MEGN 301 Fall 2025
Final Report

Arael Anaya, Tyler Long, Jordan Rivera-Escalera, Connor Shepard
Team: Decepticons, B1
Dr. Jeffrey “Chef Jeff” “The Man” Ackerman

Introduction

According to the Washington Post [1], there are currently 1.3 billion people in the world without access to electricity, as shown in Figure 1. This lack of power constrains their daily lives, forcing them to rely solely on natural daylight or purchase costly alternatives such as fossil fuels. Many of these people live in lower socioeconomic areas where the infrastructure is not built to support communities with electricity. One alternative to purchasing power or building infrastructure is to use one's own mechanical power to provide electricity. While there are many products that allow this transfer of energy to happen, they can range from $300-$500, which exceeds the price range of many potential customers.

To aid in solving this problem, this project was developed to design and build a portable mechanical generator that converts mechanical cranking power to usable electrical power. To create a solution that would provide additional value to the current generator market while maintaining feasibility, several constraints and goals were identified. The team was constrained within a $230 budget, 384 hours of in-class time, a maximum weight of 15 pounds, and a volume that would allow it to fit into a backpack.

The main objectives of this project were to continuously generate at least 5W of DC power to charge a phone and generate enough power in one minute to use a 1W LED bulb for at least 5 minutes. Additionally, it needed to include a custom UI that displayed instantaneous current and power, a custom transmission, and an ergonomic design that allowed the user to comfortably pedal without the housing slipping or the gears jamming.

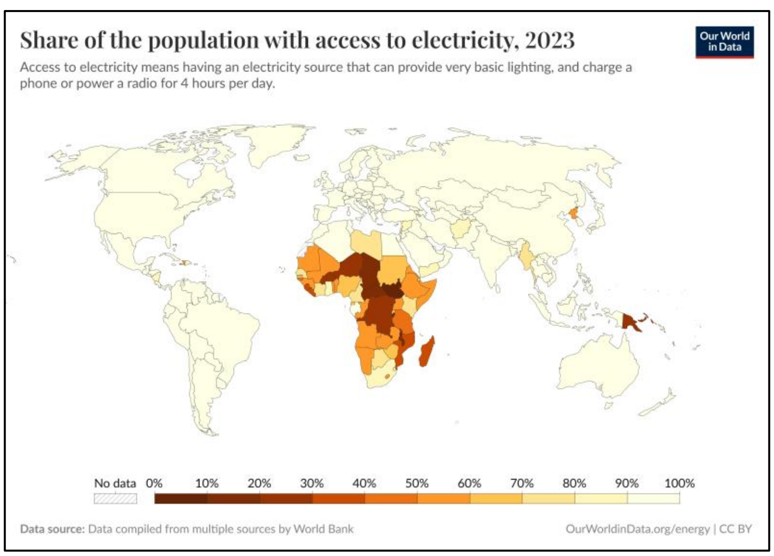

Figure 1: Share of Population with Access to Electricity [2]

Design Selection

There were four designs that were initially considered for the project. These included a pedal transmission connected to a custom axial-flux alternator (Figure 2), a hand crank transmission connected to a custom alternator (Figure 3), a swinging mass connected to a motor (Figure 4), and a water wheel connected to a motor (Figure 5).

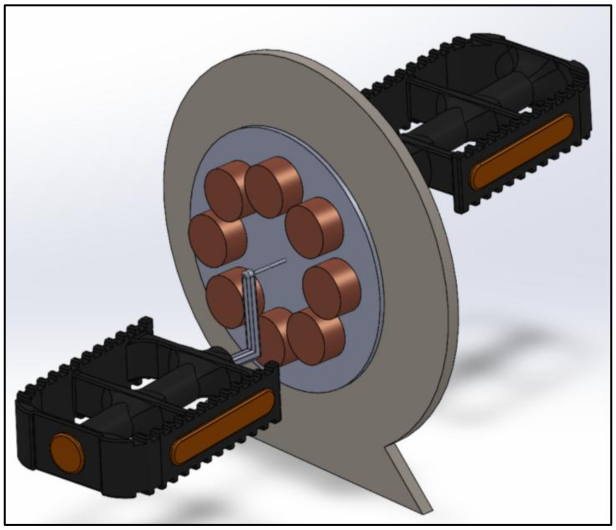

Figure 2: Pedal Alternator Concept

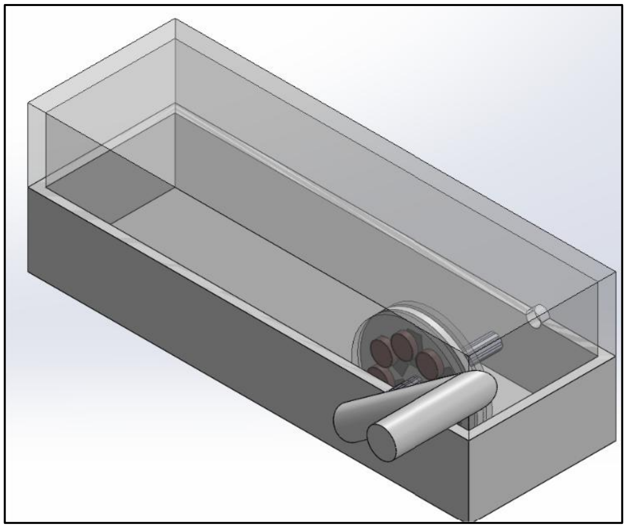

Figure 3: Hand Crank Alternator Concept

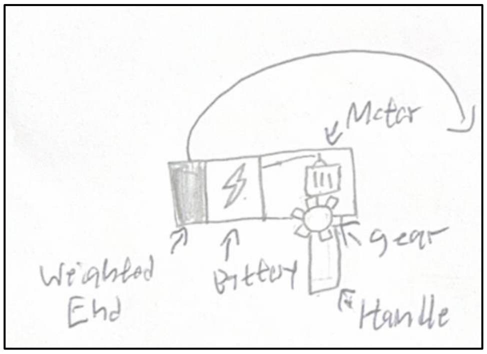

Figure 4: Swing Generator Concept

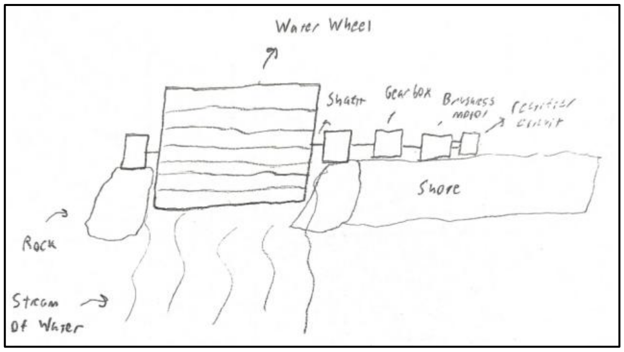

Figure 5: Water Wheel Generator Concept

These design concepts were then evaluated through an alternate solution analysis (ASA) table to compare how well each solution would fulfill required and desired design metrics (see Table 1).

