MEMS 411: The Amazing Renewable Race

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THE AMAZING RENEWABLE RACE

The project’s goal was to convey the importance of renewable energy to a 6 through 12 years old audience. This demo was designed to be installed at the St. Louis Science Center. To engage a younger audience, the renewable energy demonstration had to be interactive. As a result, a design similar to a carnival game was chosen. There are 3 stations that represent wind, hydroelectric, and solar energy. In this design, it is a multiplayer interactive race that portrays renewable energy.

The initial design was to have each form of energy produced by the users. The user at the hydro station would push a water pump that would bring water to the top of a water wheel, causing it to spin and produce energy. The wind energy system would involve the user pushing a air pump, a bellow, to turn a wind turbine. The solar station was designed to have a light powered by a hand crank. That light would power a solar panel. All the the renewable energy produced would then move conveyor belts that are connected to each station.

Unfortunately, due to many issues in the design construction process, the final prototype performs differently than how it was initially designed. The wind station used a hand crank to power both the conveyor belt and the wind turbine. The hydro station was very similar. It used a hand crank to turn both the water wheel and that stations respective conveyor belt. The final solar station was most accurate to the initial design, but instead of using a solar panel, an LDR (Light Dependent Resistor) was introduced. This resistor closes the circuit when it detects light. We therefore had the hand crank powering LEDs and a battery powering the solar conveyor belt.

Overall, the demo successfully portrayed the concept of renewable energy to children and achieved 2 of our 3 prototype goals.

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1 Introduction

Many highly populated cities have educational science centers for young children and adults to learn the principles of STEM. With the technological projections of the 21st century, it is vital to keep the youth knowledgeable and excited about the future of energy. With climate change affecting everyday life, crop production, forest fires, natural disasters due to the buildup of greenhouse gases, renewable energy is necessary to cut back carbon emissions and save the only planet we have.

After interviewing an enthusiastic visitor of the St. Louis Science Center, Dr. Potter, it was evident that there is an opportunity for a fun and innovative interactive experience to educate a new generation of creators. We used this interview to hone our idea of a Renewable Energy Demo, a thrilling demonstration of renewable energy sources. The current science center energy exhibit is an underwhelming experience that failed to convey the concepts of energy in a manner inclusive to all educational levels. Therefore, our Renewable Energy Demo for the St. Louis Science Center is a device that uses an arcade format to illustrate the engineering power of solar, wind, and hydroelectric renewable energy sources. We hope that this exhibit can communicate the principles of renewable energy in an interactive and invigorating format to children and future generations.

2 Problem Understanding

2.1 Existing Devices

Now that the renewable energy device for the St. Louis Science Center has been introduced, it is important to distinguish the proposed device from already existing devices.

2.1.1 Existing Device #1: St. Louis Science Center Existing Renewable Energy Exhibit

![Figure 1: St. Louis Science Center Existing Renewable Energy Exhibit (Source: Family blog of St. Louis Science Center)](image-url)
Description: The existing renewable energy exhibit in the St. Louis Science Center contains two systems to represent solar and wind energy. The existing exhibit compares the energy output of each system with a voltage meter. The exhibit also displays simple energy equations, making it seem as if it is intended for children above the age of 10. The interactive portion of the exhibit is limited. For the solar energy portion, it is simply raising a light bulb in a similar pattern to the rising and setting of the sun. For the wind energy portion of the exhibit, the interactive portion is limited to changing the airfoils on a small windmill.

2.1.2 Existing Device #2: Horse Racing Carnival Game

![Horse Racing Carnival Game](https://letspartysalinas.com/rental/roll-a-ball-horse-racing-carnival-game/)

Description: This race horse carnival game is a multiplayer competition game where players roll balls into a hole to advance their character further in the race. This game is electronic based where a different hole will indicate a different set amount of "steps" to the moving figurine. Once the race is over, the figurines will reset so a new game can begin. All figurines run on the same energy source (wall outlet).
2.1.3 Existing Device #3: Carnival Duck Race

Figure 3: Duck Race Carnival Game

Link: https://www.youtube.com/watch?v=tYK5yKAKN1k

Description: The Carnival Duck Race is a multiplayer competition game. The ducks are placed at the top of a declining trough. At the top of the trough, a manual lever water pump is then used to push water from a bucket below to the top of the trough. The pumped water then carries the ducks to the end of the trough.

2.2 Patents

The following are two patents of existing device that are related to the design of our Renewable Energy Demo.

