NORTHERN ARIZONA UNIVERSITY
Steve Sanghi College of Engineering

PHS Sustainability

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Fig. 1 Photo of PHS greenhouse

Project Description

Ponderosa High School (PHS) has tasked us to analyze and improve upon their off-grid renewable energy system

- Wind Turbine
- Solar Panel
- 24 Volt battery

Additionally, PHS would like interactive learning to promote STEAM education to the students at PHS

Ponderosa High School is an alternative high school located in Flagstaff, AZ. They are passionate in providing opportunities for their students

- TERRA Birds
- AOI Program

This project will expand on the school's off-grid greenhouse and continue interest in STEAM education for upcoming generations of students

Fig 2. Inside the greenhouse

Fig 3. The greenhouse bunny

Background and Benchmarking

Hybrid System

Solar, wind, hydro and a battery storage are commonly paired together to optimize the amount of energy that can be produced.

Fig 4. image of hybrid system

Bicycle Generation

These bikes are used as backup generators for small batteries, charging your phone, or lighting up LEDs. These bikes are commonly used on cloudy days when solar panels are inefficient.

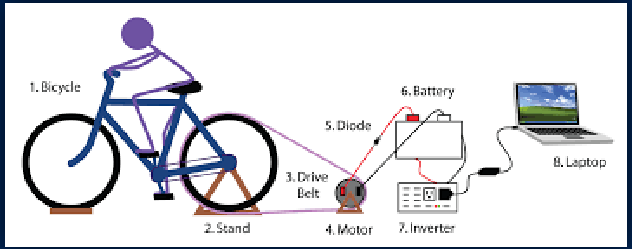


Fig 5. Bicycle Generator

Battery Storage

Depending on the size of the battery, energy generated can be directed to the battery to be stored. This energy can be from the bicycle, solar power, or wind power systems installed.

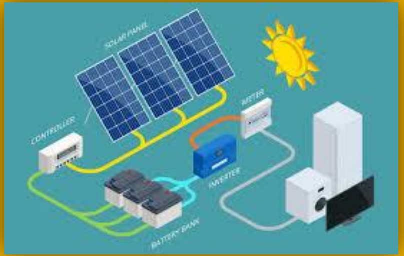


Fig 6. Diagram of PV battery storage

Customer Requirements

Full analysis on renewable energy system

- Energy audit
- Analyze saved for clients to have in records

Fully working renewable energy system

- Wind Turbine
- Solar Panels
- 24 Volt battery storage

Improved energy input/output

- Improving parts (batteries)
- Additional solar panels

Incorporating a human powered energy generation

- Bicycle power generator

STEAM education lessons for students at PHS

- Lessons about renewable energy, circuits, general energy generation
- Incorporation of art in lessons and project
- Assist students in STEAM school projects

Fig 7. planter with student art

Fig 8. diagram of underground fish tank

Engineering Requirements

Energy Audit

- Must account all inputs (wind turbine, solar panels) and all outputs (battery storage, lights, heating lamps)
- Data must be from information found at PHS greenhouse
- Analysis must include percentages of energy inputs going to outputs and a diagram of how the inputs flow to outputs

Wind Turbine

- Must have recorded energy inputs from wind turbine around/above 10kW

Solar Panels

- To improve energy input, must add at least 2 solar panels to roof system
- Must have recorded energy inputs from additional solar panels around/above 20kW

24 Volt Battery Storage

- Must conduct analysis to ensure quality of batteries is above 80%
- If not, batteries must be fully replaced