Statement of Purpose: Use numerical analysis to select the best solution to the problem proposed										
Evaluation Criteria	**Required Criteria**		**Alt 1: Pedal Alternator**	**Yes / No**	**Alt 2: Cranker**	**Yes / No**	**Alt 3: David vs. Goliath**	**Yes / No**	**Alt 4: Water Wheel**	**Yes / No**
R1	Size			Yes		Yes		Yes		Yes
R2	Power Bulb			Yes		Yes		Yes		Yes
R3	Custom UI			Yes		Yes		Yes		Yes
R4	Charge Phone			Yes		Yes		Yes		Yes
	Desired Criteria	**Value**	**Score**	**Weight Score**	**Score**	**Weight Score**	**Score**	**Weight Score**	**Score**	**Weight Score**
D1	Ergonomic	9	10	90	7	63	5	45	10	90
D2	Cost / Manufacturability	8	5	40	7	56	5	40	4	32
D3	Durability	10	4	40	7	70	4	40	1	10
D4	Efficiency	6	9	54	6	36	5	30	5	30
D5	Enjoyable	3	10	30	5	15	10	30	10	30
D6	Asthetics	2	5	10	3	6	8	16	5	10
D7	Lightweight	3	2	6	8	24	8	24	10	30
	WEIGHTED TOTAL SCORES			270		270		225		232

Table 1: Generator Concept ASA Comparison Table

As Table 1 shows, each concept met the minimum requirements, so the team used the desired criteria to choose the final concept. The team gave weights to each of the 7 desired criteria. Each concept was then evaluated on how it would meet the desired criteria. After the scores were totaled, the concepts with the highest total scores were the hand crank and pedal alternator concepts. From these results, the team decided to advance by researching requirements for a generator powered by either cranking or pedaling with the final decision being based on the results of the power system analysis.

The power analysis calculated the power requirements needed to meet the required design parameters for flashlight and phone charging. See Tables 2 and 3 below for the required power and battery capacity requirements. Power analysis found that pedaling would provide significantly more power than cranking. This meant that going with a pedal design would make it more likely for the generator to meet the power requirements and that the required efficiency for the alternator or motor would be reduced (see Figure 6 to fo cranking power and efficiency calculations).

	Voltage (V)	Current (mA)	Power (W)	Energy (Wh)
LED	3.7	350	1.295	0.27
Charger	5	1000	5	0.833

Table 2: Power Analysis

	Minimum battery capacity (mAh)	Max. Required charging power (W)
Battery	91.416	16.2

Table 3: Battery Charging Requirements

$$P_{crank} := 30\ W \qquad P_{pedal} := 100\ W$$

$$E_{LED} := 0.27\ W \cdot hr$$

$$P_e := 10\ W \qquad P_{LED\_charge} := \frac{E_{LED}}{1\ min} = 16.2\ W$$

$$Eff_{crank} := \frac{P_{LED\_charge}}{P_{crank}} = 0.54 \qquad Eff_{pedal} := \frac{P_{LED\_charge}}{P_{pedal}} = 0.162$$

Figure 6: Input and Required Power Calculations

To verify that the initial model for the housing was strong enough to handle the forces during pedaling, FEA analysis was performed in SolidWorks Simulation. The results of this simulation can be found in Figure 7 below. The simulation resulted in a maximum von Mises stress of 19 MPa. With a yield strength of 250 MPa for the A36 steel housing material, this resulted in a factor of safety of ~13, which validated that the initial base design would be more than capable of withstanding forces during pedaling.

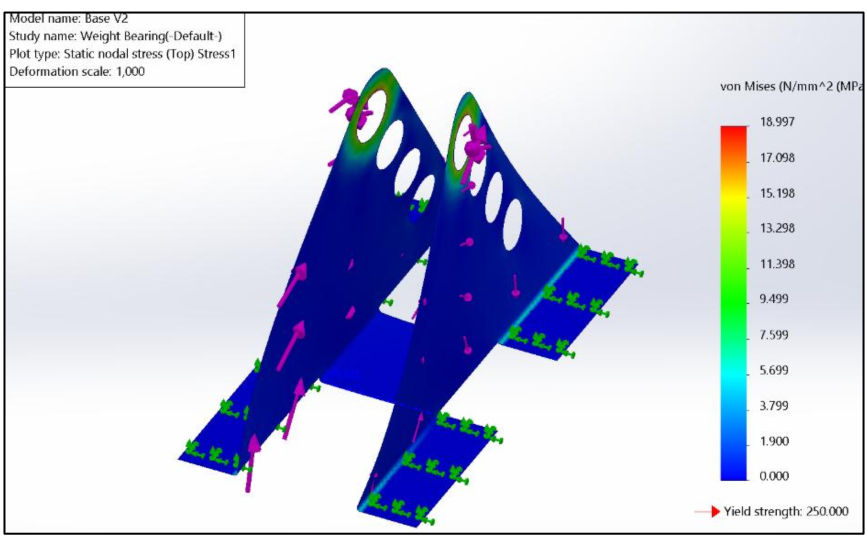

Figure 7: Initial Base Design FEA Von Mises Stress Plot

Ultimately, this process provided the team with a quantitative method to select a design that would best meet the requirements and desired qualities. After selecting the pedal design, the team continued further developing this idea.

Initial Prototype Development

The initial prototype concept was composed of pedals that turn a gearbox attached to a custom alternator. The transmission was composed of standard and compound herringbone gears to achieve a gear ratio of 1:100. Since a custom alternator was being designed, the optimal gear ratio would have to be found through unique power and efficiency testing. This initial gear ratio was set higher with the proactive goal of providing more RPMs than needed to meet the required power. This would allow the team to develop strong skills in creating gearboxes while providing high enough RPMs to get the required power out of a less efficient alternator. It would also allow the team to quickly pivot to a lower gear ratio with confidence if the custom alternator required lower speed or needed to be replaced with a motor. See Figure 8 for the initial CAD assembly of the alternator, base, and circuit housing design.

