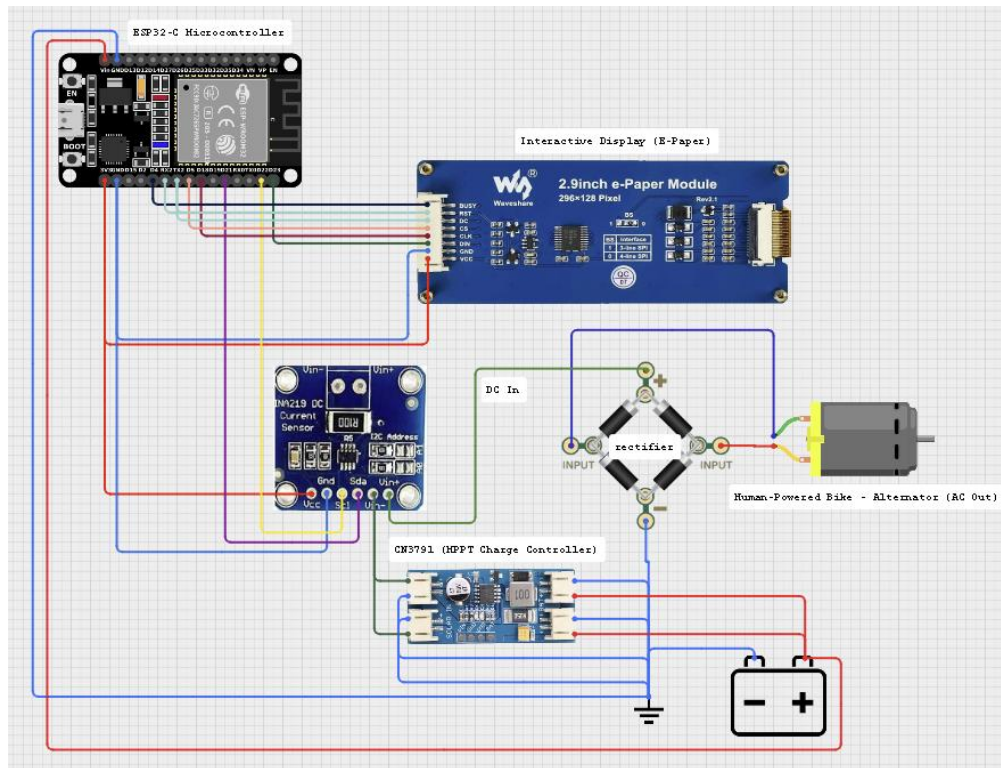


Fig 60. Interactive Display Circuit Diagram [68][69][70][71][72]

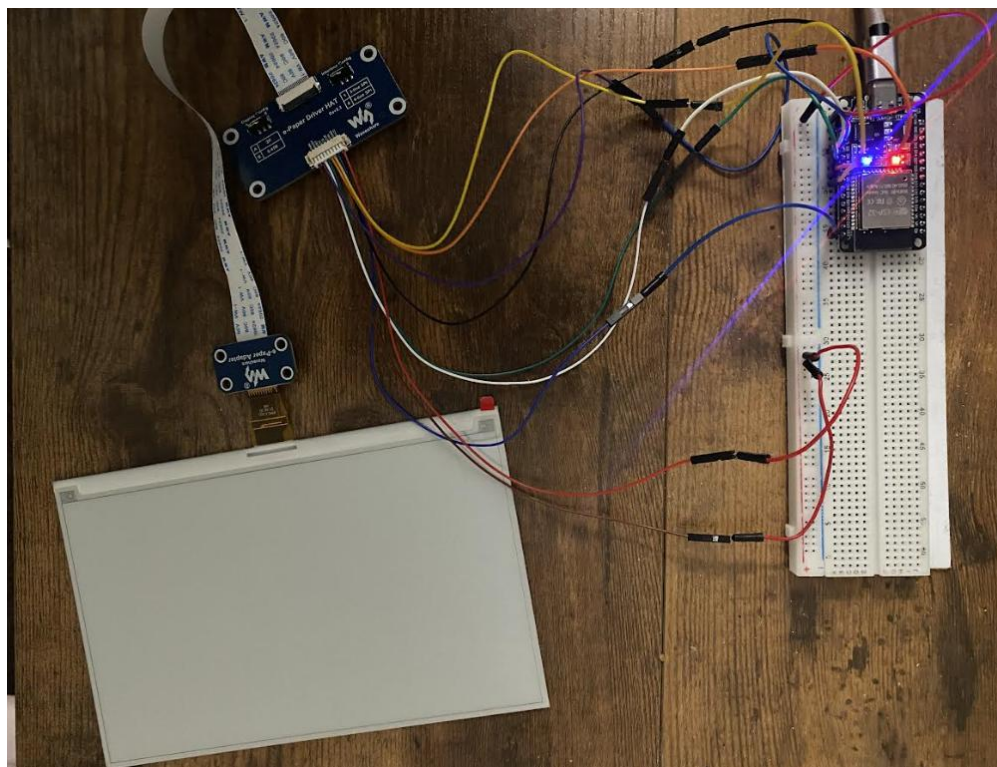


Fig 61. Interactive Display Circuit Prototype

At the time of writing, the display circuit prototype has is under assembly as seen in Figure 61. Empirical power consumption measurements across relevant operating conditions, including active refresh, idle hold, and sleep states, are pending and will be incorporated into the final power budget once collected.

Based on the known characteristics of the selected e-ink display technology, parasitic draw is anticipated to be minimal relative to total bicycle generation output, though this assumption remains to be confirmed experimentally. The characterized circuit will serve as a performance baseline against which future display modifications or alternative technologies can be evaluated prior to integration into the complete assembly.

8.4 Other Engineering Calculations

8.4.4 Alexandra Miller

Battery Analysis: types and comparison

This section of mathematical modeling will highlight key factors for the replacement batteries at PHS and compare common battery types used for renewable energy storage. One of the goals tasked to the team by the clients is to research and propose new batteries to store additional solar power, wind power, and human powered generation at the PHS greenhouse. The current batteries being used are about 8-10 years old and have shown decent battery health degradation in the past 2 years. The initial goal from this research and mathematical modeling is to find optimal batteries for a renewable energy system like the PHS greenhouse.

Battery Types Suitable for Renewable Energy Systems

The main batteries considered for renewable energy system storage are listed below with a short description, advantages, and disadvantages.

Table XXI

Battery Types Suitable for Renewable Energy System

Battery Type	Description [16]	Advantages	Disadvantages
Lithium-ion	Lithium-ion batteries use lithium ions in their discharge reaction to produce a more efficient discharge rate.	High energy density High efficiency Fast discharge rates	Expensive Sensitivity to extreme temp change (needing thermal management)
Lead-acid	Lead-acid batteries use a positive and negative plate to create a reversible chemical reaction. During discharge, the plates with release electrons when transitioning to lead sulfate.	Low cost Recycable Maintenance free (generally)	Shorter lifespan (5-10 years) Slower charge times Less efficient
Sodium-ion	Similarly to lithium-ion batteries, Sodium-ion batteries used sodium ions in	Eco-friendly Lower cost	Lower energy density Expensive

	their discharge reaction to produce an efficient and eco-friendly battery.	Safe	
Flow	Flow batteries use liquid electrolytes to store energy. These batteries are more eco-friendly	Eco-friendly High efficiency Long life span (25 years)	Newer (less research) Expensive up front

After researching different battery types, the team decided to focus on batteries that are more established and have more research to ensure the battery will be a safe choice for the client long term. This left lithium-ion, sodium-ion, and lead-acid batteries for comparison.

Comparison of Battery Types

There are many different variables that can be used to compare between different batteries and establish which battery would be suitable for the given system. Common values to look at are the amperage-hour capacity [Ah], the wattage capacity [kWh], and the continuous discharge rate [A]. These values can be calculated using the mathematical equations shown below, respectively.

Amperage-hour capacity [Ah]

$$Q = \int i dt \quad (24)$$

Where:

Q= capacity [Ah]

i = current with respect to time [A]

Wattage Capacity [kWh]

$$Q_{kWh} = V * Q \quad (25)$$

Where:

Q_{kwh} = kWh capacity [kWh]

V = voltage [V]

Q = capacity [Ah]

Continuous Discharge Rate [A]

$$i(A) = \frac{Q}{t} \quad (26)$$

Where:

$i(A)$ = continuous discharge current [A]

Q = capacity [Ah]

t = time [h]

Additionally, the PHS greenhouse requires battery storage of 24 volts because the charge controller for the solar power generation is also using 24 volts. This means that when finding batteries to use for the greenhouse, it is important to know whether the batteries can be put into series or parallel so the battery storage can reach the correct voltage. After establishing which values to compare, four batteries were compared to the current battery storage in the PHS greenhouse. The values for those calculations are shown below.

Table XXII
Comparison of Suitable Batteries for PHS Greenhouse

Battery	Company /Place for Purchase	Ah Capacity (Ah)	kWh Capacity (kWh)	Parallel or Series	System Voltage (V)	Cont. Discharge Current (A)
DC224-6 (Current) Lead Acid based (AGM)	[64]	224	1.344	Series and/or Parallel	6	11.2
FHSKY-24051-G2-INV LiFePO4	[65]	200	5.12	Parallel (up to 16 times)	24	200
GWN12200 Sodium ion	[66]	200	2.4	Series and/or Parallel (4P4S)	12	200
GWN12100 Sodium ion	[66]	100	1.2	Series and/or Parallel (4P4S)	12	100
BAT524120740 LiFePO4	[67]	100	2.56	Parallel	25.6	200

The results from this table allow the team to compare these batteries and keep the current battery storage as datum. A higher amperage-hour capacity will increase the runtime of the batteries. A higher wattage capacity gives a large energy capacity and allows for more storage during the evening and cloudy days. A higher continuous discharge current will lower the runtime because of thermal damage. The voltage and parallel/series segments are to check that 24 volts could be maintained by the proposed battery storage.

Final choices from battery analysis

Below are the top three choices for the new battery system at the PHS greenhouse,

- **FHSKY-24051-G2-INV (LiFePO₄)**

This battery has a high energy density with a high Ah and kWh capacity. This battery would provide a long lifespan and a large energy capacity during the evening. Although there is a higher continuous discharge rate than the FullRiver DC224-6, the benefits from a lithium phosphate design will be a suitable improvement for the PHS greenhouse.

- **BAT524120740 (LiFePO₄)**

Similarly to the FHSKY-24051-G2-INV, this battery is also a lithium phosphate battery with a high energy density. The kWh capacity is about half compared to the top choice. One interesting piece about the battery is that the manufacturer, Victron, provides an app to monitor the current battery health and the project degradation for the battery. This could be useful information for the clients as well as an educational opportunity for the students on battery life.