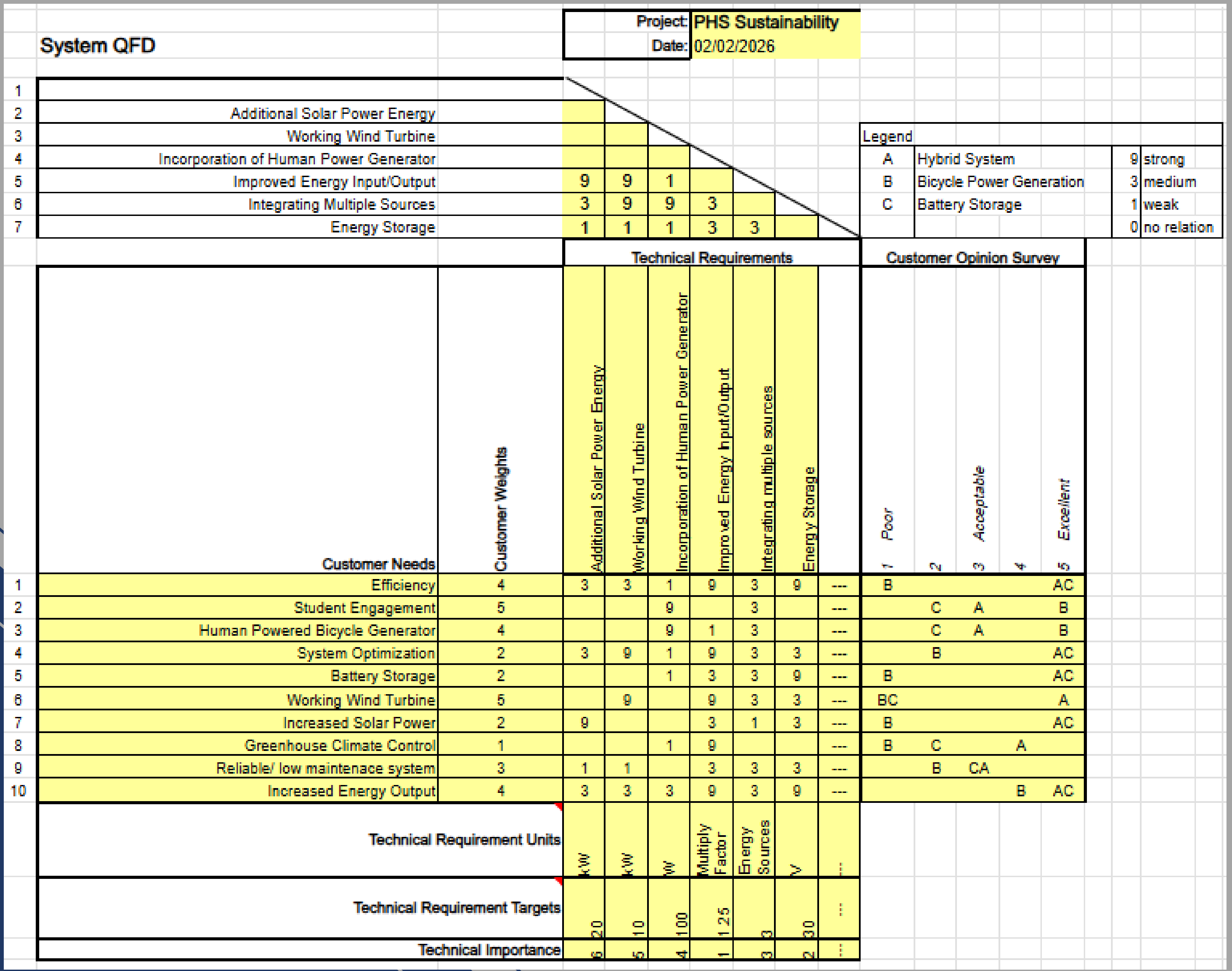
Power Bicycle Generator

- Must have at least 1 power bicycle generator installed in greenhouse system

STEAM Education

- Must have monthly lesson plan/project building event with students at PHS
- At least 1 of those lesson plans/project building must have art component for the students

QFD



System QFD

Project: PHS Sustainability

Date: 02/02/2026

		Additional Solar Power Energy	Working Wind Turbine	Incorporation of Human Power Generator	Improved Energy Input/Output	Integrating Multiple Sources
1						
2	Additional Solar Power Energy					
3	Working Wind Turbine					
4	Incorporation of Human Power Generator					
5	Improved Energy Input/Output	9	9	1		
6	Integrating Multiple Sources	3	9	9	3	
7	Energy Storage	1	1	1	3	3

Legend

A	Hybrid System	9	strong
B	Bicycle Power Generation	3	medium
C	Battery Storage	1	weak
		0	no relation

	Customer Needs	Customer Weights	Additional Solar Power Energy	Working Wind Turbine	Incorporation of Human Power Generator	Improved Energy Input/Output	Integrating multiple sources	Energy Storage		1 Poor	2	3 Acceptable	4	5 Excellent
1	Efficiency	4	3	3	1	9	3	9	---	B				AC
2	Student Engagement	5			9		3		---		C	A		B
3	Human Powered Bicycle Generator	4			9	1	3		---		C	A		B
4	System Optimization	2	3	9	1	9	3	3	---		B			AC
5	Battery Storage	2			1	3	3	9	---	B				AC
6	Working Wind Turbine	5		9		9	3	3	---	BC				A
7	Increased Solar Power	2	9			3	1	3	---	B				AC
8	Greenhouse Climate Control	1			1	9			---	B	C		A	
9	Reliable/ low maintenace system	3	1	1		3	3	3	---		B	CA		
10	Increased Energy Output	4	3	3	3	9	3	9	---				B	AC
	Technical Requirement Units		kW	kW	W	Multiply Factor	Energy Sources	V	...					
	Technical Requirement Targets		20	10	100	1.25	3	30	...					
	Technical Importance		6	5	4	1	3	2	...					

Technical Requirements

Customer Opinion Survey

Wind Energy

Reference	Explanation
Wind Energy Explained: Theory, design and Application [1] (book)	-Wind energy textbook -Comprehensive overview of wind energy fundamentals -**Application: Inform design decisions and performance calculations**
Aerodynamics of Wind Turbines: A Physical Basis for Analysis and Design [2] (book)	-Predicting turbine performance using analytical modeling approaches -Momentum theory, blade element theory, and wake effects -**Application: Aerodynamic modeling and design blade analysis**
Analysis of wind turbine usage in greenhouses: wind resource assessment, distributed generation of electricity and environmental protection [3] (paper)	-Sustainability benefits of distributed wind generation -Integrates small-scale wind turbines into greenhouses -**Application: Real world case study for distributed wind energy systems**
Design and Optimization of a Hybrid Solar-Wind Power Generation System for Greenhouses [4] (paper)	-Design methodology strategies for combining wind and solar -Analyzes benefit of hybrid renewable energy -**Application: Evaluation of combining wind and solar resources**
Space, Time, and Size Dependencies of Greenhouse Gas Payback Times of Wind Turbines in Northwestern Europe [5] (paper)	-Greenhouse gas varies by geographic location -Comprehensive comparison of environmental impacts -**Application: Estimating greenhouse gas and justifying sustainability benefits**

Mathematical Modeling: Wind Energy

Question to answer

- How does wind turbine power change with wind speed?