2.2.1 Traditional Hand-Operated Water Pump (EP2508682A2)

This patent covers manual water pump technology. It requires that the device have a small tank and a pipe that connects the hand pump to the tank. The patent specifies that the water pump is autonomous, meaning that it can be “installed and operated at any location.” A check valve is in place to verify that the pump functions correctly. Figure 4, shown below, is a schematic of the water pump.
2.2.2 Water Mill (EP0708240A1)

This patent details the function of an electricity-generating water mill. In the design, the water is pumped from a pipe into the containers on the wheel. The weight of the full containers causes the wheel to rotate. Empty containers are then filled with water while full containers discard their water. The cyclic process continues while the water mill is functional. Additionally, the water mill can be installed in any location, “without relying on natural reservoirs.” This allows the water mill to be used in more diverse applications. Figure 5, below, shows the water mill design.
2.2.3 Photovoltaic Cell and Solar Cell Panel (US3411952A)

This patent falls under the classification H01L23/48, "arrangements for conducting electric currents to or from the solid state body in operation." It is a patent covering photovoltaic cells and solar panels, specifically the connecting of a multitude of small cells. The novel arrangement of many small cells connected together avoids the issue of efficiency decreasing as cell area increases. As a result, the power generated by the group of small cells increases, compared to a single cell of the same area. Figure 6 is an image of the photovoltaic and solar cell panels.

2.2.4 Wind Turbine & Wind Turbine Blade (WO2008070917A1)

This patent covers a wind turbine with a specific blade configuration. It requires that the wind turbine be configured such that its rotation generates electricity. The turbine blades must be oriented “between 19° to 21° relative to the plane of rotation of the hub.” Figure 7, below, shows an image of the wind turbine.

Source: https://patents.google.com/patent/WO2008070917A1

2.3 Codes & Standards

2.3.1 Toy Safety Standard (ASTM F963-17)

The American Society for Testing and Materials, ASTM, has standard F963-17 pertaining to safety specifications for toys. This is a comprehensive standard that addresses labeling requirements, folding mechanisms and hinges, sharp edges, etc. to ensure child safety. This will be a necessary standard for designing an interactive museum exhibit directed at children.

2.3.2 Museum Code (NAICS 712110)

The North American Industry Classification System, NAICS, has code 712110. This code focuses on museums. This code pertains to historical, cultural, and/or educational exhibits. When designing the renewable energy exhibit to be placed in the Science Center, it will be important to reference the “Science and Technology Museum” and “Interactive Museum” entries of code 712110.
2.4 User Needs

Following an interview with our client, we were able to further interpret the needs of this project and produce qualitative and quantitative analysis and criterion in order to meet our project goals. Detailed interview notes, a user needs table, and a target specifications table are included below.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Zoom Meeting Call
Date: February 5th, 2021
Setting: We shared our science center demo ideas with Dr. Potter while asking about necessary measures that needed to be met. During this interview, we were able to brainstorm additional solutions and refine our project idea. The interview was conducted via Zoom, and took approximately 45 min.

Interview Notes:
What is the targeted age group and education level for this demo?
- Primarily 7-14 year olds.
- Take into account adults (parents) and toddlers (siblings).

Are there any size limitations?
- Should work at an adult height but can lowered to different heights.
- Try to design as a table top device that can be placed on different platforms.

Could the cars move along a lead screw/rod or should they move on their own?
- A lead screw would be easier and more ideal, but just try getting the motors to work first.
- Consider using timing belts and flags or other icons to represent the three players.

What is the desired life expectancy for this demo?
- Focus on functionality over durability and maintenance.

What child safety concerns need to be taken into account?
- Sharp points and edges
- Pinch hazards
- Temperature hazards

2.4.2 Interpreted User Needs

Table 1 below depicts a compiled list of user needs as translated from the client interview with Dr. Potter. Each need is ranked by overall importance to the success and completion of the demo with 5 being the highest importance and 1 being the lowest importance.
Table 1: Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Demo is safe for children</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Demo easily conveys concept of renewable energy</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Demo is a table top device</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Demo is engaging</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Demo is a fun and interactive experience</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Demo is visually appealing</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Demo is highly functional</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Demo converts mechanical energy to electrical energy</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Demo is child accessible and ease to use</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Demo is inexpensive</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Demo requires easy and minimal resetting</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Demo compares realistic energies</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Demo has easy maintenance</td>
<td>1</td>
</tr>
</tbody>
</table>

For this project, we will primarily prioritize the safety of the demo, the ability to communicate the principles of renewable energy to children through high engagement and visual appeal, and making the demo a table top device for easy height accessibility.