- **GWN12200 (Sodium Ion)**

This battery utilizes a sodium ion design with a lower energy density than the previous two batteries but a similar kWh capacity to the previous battery. This design is more environmentally friendly and would be a suitable fit in the PHS greenhouse.

After completion of this battery analysis, Professor Carson Pete proposed an AGM battery that is manufactured by the same company as the current battery storage. With his experience, Pete advised that the team continues forward with his recommendation for simplicity and ease during ME486C. Therefore, future battery analysis will be done for the recommended batteries (FullRiver DC400-6). Specifications for the FullRiver DC400-6 are shown in [Appendix D](#).

8.4.5 Carson Harder

This section of mathematical modeling focuses on the structural analysis of the bicycle stand in which the bike will rest on and connect to the generator to power it. To protect the students from getting injured while operating the generator, we need to calculate the force on which the bicycle will be exerting on the stand. The main topics that need to be considered for this problem are the static forces applied from the weight of the bicycle and rider that the stand will have to hold up, as well as the dynamic force done via torque onto the shaft which is connected to the stand.

Table XXIII

Known Values and Assumptions.

Known Values and Assumptions	
Pedal Crank Length [m]	0.17
Rear Shaft Diameter [m]	0.01

Weight of Bike [kg]	7
Weight of Rider [kg]	75
Bicycle Chain Loss	0.03%

For these calculations, the team is using the specifications of the bicycle being used for the groups prototyping. As for the weight of the rider, an average adult weights anywhere from 60 to 70 kilograms, to be on the safer side; the team is assuming the weight of a rider will be 75 kg. As for the bicycle chain losses, the losses should be close to minimal but still need to be considered as it's a single-speed bicycle.

To calculate the force being applied to the rear bicycle wheel shaft, we need to calculate the torque being applied from the cyclists pedaling. Torque can be calculated with Eq. (27).

$$\tau_{crank} = F_{pedal} \cdot r_{crank} \quad (27)$$

Using the torque equation, we can determine the torque in the pedal sprocket as the torque connected via a shaft all have the same amount of torque deriving Eq. (28), as seen below.

$$\tau_{Sprocket,Fr} = \tau_{crank} \quad (28)$$

Since the sprockets are connected via a bicycle chain their torques are near identical but the torque losses from the chain still need to be considered, resulting in Eq. (29)

$$\tau_{Sprocket,R} = \tau_{Sprocket,FR} \cdot (1 - n_{loss}) \quad (29)$$

As we now have the torque in the rear shaft, we can now calculate the force acting on the shaft by taking the torque in the sprocket and dividing it by the radius of the shaft. Using this method and dividing by 2, the forces acting on each stand can be calculated. For the sake of this analysis, we will consider the force acting in the vertical axis. The equations are shown below in Eq. (30) and Eq. (31) respectively.

$$F_{Shaft,R} = \frac{\tau_{Sprocket,R}}{r_{Shaft,R}} \quad (30)$$

$$F_{Stand} = \frac{F_{Shaft,R}}{2} \quad (31)$$

Using the equations, we can determine the force on the stand depending on the force the rider exerts on the pedal, depending on if the rider is casually pedaling or putting in high amounts of force. Using forces of 50, 100, 150, and 200 newtons the torques on the bicycle and therefore the force on the stand are calculated in the table below.

Table XXIV
Comparison of Forces and Torques

Pedal Force (N)	Crank Torque (Nm)	Rear Sprocket Torque (Nm)	Force on rear shaft (N)	Force on each stand (N)
50	8.5	8.245	824.5	412.25
100	17	16.49	1649	824.5
150	25.5	24.735	2473.5	1236.75
200	34	32.98	3298	1649

Shifting towards the static loads on the stand, we only need to account for the weight of both the rider and bicycle times the gravitational constant. The downward forces will be divided by two as the bicycle is held at both the rear wheel and front wheel resulting in Eq. (32). The forces in the rear wheel will be divided by 2 again as the rear wheels' forces are split between the 2 shafts holding the back tire up as demonstrated in Eq. (33).

$$W_{Wheel} = \frac{g \cdot (m_{rider} + m_{bike})}{2} \quad (32)$$

$$W_{Wheel,Rear} = \frac{W_{Wheel}}{2} \quad (33)$$

The resulting force in the wheels is **402.21N** and the forces acting on each of the stands 2 peg holders is **201.105N**. Using these results, we can start analyzing the structural forces that the stand must be able to hold to prevent the stand from breaking. We start off by breaking the stand into multiple components. Since the stand is symmetrical, we can calculate the forces on one half of the stand's sides and translate it over to the other. This is demonstrated in the figure below.

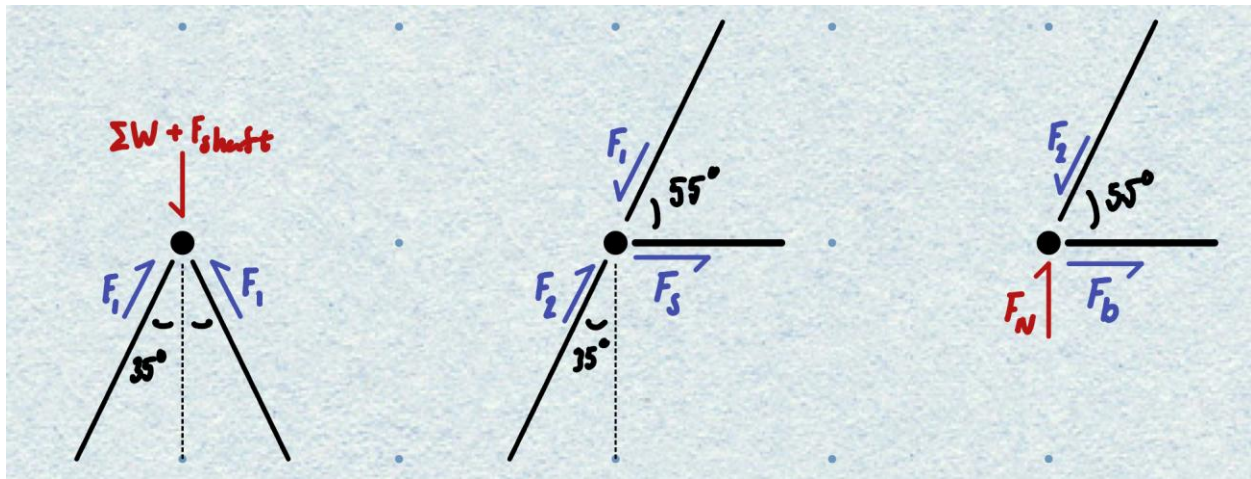


Fig 62. Structural Analysis of Stand Sides

Using this figure, we can calculate the forces in each connection point of the stand. Starting on the far left we can calculate the sum of the forces in the horizontal and vertical axes using the static equilibrium. Starting with the upper point of the stand we use Eq. (34) to calculate the vertical forces.

$$F_1 = \frac{(F_{Shaft} + W_{Wheel,R})}{2 \cos(35^\circ)} \quad (34)$$

The forces in the horizontal axis end up cancelling each other out and do not need to be calculated, as for the vertical forces the max force using a pedal force of **200[N]** results in $F_1 = 1129.28[N]$. If the dynamical force caused by the cyclist pedal force ends up acting in the horizontal axis, then we do need to consider it. As previously mentioned, it will only be considered in the vertical axis. Shifting over to the middle support beam we will use Eq. (35) and Eq. (36) to find the forces acting on that critical point.

$$F_2 = \frac{F_1 \cos(35^\circ)}{\cos(35^\circ)} \quad (35)$$

$$F_s = F_1 \cdot \sin(35^\circ) - F_2 \sin(35^\circ) \quad (36)$$

The resulting forces are $F_2 = 1129.28[\text{N}]$ and $F_s = 0[\text{N}]$. Lastly considering the forces at the base of the stand, we can derive equations Eq. (37) and Eq. (38).

$$F_N = F_2 \cdot \cos(25^\circ) \quad (37)$$

$$F_b = F_2 \cdot \sin(25^\circ) \quad (38)$$

The resulting forces acting on the base are keeping it up are $F_N = 925.05[\text{N}]$ and the force of the bottom beam $F_b = 647.73[\text{N}]$. For the stand to be safe for students, the team is in the process of selecting a structurally sound material to ensure a rider's safety by continuing this structural analysis and conducting a fatigue and bending stress analysis of differing metal materials.

8.4.6 Ethan Schalnath

Bicycle Net Power Output

Using the established bicycle generator's peak output from earlier calculations, the next consideration is how much of that power is consumed by the system's own electronics, and more specifically, the interactive display used to show real-time energy metrics to students. To quantify this overhead, the average power draw of the display subsystem was modeled as a function of screen refresh interval, using electrical specifications drawn directly from component datasheets.

The display subsystem consists of three active components: an ESP32 microcontroller, a 7.5" E-Ink display panel, and an INA219 current sensor, all operating from a regulated board source voltage of $v_s = 3.3 \text{ V}$. Each component operates in one of two states at any given moment: an active draw state during a refresh event, and a low-power standby state between refreshes. Because the E-Ink display retains its image without any power once a refresh is complete, most operating time is spent in standby. This makes average current consumption highly sensitive to how frequently the display is refreshed. The datasheet-specified current draws and wake times for each component are provided in Table XXIII, along with the baseline components, an Arduino Uno and a 16x2 LCD, for comparison.

Table XXV

Component Specifications

Component	Active Draw i_a (mA)	Standby Draw i_s (mA)	Wake Time t_w (ms)	Source
ESP32	11	0.8	12	[68]
7.5" E-Ink	7.9	0.001	200	[69]
INA219	1	0.006	1	[70]
Arduino Uno	50	-	-	[71]
16x2 LCD	25	-	-	[72]

For a given refresh interval T , the total active time per cycle is found by summing the wake time of each component, as given by Eq. (39).

$$t_r = \sum t_w \quad (39)$$

The active and standby current contributions are then time-weighted over the refresh cycle. During the wake period t_w , each component draws its active current i_a . For the remainder of the cycle, each draws its standby current i_s . These are expressed in Eq. (40) and Eq. (41), respectively.

$$I_{active} = \left(\sum i_a \right) \left(\frac{t_r}{T} \right) \quad (40)$$

$$I_{standby} = \left(\sum i_s \right) \left(\frac{T - t_r}{T} \right) \quad (41)$$

Average current is the sum of these two contributions, given by Eq. (42).

$$I_{avg} = I_{active} + I_{standby} \quad (42)$$

Average power consumption of the subsystem is then calculated from the standard electrical power relation, Eq. (43), and net power delivered to the battery subtracts this overhead from the generator output, Eq. (44).

$$P_{avg} = I_{avg} \times v_s \quad (43)$$

$$P_{net} = P_{out} - P_{avg} \quad (44)$$

These equations were evaluated across five refresh intervals ranging from 2 s to 60 s. Results are summarized in Table XXIV.