What is the answer

- Average wind speed in Flagstaff in January 2024 was 14.6 mph. Using this wind speed, we can estimate the available power to be approximately 13,474 W of instantaneous power.

Validate

- Compare against physical limits using the maximum possible power coefficient (Betz limit) Cp,max = 0.593.
- Literature comparison. A typical small-scale wind turbine with a radius of 0.3m at 10 m/s is around 100W. [1]

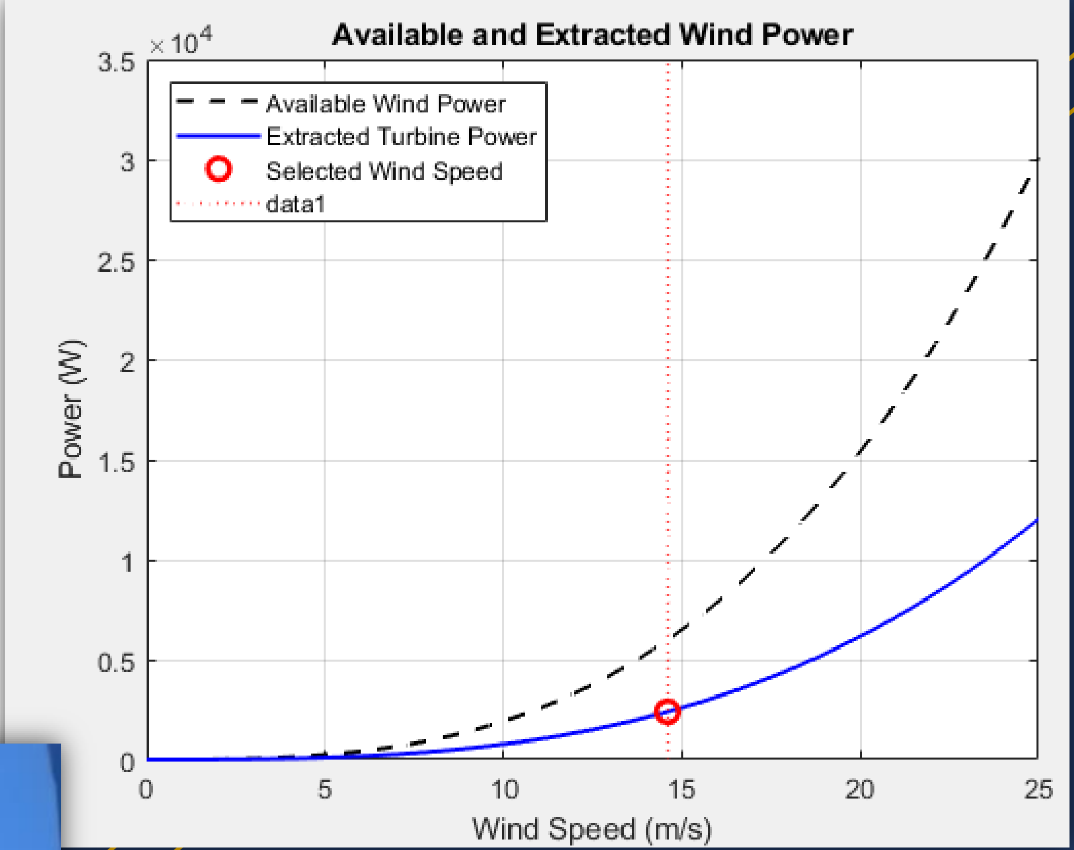


Fig 10. Wind speed vs. Power

Equations

Wind Turbine Power Coefficient

$Cp = P/((\frac{1}{2})pAV^3)$

Rotor swept area

$A = piR^2$

Available Wind Power

$Pavailable = (\frac{1}{2})pAV^3$

Extracted Power

$Pextracted = CpPavailable$

Energy from Power Over Time

$E = Pt$

Where,

Cp = power coefficient
P = power
p = density of air
A = area of the rotor
V = wind speed
E = energy
T = time

Fig 9. PHS wind turbine

How does this answer inform your design

Based on historic wind speed data for Flagstaff, we can work to estimate the maximum energy potential of the small-scale wind turbine located on top of the PHS greenhouse. This energy combined with the power provided by the existing solar panels will give us our total energy potential for the system.

Optimization of Renewable Systems

Reference	Explanation
Optimizing Off-grid Energy Solutions: a Hybrid Approach Leveraging Solar, Wind, and Biomass for Sustainable Development [6] (paper)	-Study in Morocco -Different regions and respective hybrid systems -**Application: large scale version of PHS greenhouse**
Applications of Hybrid Wind Solar Battery Based Microgrid for Small-Scale Stand-Alone Systems and Grid Integration for Multi-Feeder Systems [7] (book)	-Hybrid renewable energy system (HRES) -Controlled by algorithm -Produces constant voltage with renewable load variation -**Application: learn how to manage load variation**
Stochastic Optimization a New Method Based on for Solving Dynamic Reactive Power Optimization Problems Involving Renewable Energy and Storage [8] (paper)	-Scholastic optimization for variable loading -Using partial sample average approximation (PSAA) -**Application: understanding of theory behind hybrid system optimization**
Solar-Wind Hybrid Energy System Using MPPT [9] (conference paper)	-Differences in wind, solar and hybrid -Data showing hybrid increases energy input -**Application: evidence for importance of hybrid system in PHS greenhouse**
Modeling and Optimization of Renewable Energy Systems [10] (book)	-Different applications of hybrid systems -Definitions of components of hybrid systems -**Application: general understanding of hybrid systems**

Mathematical Modeling: Hybrid System

Question to answer

- Is a hybrid system optimal for the PHS greenhouse?