2.5 Design Metrics

Table 2 represents the target specifications for the demo. It provides a different perspective of our user needs table by applying quantitative values to each need, thus creating a benchmark for designing the project.

Table 2: Target Specifications

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric</th>
<th>Units</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,5,8</td>
<td>Range of stations converting to electrical energy</td>
<td>user stations</td>
<td>&gt; 2</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>Total cost</td>
<td>dollar</td>
<td>400</td>
<td>&lt; 400</td>
</tr>
<tr>
<td>3</td>
<td>4,5,6</td>
<td>Quality of design and entertainment rated by the focus group</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>4</td>
<td>1,3,9</td>
<td>Total weight</td>
<td>lbs</td>
<td>&lt; 10</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>5</td>
<td>4,7</td>
<td>Duration of demo</td>
<td>minutes</td>
<td>&gt; 5</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Codes and standards <strong>ASTM F963-17, NAICS 712110</strong></td>
<td>binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>7</td>
<td>7,11,13</td>
<td>Cycles before failure</td>
<td>integer</td>
<td>&gt; 10</td>
<td>&gt; 1000</td>
</tr>
</tbody>
</table>
3 Concept Generation

3.1 Mock-up Prototype

The mock-up changed our thoughts on the device because it required us all to articulate our ideas and agree upon which combination of ideas would we most like to explore. The first decision that came from the mock up was that our exhibit would have a stadium setup. The ascending rows would allow for each racing icon to be visible from the playing children’s point of view. We also discovered that the hidden enclosed space below the stairs would be perfect for storing hardware. The black construction paper represents the conveyor belts that we plan on using to move the icons. We also got to explore different icons and determined that we will redesign them to be more distinct from each other in future prototypes. This model is not to scale. We anticipate the full size prototype footprint to be around 7’x4’.

![Mock-up Prototype](image)

Figure 8: Top, front, and side view of mockup prototype

3.2 Functional Decomposition

A function tree for the Renewable Energy Demo is shown in Figure 9 below. The primary functions that we prioritized were the uses of the three renewable energies, a racing display format, child accessibility, and creating an attention grabbing demo.
3.3 Morphological Chart

Figure 10 is the morphological chart corresponding to the above function tree. Two to three proposed solutions are associated with each desired function of the Renewable Energy Demo.
<table>
<thead>
<tr>
<th>Uses solar energy</th>
<th>light bulb + solar panel</th>
<th>solar heating</th>
<th>concentrated solar power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses hydropower Energy</td>
<td>Archimedes screw</td>
<td>water mill + pump</td>
<td>tidal power</td>
</tr>
<tr>
<td>Uses wind energy</td>
<td>flame fan + wind turbine</td>
<td>blow dryer + wind turbine</td>
<td>air pump</td>
</tr>
<tr>
<td>3-player racing display</td>
<td>horizontal</td>
<td>vertical</td>
<td>stadium</td>
</tr>
<tr>
<td>Child accessible</td>
<td>table top</td>
<td>no sharp edges</td>
<td>steps to device</td>
</tr>
<tr>
<td>Attention grabbing</td>
<td>water theme</td>
<td>colorful + light up</td>
<td>interactive</td>
</tr>
</tbody>
</table>

Figure 10: Morphological chart for Renewable Energy Demo
3.4 Alternative Design Concepts

3.4.1 Hydro Carnival Race

Figure 11: Preliminary sketches of the Carnival Race design

Figure 12: Final sketches of the Carnival Race design

Description: The Hydro Carnival Race design incorporates a water mill, pump or water source, and a racing game on a kid-friendly tabletop. To demonstrate the effects of hydropower, the water mill spinning powers the racing game. A water source pumps water onto the water mill. An electrical component converts the mechanical spinning of the water mill into electricity. The electric current is then used to power the racing game. The demo represents hydroelectric renewable energy. It is also colorful and kid-height to allow the targeted audience to use the device.
3.4.2 Renewable Racing Cars

Description: This is a 3-player game experience that races cars and teaches children about renewable energy. The solar energy is interactive through a crank that once in motion, powers the light bulb. The light is picked up on the solar panel and used to race the car. The wind energy is started from pumping the bike pump and the air flow is directed at a wind turbine that powers another car. The last car is powered by hydroelectric power from tidal devices. Waves are created by pushing and pulling the flexible membrane of the front panel.
3.4.3 Vertical Race Demo

Description: This demo is a 3-player vertical race, similar to an arcade or carnival game. Player 1 uses a simple air pump to produce wind energy that converts to electrical energy in order to move their icon upwards. Player 2 would shine a flashlight on a solar panel to convert solar energy to
electrical energy and move their icon. Player 3 uses a crank attached to a water mill to create hydro energy that transfers to electrical energy to move their player as well. The first player to get their icon to pass the finish line wins.