Table XXVI
Net Power Results

T (s)	I_{avg} (mA)	P_{avg} (mW)	P_{avg} (Arduino & LCD)	P_{net} (W)	Power Improvement (%)
2	2.840	9.373	247.5	139.990	96.21
5	1.620	5.347	247.5	139.995	97.84
10	1.213	4.005	247.5	139.996	98.38
30	0.942	3.110	247.5	139.997	98.74
60	0.874	2.886	247.5	139.997	98.83

Across all tested refresh intervals, the display subsystem has a negligible effect on net power output. At the minimum permissible refresh period of 2 s, the maximum update rate supported by the E-Ink panel, active power draw dominates and average consumption reaches **9.4 mW**, yielding a net output of **139.99 W**. As the refresh interval increases, standby current becomes the dominant term. At 10 s, average power draw falls to **4.0 mW**, and at 60 s it approaches a practical floor of **2.9 mW**, limited by the residual

standby currents of all three components running continuously between refreshes.

In all cases, the ESP32 and E-Ink combination reduces parasitic consumption by over **96%** compared to the Arduino Uno and 16×2 LCD baseline, which draws a constant **247.5 mW**. The ESP32 and E-Ink architecture achieves this reduction through both the microcontroller's aggressive standby mode, which drops current draw from 11 mA to 0.8 mA between refreshes, and the E-Ink panel's display technology, which draws virtually no standby current once an image is written. The INA219 current sensor contributes minimally to total draw in both active and standby states.

At the chosen 10 s refresh interval, the power improvement exceeds **98%** over the baseline, confirming that component selection for the display subsystem was well-optimized for low standby power and that the interactive display imposes no meaningful penalty on system energy output.

8.4.7 Jenna Sterry

Battery Heat Loss

This mathematical modeling focuses on the battery of the bike. To protect the students, an analysis for overheating is done. The main part that would overheat and the students could encounter is the battery connected to the bike.

Table XXVII
Battery Specifications

Battery Specs	
Volume (mm ³)	242.5 x 176 x 189
Temp Range (C)	-29 66
Charging Voltage	14.6 V
n_sys	61%
Resistance (ohm)	0.04
Specific Heat (kJ/kg K)	1.1
Conductivity (W/m K)	2.5
Convection (W/m ² K)	12

Table XXVIII
Temperature Highs-Mediums-Low averages during the seasons

Temperature			
C	Winter	Spring	Summer
H	18.89	26.48	34.259
M	0.0185	8.25	19.04
L	-20.56	-9.074	-0.93

Battery specs from a 12 Volt battery are listed above as constants for the analysis. The efficiency of the system calculation was done by Ethan Schalnat in section 5.4.6

Table XXIX
Heat Generation with different Wattage

Human Watts	75	150	350	400
Power (W)	45.75	91.5	213.5	244
current (A)	3.13	6.27	14.62	16.71
Heat Gen (W)	0.39	1.57	8.55	11.17

The average human produces 75-150 watts when riding a bike. An athlete produces 350-400 watts. Using the high and low ends of watts produced, the power, current, and heat generated could be calculated.

Table XXX
Temperature High-Med-Lows in each Seasonal Quarter

Celsius	Winter							
	Q1	Q2	Q3	Q4				
T-high	19.05179	19.54132	22.43702	23.52394				
T-Med	0.180294	0.669824	3.565517	4.65244				
T-Low	-20.3982	-19.9087	-17.013	-15.9261				
Spring/Fall				Summer				
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	26.64179	27.13132	30.02702	31.11394	34.42079	34.91032	37.80602	38.89294
	8.411794	8.901324	11.79702	12.88394	19.20179	19.69132	22.58702	23.67394
	-8.91221	-8.42268	-5.52698	-4.44006	-0.76821	-0.27868	2.617017	3.70394

To solve for steady state heat loss, the high, medium, and low temperatures were evaluated in respect to each human's wattage. Q1 represents the temperature at heat generated for 75 human watts. Same for the other Q# columns, following 150 watts, 350 watts, and 400 watts. The high medium and low temperatures are gathered from data in table XXIX. This table shows the heat of the battery at certain temperatures during certain seasons.

Table XXXI
Temperature-Transient through Season

Celsius	Temperature-Transient		
	Winter	Spring/Fall	Summer
T-high	19.2355	26.8255	34.6045
T-Med	0.364	8.5955	19.3855
T-Low	-	-8.7285	-0.5845

For transient state temperatures, the transient state equations were used from table XXX. θ^* was a constant equated from Fourier's and Biot number to isolate the surface temperature. The surface temperatures calculated are shown above.

Table XXXII
Steady State and Transient State Equations

Steady State Equations	Transient State Equations
$P = W_{human} * \eta_{sys}$	$Fo = \frac{kt}{\rho c L^2}$
$I = \frac{P}{V}$	$Bi = \frac{hL_c}{k}$
$\dot{Q}_{gen} = hA(T_s - T_\infty)$	$L_c = \frac{V}{A_s}$
$\dot{Q}_{gen} = I^2 R$	$\theta^* = \frac{T_s - T_\infty}{T_i - T_\infty}$

P = Power Generated

W_{human} = Watts of a human

η_{sys} = efficiency of the system

I = current

V = charging voltage

Q_{gen} = heat generated

h = convection coefficient

A or A_s = surface area

T_s = surface temperature

T_∞ = surrounding temperature

T_i = initial surface temperature

R = Resistance

Fo = Fourier's number

k = conduction coefficient

t = time

ρ = density

L or L_c = specific length

c = specific heat capacity

This calculation ensures safety for the students and shows that the temperatures will not reach the limits of temperature range for the battery.

8.4.8 Kaitlyn Phillips

Alternator Analysis for Human-Powered Generator

The alternator analysis evaluates the performance of the human-powered bicycle generator by examining the relationships between pedal speed, rotational generator speed, electrical output, and mechanical reliability. The analysis focuses on three key aspects: system efficiency, voltage generation as a function of speed, and bearing life as it relates to gear ratio. These factors collectively inform the design trade-offs between electrical performance and mechanical durability.

Efficiency vs. RPM

The efficiency of the generator system is defined as the ratio of electrical power output to mechanical power input from the rider:

$$\eta = \frac{P_{out}}{P_{human}} \quad [53] \quad (45)$$

Where:

$$P_{out} = V \times I$$

$$P_{in} = T \times \omega$$

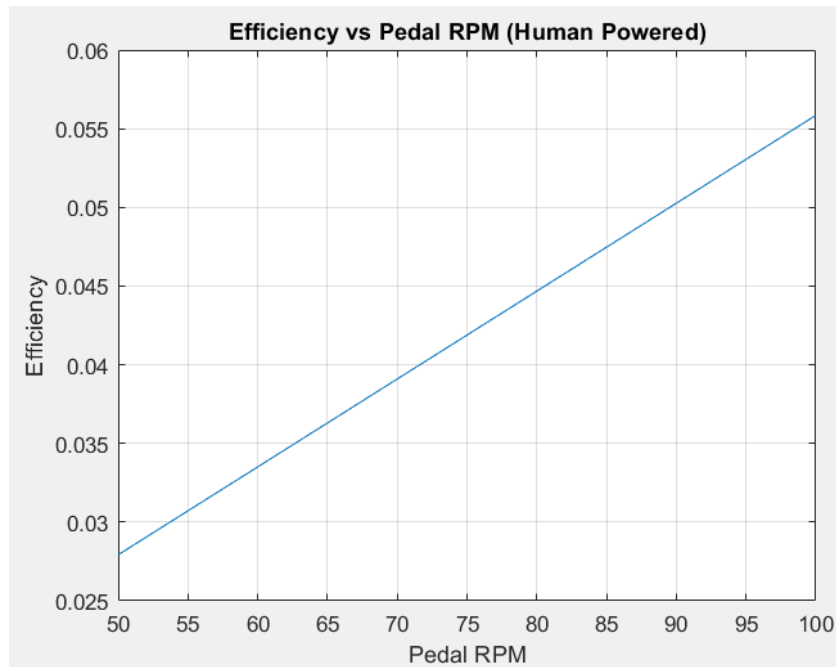


Fig 63. Efficiency vs. RPM

As shown in Figure 63 above, efficiency increases with pedal RPM. At low RPM, voltage and current are minimal, and system losses such as friction, electrical resistance, and misalignment dominate, resulting in low efficiency. As pedal speed increases, electrical output rises more rapidly than losses, leading to improved efficiency.

Generator RPM and Voltage Output

The relationship between pedal speed and generator speed is governed by the gear ratio:

$$RPM_{gen} = G \times RPM_{pedal} \quad [54] \quad (46)$$

The generated voltage is proportional to angular velocity:

$$E = (k_e)(\omega) \quad [53] \quad (47)$$

Where angular velocity is related to rotational speed.

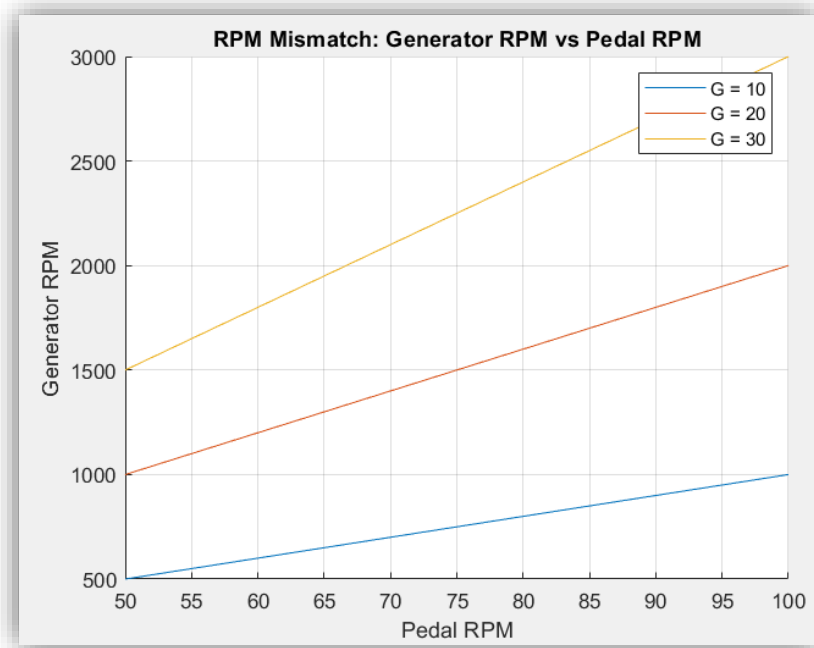


Fig 64. Generator RPM vs. Pedal RPM

As shown in Figure 64 above, generator RPM increases linearly with pedal RPM, with the slope determined by the selected gear ratio. This graph highlights the importance of gearing and the relationship between human input speeds and generator operating requirements.