What is the answer

- Peak hours for collection times
- Wind power: **9,701 kW/ month** (Wind Energy analysis)
- Solar power: **46,320 kW/month** (PHS Greenhouse data)
- % increase with hybrid system: **20.94%**

Validate

- Confirm that the graphing is accurate representation of data
- Use wind speed and angle of altitude data from Flagstaff for accurate results

Application to design

- Results show additional power generated
- Power added can be used for greenhouse additions clients want

Tools
Excel graphing
Weather reporting

Symbols
P' = new power output
P = original power output
ρ =density of air
A = swept area
v= wind speed
Cp = efficiency of wind turbine

Equations

Percent difference
$|(P'-P)/P|*100$

Power formula
$Pw=(½)*ρA(v^3)(Cp)$

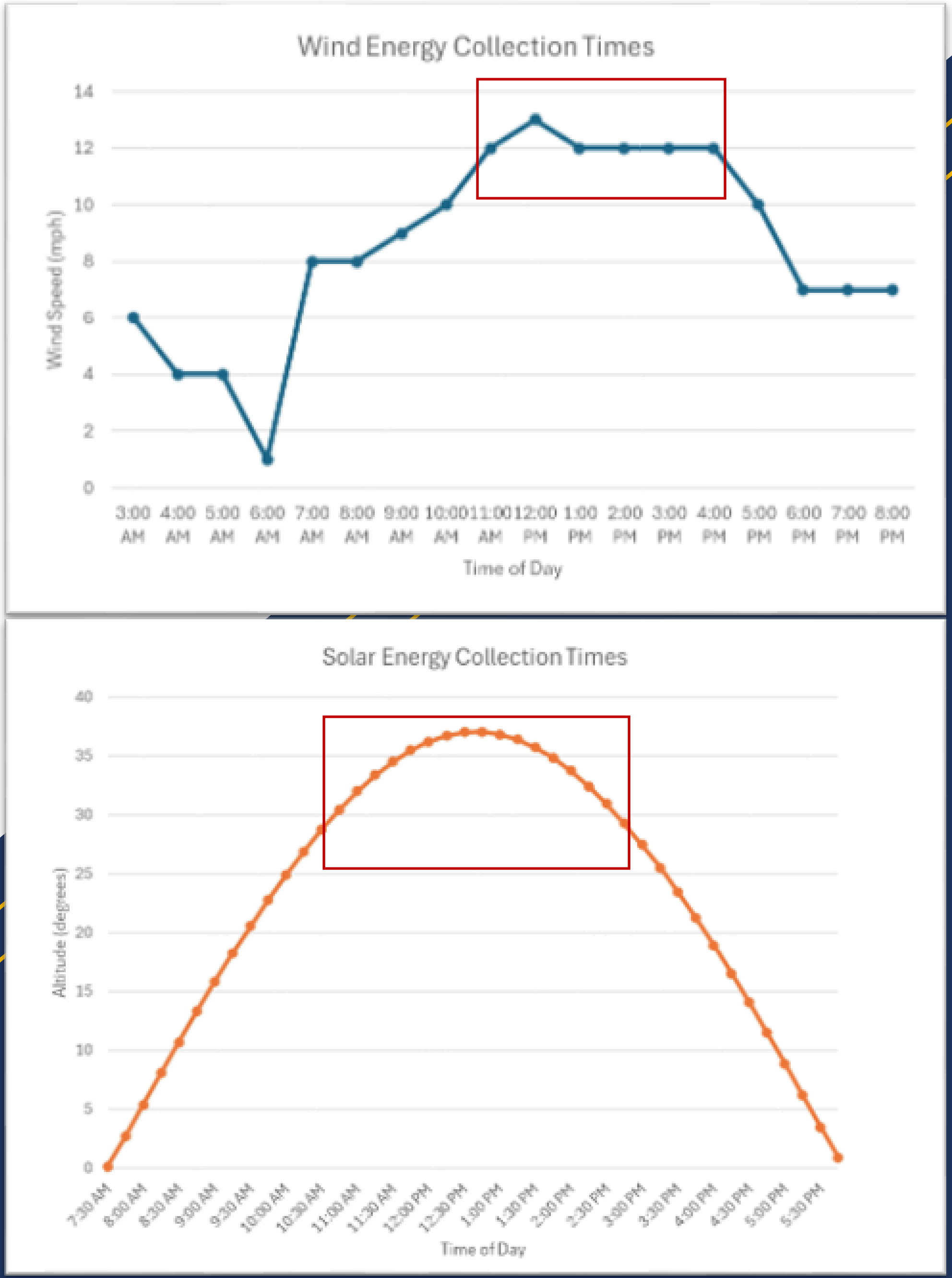


Fig 11. Wind and Solar Energy collection times [11] [12]

Green House Operation

Reference	Explanation
Sustainable Agricultural Engineering Technologies and applications [13] (book)	-Methods to reduce heat loss -use of thermal screens to reduce heat loss -thermal conductivity, capacity, convection for dirt **-Application: Thermal coefficients and new methods to improve greenhouse systems**
Agricultural Engineering: A Practical Manual First Edition [14] (book)	-how to calculate heat transfer -Light intensity for crops **-Application: Crop focused and heat transfer equations**
Greenhouse Applications of Solar Photovoltaic Driven Heat Pumps in Northern Environments [15] (article)	-average heating requirements -pump systems for energy efficiency -ideal temperatures **-Application: Adaptation for optimizing heat loss**
Top 10 Greenhouse Gardening Mistakes [16] (blog)	-ideal temperature -shade areas -ventilation and fungi **-Application: Improving energy loss**
Horticulture and Landscape Architecture Temperature Control in Greenhouses [17] (paper)	-Shade cloth -forced ventilation **-Application: Temperature control**

Mathematical Modeling: Heat Transfer

How much heat is the greenhouse losing and how can we decrease that value?