3.4.4 Light Up Competition

Figure 17: Preliminary Concept sketch of Light Up Competition Demo
Description: The light up competition demo is an interactive experience. This demo can be used by 3 participants at once. Each participant picks a different energy source; wind, hydroelectric, or solar. The wind system is composed if a flame fan the pushes air onto a vertical wind turbine which converts the energy into electricity that then lights up a light panel. The hydroelectric portion uses an Archimedes screw to pour water onto a water mill which then converts mechanical energy to electricity to power the light up board. The solar portion of the demo consists of a swinging sun lamp. The user then has to angle to solar panel with the swinging lamp to increase the amount of solar energy used. The user that lights the most lights wins.
4 Concept Selection

4.1 Selection Criteria

In order to decide on a concept we determined 5 criteria to score the designs against. These criteria were based off of our customer needs and design metrics. Figure 19 shows the analytical hierarchy process we used to determine the weight of these criteria.

<table>
<thead>
<tr>
<th></th>
<th>Child Safe</th>
<th>Concept Comprehension</th>
<th>Inexpensive</th>
<th>Engaging/Entertaining</th>
<th>Easy to Use</th>
<th>Row Total</th>
<th>Weight Value</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Child Safe</td>
<td>1.00</td>
<td>3.00</td>
<td>9.00</td>
<td>5.00</td>
<td>3.00</td>
<td>21.00</td>
<td>0.36</td>
<td>36.18</td>
</tr>
<tr>
<td>Concept Comprehension</td>
<td>0.33</td>
<td>1.00</td>
<td>9.00</td>
<td>3.00</td>
<td>0.33</td>
<td>13.67</td>
<td>0.24</td>
<td>23.55</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>0.11</td>
<td>0.11</td>
<td>1.00</td>
<td>0.14</td>
<td>0.14</td>
<td>1.51</td>
<td>0.03</td>
<td>2.60</td>
</tr>
<tr>
<td>Engaging/Entertaining</td>
<td>0.20</td>
<td>0.33</td>
<td>7.00</td>
<td>1.00</td>
<td>1.00</td>
<td>9.53</td>
<td>0.16</td>
<td>16.43</td>
</tr>
<tr>
<td>Easy to Use</td>
<td>0.33</td>
<td>3.00</td>
<td>7.00</td>
<td>1.00</td>
<td>1.00</td>
<td>12.33</td>
<td>0.21</td>
<td>21.25</td>
</tr>
</tbody>
</table>

Column Total: 58.04 1.00 100.00

Figure 19: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Once the criteria weights were determined, we used them to evaluate each alternative design concept. The concepts were assigned a value on the scale of 1-5 on how well the design met the criteria. Figure 20 shows how each assigned score was weighted to determine which design best fit the criteria. The five criteria are listed in order of importance as follows: Child Safe, Concept Comprehension, Easy to Use, Engaging/Entertaining, and Inexpensive.
4.3 Evaluation Results

Based on the results of the scoring matrix, the winning concept is the Vertical Race Demo. The ranking of the Vertical Race Demo was comparable to the Renewable Racing Cars Concept. Both concepts were scored 5’s in terms of “Easy to Use” and “Engaging/Entertaining”, meaning that we felt children from all ages would be able to use the demos as well as want to use them. In terms of “Concept Comprehension” both concepts were judged to reasonably demonstrate how energy is generated from each of the 3 renewable energy sources. Similarly, both concepts were deemed child safe. With these four criteria, the Renewable Racing Cars Demo and the Vertical Race Demo were tied in terms of ranking. However, the Vertical Race Demo was deemed the best because the concept was less expensive than the Renewable Racing Cars Demo. This is because the Renewable Racing Cars demo required more (and heavier) frame material, as well as glass, than the Vertical Race Demo.

4.4 Engineering Models/Relationships

The following are existing models and relationships that have heavily influenced our design decisions. These will help with quantitative analysis and ensure that our design can produce the necessary torques, power outputs, and more for users to successfully operate the demo.