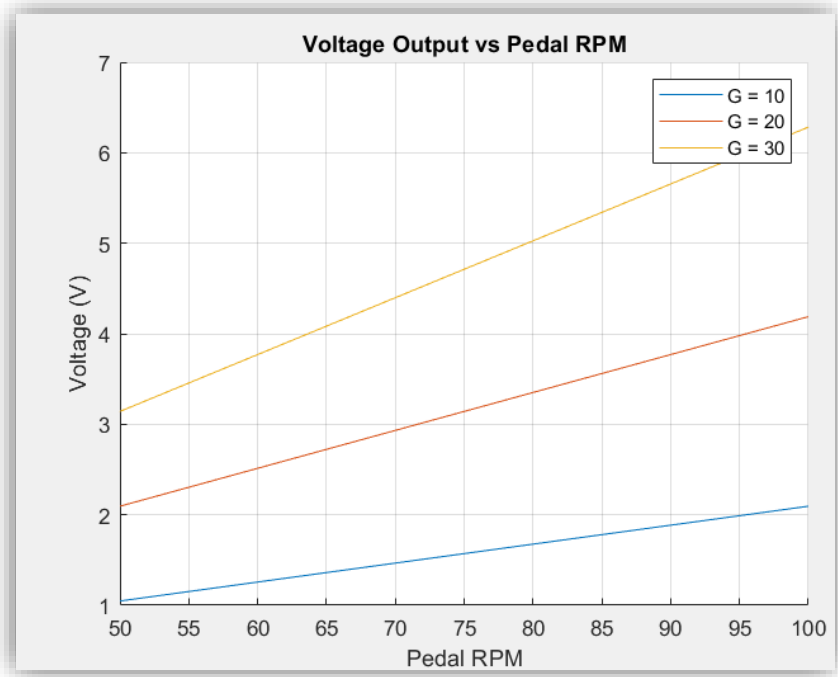


Fig 65. Voltage vs. RPM

In Figure 65 above, we can observe that voltage output is also linearly proportional to generator RPM. At typical pedaling speeds, the resulting voltage remains low. This tells us that the generator requires either a higher gear ratio or a higher voltage constantly to meet system requirements.

Bearing Life vs. Gear Ratio

Mechanical reliability of the system is evaluated using bearing life calculations based on load and rotational speed:

$$L_{10} = \left(\frac{C}{p}\right)^p \quad [55] \quad (48)$$

$$L_{10h} = \frac{L_{10} \cdot 10^6}{60 \cdot RPM_{gen}} \quad [55] \quad (49)$$

Below shows that the bearing life decreases as gear ratio increases. Higher gear ratios result in increased generator RPM, which reduces bearing life when expressed in operating hours. While distributing the load across multiple bearings can improve lifespan, rotational speed remains a dominant factor.

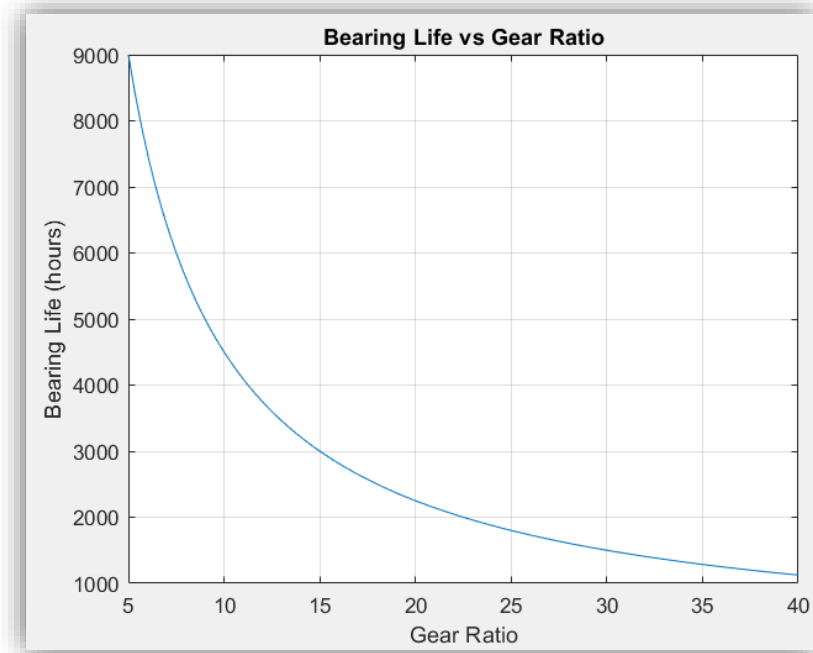


Fig 66. Bearing Life vs. Gear Ratio

The combined analysis of efficiency, voltage output, and bearing life reveals several key trade-offs in the design of the human-powered generator:

- Increasing gear ratio improves voltage output but reduces bearing life
- Efficiency improves with increasing RPM up to an optimal range
- Human pedaling limitations constrain achievable generator speeds

8.4.9 Summary of Other Engineering Calculations

Table XXXIII
Summary of Other Engineering Calculations

Analysis Conducted	Team Member Responsible	ER validated	Results/Next Steps
Battery Analysis	Alexandra Miller	Replacement of battery storage	Batteries are chosen for replacement. Additional analysis on life cycle
Stress Analysis	Carson Harder	Structural integrity of HPE	Potential forces acting on the stand are calculated. Additional research into materials and stress analysis.
Net Power Generation	Ethan	Power output of HPE	Confirm results through testing, conduct efficiency and power loss

	Schalnat		analysis
Battery Heat Loss	Jenna Sterry	Runtime	Confirmed the battery won't overheat and will be safe for students. This analysis will be applied to the new chosen batteries.
Alternator Analysis	Kaitlyn Phillips	Power output of HPE	Additional design modifications are required to ensure the generator can meet system requirements. Experimental validation and user performance evaluation.

8.5 Future Testing Potential

- **Testing**
 - Voltage vs Pedal RPM: confirm the rpm is fast enough to produce 24 volts for battery storage.
 - Outputs and Efficiencies: confirm that the outputs and efficiencies are similar or better than state-of-the-art benchmarks
 - Gear Ratio Validation: confirm that the gear ratio is optimal for maximum power output.
 - Thermal Performance: confirm that the bike is not overpowering the 24-volt battery system
 - Replacement battery efficiency: confirm that the replacement batteries are working at an optimal efficiency
 - Power input from solar panels: confirm that the additional solar panels are doubling the energy input at the PHS greenhouse
 - Wear testing on ropes for grow light pulley system: confirm that the rope for the pulley system is not showing significant wear and tear
- **Equipment**
 - Multimeter (Voltage & Current)
 - Tachometer (RPM measurement)
 - Temperature sensor
 - Monthly data collection
 - Observations
- **Space**
 - Lab or workshop space
 - PHS greenhouse
 - Electrical safety setup

9 CONCLUSIONS

This report summarizes the initial design and analysis for the Ponderosa High School greenhouse improvement and outreach project. The objective of this project is to evaluate and enhance the performance of an existing off-grid energy system that utilizes solar panels and a wind turbine to power the greenhouse. In addition to improving system performance, the team is conducting a comprehensive energy audit to better understand current system operation and identify opportunities for increased efficiency. The project also aims to expand the educational value of the greenhouse through STEAM-oriented lessons and interactive renewable energy technologies such as bicycle-powered generators.

The report establishes the foundation for the project by outlining customer requirements provided by PHS, which guides the design process. These requirements emphasize increased renewable energy generation, enhanced educational engagement for students, and improved system efficiency through detailed analysis. A house of quality (HoQ) was developed to translate customer needs into measurable engineering metrics. Key targets identified include increased energy production, improved battery storage capacity, implementation of bicycle-powered generators, and enhanced temperature regulation for tortoise habitats during colder months.

During the research and benchmarking phase, the team investigated current practices related to hybrid renewable energy systems, small-scale wind and solar power, and human-powered energy generation. Each team member conducted a comprehensive literature review to establish a strong theoretical foundation, incorporating relevant equations and engineering principles to support system analysis and design decisions. Based on this research, mathematical models were developed to estimate energy generation from solar panels, wind turbines, and the proposed human-powered generator. These models were also used to assess the structural feasibility of additional photovoltaic installations and to estimate the thermal energy required to maintain suitable conditions within the tortoise enclosure.

In the design phase, the team focused on improving the existing greenhouse system while integrating new components. The primary design effort centered on developing a human-powered bicycle generator capable of interfacing with the existing 24V battery system and evaluating potential battery system upgrades. Concept generation began with a functional decomposition of existing bicycle generator systems to identify key subsystems. Multiple design concepts were developed and evaluated using engineering selection criteria derived from customer requirements. These criteria included educational value, cost of manufacturing, potential power output, maintenance requirements, aesthetics, and the ability to support interactive or competitive use. A weighted decision matrix was used to compare leading concepts and select the most suitable design for further development. The close scoring among top concepts provided valuable insight into critical design priorities and informed future refinement efforts.

The analyses conducted during this initial phase indicate that the proposed system improvements are both technically feasible and beneficial. Preliminary modeling suggests that integrating a human-powered generator alongside enhancements to the solar, wind, and battery systems can increase overall energy production while significantly expanding the system's educational impact.

The next phase of the project will focus on refining system models, improving efficiency predictions, and validating design assumptions. Planned efforts include the fabrication and testing of a bicycle generator prototype and a handheld generator prototype, completion of a comprehensive energy audit, development of a STEAM-based curriculum, and implementation of heating and cooling solutions for the greenhouse. Upon completion, this project will provide Ponderosa High School with an improved renewable energy system while fostering student engagement and interest in STEAM fields through hands-on experience with sustainable energy technologies.