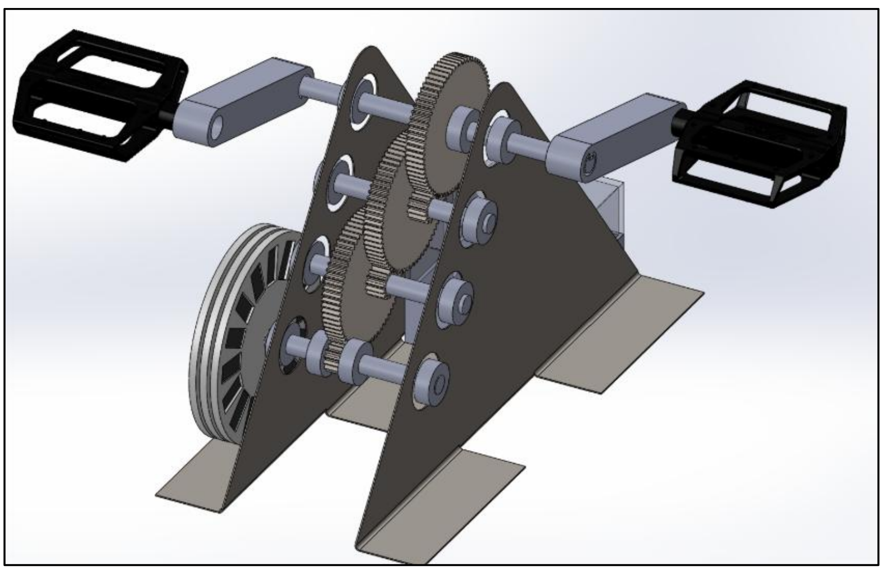

Figure 8: Initial Generator SolidWorks Assembly

To ensure that a 3D printed transmission would be able to carry pedaling forces without shearing, a 1:100 transmission was built with gears, housing, and shafts made from 3D printed PLA plastic. Due to the high input torque, many components were failing due to slipping, bending the shafts, or shearing the shafts. To rapidly prototype, the group experimented with different infill percentages on keyed shafts which allowed them to withstand the input torque required to rotate the system. After iterating gear type and configuration, the transmission was assembled, composed of two herringbone and two compound herringbone gears. See Figure 9 for the prototype transmission.

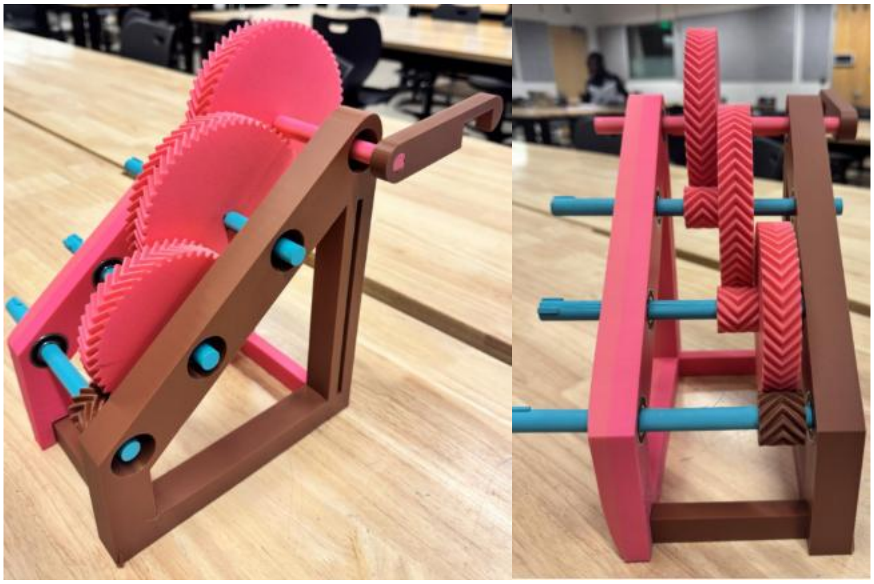

Figure 9: 1:100 3D-Printed Proof-of-Concept Transmission

After testing the transmission, it was found that the required input torque was too high for comfortable pedaling. Despite the high torque required, none of the 3D printed gears failed which validated that the gears would be able to function without switching to a stronger material. The first plastic shaft in the gearbox showed signs of fatigue after a small amount of use, so the decision was made to have the initial shaft be made of steel for the final prototype.

The initial alternator prototype consisted of a stator housing with eight 200-turn coils of enameled copper wire between two rotors with 16 N52 neodymium magnets of alternating polarities. The coils were then wired to a full bridge rectifier and a bank of high voltage electrolytic capacitors to convert the AC output of the alternator to smooth DC current.

Prototype Testing

After creating a 1:25 transmission gearbox, the team attached it to the custom alternator and tested how much power the system could create. See Figure 10 for testing setup and Table 4 for results.

