PHS Sustainability

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Project Description

Ponderosa High School (PHS) tasked us with:

- Analyzing and improving upon the existing off-grid renewable energy system
  - Wind turbine, solar panels, and 24-volt battery storage
  - Adding lighting components
- Manufacturing a bike that converts human pedaling to energy generation
- Animals (bunny, fish, and tortoise) and plants depend on renewable energy system

Importance

- Strengthens community
- Contributes to sustainable infrastructure in Flagstaff
- Hands on teaching platform
  - Encourages STEAM education and careers
- System upgrades improve PHS greenhouse for future generations

Fig 1. PHS greenhouse planter

Fig 2. Hong Vi

Clients

Fig 3. Client: Les Hauer

Les Hauer – PHS Principle

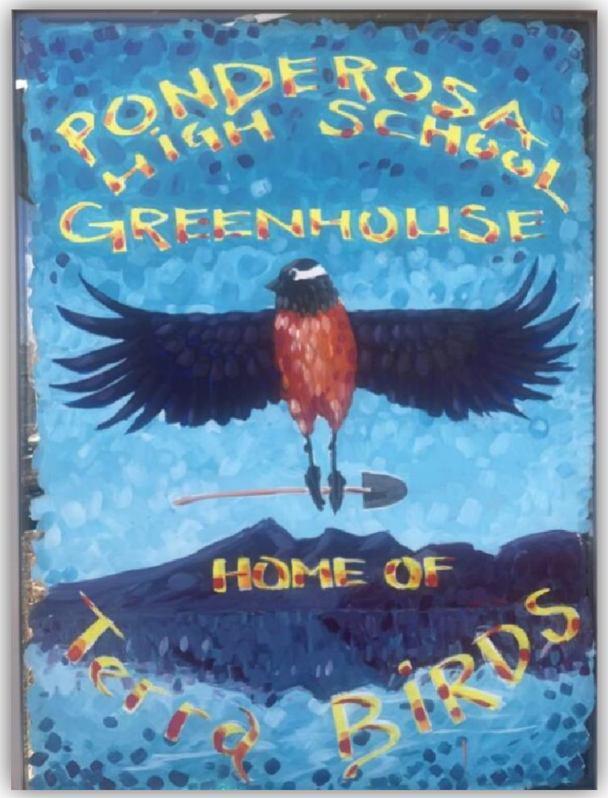


Fig 4. Client: PHS Terra Birds

PHS Terra Birds – Student led program that promotes sustainability

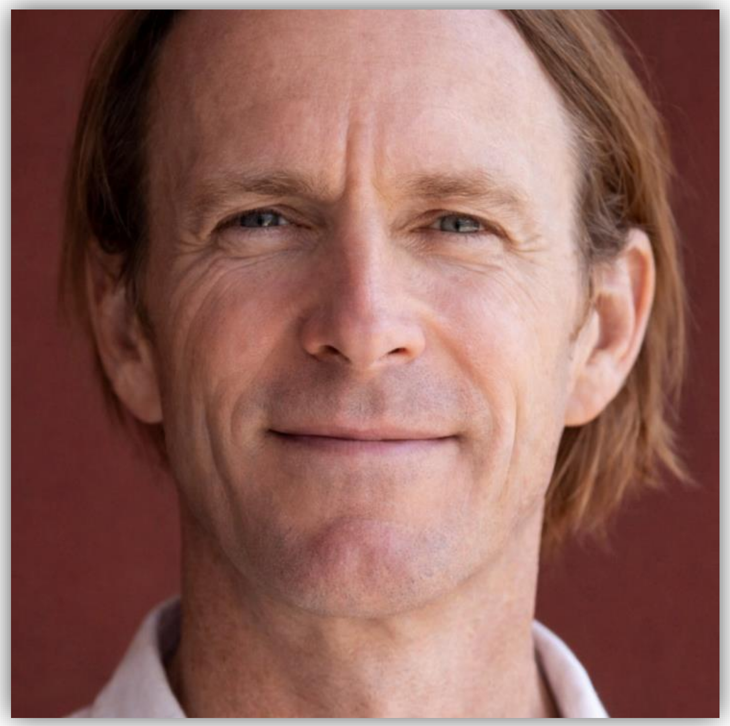


Fig 5. Client: John Taylor

John Taylor – Math Teacher & Greenhouse Consultant

Design Description

Sub Sections:

Bicycle
- Human Powered Device

Motor Contact Wheel
- Converts Rotation force from the bicycle wheel to the generator wheel

Generator
- Takes rotation movement and converts it to Direct Current

Wiring
- Supplies power to the Green house

Score Display(Voltmeter)
- Displays the voltage the user is generating

Fig 6. HPE bike design [1][2]

Virtual Demo

Circuit Diagram

Components

- DC Motor/Alternator (Input)
- Resistor Rectifier
- CN3791 (MPPT Charge Controller)
- INA219 (DC Current Sensor)
- ESP32-WROOM-32 (Microcontroller)
- WaveShare 7.5" E-Paper (Display)