10 REFERENCES

- [1] “National Renewable Energy Laboratory,” *Energy.gov*. <https://www.energy.gov/ea/national-renewable-energy-laboratory>
- [2] “Sustainable Engineering Laboratories : College of Engineering : UMass Amherst,” *College of Engineering*, 2025. <https://www.umass.edu/engineering/research/sustainable-engineering-laboratories>
- [3] M. Hsieh and D. Jair, 'Design and Realization of A 300 W Human Power Energy Generator System on a Bicycle,' *Energy and Environment Research*, vol. 4, 2014.
- [4] Waterlution, “Pedal Power: Building a bicycle-powered generator.,” *Waterlution*, Jan. 30, 2023. Available: <https://waterlution.org/pedal-power-building-a-bicycle-powered-generator/>
- [5] DIY Experiments, “Bike generator - DIY Experiments #11 - All about human power,” *YouTube*, May 10, 2020. Available: https://www.youtube.com/watch?v=y_icu6yaAxM
- [6] “Pedal Power Generator,” *Pedal Power Generator*, 2025. Available: <https://www.pedalpowergenerator.com/shop/p/bigfoot-500-watt-bicycle-generator-stand>
- [7] A. Makhoukh, A. Redouane, N. Oubouch, and A. E. Hasnaoui, “Optimizing off-grid energy solutions: a hybrid approach leveraging solar, wind, and biomass for sustainable development,” *Global Energy Interconnection*, Aug. 2025, doi: <https://doi.org/10.1016/j.gloi.2025.05.008>
- [8] P. Satish Kumar, *Applications of Hybrid Wind Solar Battery Based Microgrid for Small-Scale Stand-Alone Systems and Grid Integration for Multi-Feeder Systems*. Wiley Semiconductors, 2021, pp. 517–533.
- [9] X. Hu, J. Feng and F. Yang, "Stochastic Optimization a New Method Based on for Solving Dynamic Reactive Power Optimization Problems Involving Renewable Energy and Storage," 2024 Second International Conference on Cyber-Energy Systems and Intelligent Energy (ICCSIE), Shenyang, China, 2024, pp. 1-6, doi: 10.1109/ICCSIE61360.2024.10698590.
- [10] L. G. Vasant and V. R. Pawar, "Solar-wind hybrid energy system using MPPT," 2017 International Conference on Intelligent Computing and Control Systems (ICICCS), Madurai, India, 2017, pp. 595–597, doi: 10.1109/ICCONS.2017.8250531.
- [11] Arzu Sencan Sahin, *Modeling and Optimization of Renewable Energy Systems*. IntechOpen, 2012. doi: 10.5772/2283.
- [12] whdsolutions, “Turn pedals into power: A practical guide to human-powered energy - The Institution of Electronics,” *The Institution of Electronics*, Aug. 11, 2025. Available: <https://institutionofelectronics.ac.uk/turn-pedals-into-power-a-practical-guide-to-human-powered-energy/>

- [13] B. Zheng *et al.*, “A comprehensive review of lithium-ion battery modelling research and prospects: in-depth analysis of current research and future directions,” *Applied Energy*, vol. 401, p. 126688, Sep. 2025, doi: <https://doi.org/10.1016/j.apenergy.2025.126688>. Available: <https://www.sciencedirect.com/science/article/pii/S0306261925014187#s0015>
- [14] P. Tagade *et al.*, “Deep Gaussian process regression for lithium-ion battery health prognosis and degradation mode diagnosis,” *Journal of power sources*, vol. 445, Art. no. 227281, Jan. 2020, doi: 10.1016/j.jpowsour.2019.227281.
- [15] Enphase Energy, “Types of solar batteries: A guide to solar energy storage,” *Enphase.com*, 2024. Available: <https://enphase.com/blog/homeowners/types-of-solar-batteries-chemistry>
- [16] “Different Types of Battery Energy Storage Systems (BESS),” *Acebattery.com*, 2025. Available: <https://www.acebattery.com/blogs/different-types-of-battery-energy-storage-systems-bess>
- [17] A. Center, Stand-alone Photovoltaic Systems. 1995.
- [18] NABCEP PV Certification Study Guide, 8th ed. NABCEP, Clifton Park, NY, 2019.
- [19] “OSHA 10-Hour General Industry,” 360training, 2023. <https://www.360training.com/course/osha-10-hour-outreach-general-industry-free-study-guide>
- [20] National Renewable Energy Laboratory, “PVWatts Calculator,” pvwatts.nrel.gov.
- [21] J. K. Kaldellis, M. Kapsali, and K. A. Kavadias, “Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece,” *Renewable Energy*, vol. 66, pp. 612–624, Jun. 2014, doi: <https://doi.org/10.1016/j.renene.2013.12.041>.
- [22] M. K. Panjwani and G. B. Narejo, (PDF) effect of humidity on the efficiency of solar cell (photovoltaic), https://www.researchgate.net/publication/309104096_Effect_of_humidity_on_the_efficiency_of_solar_cell_photovoltaic.
- [23] H. M. S. Hussein, G. E. Ahmad, and H. H. El-Ghetany, “Performance evaluation of photovoltaic modules at different tilt angles and orientations,” *Energy Conversion and Management*, vol. 45, no. 15–16, pp. 2441–2452, Sep. 2004, doi: <https://doi.org/10.1016/j.enconman.2003.11.013>.
- [24] Instructables, “Most Efficient Electricity Generating Stationary Bike,” Instructables, Nov. 23, 2022. <https://www.instructables.com/Most-Efficient-Electricity-Generating-Stationary-B/>
- [25] J. L. Meriam and L. G. Kraige, *Engineering Mechanics. Vol. 2, Dynamics*. Hoboken, N.J, Chichester: Wiley ; John Wiley distributor, 2012.
- [26] R. G. Budynas and J. K. Nisbett, *Shigley’s Mechanical Engineering Design*. New York, NY: McGraw-Hill Education, 2014.

- [27] J. Sunil et al., BICYCLE POWER GENERATION AND ITS FEASIBILITY, 2015.
- [28] F. R. Whitt and D. G. Wilson, *Bicycling Science*, 2nd ed. MIT Press, 1982.
- [29] Q. Ding, J. Yang, and W. Cui, 'Converting Human Power into Electricity: Current Status and Future Directions,' Preprints, Nov. 2023.
- [30] A. Cicchella, 'Human Power Production and Energy Harvesting,' *Encyclopedia*, vol. 3, no. 2, 2023.
- [31] M. Carbajales-Dale and B. Douglass, 'Human-Powered Electricity Generation as a Renewable Resource,' *BioPhysical Economics and Resource Quality*, vol. 3, 2018.
- [32] R. K. Megalingam et al., 'Pedal Power Generation,' *International Journal of Applied Engineering Research*, vol. 7, no. 11, 2012.
- [33] V. O. Oner, *Hands-On ESP32 with Arduino IDE*. Birmingham, UK: Packt Publishing, 2023.
- [34] N. Kolban, *Kolban's Book on ESP32*. Leanpub, 2017. [Online]. Available: <https://leanpub.com/kolban-ESP32>
- [35] F. Mumtaz, N. Z. Yahaya, S. T. Meraj, B. Singh, R. Kannan, and O. Ibrahim, "Review on non-isolated DC-DC converters and their control techniques for renewable energy applications," *Ain Shams Engineering Journal*, vol. 12, no. 4, pp. 3747–3763, 2021, doi: 10.1016/j.asej.2021.03.022.
- [36] K. Nemali, "Horticulture and Landscape Architecture Temperature Control in Greenhouses," Purdue University, Feb. 2021.
- [37] N. Asgari, K. S. Hayibo, J. Groza, S. Rana, and J. M. Pearce, "Greenhouse applications of solar photovoltaic driven heat pumps in northern environments," *Renewable & sustainable energy reviews*, vol. 207, Art. no. 114920, 2025, doi: 10.1016/j.rser.2024.114920.
- [38] N. Faires, "Top 10 Greenhouse Gardening Mistakes," *Eartheasy Guides & Articles*, Jun. 02, 2017.
- [39] M. Sultan, Y. Zhou, W. Den, and U. Sajjad, *Sustainable Agricultural Engineering Technologies and Applications*. Basel: MDPI - Multidisciplinary Digital Publishing Institute, 2022, pp. 145-174
- [40] "The Ideal Temperature Conditions For 3-Toed Box Turtles | PetShun," *Petshun.com*, Sep. 26, 2023. <https://petshun.com/article/what-temperature-condition-for-3-toed-box-turtle> (accessed Mar. 01, 2026).
- [41] D. Diego, "Understanding the U-Value of Windows," *Window Depot USA of Tyler, Texas*, Jun. 2023. <https://windowdepottylertx.com/understanding-the-u-value-of-windows/> (accessed Mar. 02, 2026).
- [42] "The Energy Costs of Running Reptile Enclosures," www.monkfieldreptile.com. <https://www.monkfieldreptile.com/blog/the-energy-costs-of-running-reptile-enclosures>

- [43] M. Scott, “How to Build a Tortoise Enclosure - Leopard Tortoises,” *Leopard Tortoises*, Mar. 18, 2016. Available: <https://leopardtortoises.com/tortoise-enclosure-hatchlings/>
- [44] L. Hewitt, “Reptile Enclosure Materials: Which is The Best for You? - Vision Products,” *Vision Products*, Aug. 10, 2023. Available: https://www.visionproducts.us/blog/reptile-enclosure-materials/?srsltid=AfmBOorIL_saAgPYsHohvfQuXgoPXcf5lo1pmwaq_9bBc1vtXxV0g6kD.
- [45] “Three-Toed Box Turtle Care Sheet,” *ReptiFiles®*, Oct. 23, 2024. Available: <https://reptifiles.com/three-toed-box-turtle-care-sheet/>
- [46] James F. Manwell, Jon G. McGowan, and Anthony L. Rogers, *Wind Energy Explained: Theory, Design and Application*, 2nd ed. Chichester, U.K.: John Wiley & Sons, 2010.
- [47] Martin O. L. Hansen, *Aerodynamics of Wind Turbines: A Physical Basis for Analysis and Design*, 3rd ed. New York, NY, USA: Routledge, 2015.
- [48] A. C. Duman and Ö. Güler, “Analysis of Wind Turbine Usage in Greenhouses: Wind Resource Assessment, Distributed Generation of Electricity and Environmental Protection,” *Renewable Energy*, vol. 99, pp. 1172–1180, Dec. 2016.
- [49] M. A. Hossain, H. R. Pota, M. A. Mahmud, and R. A. Ramos, “Design and Optimization of a Hybrid Solar-Wind Power Generation System for Greenhouses,” *Renewable Energy*, vol. 85, pp. 539–547, Jan. 2016.
- [50] N. Tremeac and F. Meunier, “Life Cycle Analysis of 4.5 MW and 250 W Wind Turbines,” *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2104–2110, Oct. 2009.
- [51] Tony Burton, Nick Jenkins, David Sharpe, and Ervin Bossanyi, *Wind Energy Handbook*, 2nd ed. Chichester, U.K.: John Wiley & Sons, 2011.
- [52] Paul Gipe, *Small Wind Turbines for Electricity Generation*. White River Junction, VT, USA: Chelsea Green Publishing, 2004.
- [53] Chapman, S. (2011). *Electrical Machinery Fundamentals*. McGraw Hill.
- [54] Hibbeler, R. C., & Schiavone, P. (2017). *Engineering mechanics: Statics and engineering mechanics: Dynamics plus study packs, Si edition*. Pearson.
- [55] Shigley, J. E., Nisbett, J. K., & Budynas, R. G. (2008). *Shigley’s Mechanical Engineering Design: Richard G. Budynas, J. Keith Nisbett*. McGraw-Hill Higher Education.
- [56] “SunCalc sun position- und sun phases calculator,” *Suncalc.org*, 2026. Available: <https://www.suncalc.org/#/35.2097>.
- [57] T. W. Channel, “Hourly Weather Forecast for Flagstaff, Arizona 86004 - The Weather Channel | Weather.com,” *The Weather Channel*, 2024.