Assumptions
No insulation
k= .17 W/(m*K) [18]
To=
  Summer: 293.65 K
  Winter: 271.6K
Ti=
  Summer: 304.76K
  Winter: 282.7K

L= 3b
b=h=17ft=5.1816m

Qsummer= 152.13 W
Qwinter= 152 W

Equations
Q=k*A*(Ti-To)

Tools
Thermometers
Laser rulers

Symbols

Q= net heat transfer out of the greenhouse (W)
k= Heat transfer coefficient of the material (W/(m^2 *K)
A= surface area of the material (m^2)
Ti= inside temperature (K)
To=outside temperature (K)

Solar Panel

Reference	Explanation
Stand-Alone Photovoltaic Systems - A Handbook of Recommended Design Practices [19] (Textbook)	-Examples of practical problems of energy calculations -Diagrams of different connected solar array systems -**Application: Identifying different systems and connections**
PVWatts® Calculator [20] (Mathematical Calculator Website)	-Uses location data from over 30 years in specific reason of the world -Provides a detailed outline of information on Solar Radiation and AC Energy -**Application: Use data on Solar Radiation check mathematical formulas based on estimations**
NABCEP-2019-PV-Certification-Study-Guide [21] (Textbook)	-Equations for Solar Energy Generation -Official document created for Test Certifications -**Application: Use of Industry standards and design practices**
Improvement in solar panel efficiency using solar concentration by simple mirrors and by cooling [22] (Article)	-Goes into detail on differing factors that affect efficiency -Detailed explanations on the significance of temperature and sunlight on the performance of solar panels. -**Application: Optimization of Solar energy production**
Solar Panel Mathematical Modeling Using Simulink [23] (Research Article)	-Proves equations for the calculation of power, voltage, and current -Diagrams of different currents and relating equations -**Application: Use of models to compare current data and verify computations**

Mathematical Modeling: Solar Energy

Question to answer

- How much energy is produced by the current solar panels?

What is the answer

- Using the data values from PVWatts Calculator [20] as a reference point, we can start basic calculation on what the Ideal solar energy generation would be compared to what the actual potential can be by using a Performance Ratio of 75%. Further calculations will still need to be made once more info on the solar panels is gathered.

Validate

- Literature Comparisons:
  - Use data from PVWatts [20] which uses location data from the past 30 years

Symbol

P = power [Wh]
A = area if the panels [m^2]
R = Solar Irradiance [Wh/m^2]
β = energy
n_ref = Panel's efficiency at T_ref
T_ref = 25°C
T_cell = Temperature of Solar Cell

Equations

Solar Power
P = n*A*R
Efficiency
n = P_out/P_in
Thermal Efficiency
n(T) = n_ref(1+β(T_cell-T_ref))

Fig 12. PHS Greenhouse Solar Panels

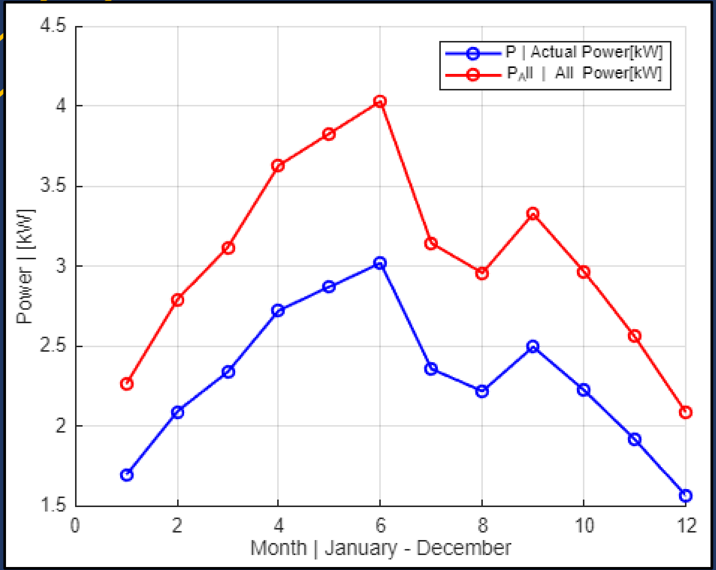


Fig 13. Ideal Solar Power Generation vs Actual Solar Power Generation

Human-Powered Energy Generation

Reference	Explanation
Bicycling Science [24] (Book)	- Human efficiency during cycling, with Mech. Adv. analysis - Biomechanics of Pedaling - **Application: Optimizing bicycle generator design for maximum efficiency**
Bicycle Power Generation and Its Feasibility [25] (Book)	- Practical Generator examples rated for power and efficiency - Cost-benefit analysis - **Application: Affordable pedal power generation for off-grid systems**
Converting Human Power into Electricity: Current Status and Future Directions [26] (Article)	- Overview of current technologies (2023) - Future innovation directions for energy capture - **Application: Identify emerging HPE generation technologies**
Harvesting Energy from the Counterbalancing (Weaving) Movement in Bicycle Riding [27] (Article)	- Novel Method using natural bike oscillation - Significant energy capture without pedaling - **Application**: **Supplemental energy harvesting**
Human-Powered Electricity Generation as a Renewable Resource [28] (Article)	- Metabolic energy output from exercise used to supplement gym power requirements - Feasibility analysis with comparison to solar - **Application**: **HPE use within large-scale electrical systems**
Pedal Power Generation [29] (Article)	- Dynamo and alternator conversion methods - Battery storage for rural off-grid use - **Application**: **Integrated battery systems for portable power storage**