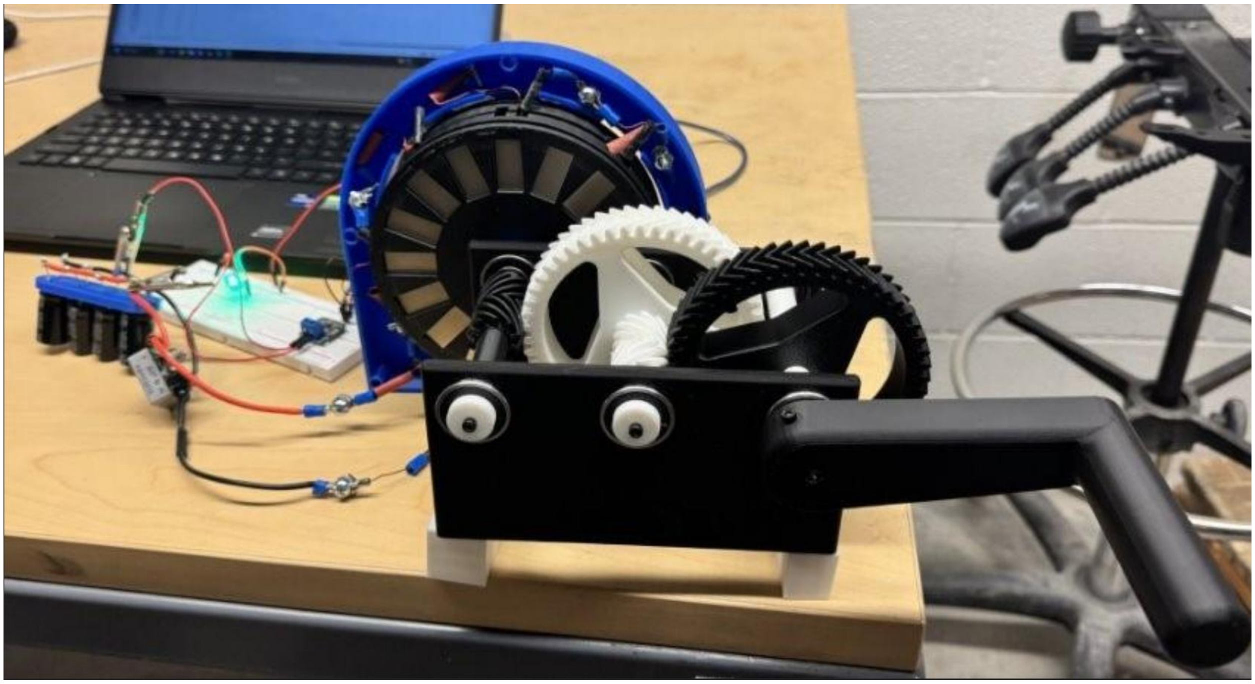

Figure 10: 1:25 Transmission and Alternator Integration

Alternator Output	Max Measured Value	Max RPM while measuring
Max Output Voltage (V)	22.95 V	225
Current w/ Load (mA)	12.98 mA	225
Output Power (W)	0.3 W	225

Table 4: Alternator Power Analysis

While testing, the custom alternator was able to power a small LED, but not enough to charge the light bulb purchased for the final prototype. Because of this, the team quickly pivoted to back driving a Nema 23 stepper motor. To continue to make progress on the overall project, subsystems were tested individually to verify if their requirements were met.

As shown in Video 1, the housing/gearbox subsystem was tested individually to ensure the gears withstood high RPMs that would be experienced by a user pedaling the system for an extended period of time. To account for the fact that the system was disconnected from the electrical load, a larger gear ratio of 1:100 was tested to verify if the gears or housing would fatigue. The video below shows the prototype that was tested to ensure the gear ratio was correct, and the PLA gears and housing would withstand the required forces. This test passed because the gear ratio was met and the PLA gears showed no fatigue after testing.

Video 1: Gearbox/Housing Testing

The Nema 23 motor was also tested individually with a faulty transmission. The results of Figure 11 showed that at low speed, 1/10 of the angular velocity that would be used with the final prototype, the system could easily produce around 1.5 Watts. The team then determined that this power would be much greater when pedaled at a faster speed, so the Nema 23 was verified to meet the power requirements.

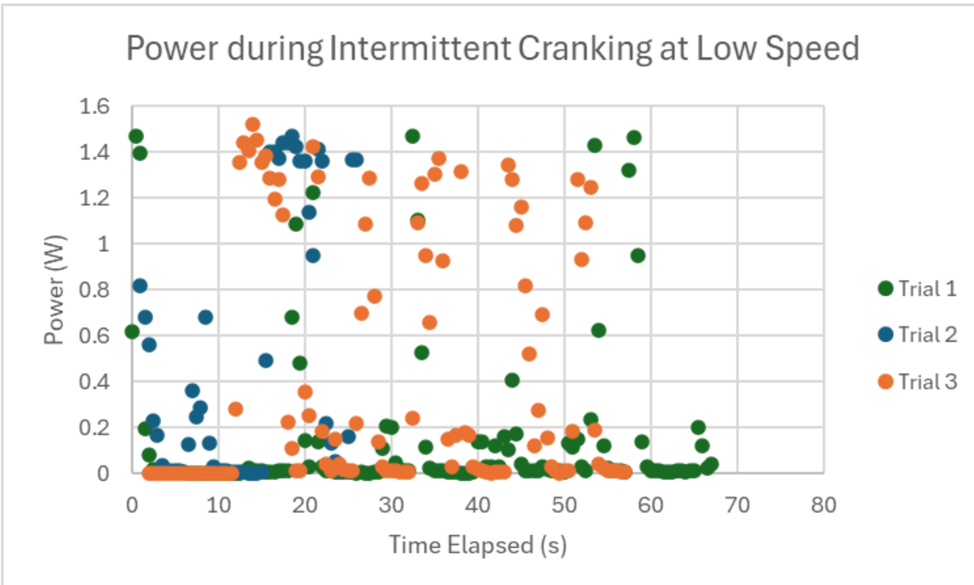

Figure 11: Power Produced with a Faulty Transmission with Low Intermittent Cranking.

Since the alternator design could not provide sufficient power for the flashlight battery charging goal, a DC power supply capable of supplying the minimum required charging power (5 W) was used with the lithium-ion charging module to test the capability of the charging circuit. After one minute of charging, the battery was connected to a 1W lightbulb and successfully powered the bulb for over five minutes. This test demonstrated that the charging circuit was capable of powering the bulb for the required time.

After verifying that each individual subsystem met their requirements, the housing was quickly reprinted to incorporate each new subsystem. Overall, this testing phase provided valuable insight on the progress of the project and a warning to quickly pivot.

Prototype Refinement

After deciding to pivot from the alternator design, the team quickly remodeled and 3D printed a bare-bones prototype to validate that the Nema 23 stepper motor would produce enough power. When this motor was integrated with the other subsystems, in Figure 12, it was found that at least 25 Watts of power were produced which burnt out the shunt resistor of an INA219 power measuring module.