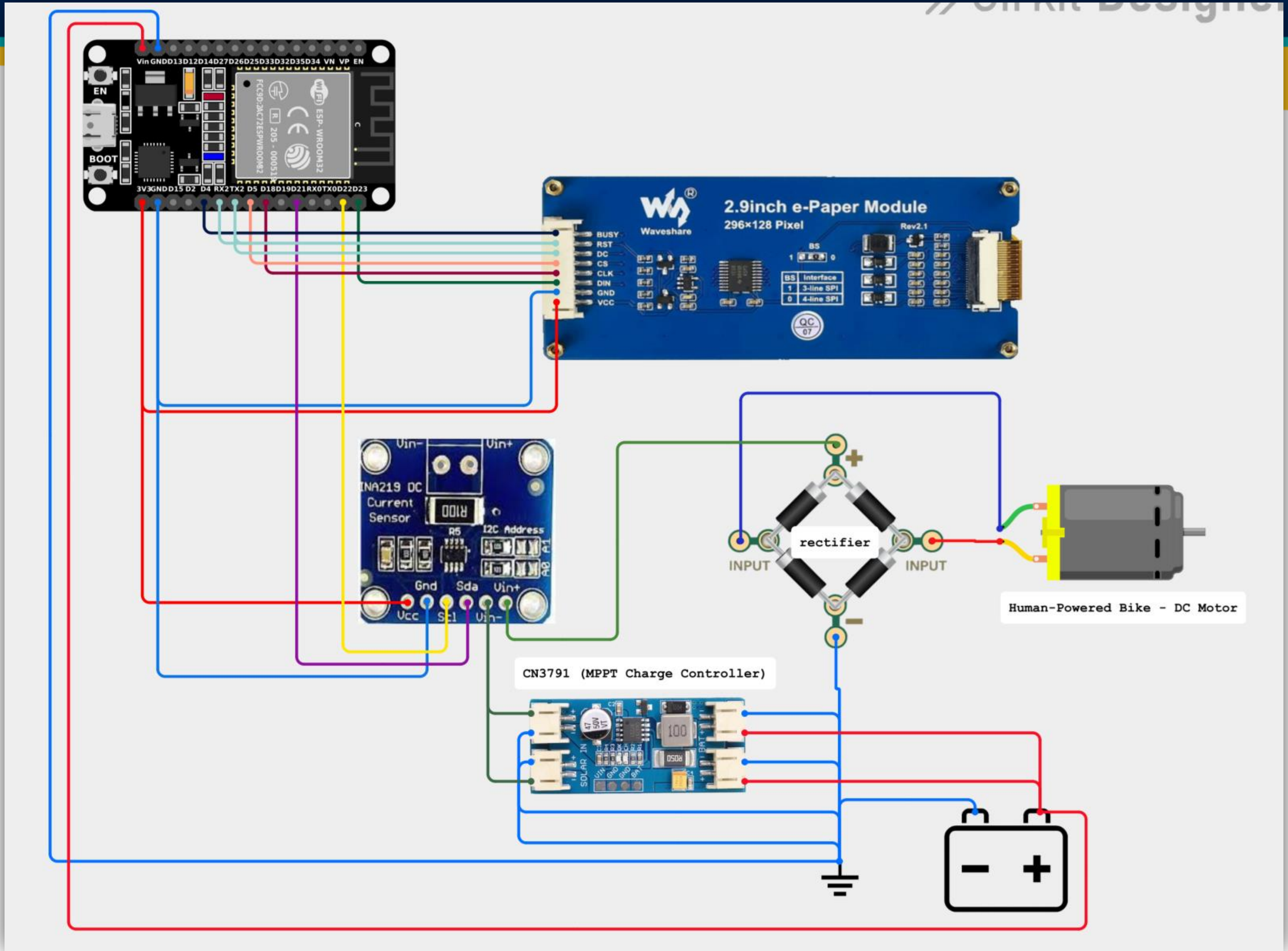


Fig 7. Circuit Diagram [3][4][5][6][7]

Design Requirements Greenhouse

Customer Requirements
- Full analysis on renewable energy system
- Improvements to energy input/output
- Improvements to turtle habitat
- Inclusion of human-power generation
- STEAM education for PHS students

Engineering Requirements
- Wind turbine generation
  - 300W
- HPE Bike generation
  - 150W
- Solar power generation
  - 3500 kW
- Turtle habitat temperature regulation
  - 80 ± 10 °F
- Greenhouse energy consumption
  - 60%

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								

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

	Customer Needs	Customer Weights	Technical Requirements: Greenhouse Energy Consumption	Turtle habitat temperature regulation	Solar Power Generation	Human Power Generation	Wind Turbine Generation			Customer Opinion Survey: 1 Poor	2	3 Acceptable	4	5 Excellent
1	Efficiency	4	9	3	9	1	3	---	---		C		B	A
2	Student Engagement	5		3	1	9	1	---	---			AB		C
3	Human Powered Bicycle Generator	4	1			9		---	---					C
4	System Optimization	2	9	1	9	1	3	---	---		C		B	A
5	Battery Storage	2	9	1	9	1	3	---	---	C				AB
6	Working Wind Turbine	5	3				9	---	---	C		B		A
7	Increased Solar Power	2	9		9			---	---	C			B	A
8	Turtle Enclosure	1	3	9	1		1	---	---					
9	Reliable/ Low Maintenace System	3		1	9	3	3	---	---			A	B	C
10	Increased Energy Output	4	9	3	9	1	3	---	---			B	C	A
	Technical Requirement Units		%	°F	kW	W	W	---	---					
	Technical Requirement Targets		50	80±10	3500	150	300	---	---					
	Technical Importance		2	4	1	5	3	---	---					

Fig 8. Greenhouse QFD

Design Requirements HPE Bike

Customer Requirements

- Competition element
- Student engagement
- Educational value
- Energy input
- Fits in PHS greenhouse

Engineering Requirements

- Battery performance
  - 85%
- Manufacturing costs
  - $500
- Power output
  - 150W
- Maintenance
  - 4000 km till maintenance needed
- Structural Integrity
  - Can hold 800 N without failure

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

Legend			
A	Waterlution	9	strong
B	DIY Bike Power Output	3	medium
C	HPEG system	1	weak
		0	no relation

	Customer Needs	Customer Weights	Battery Performance	Manufacturing Cost	Power Output	Maintenance	Structural Integrity			1 Poor	2	3 Acceptable	4	5 Excellent
1	Interactive Display	3		9	9	3		---	---	ABC				
2	Durability	5	9	9	1	9	9	---	---	AB			C	
3	Supplemental Energy	5	9	3	9			---	---			A		BC
4	Educational Value	4			3			---	---		C		AB	
5	Adjustable	2		3		3	3	---	---			A	BC	
6	Shows Power Generated	3			1			---	---	C	B		A	
7	Safe to Use	5				9	9	---	---				AB	C
8	Asethetics	1		9				---	---		AB	C		
9	Student Participation	4			1			---	---	ABC				
10	Size	4	3	3			3	---	---		A	B		C

Technical Requirements / Customer Opinion Survey

	Battery Performance	Manufacturing Cost	Power Output	Maintenance	Structural Integrity		
Technical Requirement Units	%	$	W	km	N	...	...
Technical Requirement Targets	85	500	150	4000	800	...	...
Technical Importance	5	3	1	4	2	...	...

Fig 9. HPE Bike QFD

Power Generation

Question

- How does gear selection affect electrical power output for a recreational cyclist?