Available: <https://weather.com/weather/hourbyhour/l/64292612858285d87c84dd9356769888060a76574fb3fd5f6cb13d664cc6363>.

[58] “Step 11: Timber guide,” *TheTreehouse.Shop*, 2017. Available: https://thetreehouse.shop/en/pages/timber-beam-dimension-calculate?srsltid=AfmBOopBYa3-ZnuRG-hIF3TTsz3jWn5mWstcp_VmQpHKoF3HoXIXNaHh.

[59] “Structural Wood Beams Guide for Builders and Homeowners,” *Sierralogandtimber.com*, 2026. Available: <https://sierralogandtimber.com/structural-wood-beams/>.

[60] B.C. Hibbeler, *Mechanics of Materials*, 10th ed. Hoboken, NJ, USA: Pearson, 2015

[61] “Buy Solar Module REC REC285TP2 BLK | pvXchange.com,” Buy Solar Module REC REC285TP2 BLK | pvXchange.com, 2017. https://www.pvxchange.com/Solar-Modules/REC/REC285TP2-BLK_1-996000208.

[62] “SolarWorld 285 Watt Mono Solar Panel 4.0 - 33mm Frame - SW 285,” EcoDirect, 2025. https://www.ecodirect.com/SolarWorld-SW-285-285-Watt-Mono-Solar-Panel-4-0-p/solarworld-sw285-mono-4-0.htm?srsltid=AfmBOopm-ZtOJGniQNr41HNKFMbM-OA_oTpeNhyNeHSTNkWktXptoDLZ.

[63] “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).

[64] “DC224-6 (Grp GC2) Battery,” *The Battery Dude*, 2026. Available: https://thebatterydude.com/dc224-6/?setCurrencyId=1&sku=DC224-6&gad_source=1&gad_campaignid=17328394448&gbraid=0AAAAAojvVJkOm3FwGD8k1Q91A8262A9PX&gclid=Cj0KCQjwm6POBhCrARIsAIG58CKFcJOXVVWQCtOTnhrUHeCBp1ImEx6fzE1FaTwuxcyJtPjzu0n_RDIaAqFwEALw_wcB.

[65] “24V HUSKY 2 INV Lithium Battery 5.12kWh 200Ah | LiFePO4 | Inverter Comms | RV | Off-Grid | Marine Battery,” *BigBattery.com*, Mar. 16, 2026. Available: https://bigbattery.com/products/24v-husky-2-5-12kwh-lifepo4-battery-with-5-16-ring-terminal-cable/?ref_cat=off-grid-solar.

[66] “GoKWh 12V 200Ah Sodium ion Battery - Battery Finds,” *Battery Finds*, Sep. 03, 2024. Available: <https://batteryfinds.com/product/gokwh-12v-200ah-sodium-ion-battery/>

[67] “Victron Energy Lithium SuperPack 12,8V/200Ah NG,” *Solar-electric.com*, 2024. Available: <https://www.solar-electric.com/victron-energy-lithium-superpack-12-8v-200ah-ng.html>.

[68] Espressif Systems, "ESP32 Series Datasheet," v4.3, 2024. [Online]. Available: https://documentation.espressif.com/esp32_datasheet_en.pdf

[69] Waveshare, "7.5inch e-Paper HAT," *Waveshare Wiki*. [Online]. Available: https://www.waveshare.com/wiki/7.5inch_e-Paper_HAT

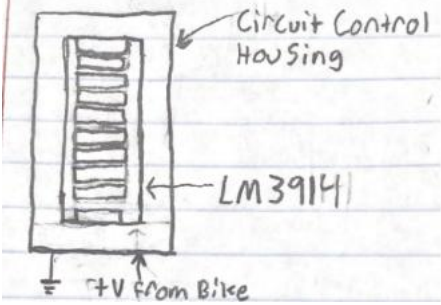
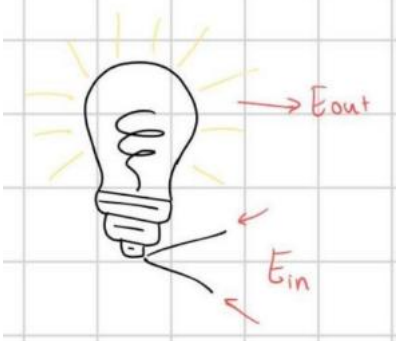
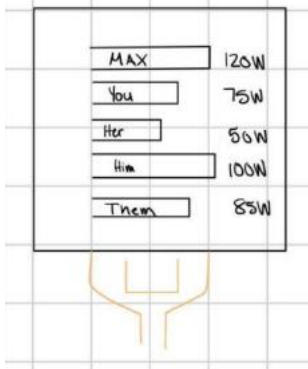
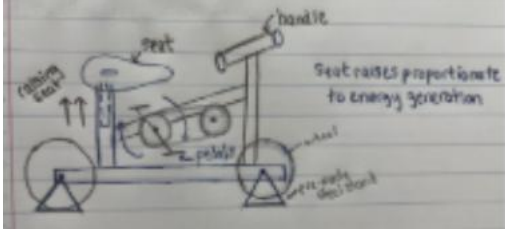
[70] Texas Instruments, "INA219 Zero-Drift, Bidirectional Current/Power Monitor With I2C Interface," SBOS448G, May 2015. [Online]. Available: <https://www.ti.com/lit/ds/symlink/ina219.pdf>

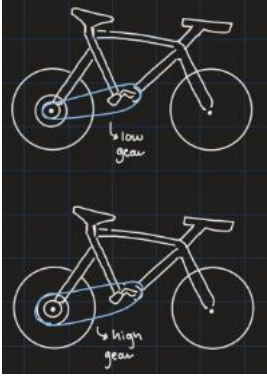
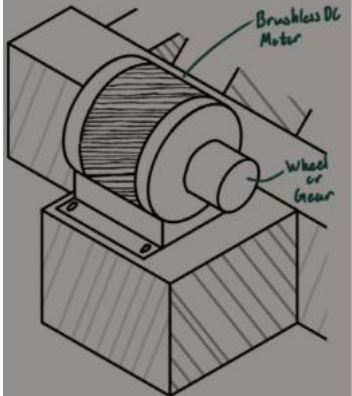
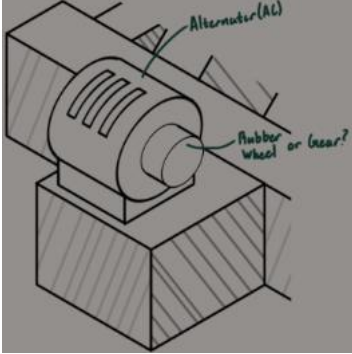
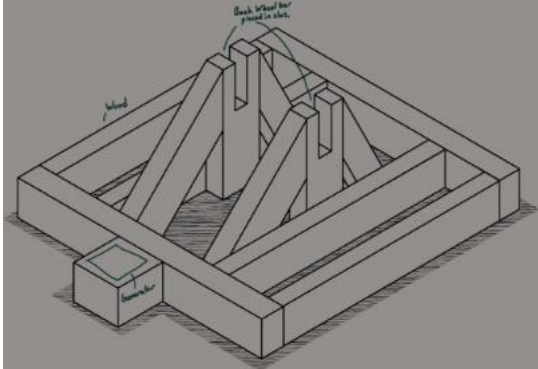
[71] Arduino, "Arduino Uno Rev3," *Arduino Documentation*. [Online]. Available: <https://docs.arduino.cc/hardware/uno-rev3/>

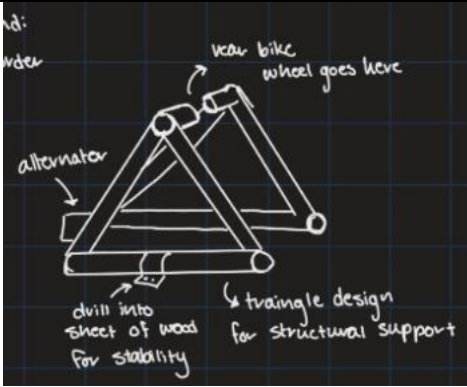
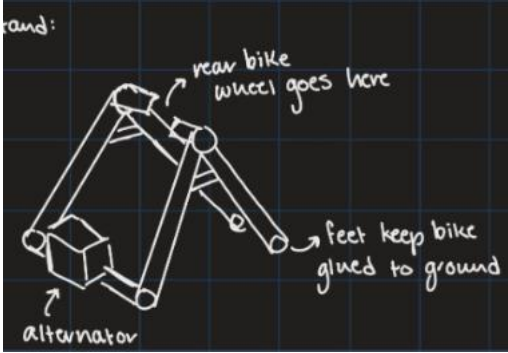
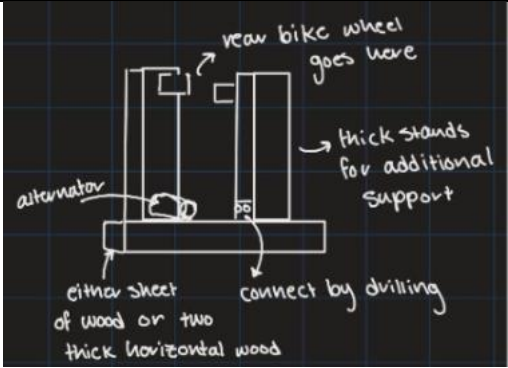
[72] Mouser Electronics, "1602 LCD Datasheet," Document No. 1487230. [Online]. Available: <https://www.mouser.com/datasheet/2/272/lcd-2x16-datasheet-1487230.pdf>