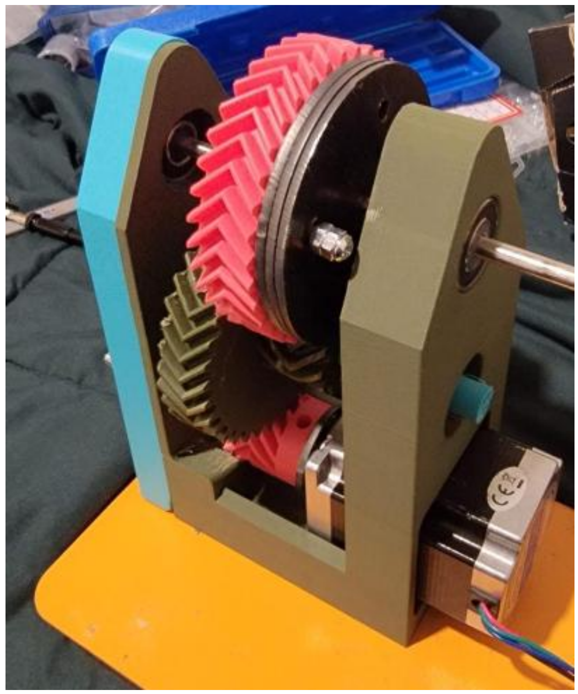

Figure 12: First Full Prototype with Nema 23

However, there were still a couple of key issues the team had to address for the final prototype. The d-shaft that was ordered had a small d that would shear through plasma cut steel brackets. The pedals had still not been implemented into the system. Additionally, Newton's 3rd law had still not been addressed, meaning that the prototype would slide when forces were applied to rotate the gears.

To address the problems with the d-shaft, the team first attempted adding multiple brackets to prevent the shaft from shearing through them. While this was working, the team decided to purchase an 8" carriage bolt to replace this. Pedals were also acquired and press fit into the crank shaft. These two changes led to the prototype tested in Video 2.

Video 2: Integrated Working Prototype

As seen in Video 2, this prototype was successful in integrating the mechanical and electrical subsystems. The final changes left were to print the finalized housing, which would hold the user interface and prevent the system from slipping, and to choose the final components for the circuitry.

To prevent the system from slipping, adhesive rubber pads were purchased. These were integrated in the final prototype, increasing the maximum static friction between the generator and the table or floor, which resulted in no unintended movement of the system during pedaling, as defined in the project objectives. As for the components, an ACS712 was chosen over the INA219 over a much higher current limit.

Final Prototype

The final prototype, shown in Figure 13, is powered by a Nema 23 stepper motor back driven by a 1:9 gear ratio. The two-phase AC output is then converted to DC power through two full bridge rectifiers, which then goes through a bank of high voltage electrolytic capacitors to ensure a smooth output. The final prototype includes a user interface that displays the power and current generated during pedaling on an LCD screen which is powered by an Arduino UNO. The Arduino is powered by the buck converter which outputs a continuous 5V at a varying current that is dependent on the user. The prototype features a removable flashlight and phone charger which allows the user to carry around the flashlight without needing to move the entire generator. This design also allows the generator to better fit in a backpack for transport by removing one of the pedals. The detachable flashlight includes a charging board that powers two 18650 lithium-ion batteries when the flashlight is attached to the generator. This board also functions as an uninterruptible power supply, so if it receives power from the generator while a phone or lightbulb is connected, current will bypass the battery and go directly to the load being powered. The complete circuit diagram for the final prototype can be found in Figure 14 below.

Figure 13: Final Prototype

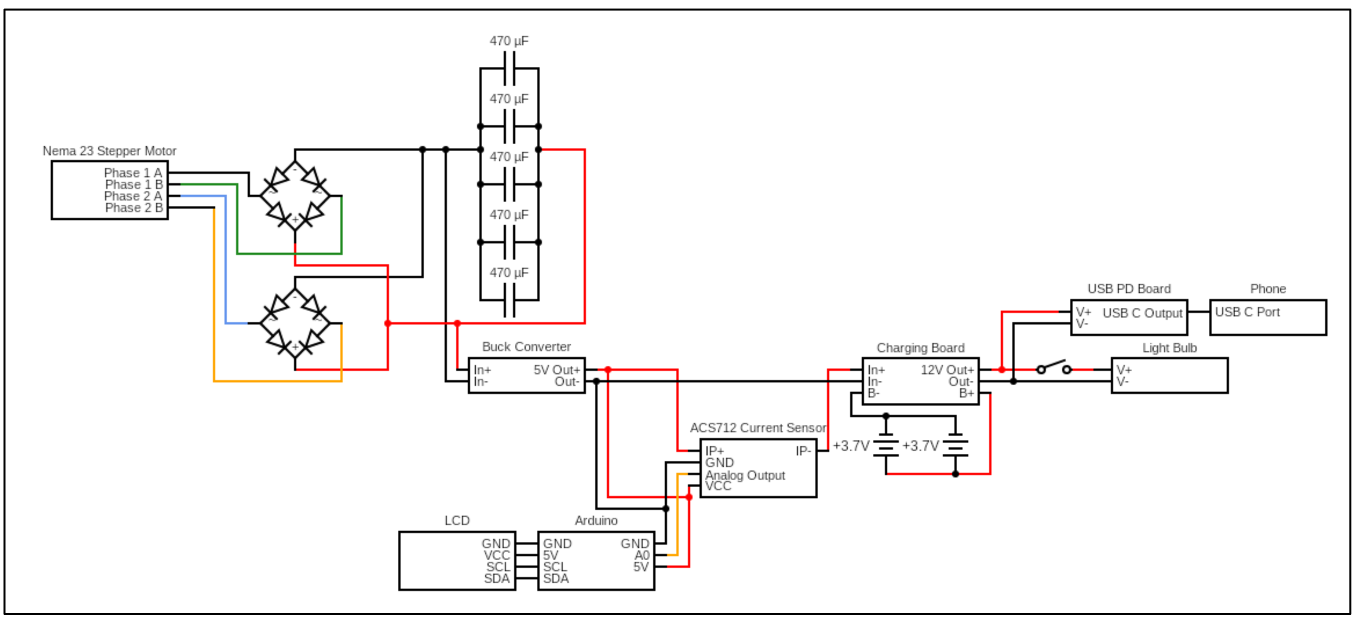

Figure 14: Final Prototype Circuit Diagram

Video 3: Final Prototype Presentation

Video 3 above leads to a link to the presentation. This presentation demonstrates the system functioning and meeting all of the project goals.

Design Goal	Met?
Continuous flow of 5W of power to charge a phone	Yes
Charges a light bulb for 1 minute after 5 minutes of pedaling	Yes
User interface displaying current and power	Yes
Custom Transmission	Yes
Ergonomic design allowing user to pedal comfortably with no slippage or binding	Yes

Table 5: Design Goal Completion

Constraint	Met?
Weigh less than 15 lb	Yes
Fit into a backpack	Yes
Under $230	Yes
384 in-class hours	Yes

Table 6: Design Constraints Met

Tables 5 and 6 show the original constraints of the project and the goals it sought to achieve. The video link above shows the presentation of the final prototype. This video shows that the project fell within each of the constraints and met all the design goals. Ultimately, the group's goal of creating an affordable power generator was met by designing and manufacturing a system that could output the required power for $212.23 (BOM can be seen in Table 8 of the "Additional Work" section below).