4.4.1 Model 1

In the demonstration, a water mill will be used to power the racing game. Water will be poured on the water mill from a hand pump. The water flow will cause the wheel to rotate and turn a dynamo to generate electricity.

To model the power output from the water mill, the equations below were used:

\[ T = r \times F \]  \hspace{1cm} (1)
Where \( T \) is the torque \([N \cdot m]\), \( r \) is the radius of the water mill \([m]\), and \( F \) is the force of the water moving the water mill \([N]\).

\[
P = T \omega = IV
\]  \hspace{1cm} (2)

Where \( P \) is power \([W]\), \( I \) is the current \([A]\), and \( V \) is the voltage \([V]\).

Figure 21, below, summarizes the model used to determine the torque and power values for the water mill.

The model can be used to help determine what radius of water mill and what dynamo is needed to power the demonstration’s racing game.
4.4.2 Model 2

For the racing component of the demonstration, conveyor belts will be used to move flags or icons across a racetrack towards a finish line. To determine the torque needed to move the conveyor belts, the following equation was used:

\[ T = \frac{1}{2}(2R)(\mu mg) \]  

Where \( R \) is the radius of the conveyor belt wheel [m], \( \mu \) is the friction coefficient \([N/m]\), \( m \) is the mass of the object on the conveyor belt [kg], and \( g \) is the acceleration due to gravity \([m/s^2]\) [conveyortorque].

Figure 22 shows an illustration of the model.

![Conveyor belt model with equation](image)

This equation/model can be used to determine the required torque for the conveyor belt motor.

4.4.3 Model 3

For the solar energy component of our demo, a light bulb will be powered manually that will shine on a light sensor and power the race. The “Rollerbot” lab assignment from the Fall 2018 semester of ESE230 (Intro to Circuits) used a flashlight and a circuit consisting of a photodiode, transistor, battery, resistor, and DC motor to power a cart. Specifically, when the light shines on the photodiode, an electrical current is created to power the DC motor causing the rubber band
to rotate the sponge wheel and move the device forward [1]. The full assembly of the Rollerbot is shown in Figure 23 below.

![ESE230 Rollerbot model](image)

Figure 23: ESE230 Rollerbot model

This model will help us determine the circuitry needed to power the player using an incandescent light bulb and a light dependent resistor.

### 4.4.4 Model 4

The last model that will help with design decision making is one reflecting the relationship between the bellow and wind turbine. This model would help ensure that an average fire bellow could produce a strong enough air velocity to propel the blades and power the turbine. For this, the structure of the bellow was simplified and the air flow was modeled laminar pipe flow. This is depicted in Figure 24.

![Bellow pipe flow schematic](image)

Figure 24: Bellow pipe flow schematic

The velocity of the airflow out of the bellow, $V_b$, was calculated and compared to the minimum air velocity required to power a small wind turbine, $V_t$. This turbine velocity is $V_t=2$ m/s [2]. The
area of the bellow nozzle was determined using a diameter size of 0.5 in, which is average for a bellow according to Instructables Workshop [3]. The volume flowrate of an average bellow, $Q=5 \text{ ft}^3/\text{min}$ [4]. The calculations are as follows:

$$D = 0.5 \text{ in} = 0.0127 \text{ m}$$
$$Q = 5 \text{ ft}^3/\text{min} = 0.00236 \text{ m}^3/\text{s}$$

$$V_b = \frac{Q}{\pi d^2} = \frac{0.00236 \text{ m}^3/\text{s}}{0.25\pi (0.0127 \text{ m})^2} = 18.63 \text{ m/s}$$

Because $V_b > V_t$, the air flow produced from the bellow is more than enough to power the wind turbine, thus, the user at the wind power station should be able to move their player forward in the race using this method.

## 5 Concept Embodiment

### 5.1 Initial Embodiment

This section outlines the parameters describing the design of our renewable energy demo including parts, shape, and properties. Figure 25 depicts the projected views and overall dimensions of the design, the isometric view with a bill of materials (BOM) is shown by Figure 26, and Figure 27 details an exploded view of the design with balloon callouts to the BOM.