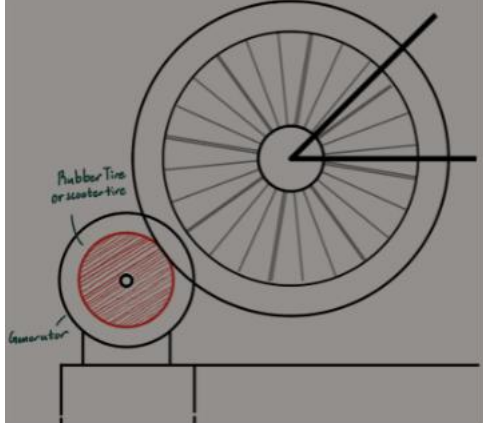
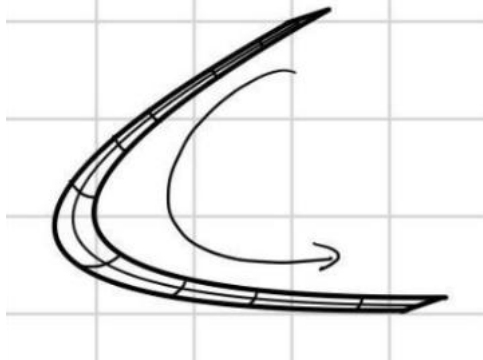
11 APPENDICES

11.2 Appendix A: Sub-Assembly Designs

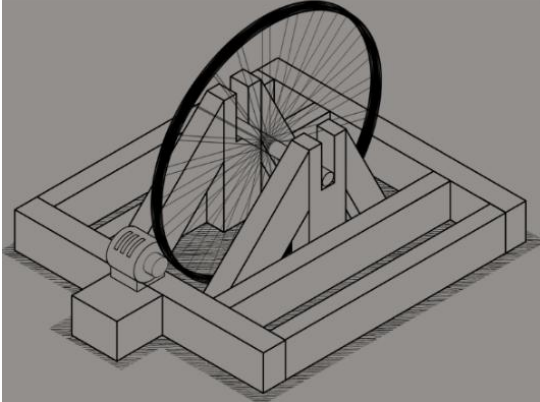
 <p>Appendix A1. Sub Assembly A1</p>	<p>Description: Energy display bar</p> <p>Advantages:</p> <ul style="list-style-type: none"> • High Educational Value <p>Disadvantages:</p> <ul style="list-style-type: none"> • Uses a large amount of energy generated from bicycle • Complex Voltmeter
 <p>Appendix A2. Sub Assembly A2</p>	<p>Description: light bulb displaying energy input</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Some Educational Value • Uses very little energy <p>Disadvantages:</p> <ul style="list-style-type: none"> • Uses energy generated from bicycle • Hard to translate to a value
 <p>Appendix A3. Sub Assembly A3</p>	<p>Description: high score display screen</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Encourages Student Competition <p>Disadvantages:</p> <ul style="list-style-type: none"> • Uses a large amount of energy
 <p>Appendix A4. Sub Assembly A4</p>	<p>Description: raised seat with power input</p> <p>Advantages:</p> <ul style="list-style-type: none"> • High Educational Value <p>Disadvantages:</p> <ul style="list-style-type: none"> • Difficult to Maintain • Complex machinery

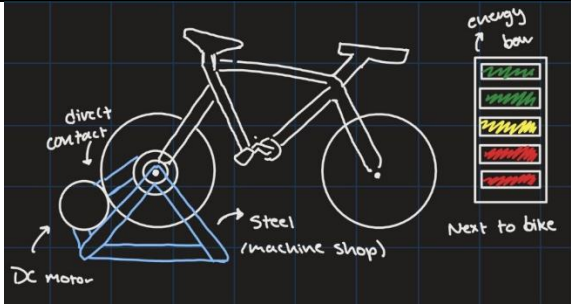
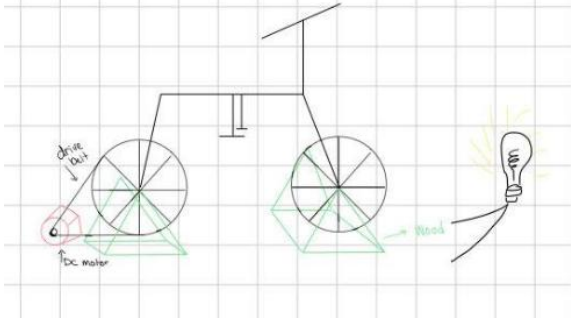
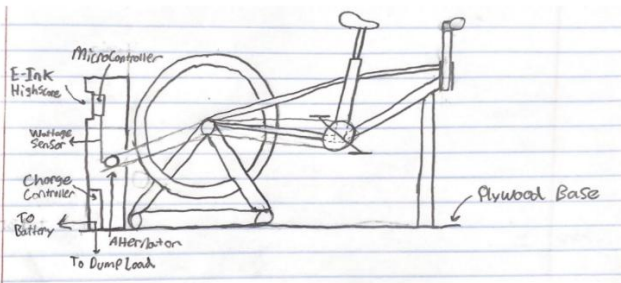
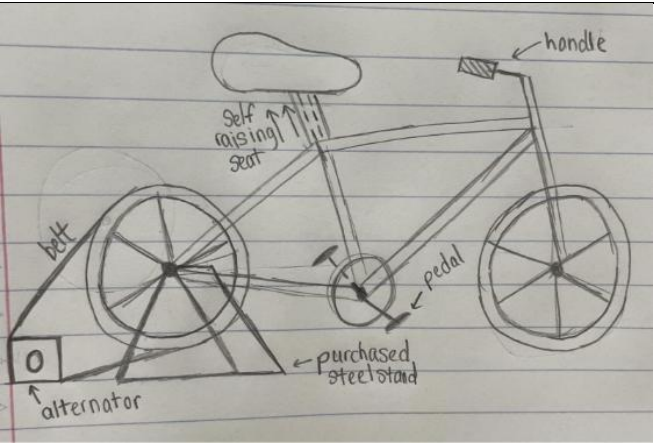
 <p>Appendix A5. Sub Assembly A5</p>	<p>Description: high gear vs low gear power generation</p> <p>Advantages:</p> <ul style="list-style-type: none"> • High Education Value • Makes use of Gear Ratios <p>Disadvantages:</p> <ul style="list-style-type: none"> • Maintenance
 <p>Appendix A6. Sub Assembly B1</p>	<p>Description: brushless DC motor</p> <p>Advantages:</p> <ul style="list-style-type: none"> • DC Energy Generation • Cost Effective <p>Disadvantages:</p> <ul style="list-style-type: none"> • Low Energy Generation
 <p>Appendix A7. Sub Assembly B2</p>	<p>Description: Alternator</p> <p>Advantages:</p> <ul style="list-style-type: none"> • High Energy Generation <p>Disadvantages:</p> <ul style="list-style-type: none"> • Expensive Pricing
	<p>Description: removable bike stand</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Cost Effective • Easily buildable • Stable <p>Disadvantages:</p> <ul style="list-style-type: none"> • Environmental Decay • Human Error

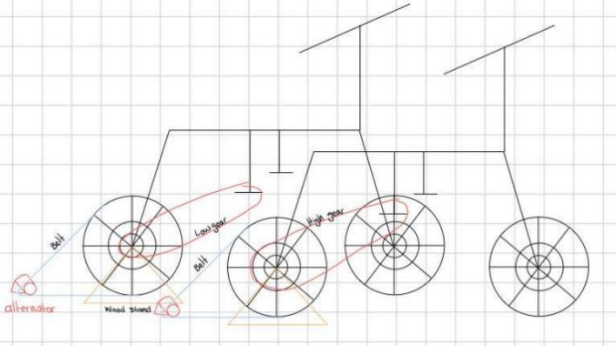
<p>Appendix A8. Sub Assembly C1</p>  <p>Appendix A9. Sub Assembly C2</p>	<p>Description: steel stand (machine shop)</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Structurally Strong • Long term maintenance <p>Disadvantages:</p> <ul style="list-style-type: none"> • Expensive pricing • Human Error
 <p>Appendix A10. Sub Assembly C3</p>	<p>Description: pre-made exercise stand</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Factory Made • Easy Assembly <p>Disadvantages:</p> <ul style="list-style-type: none"> • Expensive pricing
 <p>Appendix A11. Sub Assembly C4</p>	<p>Description: self-made wooden stand</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Cost Effective <p>Disadvantages:</p> <ul style="list-style-type: none"> • Low Durability • Hard to Maintain over time

 <p>Appendix A12. Sub Assembly D1</p>	<p>Description: direct contact</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Direct power transfer; increase efficiency • Less maintenance <p>Disadvantages:</p> <ul style="list-style-type: none"> • Potential Slippage • Degradation of wheels due to friction
 <p>Appendix A13. Sub Assembly D2</p>	<p>Description: drive belt between rear wheel and motor</p> <p>Advantages:</p> <ul style="list-style-type: none"> • Quiet, minimal vibration • Cheap <p>Disadvantages:</p> <ul style="list-style-type: none"> • Limited life span • Risk of Failure

11.3 Appendix B: Top Level Designs

 <p>Appendix B1. Design #1</p>	<p>Components used: A5 B1 C1 D1</p> <p>Advantages: easy maintenance, cheap</p> <p>Disadvantages: weak energy display and aesthetics</p>
---	---

 <p>Appendix B2. Design #2</p>	<p>Components used: A1 B2 C2 D1</p> <p>Advantages: strong energy display, strong durability</p> <p>Disadvantages: expensive stand and motor</p>
 <p>Appendix B3. Design #3</p>	<p>Components used: A2 B2 C4 D2</p> <p>Advantages: strong energy display, cheap stand</p> <p>Disadvantages: weak durability, weak ease of maintenance</p>
 <p>Appendix B4. Design #4</p>	<p>Components used: A3 B1 C4 D2</p> <p>Advantages: strong energy display, cheap motor</p> <p>Disadvantages: difficult maintenance</p>
 <p>Appendix B5. Design #5</p>	<p>Components used: A4 B1 C3 D2</p> <p>Advantages: easy maintenance, easiest stand to get</p> <p>Disadvantages: expensive stand, medium energy display</p>


Appendix B5. Design #5	
	<p>Components used: A5 B1 C4 D2</p> <p>Advantages: cheap stand, cheap motor</p> <p>Disadvantages: weak durability, weak energy display</p>
Appendix B6. Design #6	


11.4 Appendix C: Solar Panel Information



Appendix C1. Small, 120W Rated Power Solar Panel

11.5 Appendix D: FullRiver DC400-6





DC400-6

DEEP CYCLE

400AH @ 20Hr
6-Volt

Group Size: L16 / 903

Maintenance-Free
Sealed AGM Battery

CYCLING CAPACITY

20 Hour Rate	415 Amp Hours
--------------	----------------------

RESERVE CAPACITY

Reserve @25 AMPS	885 Minutes	Reserve @75 AMPS	229 Minutes
------------------	--------------------	------------------	--------------------

ELECTRICAL SPECIFICATIONS

Nominal Voltage	6 Volt
C100	460AH
C20	415AH
C10	374AH
C5	340AH
CCA	1500
CA or MCA	1800
HPCA	2000 Amps
Internal Resistance	1.6m Ω