Constants

- Sustainable pedaling cadence (ω) 45-75 RPM
- Sustainable Tan. Pedal Force (F) 125-250 N
- Bicycle Crank Length (r) 0.19 m
- Wheel Radius (R) 0.356 m
- Alternator Roller Radius (r_{alt}) 0.025 m
- 7-Speed Cassette (n) G1-G7
- Chainring (N) 34 teeth
- Alternator Efficiency (η_{alt}) 70%
- Drivetrain Efficiency (η_{drive}) 96%
- Direct Contact Efficiency ($\eta_{contact}$) 96%
- Charge Controller Efficiency (η_{charge}) 95%

Equations

- $G_{bike} = \frac{N}{n}$
- $G_{alt} = \frac{r}{r_{alt}}$
- $\omega_{alt} = \omega G_{bike} G_{alt}$
- $\tau\ [N * m] = Fr$
- $P_{mech}\ [W] = \tau\omega$
- $\eta_{sys} = \eta_{alt}\eta_{drive}\eta_{contact}\eta_{charge}$
- $P_{out}\ [W] = P_{mech}\ \eta_{sys}$

Tools

- MATLAB

Power Generation: Results

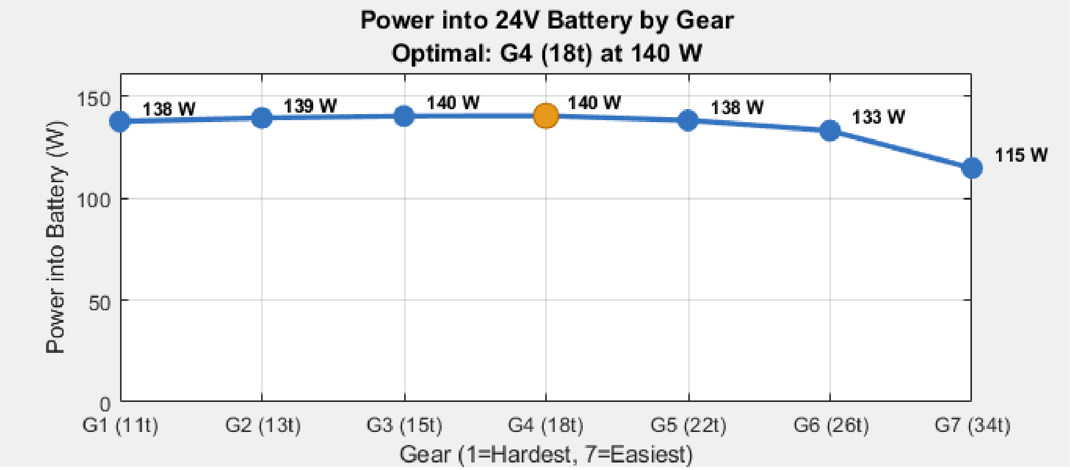
Results

- G4 (18 teeth) and G3 (15 teeth) produce optimal (140W) output to batteries
- System Efficiency (η_{sys}) is 61%
- Model assumes linear force-cadence tradeoff; physical testing required

Literature Comparison

- Typical sustained power output for recreational cyclists is 75 to 150 W [8]
- Professional cyclists sustain 350-400 W [9]
- Peak power output occurs at moderate resistance [8][9]

Fig 10. Power into Battery vs. Gear



Gear	Teeth	ω (RPM)	F (N)	ω_{alt} (RPM)	P_{out} (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

Table 1. Gear Specs

Net Power Generation

Question

- How much impact does the interactive screen have on net power generation?

Constants

- E-ink max refresh frequency $t_{min} = 2$ s [2]
- Board Source Voltage $v_s = 3.3$ v [1]
- Component Constants

Component	Active Draw i_a (mA)	Standby Draw i_s (mA)	Wake Time t_w (ms)	Source
ESP32	11	0.8	12	[1]
7.5” E-Ink	7.9	0.001	200	[2]
INA219	1	0.006	1	[3]
Arduino Uno	50	-	-	[4]
16x2 LCD	25	-	-	[5]

Table 2. Draw Specs

Equations

- $t_r = \sum t_w$
- $I_{active} = (\sum i_a)(\frac{t_r}{T})$
- $I_{standby} = (\sum i_s)(\frac{T-t_r}{T})$
- $I_{avg} = I_{active} + I_{standby}$
- $P_{avg} = I_{avg} \times v_s$
- $P_{net} = P_{out} - P_{avg}$

Results

- Negligeable effects on net power output
- ESP32 & E-Ink reduces power consumption by >96% over Arduino & LCD baseline
- Efficiency scales with refresh frequency:
  At 10s, average draw is just 4 mW

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

Table 3. Power Improvement

Stand Stress Analysis

Static Loads:

$$\sum F_y = 0 \Leftrightarrow 2R_{Bar} + R_{F,Wheel} = W_{Bicycle} + W_{Rider}$$

$$\sum F_y = 0 \Leftrightarrow 2F_{Bar} = 2R_{Support}$$

Dynamic Forces:

Torque: $T_{Crank} = F_{Pedal} \bullet r_{PedalArm} \bullet sin(\theta)$

Tension: $F_{Chain} = T_{Crank}$

Constants:

- Mass of Cyclist (m_{human}) = 60 - 75 [kg]
- Mass of Bicycle ($m_{Bicycle}$) = 7 - 9 [kg]
- Force on Pedal (F_{Pedal}) = 100 [N]
- Length of Pedal Crank Arm ($r_{PedalArm}$) = 0.170 [m]
- Angle of forced movement (θ) = 120°

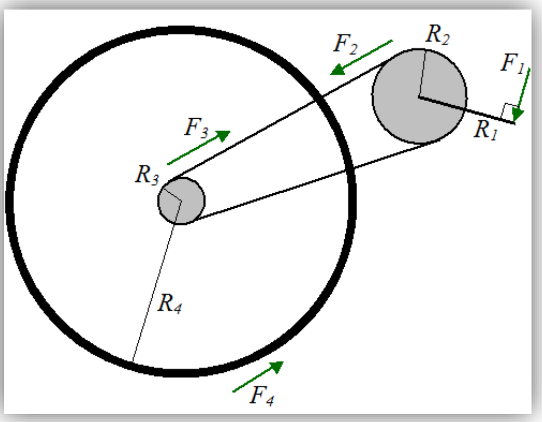


Fig 11. Torque Analysis [10]

Stress Analysis:

- Fatigue Strength(Basquin's Equation) : $S_f = aN^b$
  - $a = \frac{(f S_{ut})^2}{S_e}$
  - $b = -\frac{1}{3} log(\frac{f S_{ut}}{S_e})$
  - $N = (\frac{\sigma_{ar}}{a})^{1/b}$
- Endurance Limit(Marin's Equation) : $S_e = k_a k_b k_c k_d k_e k_f S_e'$
  - Values found through textbooks and online sources

Tools:

- SOLIDWORKS
- MatLAB

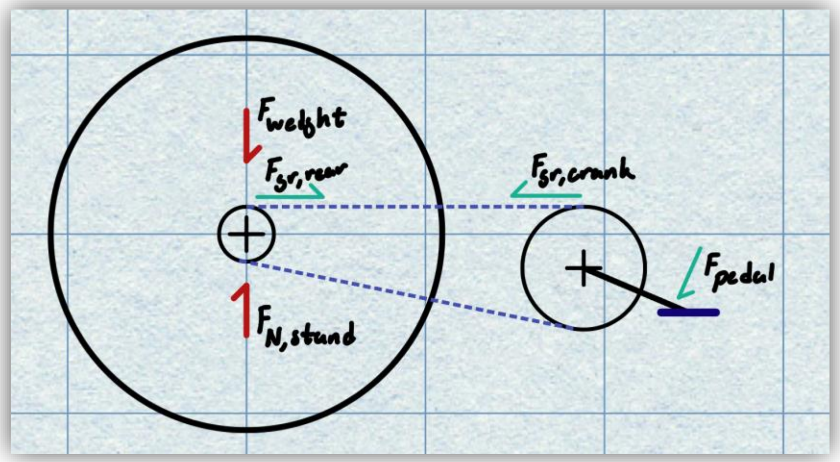


Fig 12. Analysis of all potential forces on bicycle stand

Alternator Analysis

Efficiency vs. RPM

$$\eta = \frac{P_{out}}{P_{human}} \text{ [11]}$$

where,

P_{out} = V x I

P_{in} = T x ω

Efficiency depends on how effectively human mechanical input power is converted into electrical power.