Mathematical Modeling: Pedal-Driven Energy Generation

Tools
MATLAB - Calculations
Arduino IDE – Circuit Logic
LTSpice – Circuit Simulation

Question

- How much power can a cyclist realistically generate through sustained pedaling for energy generation applications?

Answer

- An average recreational cyclist can sustain 120 to 167.5 W depending on pedaling cadence and force, with an average of 143.5 W.

Validation

- Literature comparisons:
  - Typical sustained power output for recreational cyclists is 75 to 150 W [24]
  - On rural terrain, typical human power output is approx. 150 W [29]
  - Professional cyclists sustain 350-400 W [28]

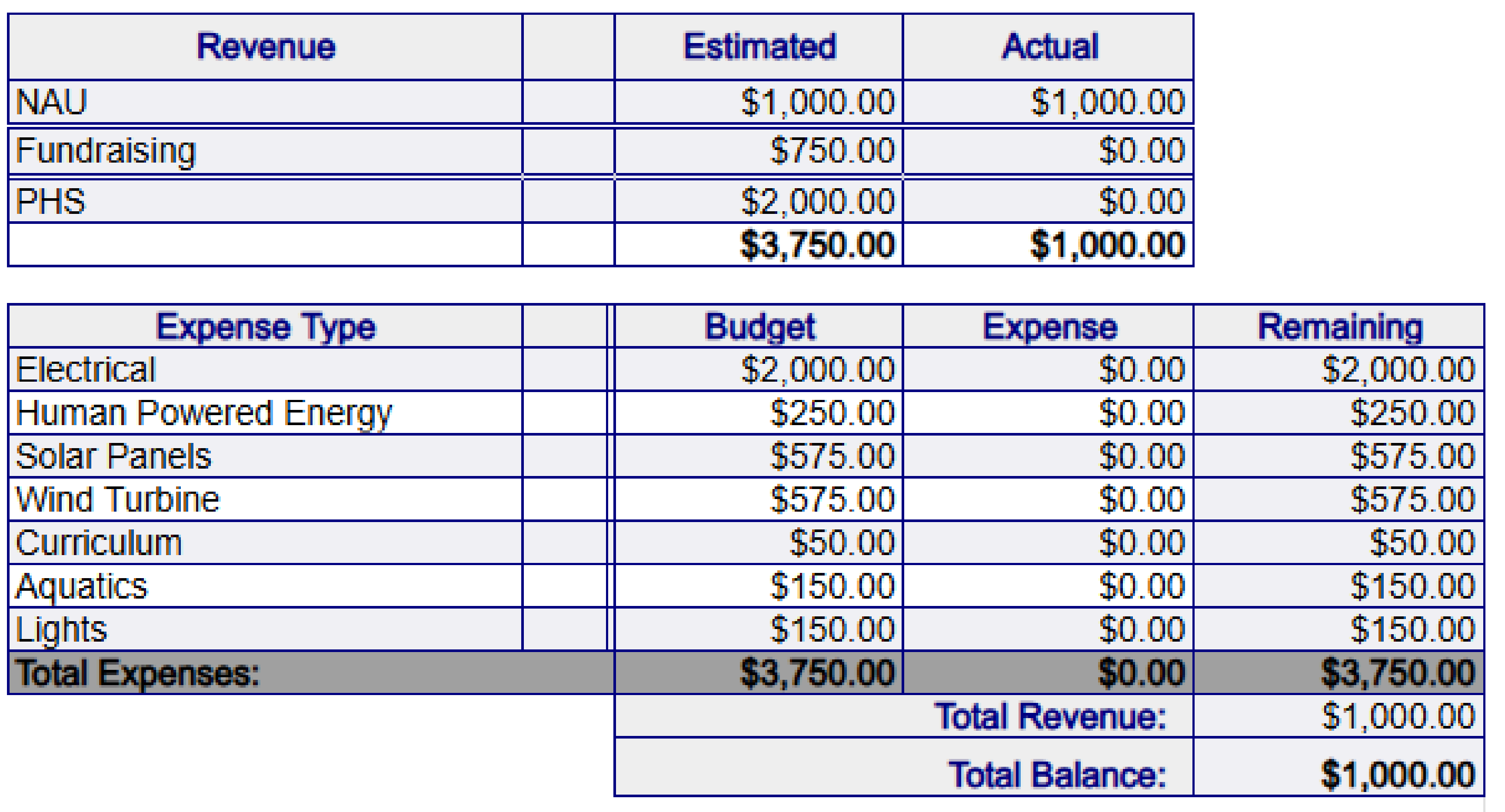
Constants

- Recreational pedaling cadence (ω) 50 to 70 RPM [1]
- Standard Bicycle Crank Length (r) 170 mm
- Avg. Tangential Pedal Force (F) 200 N [1]
- Alternator Efficiency (η_{alt}) 70% [6]
- Drivetrain Efficiency (η_{drive}) 96% [1]