Additional Work

Group Number: B1

Part	Description	Total Weight	Unit Cost	Shipping Cost	Quantity	Total Cost	Link to part
Transmission							
PLA	Material for the housing		$14.44	$0.00	1	$14.44	https://www.amazon.com/eSUI
Full Bridge Rectifier	Rectifier to convert motor output from AC->DC	1.41 oz	$5.99	$0.00	1	$5.99	https://a.co/d/amVmw5D
1/2 in Bearings	Bearings for housing	1.2 oz	$7.99	$0.00	1	$7.99	https://a.co/d/2TRUn24
Capacitors	High voltage capacitors to smooth out the rectifier output	0.83 oz	$6.99	$0.00	1	$6.99	https://a.co/d/5oV8HBH
Buck converters	Adjustable DC voltage	1.76 oz	7.99	0	1	$7.99	https://www.amazon.com/JTAR
Rubber feet	These are used to stop the hosuing from slipping	0.1 oz	$9.99	$0.00	1	$9.99	https://a.co/d/eYWHTkk
Flashlight Battery System							
Toggle Switch	Switch to turn light bulb on and off	2 oz	$9.99	$0.00	1	$9.99	https://a.co/d/0KjaVxK
JST connector	Connector to quickly connect and disconnect the flashlight from the transmission system	1.37 oz	$5.99	$0.00	1	$5.99	https://a.co/d/7raXkXx
Light bulb	A low voltage lightbulb to emit light	0.9 oz	$15.55	$0.00	1	$15.55	https://a.co/d/c5KFnK9
Ceramic medium light socket	Socket to insert light bulb into the power it	1.1 oz	$9.36	$0.00	1	$9.36	https://a.co/d/dOWPfAU
Unneeded Components							
Enameled Copper Wire	Wire for Alternator	1lb	26.99	0	1	$25.99	https://www.amazon.com/Emt
USB C PD Modules	For phone charging w/ adjustable output voltage/current	1.13 oz	$8.99	$0.00	1	$8.99	https://www.amazon.com/AITR
Buck converter	Buck converter that could not handle the power	1.76 oz	7.99	0	1	$7.99	https://www.amazon.com/JTAR
Magnets	Magnets for Alternator	5.61 oz	$22.79	0	1	$23.99	https://www.amazon.com/dp/E
Bearings	Extra bearings	TBD	7.99	0	1	$7.99	https://www.amazon.com/DEE
18650 Lithium Battery Charging Modules	Did not charge enought	0.01 Kg	$5.69	$0.00	1	$5.69	https://www.amazon.com/WSD
1/4" D Shaft Steel	Key on shaft was too small and it would shear plasma cut components		$8.49	$5.19	1	$13.68	https://www.servocity.com/0-2
1/4" Bearings	Did not need 1/4" D shaft		$9.49	$0.00	1	$9.49	https://www.amazon.com/FR16
1/4" Bearings	Bearings for transmission Shaft		$8.99	$0.00	1	$8.99	https://www.amazon.com/uxce
Shaft Collar	Not used due to time constraints		$7.99	$5.19	2	$21.17	https://www.servocity.com/131
Rubber tape	Rubber tape not used due to rubber feet being adequate		$9.29	$0.00	1	$9.29	https://www.amazon.com/Adh
					Total $ Spent:	$228.25	

Table 7: Prototype BOM

Table 7 shows the BOM for prototyping this semester. This includes all components that were purchased when developing the project throughout the course of the semester, regardless of if they were used in the final prototype. The final prototype cost $228.25. The team received the Nema 23 motor for free along with access to sheet metal and the plasma cutter.

Part	Description	Total Weight	Unit Cost	Shipping Cost	Quantity	Total Cost	Link to part
Transmission							
Nema 23 Stepper Motor	Back driving motor to create power	2.65 lb	$23.67	$15.00	1	$38.67	https://tinyurl.com/y5hestx9
Sunlu PLA+	PLA to create circuit housing and main transmission housing	4.85 lb	$13.99	$0.00	1	$13.99	Amazon.com: SUNLU PLA 3D Pr
1/2 in. x 3 ft. Zinc Plated Steel Threaded Rod	Threaded rod for structural housing stability	2.1 lb	$8.72	$0.00	1	$8.72	https://tinyurl.com/4r2jt6d3
Full Bridge Rectifier	Rectifier to convert motor output from AC->DC	1.41 oz	$5.99	$0.00	1	$5.99	https://a.co/d/amVmw5D
1/2 in Bearings	Bearings for housing	1.2 oz	$7.99	$0.00	1	$7.99	https://a.co/d/2TRUn24
Capacitors	High voltage capacitors to smooth out the rectifier output	0.83 oz	$6.99	$0.00	1	$6.99	https://a.co/d/5oV8HBH
Buck Converter	A buck converter to take variable capacitor input into a steady 5 V output	2.46 oz	$12.99	$0.00	1	$12.99	https://a.co/d/dBn7DgS
1/8" A36 Sheet Metal	Srap sheet metal that was plasma cut and used for housing	3 lb	Free	$0.00	1	Free	
Rubber feet	These are used to stop the hosuousing from slipping	0.1 oz	$9.99	$0.00	1	$9.99	https://a.co/d/eYWHTkk
Pedals	Pedals used to turn the system	0.73 lb	$9.59	$0.00	1	$9.59	Amazon.com
Flashlight Battery System							
18650 Lithium ion Battery 2-pack	Batteries to store charge	3.5 oz	$12.98	$0.00	1	$12.98	https://a.co/d/4gKUNzv
Battery charging module	Module to charge the battery quickly and output 12V	0.7 oz	$12.99	$0.00	1	$12.99	https://a.co/d/iKxLm3X
Toggle Switch	Switch to turn light bulb on and off	2 oz	$9.99	$0.00	1	$9.99	https://a.co/d/0KjaVxK
JST connector	Connector to quickly connect and disconnect the flashlight from the transmission system	1.37 oz	$5.99	$0.00	1	$5.99	https://a.co/d/7raXkXx
Light bulb	A low voltage lightbulb to emit light	0.9 oz	$15.55	$0.00	1	$15.55	https://a.co/d/c5KFnK9
Ceramic medium light socket	Socket to insert light bulb into the power it	1.1 oz	$9.36	$0.00	1	$9.36	https://a.co/d/dOWPfAU
User Interface							
I2C 1602 LCD Display Module	LCD to display power and current	5.29 oz	$9.99	$0.00	1	$9.99	https://a.co/d/5zHczNm
Arduino UNO	Arduino to power LCD and current module	1.2 oz	Free	$16.99	1	$16.99	Amazon.com: ELEGOO UNO
ACS712	Module to measure current going through the buck output into the battery system input	0.35 oz	$8.99	$0.00	1	$8.99	https://a.co/d/9u8I2ZH
					Total Cost:	$217.75	