Low RPM:

- RMP is too low = insufficient voltage generation
- Electrical output is minimal or unusable

Optimal RPM:

- Voltage and current are well-matched
- Losses are minimized relative to output

High RPM:

- Losses increase (i.e. friction of the bearing and air drag)
- Efficiency drops

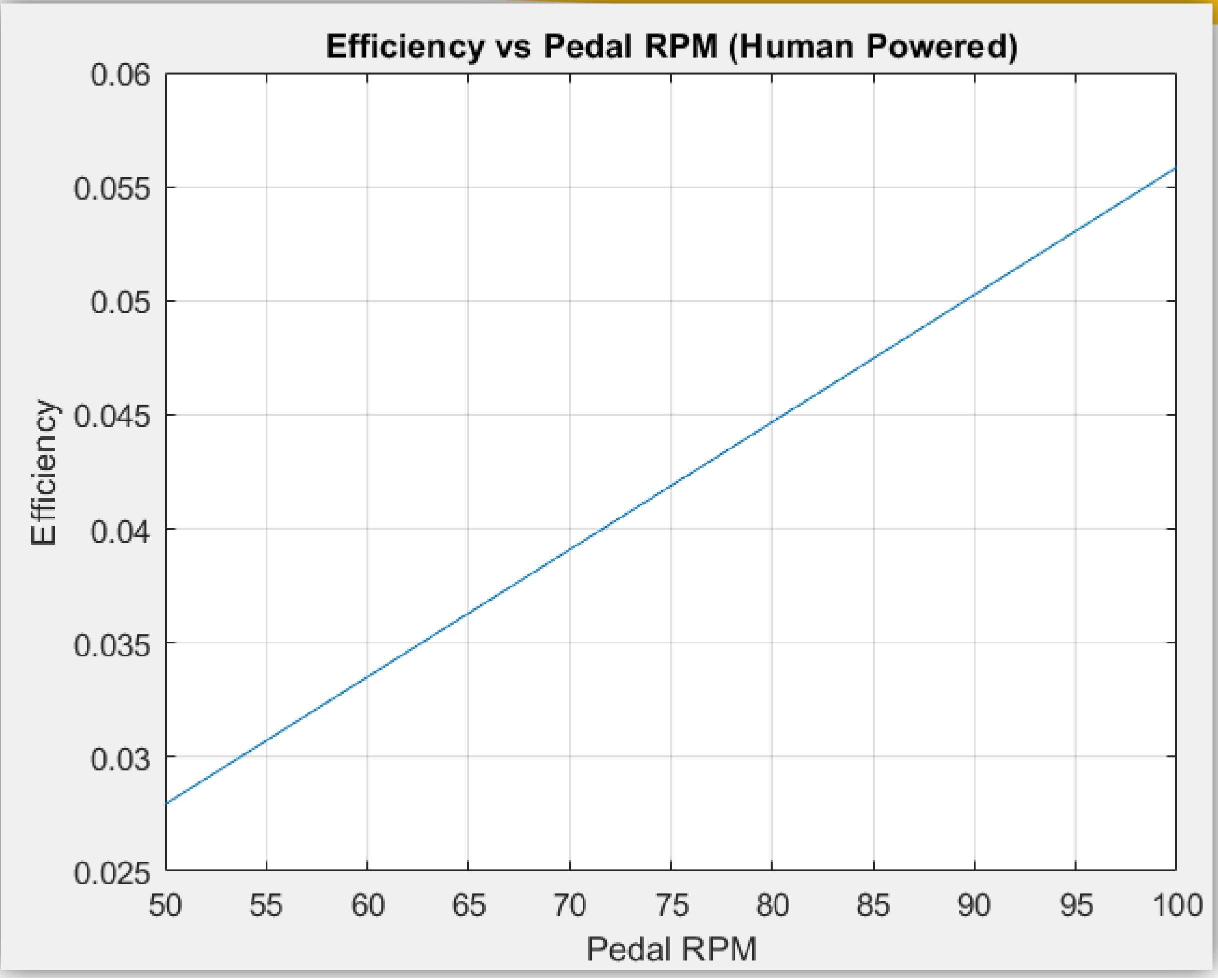


Fig 13. Efficiency vs. Pedal RPM

Alternator Analysis

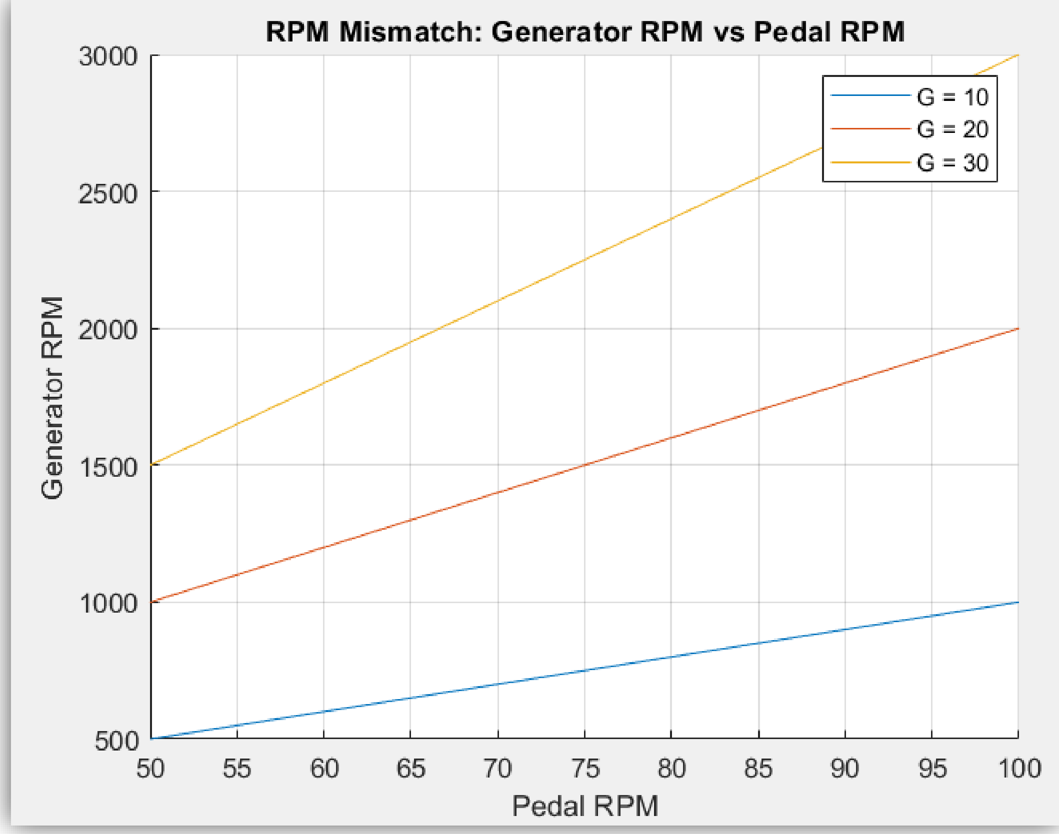


Fig 14. Generator RPM vs Pedal RPM

Voltage Output vs. RPM

$E = (k_e)(\omega)$ [11]