Equations

- $\omega\,[\frac{rad}{sec}] = (\omega \frac{rev}{min})(2\pi \frac{rad}{rev})/(60 \frac{sec}{min})$
- $\tau\,[N * m] = Fr$
- $P_{mech}\,[W] = \tau\omega$
- $P\,[W] = P_{mech}\,\eta_{alt}\eta_{drive}$

PHS Sustainability Budget

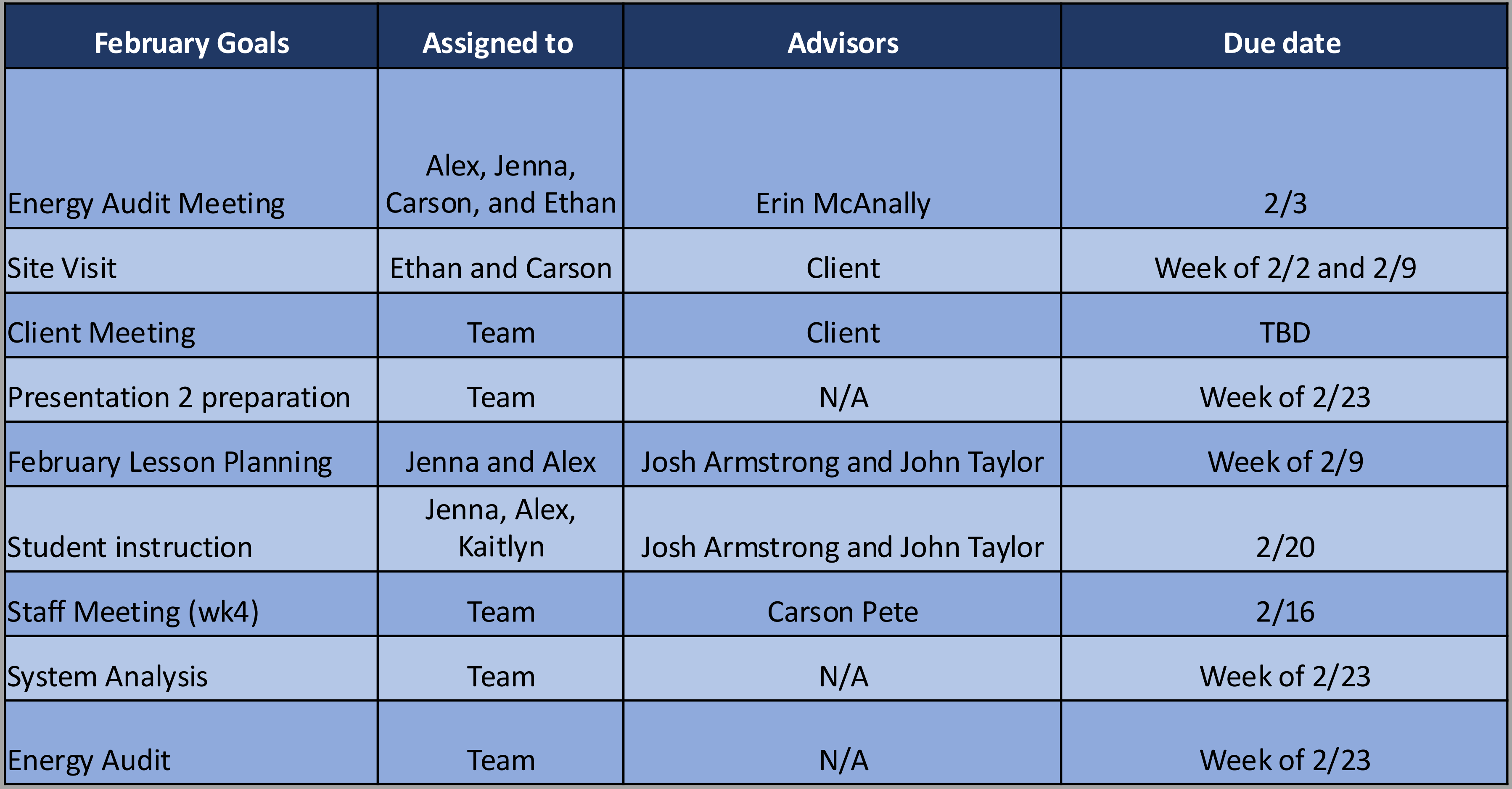


Revenue		Estimated	Actual
NAU		$1,000.00	$1,000.00
Fundraising		$750.00	$0.00
PHS		$2,000.00	$0.00
		$3,750.00	**$1,000.00**

Expense Type		Budget	Expense	Remaining
Electrical		$2,000.00	$0.00	$2,000.00
Human Powered Energy		$250.00	$0.00	$250.00
Solar Panels		$575.00	$0.00	$575.00
Wind Turbine		$575.00	$0.00	$575.00
Curriculum		$50.00	$0.00	$50.00
Aquatics		$150.00	$0.00	$150.00
Lights		$150.00	$0.00	$150.00
Total Expenses:		**$3,750.00**	**$0.00**	**$3,750.00**
			Total Revenue:	$1,000.00
			Total Balance:	**$1,000.00**

Table 1. PHS Sustainability Budget

Schedule



February Goals	Assigned to	Advisors	Due date
Energy Audit Meeting	Alex, Jenna, Carson, and Ethan	Erin McAnally	2/3
Site Visit	Ethan and Carson	Client	Week of 2/2 and 2/9
Client Meeting	Team	Client	TBD
Presentation 2 preparation	Team	N/A	Week of 2/23
February Lesson Planning	Jenna and Alex	Josh Armstrong and John Taylor	Week of 2/9
Student instruction	Jenna, Alex, Kaitlyn	Josh Armstrong and John Taylor	2/20
Staff Meeting (wk4)	Team	Carson Pete	2/16
System Analysis	Team	N/A	Week of 2/23
Energy Audit	Team	N/A	Week of 2/23

Table 2. February PHS Sustainability Schedule

References

[1] Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: Theory, design and Application* (Second). Wiley.