Table 8: Production BOM

Table 8 shows how much the materials to manufacture the system would cost. This cost of $217.75 is lower than the prototype cost. This is because not all parts purchased during the prototyping process were utilized for the finalized prototype. Additionally, it includes parts that were purchased by the group. To provide a fair comparison to the prototype BOM, the labor required to produce the system was set equal to what the students were paid during the school year to manufacture the prototype, $0.

Finalized CAD Assembly

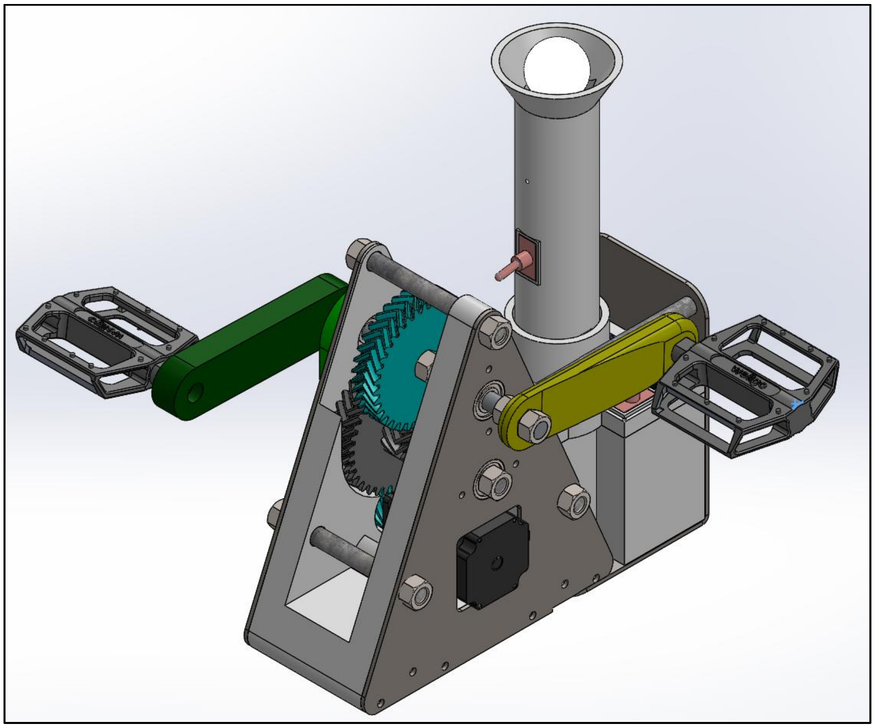

Figure 15: Finalized CAD Assembly Isometric View

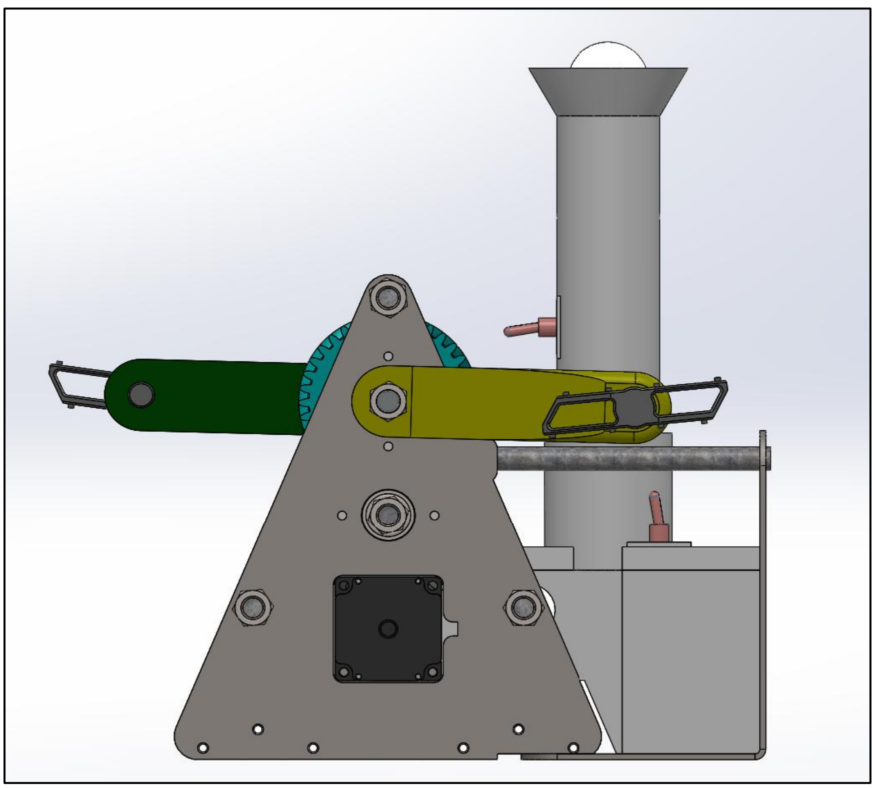

Figure 16: Finalized CAD Assembly Side View

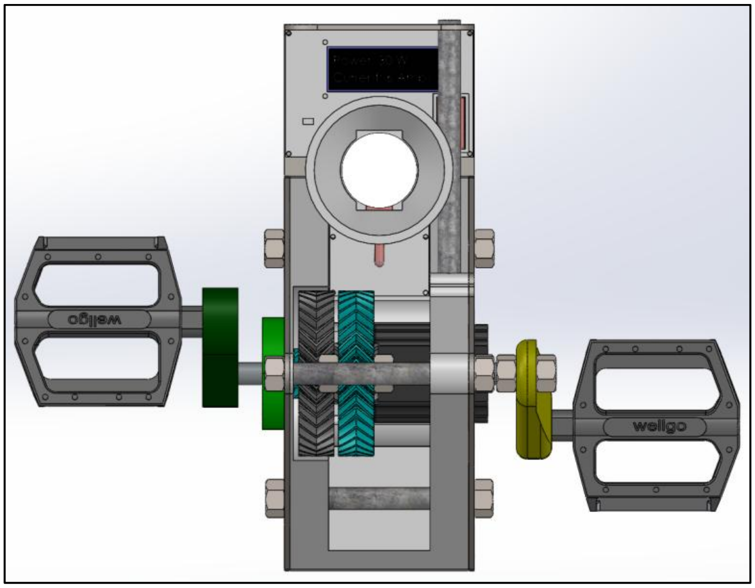

Figure 17: Finalized CAD Assembly Top View

Figures 15-17 show the finalized CAD assembly developed in SolidWorks. This was developed by creating models of each part that was implemented in the final prototype, applying material properties, and applying colors to provide an easy-to-understand visualization of how the CAD model represents the final prototype.