E = Generated Voltage

k_e = machine constant

ω = angular velocity

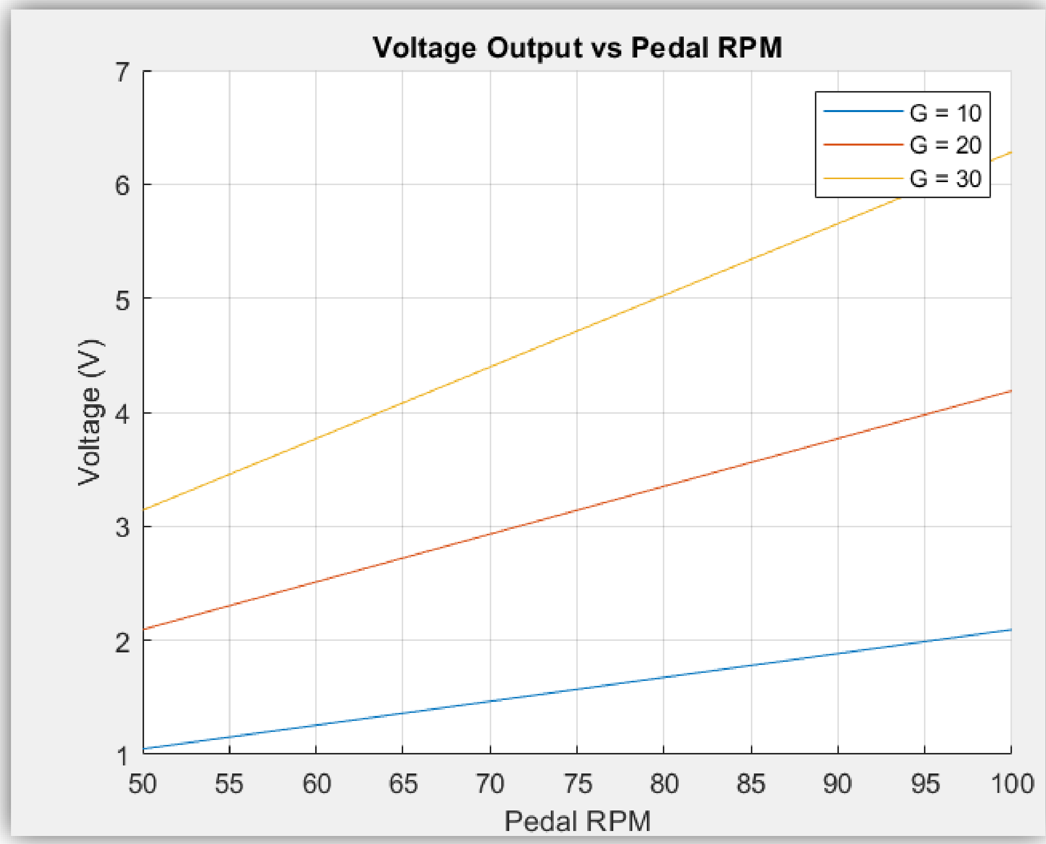


Figure 15. Voltage vs. RPM

RPM Mismatch & Gear Ratio

$RPM_{gen} = G\ x\ RPM_{pedal}$ [12]

Alternator Analysis

Bearing Life

$$L_{10} = \left(\frac{C}{P}\right)^{p} \quad [13]$$

where,

C = dynamic load rating
P = equivalent load
p = life exponent
Ball bearings = 3
Roller bearings = 10/3

Results:

L10 Life: 216 million revolutions
L10 Life: 1800 hours

How does Gear Ratio affect bearing life?

As the gear ratio increases:

- Generator RMP increases
- Bearing life (in hours) decreases

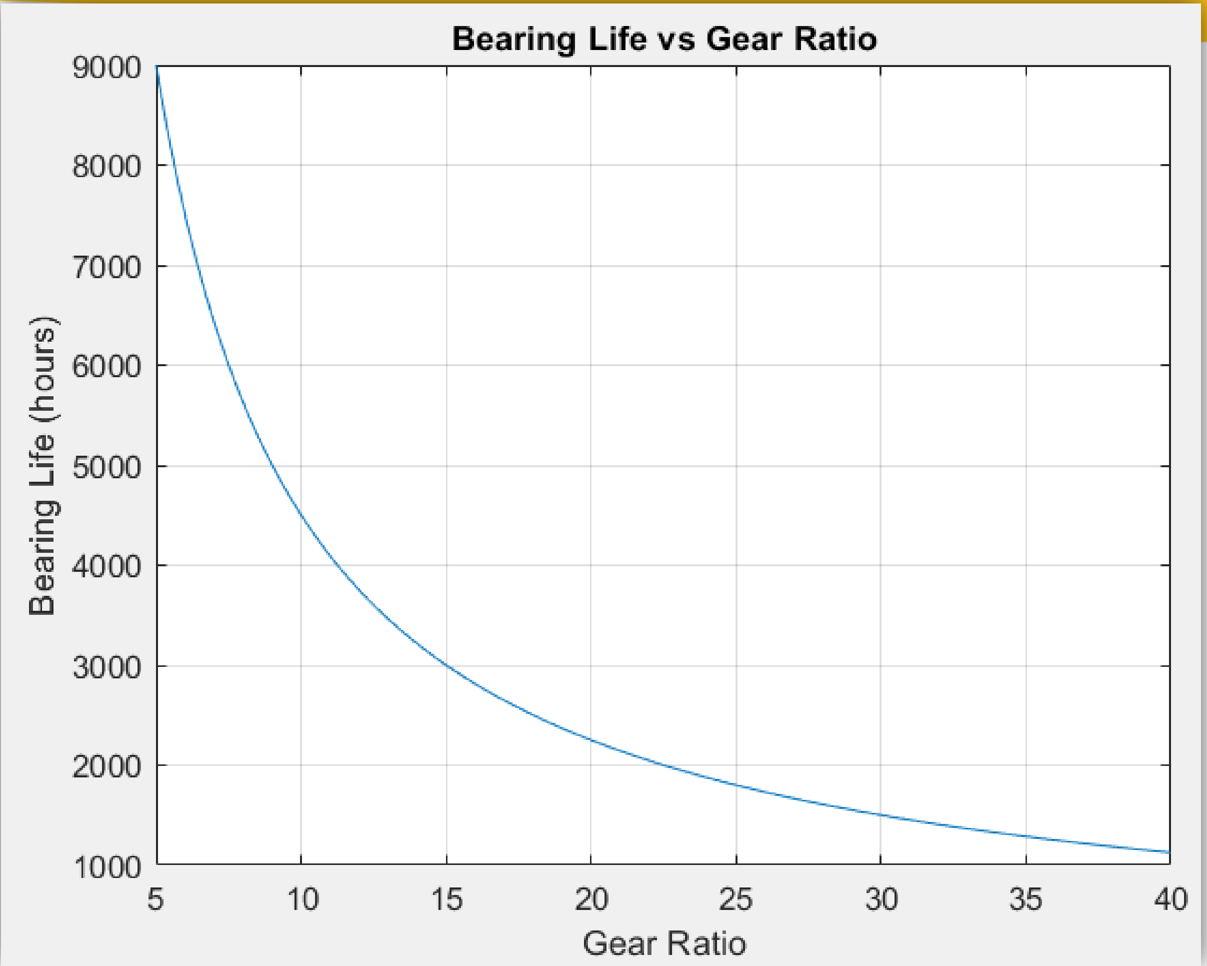


Figure 16. Bearing Life vs. Gear Ratio

Battery Performance Analysis

ER/CR focus:
improvements to renewable energy system (battery)

Equations

Ah Capacity [14]:

$$Q = \int i\, dt$$

Where,
Q is the capacity [Ah]
i is the discharge current [Amp]
t is the time [hr]

kWh Capacity [14]:

$$Q_{kWh} = V * Q$$

Where,
Q_{kWh} is the kWh capacity [kWh]
V is the voltage [V]
Q is the Ah capacity [Ah]

Cont. Discharge Current [14]:

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

Where,
i(A) is the cont. discharge current [A]
Q is the capacity [Ah]
t is the time [hr]

Battery Specifications

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)	Battery Dude [15]	224	1.344	Series and/or Parallel	6	11.2
FHSKY-24051-G2-INV LiFePO4	Big Battery [16]	200	5.12	Parallel (up to 16 times)	24	200
GWN12200 Sodium ion	Battery finds [17]	200	2.4	Series and/or Parallel (4P4S)	12	200
GWN12100 Sodium ion	Battery finds [17]	100	1.2	Series and/or Parallel (4P4S)	12	100
BAT524120740 LiFePO4	Solar Electric [18]	100	2.56	Parallel	25.6	200

Table 4. Battery Specifications

Battery Performance Analysis Cont.

1. **FHSKY-24051-G2-INV (LiFePO4)**

   cost: $2050

Fig 17. FHSKY-24051-G2-INV

2. **BAT524120740 (LiFePO4)**

   cost: $1785

Fig 18. BAT524120740

3. **GWN12200 (Sodium Ion)**

   cost: $2040

Fig 19. GWN12200

Further Analysis:
Thermal degradation with cycle life
Cycle life vs depth of discharge

Battery Heat Loss Analysis

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

Table 5. Client and Battery Information

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

Table 6. Temperature Ranges

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/m2 K)	12	

Table 7. Battery Specs

Steady State Equations

$$P = W_{human} * \eta_{sys}$$

$$I = \frac{P}{V}$$

$$\dot{Q}_{gen} = hA(T_s - T_\infty)$$

$$\dot{Q}_{\text{gen}} = I^2 R$$

Transient Equations

$$\text{Fo} = \frac{kt}{\rho c L^2}$$

$$\text{Bi} = \frac{hL_c}{k}$$

$$L_c = \frac{V}{A_s}$$

$$\theta^* = \frac{T_s - T_\infty}{T_i - T_\infty}$$

	Winter				Spring/Fall				Summer			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
T-high	19.05179	19.54132	22.43702	23.52394	26.64179	27.13132	30.02702	31.11394	34.42079	34.91032	37.80602	38.89294
T-Med	0.180294	0.669824	3.565517	4.65244	8.411794	8.901324	11.79702	12.88394	19.20179	19.69132	22.58702	23.67394
T-Low	-20.39821	-19.90868	-17.01298	-15.92606	-8.912206	-8.422676	-5.526983	-4.44006	-0.768206	-0.278676	2.617017	3.70394

Table 8. Steady State Temperatures

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	-20.2145	-8.7285	-0.5845

Table 9. Transient Temperature

Design Validation

Risk Trade-Off Analysis

Design Choice	Benefit	Risk
Higher Gear Ratio	Increased voltage	Higher RPM = reduced bearing life
Lower Gear Ratio	Easier Pedaling	Insufficient voltage
Higher Electrical Load	More power output	Increased rider effort, overheating
Additional Bearings	Increased lifespan	Additional cost

Table 10. Risk Trade-Off Analysis

Design validation will be conducted through a combination of analytical modeling, and mechanical reliability under realistic operating conditions. The testing procedures are designed to directly assess whether the system meets defined engineering requirements while evaluating trade-offs between performance, durability and user constraints.

Testing Procedure

Validate that the system meets all Engineering Requirements through experimental testing.