[2] Schmitz, S. (2020). Aerodynamics of wind turbines: A Physical Basis for Analysis and Design. John Wiley & Sons.

[3] Shahbazi, R., Kouravand, S., & Hassan-Beygi, R. (2023). Analysis of wind turbine usage in greenhouses: wind resource assessment, distributed generation of electricity and environmental protection. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(3), 7846–7866.

[4] Baxevanou, C., Fidaros, D., Papaioannou, C., & Katsoulas, N. (2023). Design and optimization of a hybrid solar–wind power generation system for greenhouses. Horticulturae, 9(2), 181

[5] Dammeier, L. C., Loriaux, J. M., Steinmann, Z. J., Smits, D. A., Wijnant, I. L., van den Hurk, B., & Huijbregts, M. A. (2019). Space, time, and size dependencies of greenhouse gas payback times of wind turbines in Northwestern Europe. Environmental Science & Technology, 53(15), 9289–9297.

[6] 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.gloei.2025.05.008

[7] 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.

[8] 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.

[9] 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.

[10] Arzu Sencan Sahin, *Modeling and Optimization of Renewable Energy Systems*. IntechOpen, 2012. doi: 10.5772/2283.

[11] “SunCalc sun position- und sun phases calculator,” *Suncalc.org*, 2026. Available: https://www.suncalc.org/#/35.2097.

[12] 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/64292612858285d87c84ddf9356769888060a76574fb3fd5f6cb13d664cc6363.

[13] 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

[14] P. Kandaswamy, *Agricultural Engineering : A Practical Manual*, First edition. New Delhi: New India Publishing Agency, 2020, pp. 151-173

References cont.

[15] 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.

[16] N. Faires, “Top 10 Greenhouse Gardening Mistakes,” *Eartheasy Guides & Articles*, Jun. 02, 2017.

[17] K. Nemali, “Horticulture and Landscape Architecture Temperature Control in Greenhouses,” Purdue University, Feb. 2021.

[18] Engineering Toolbox, “Thermal Conductivity of common Materials and Gases,” *Engineeringtoolbox.com*, 2003. Available: https://www.engineeringtoolbox.com/thermal-conductivity-d429.html

[19] A. Center, Stand-alone Photovoltaic Systems. 1995.

[20] National Renewable Energy Laboratory, “PVWatts Calculator,” pvwatts.nrel.gov. https://pvwatts.nrel.gov/

[21] NABCEP PV Certification Study Guide, 8th ed. NABCEP, Clifton Park, NY, 2019.

[22] R. Arshad, S. Tariq, M. U. Niaz and M. Jamil, "Improvement in solar panel efficiency using solar concentration by simple mirrors and by cooling," 2014 International Conference on Robotics and Emerging Allied Technologies in Engineering (iCREATE), Islamabad, Pakistan, 2014, pp. 292-295, doi: 10.1109/iCREATE.2014.6828382. keywords: {Cooling;Mirrors;Photovoltaic cells;Photovoltaic systems;Sun;Efficiency improvement;passive cooling;simple mirrors;concentrated photovoltaic;four sun technology},

[23] C. Sharma and A. Jain, “Simulink Based Multi Variable Solar Panel Modeling,” TELKOMNIKA Indonesian Journal of Electrical Engineering, vol. 12, no. 8, Aug. 2014, doi: https://doi.org/10.11591/telkomnika.v12i8.6044.

[24] J. Sunil, B. Priyan, L. Anish, A. Muthuvel, and T. Daniel, *BICYCLE POWER GENERATION AND ITS FEASIBILITY*. 2015.

[25] F. Rowland. Whitt and D. G. Wilson, *Bicycling science*, 2nd ed. Cambridge, Mass: MIT Press, 1982.

[26] Q. Ding, J. Yang, and W. Cui, “Converting Human Power into Electricity: Current Status and Future Directions,” *Preprints*, Nov. 2023, doi: 10.20944/preprints202311.0179.v1.

[27] Y. Yang, J. Yeo, and S. Priya, “Harvesting Energy from the Counterbalancing (Weaving) Movement in Bicycle Riding,” *Sensors*, vol. 12, no. 8, pp. 10248–10258, 2012, doi: 10.3390/s120810248.

[28] M. Carbajales-Dale and B. Douglass, “Human-Powered Electricity Generation as a Renewable Resource,” *BioPhysical Economics and Resource Quality*, vol. 3, no. 1, Mar. 2018, doi: 10.1007/s41247-018-0036-5.

[29] R. K. Megalingam, P. S. Veliyara, R. M. Prabhu, R. Katoch, and others, “Pedal power generation,” *International Journal of Applied Engineering Research*, vol. 7, no. 11, pp. 699–704, 2012.

THANK YOU

Any Questions?