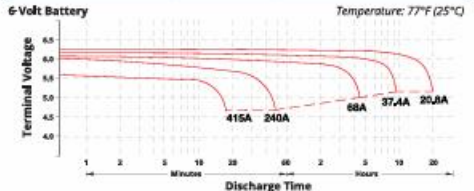
MECHANICAL SPECIFICATIONS

Group Size	L16 / 903	
Terminal Type	DTW	
Terminal Torque	See reverse side	
Height (w/ terminal)	16.69"	424mm
Height (case only)	15.90"	404mm
Width	7.05"	179mm
Length	11.61"	295mm
Weight	123.2 lbs.	56 kg
Case Type	ABS Plastic - Flame Res. Rating UL94-HB	

DISCHARGE TABLE (Constant Current)

Time	Amps	Rate
20hr	20.8	0.05CA
10hr	37.4	0.10CA
8hr	45.1	0.13CA
5hr	68.0	0.25CA
3hr	93.9	0.33CA
2hr	123	0.50CA
1hr	232	1.00CA

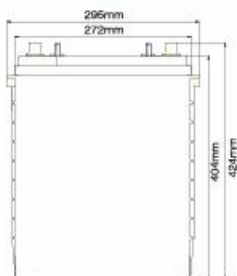
DISCHARGE PROFILE (Constant Current)




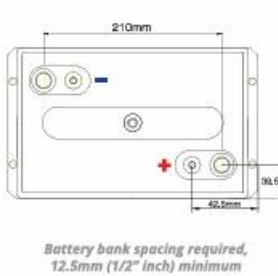
6-Volt Battery Temperature: 77°F (25°C)

- All listed ratings are @ 100% SoC, T=77°F (25°C), 1.75VPC unless otherwise specified.
- Specifications listed are for estimation purposes only. Battery performance can vary depending on application. Battery design subject to change.

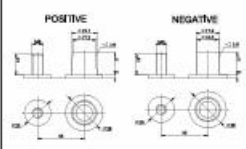
BATTERY & TERMINAL DIMENSIONS (All units shown in mm)







Terminal: DTW (Dual AP & Stud)



Battery bank spacing required, 12.5mm (1/2" inch) minimum

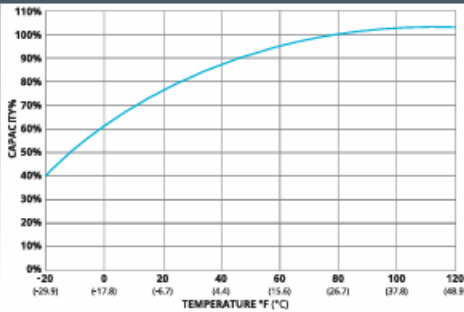
021015

Appendix D1. Specifications of FullRiver DC400-6 (page 1)

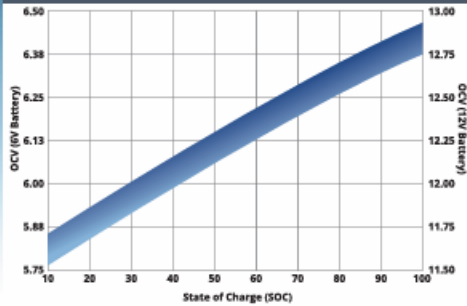


DC400-6 DATA SHEET fullriverbattery.com

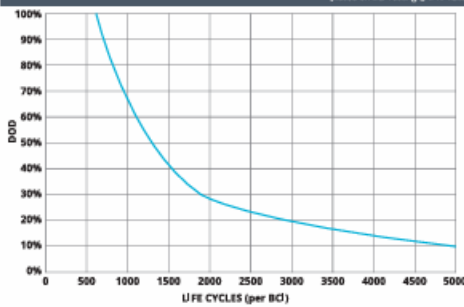
TEMPERATURE vs CAPACITY



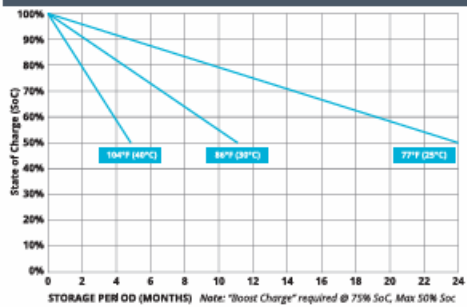
STATE OF CHARGE (SOC) vs OPEN CIRCUIT VOLTAGE (OCV)



CYCLE LIFE vs DEPTH OF DISCHARGE (DOD) (Based on DOD Testing @ 2-hr Rate)



SELF DISCHARGE vs TIME/TEMPERATURE



TEMPERATURE RANGE SPECIFICATIONS

Condition	Recommended	Maximum	Recommended	Maximum
Storage	5°F to 122°F	-40°F to 160°F	-15°C to 50°C	-40°C to 71°C
Operation	5°F to 104°F	-40°F to 160°F	-15°C to 40°C	-40°C to 71°C
Charge with TC	5°F to 122°F	-40°F to 160°F	-15°C to 50°C	-40°C to 71°C
Charge w/o TC	32°F to 104°F	5°F to 122°F	0°C to 40°C	-15°C to 50°C

*TC= Temperature Compensation

CHARGE VOLTAGES

Charge Stage	Battery Voltages			
	12V	24V	36V	48V
Bulk	14.7V	29.4V	44.1V	58.8V
Absorption	14.7V	29.4V	44.1V	58.8V
Float	13.6V	27.2V	40.8V	54.6V

TC Factor: (-2mV°F/cell) or (-4mV°C/cell)

TERMINAL TORQUE SPECS

Terminal Type	ft-lbs	in-lbs	Nm
AP, DT (AP), M6, M6M (Stud), TP07 (AP), TP08 (AP)	4.2 - 6.0	50-70	5.6 - 7.9
FR45	6.0 - 7.5	70-90	7.9 - 10.1
M8	7.1 - 8.0	85-95	9.6 - 10.7
DT (Stud), M10M (Stud)	9.2 - 10.4	110-125	12.2 - 14



9001:2008 Quality Management System
 14001:2004 Environmental Management System
 18001:2007 Occupational Health & Safety Management System



DELIVERY APPROVED:
**LAND, SEA
 & AIR**

Fullriver batteries are sealed lead acid batteries made with Absorbed Glass Mat (AGM) technology. The electrolyte is absorbed into the fiberglass separator material rather than in a free-flowing liquid form. Fullriver batteries are non-spillable electric storage batteries. They are exempted from the requirements of DOT's hazardous materials regulations, since they adhere to the requirements of code 49 CFR Section 173.159(D) - (CLASSIFIED APPROVED: DOT, CFR, HMR49, IATA, ICAO67, IMDG27)

11.6 Appendix E: Prototype Bill of Materials (BOM)

Table E1.

Prototype Bill of Materials (BOM)

PART NAME	DESCRIPTION	VENDOR	UNITS	UNIT COST	AMOUNT
Bicycles	1 non shifting bike donated to use to create the human powered energy generation stationary bike	Donated	1	\$ -	\$ -
Alternator	Converts mechanical energy into electrical energy	Donated	1	\$ -	\$ -
Wood 2 X 8	To build a wooden frame to fix the back tire of the bicycles and hold them in place	Donated	4	\$ -	\$ -
Plywood Sheet	Flat plywood surface to be place under the frame and secured	Donated	2	\$ -	\$ -
Prime-Line carriage nuts and bolts	1/4 inch-20 teeth per inch (TPI) measuring 1/4 inch diameter x 1-7/8 inch length.	Donated	10	\$ -	\$ -
LED Light bulb (4.5 Watts)	Attached to the bike to show energy is being generated	Donated	1	\$ -	\$ -
Concord BMX Freestyle Bike Pegs	Alloy bike pegs used to fix bike to the frame stand.	Walmart	1	\$ 10.89	\$ 10.89
7/16" Bolts	Bolts added to fix alternator	Home Depot	2	\$ 3.75	\$ 7.50
TOTAL PARTS:			22	TOTAL COST: \$	18.39

11.7 Appendix F: Greenhouse QFD

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

Appendix F1. ER correlations

Customer Needs	Customer Weights	Technical Requirements							
		Greenhouse Energy Consumption	Turtle habitat temperature regulation	Solar Power Generation	Human Power Generation	Wind Turbine Generation	Battery Capacity	Runtime	
Efficiency	4	9	3	9	1	3	9	9	--
Student Engagement	5		3	1	9	1			--
Human Powered Bicycle Generator	4	1			9		1	1	--
Battery Storage	2	9	1	9	1	3	9	9	--
Working Wind Turbine	5	3				9	3	3	--
Increased Solar Power	5	9		9			9	9	--
Turtle Enclosure	1	3	9	1		1	1		--
Reliable/ Low Maintenance System	3		1	9	3	3	9	9	--
Increased Energy Output	4	9	3	9	1	3	9		--

Appendix F2. CR correlations

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

Customer Opinion Survey				
1	2	3	4	5
<i>Poor</i>		<i>Acceptable</i>		<i>Excellent</i>
	C		B	A
		AB		C
				C
C				AB
C		B		A
C			B	A
		A	B	C
		B	C	A

Appendix F3. Benchmark opinion survey

Technical Requirement Units	%	°F	kW	W	W	Ah	years	
Technical Requirement Targets	50	80±10	3500	150	300	1400	10	
Technical Importance	4	7	2	6	3	1	5	

Appendix F4. Technical importance

11.8 Appendix G: Bike QFD

Battery Performance		9					
Manufacturing Cost		3	9				
Power Output		3		9			
Maintenance		9			9		
Structural Integrity			3		9	9	

Appendix G1. ER correlations

		Technical Requirements							
		Battery Performance	Manufacturing Cost	Power Output	Maintenance	Structural Integrity			
Customer Needs	Customer Weights								
Interactive Display	3		9	9	3		---	---	
Durability	5	3	1	1	9	9	---	---	
Supplemental Energy	5	9	3	9			---	---	
Educational Value	4			3			---	---	
Safe to Use	5		3		9	9	---	---	
Aesthetics	1		9				---	---	
Student Participation	4			1			---	---	
Size	4		3		1	3	---	---	

Appendix G2. CR correlations

Legend	
A	Waterlution
B	DIY Bike Power Output
C	HPEG system
D	BigFoot

Customer Opinion Survey				
1	2	3	4	5
Poor		Acceptable		Excellent
ABC				D
AB			C	D
		A		BCD
	C		AB	D
			AB	CD
	AB	C	D	
ABC				D
	A	B	D	C

Appendix G3. Benchmark correlations

Technical Requirement Units	%	\$	W	km	N	---	---
Technical Requirement Targets	85	500	100	4000	800	---	---
Technical Importance	5	3	1	4	2	---	---

Appendix G4. Technical importance