Testing:

- Voltage vs Pedal RPM
- Outputs and Efficiencies
- Gear Ratio Validation
- Thermal Performance

Equipment:

- Multimeter (Voltage & Current)
- Tachometer (RPM measurement)
- Temperature sensor

Space

- Lab or workshop space
- Electrical safety setup
- Safe area for testing

FMEA Design Validation

Part	Potential Failure Mode	Potential Causes of Failure	Potential Effects of Failure	RPN	Recommended Action
Stand	Force-Induced Deformation High-Cycle Fatigue	Overstressing Cyclic Failure Tangential Stress	Structural Collapse Vehicle Instability Rider Tip-Over	120	• Add Reinforcement • Locking Fasteners • Perform Load Testing
Bike Assembly	Force-Induced Deformation High-Cycle Fatigue	Overstressing Cyclic Failure Tangential Stress	Generator Assembly Failure Damage to Alternator Rider Injury	216	• Consistent Inspection • Reinforce Joints
Interactive Display Circuit	Abrasive Wear Circuit Overloading	Faulty Wiring Cyclic Failure Component Failure	Damage to Battery Fire Hazard Power Loss	120	• Overcurrent Protection • Clean Circuit Wiring
Circuit & Alternator Housing	Force-Induced Deformation	High-Impact Loads	Live Electrical Exposure Moisture Ingress Power Loss	240	• Strong Polymer • Rounded Corners
Alternator Generator	Force-Induced Deformation High-Cycle Fatigue	Cyclic Failure	Power Loss Battery Drain	110	• Integrate ventilation opening • Alignment verification

Table 11. FMEA

Schedule: Course Deliverables

Project start date: 1/17/2026

Scrolling increment: 40

Milestone description	Category	Assigned to	Progress	Start	End	Days
Course Deliverables						
Team Charter	On Track	Team	100%	1/18/2026	1/23/2026	6
Presentation 1	On Track	Team	100%	1/26/2026	2/2/2026	8
Presentation 2	On Track	Team	100%	2/20/2026	3/2/2026	10
Self Learning (HW3)	On Track	Individual	100%	2/6/2026	2/27/2026	12
Report #1	Milestone	Team	100%	3/2/2026	3/8/2026	7
Website Check #1	Goal	Carson	100%	3/2/2026	3/16/2026	14
Analytical Analysis Memo	On Track	Team	100%	3/16/2026	3/23/2026	5
Presentation 3	On Track	Team	100%	3/16/2026	3/30/2026	15
1st Proto Demo	Goal	Carson	100%	3/16/2026	3/30/2026	15
Report #2	Milestone	Team		3/30/2026	4/17/2026	1
Mathematical Analysis (HW4)	On Track	Individual	40%	3/16/2026	4/26/2026	10
Final CAD/BOM		Carson and Kaitlyn		3/30/2026	4/25/2026	
Project Management				4/20/2026	5/1/2026	
2nd Proto Demo				4/20/2026	4/27/2026	
Website Check #2	Low Risk	Carson	10%	4/20/2026	5/3/2026	

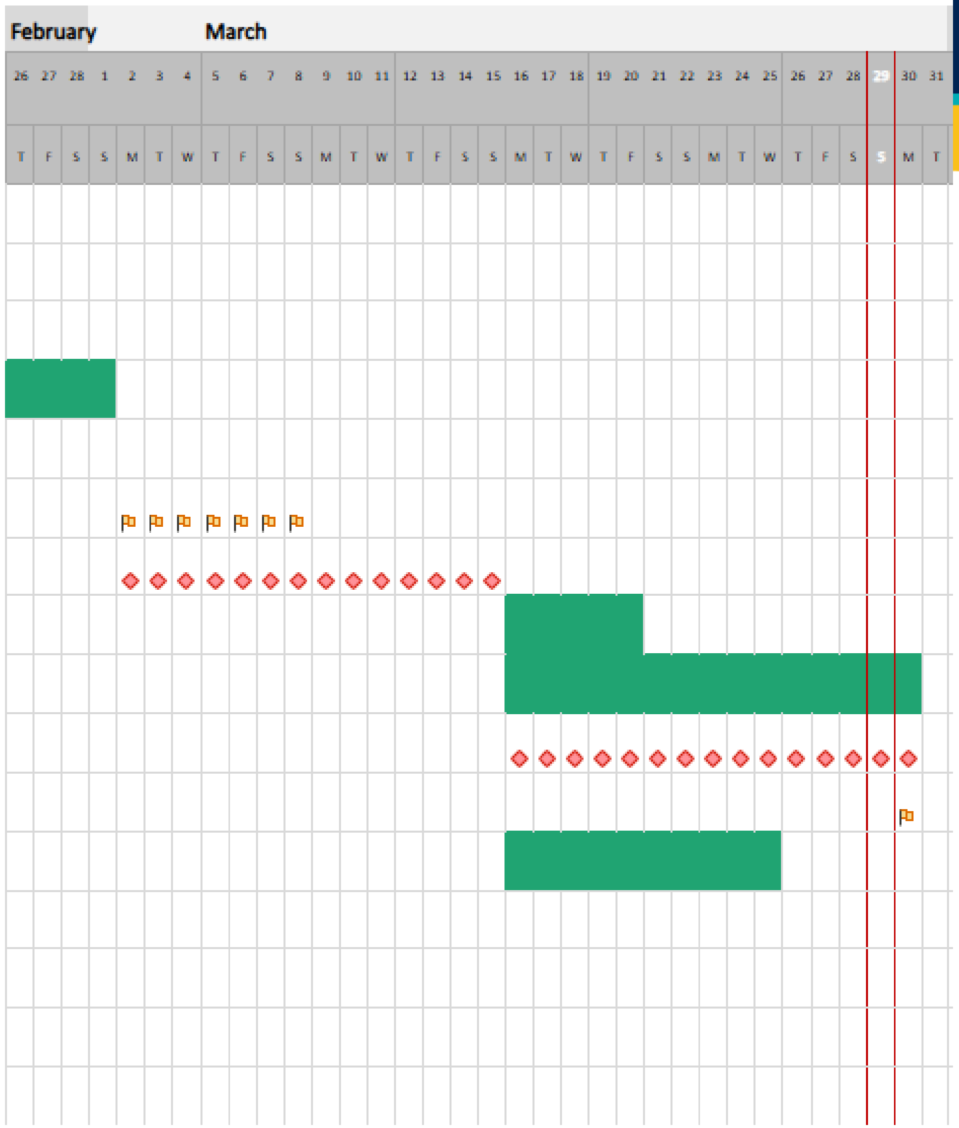


Fig 20. Course Deliverables

Ahead: CAD, website building, HW04 analysis - **On Track:** lesson plan, report 2 - **Behind:** system analysis, energy audit

Schedule: Client Deliverables

Client Deliverables

Energy Audit Report	Goal	Team	60%	2/20/2026	4/20/2026	39
System Capacity and Performance Analysis	Goal	Team	30%	3/16/2026	4/27/2026	15
Improvement/Expansion Reccommendations	Milestone	Kaitlyn and Alex	10%	3/16/2026	5/6/2026	15
Human Powered Bicycle Generator	On Track	Ethan	80%	2/3/2026	5/6/2026	56
Education Curriculum Materials	On Track	Jenna	25%	2/15/2026	11/30/2026	44
Final Written Report and Presentation	Milestone	Team		5/4/2026	12/10/2026	