Video 4: [Assembly Motion Video]

Video 4 shows a SolidWorks motion study of the final CAD model.

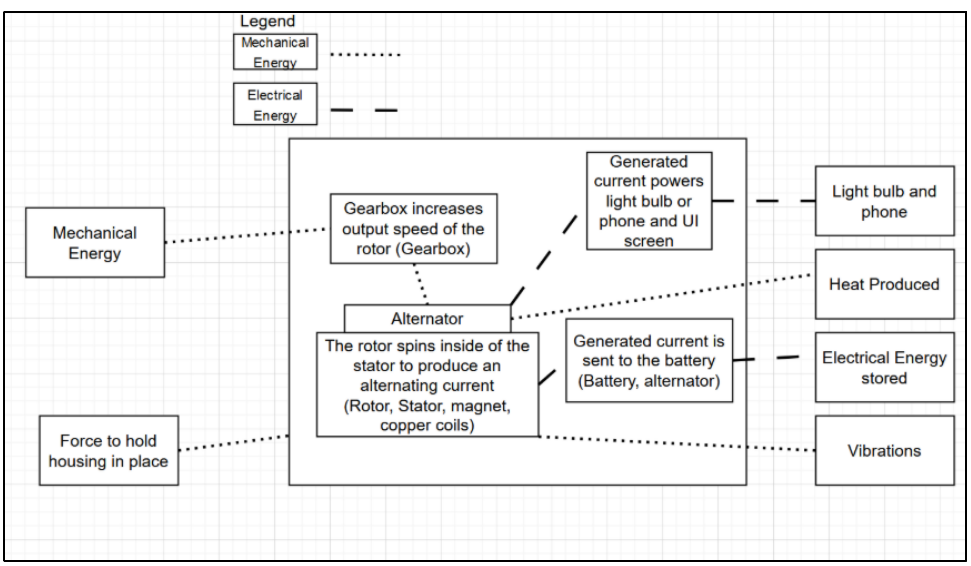

Figure 18: Glass Box Diagram

Figure 18 shows the glass box diagram for the system. This shows the inputs and outputs of the system which were defined from the beginning and helped the team to understand how the system needed to function.

Operating Instructions

1. Take the generator out of your backpack and place it on a solid surface.
2. (Foot Crank) Put back bracket against a wall.
3. (Foot Crank) Take a seat on a nearby object/chair.
4. Reassemble generator by threading the arm and nuts onto the threaded rod.
5. Place flashlight inside the flashlight slot and plug it into the JST connector.
6. (Optional) Turn on the user interface to display power output.
7. (Optional) Plug in a device into the USB C cable to charge it.
8. Spin the arms using your hands or feet to generate power.
9. After producing enough power for your needs, disconnect the JST connector.
10. Take flashlight out of slot.
11. Disassemble the generator by unthreading the arm and nuts off the threaded rod.
12. Place the generator into your backpack/storage area for later use.

Future Work

If the group had more time and money, the system would be changed in several ways to improve the user's experience. First, the system could be made safer. While the current prototype functions mechanically, the gearbox is exposed which could allow the user to pinch their finger if placed near the gearbox during operation. To prevent this, clear guards would be placed around the gearbox to prevent the user from being able to pinch their fingers. Second, the current system utilizes 3D printed gears to back-drive the motors. While the group had no problems with these gears fatiguing during this project, PLA gears will fatigue much quicker than steel gears. To ensure the customer only has to purchase the system once, the group would manufacture these gears out of steel if the budget was increased. Finally, the battery system can currently store 20 watt-hours, which is enough to run the flashlight for about 1200 minutes, but the system is limited by how quickly the batteries can charge. Since the system can only take a maximum of 2 amps, the system currently generates more energy than it can handle. To improve this, the system can be easily upgraded to include a charging module and batteries that are rated for higher maximum charging current to remove this bottleneck.

Implementing these changes would increase the safety, longevity, and charging speed of the system. These changes would create a more marketable product that could be sold easily for those who are seeking a mechanical generator.

Lessons

The team has learned several valuable lessons during this design process. First, the team gained a significant amount of experience quickly iterating to develop new prototypes. However, the team also learned the limits of 3D printing. Throughout this process, many prototypes were created to address issues related to 3D printed parts bending or shearing. Moving forward, the group will perform more material analysis on the front end. This will allow the group to make confident decisions regarding purchasing components, and lead to a quicker finalized product.

Second, the team learned the value of making difficult decisions in order to stick to a set schedule. For example, the group had identified a date that they wanted to have their subsystems integrated for successful testing. However, because the group pursued the idea of creating a custom alternator for the first ¾ of the semester, when the integrated subsystem did not perform properly, the group had minimal time to pivot. Moving forward, the group will define strict deadlines and stick to them, even if this means giving up ideas that could still possibly work. While it may occasionally leave the students unsatisfied, it will prepare them for their careers when they must deliver results within a set amount of time or face occupational repercussions.

Finally, the group learned the importance of thinking about the manufacturability of the system throughout the design process. While the group did end up with a final prototype that was easy to manufacture and assemble, many of the early CAD assemblies were created without the thought of how to actually produce the final system. This led to many learning opportunities which the group worked through. But, moving forward, the group will create the CAD models while actively thinking about the components that need to be purchased or manufactured to create the system, instead of taking advantage of CAD programs like SolidWorks.

Bibliography

[1] T. Lindeman, Without electricity, 1.3 billion are living in the dark - Washington Post, https://www.washingtonpost.com/graphics/world/world-without-power/ .

[2] H. Ritchie, P. Rosado, and M. Roser, “Access to energy,” Our World in Data, https://ourworldindata.org/energy-access .