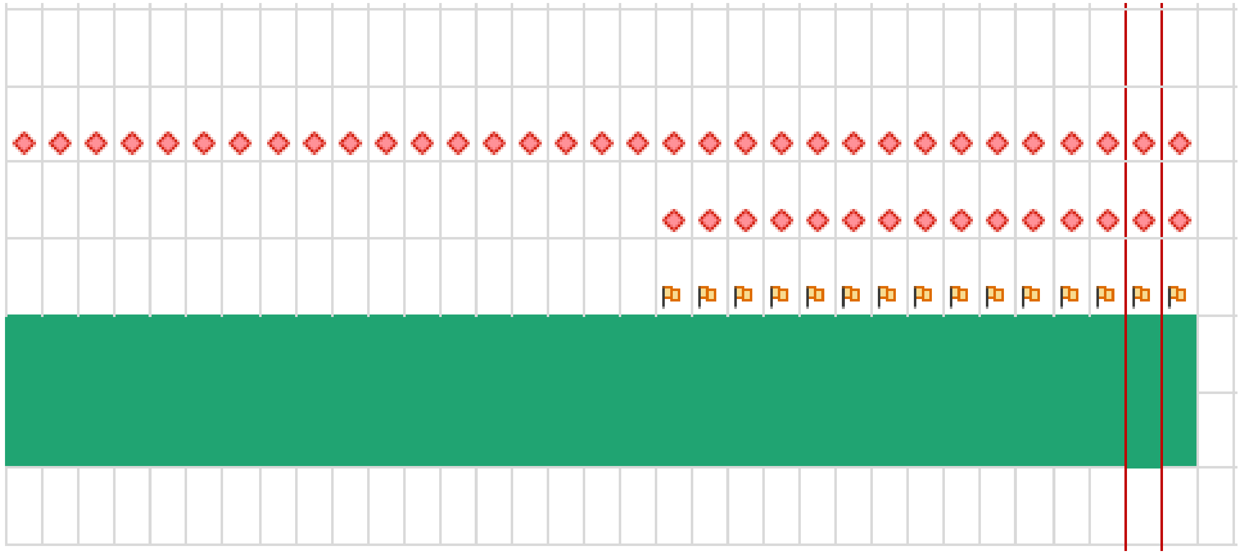


Fig 21. Client Deliverables

Ahead: CAD, website building, HW04 analysis - **On Track:** lesson plan, report 2 - **Behind:** system analysis, energy audit

Budget

PHS Sustainability Budget

Revenue		Estimated	Actual
NAU		$1,000.00	$1,000.00
Fundraising		$750.00	$750.00
Ponderosa High School		$4,000.00	$0.00
		$5,750.00	**$1,750.00**

Expense Type		Budget	Expense	Remaining
Tools		$250.00	$60.14	$189.86
Batteries		$4,000.00	$0.00	$4,000.00
Solar Panel		$505.00	$0.00	$505.00
LED Lights		$75.00	$0.00	$75.00
Human Powered Energy Bike		$500.00	$113.54	$386.46
Wind Turbine		$100.00	$0.00	$100.00
Animal Insulation		$400.00	$0.00	$400.00
Curriculum		$300.00	$16.00	$284.00
Total Expenses:		**$6,130.00**	**$189.68**	**$5,940.32**
			Total Revenue:	$1,750.00
			Total Balance:	**$1,560.32**

Table12. Budget

Donations

- Bicycles
  - Value: $150.00
- Solar Panels
  - Value: $3,000
- Alternator
  - Value: $500.00

Fundraising

- Plant Sale: April 7th 10:00AM-5:00PM
- Chipotle: April 8th 4:00PM-8:00PM

Student Instruction at PHS

February Lesson:
- Introduced main types of energy (KE,PE)
- Rollercoaster demonstration

March Lesson:
- Introduced wind energy and wind turbines
- Kid Wind competition
- Windmill demonstration

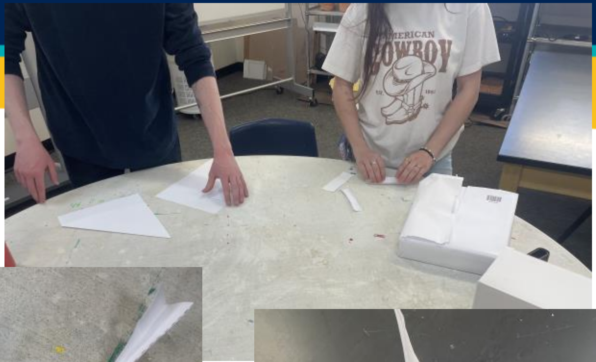


Fig 27. Carson and Jenna making windmills

Fig 28. Students' windmills

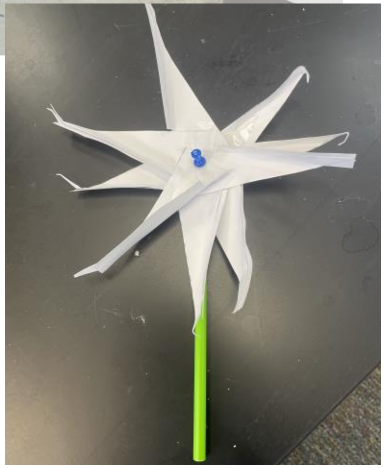


Fig 25. Students' windmills

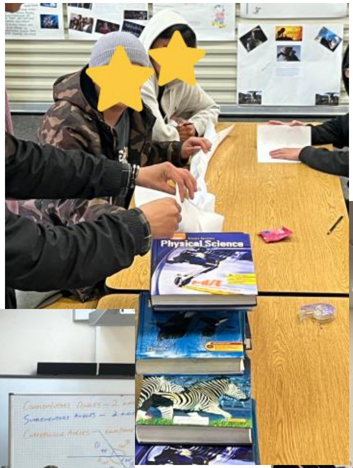


Fig 26. Students' rollercoaster

Fig 22. Students' rollercoaster

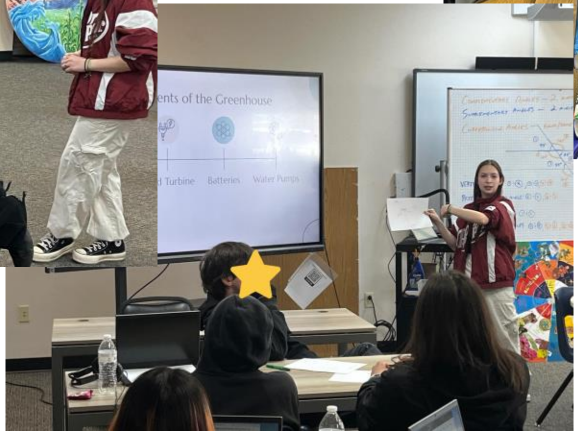


Fig 23. Jenna presenting

Fig 24. Students' rollercoaster

Future Lesson Plans:
April/May: Solar Energy
August: Introduction to Electricity

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Thank You

Questions?