The performance goals of our demo are as follows:

1. The device can demonstrate three events (hydro, wind, and solar) in ≤ 1 minute
2. The device can be run > 5 times without maintenance or manual adjustment
3. Each event can be operated using forces of ≤ 4 lbs
Figure 25: Assembled projected views with overall dimensions
Figure 26: Assembled isometric view with bill of materials (BOM)
Figure 27: Exploded view with callout to BOM
5.2 Proofs-of-Concept

Our proof-of-concept testing and prototyping was instrumental and designing our initial prototype. We built a conveyor belt out of cardboard and paper. This helped us answer questions about whether we needed a timing belt or conveyor belt and how one side of the conveyor belt would have a motor (the driving end) and the other side would not (driven). We also purchased a hand crank generator and hand crank powered flashlight. By taking the flashlight apart, we were able to see how gears were used to increase the RPMS enough before attaching to the motor.

There were many changes made between the Initial Prototype and the selected concept, “Vertical Race Demo.” The first change we made was making this vertical race horizontal. We chose to have a stadium-like oriented display so that all the icons could be easily seen and the conveyor belts would not have to work against gravity. The methods by which the user interacts and produces energy were also changed. Rather than shining a flashing on a solar panel, the user turns a hand crank to produce electricity and power a light bulb that shines on a solar panel. Additionally, the air velocity for the wind energy station is not going to be produced from a bike pump but rather a fireplace bellow. For the hydro station, rather than a crank attached to the water wheel, we decided to us a manual water pump to pour water over the wheel and turn it.

6 Design Refinement

6.1 Model-Based Design Decisions

Below are 3 models used in aiding our design process.

6.1.1 Wind Turbine and Bellow Model

The model from Section 4.4.4 depicting the relationship between the wind turbine and bellow was applied to our prototype in order to ensure that our bellow could produce enough air to power the wind turbine. For our design, the diameter at the tip of the bellow nozzle is $D = 5/16\text{in}$ and the minimum velocity of turbine blades is $V_t = 2\text{m/s}$ [2]. Because of its abnormal shape, the volumetric flowrate of the bellow was difficult to calculate accurately. In the most simplified form, it could be modeled as a cylinder cut in half diagonally in order to find the volume, as shown in Figure 28.

![Figure 28: Model of Bellow](image)

We did not find the appropriate value of the bellow flowrate, but based on our prototype and
experimentation, we believe that the bellow may not produced enough air to produce a continuous rotation of the turbine blades and power the conveyor belt. We plan to continue testing this system, but if necessary, we could replace the bellow with a stronger air source such as a bike pump or a blow dryer.

6.1.2 Water Mill Model

To determine the voltage supplied by the water mill rotation, the torque applied by the water jet had to be calculated. Using the model shown in Section 4.4.1, the torque can be converted to the voltage. The team decided to expand the water mill model to include the torque calculation, in addition to the voltage calculation, to narrow down our nozzle choice.

The figure below, Figure 29, shows a side view of the water mill setup in the demonstration.

![Diagram of water mill setup](image)

Figure 29: Side view of the water mill setup

A generator connects to a shaft, which then connects to the water mill. The water mill hangs over the side of the table platform. In total, there are 12 panels on the water mill. Figure 30 shows the panels in more detail.
Each panel is made of clear acrylic. The nozzle jets a stream of water onto the surface of the panel. It is angled such that the water jet hits at approximately 90 degrees to the surface of the panel.

To solve the equations for the torque, several variables are defined in Figure 31.
With $d$ being the diameter of the nozzle in inches, $a$ is the area of the jet in $\text{in}^2$, $\rho$ is the density of the water at room temperature in $\text{lb/in}^3$, and $v$ is the jet velocity in $\text{in/s}$. Volumetric flow rate, $Q$, is measured in $\text{in}^3/\text{s}$ and was found using the flow rate per stroke given in a similar water pump [5].

The following values were plugged into the variables based on the design:

- $\rho = 0.0361 \text{ lb/in}^3$
- $d = 0.25 \text{ in}$
- $a = \pi d^2/4 = 0.0491 \text{ in}^2$
- $Q = 1.8048 \text{ in}^3/\text{s}$
- $v = Q/a = 36.7576 \text{ in/s}$

Based on the given values, the $F_N$ value, shown on the diagram below, will be calculated.
The equation for $F_y$ was found to be [6]:

$$F_y = \rho av^2 \sin(\theta)$$  \hspace{1cm} (5)

By plugging in the values, $F_y$ was found to be 7.1846 lbf. From the torque equation given in Section 4.4.1, the torque was calculated as 43.1076 lbf*in. With the torque, different motor voltages are being compared to choose the final product.

### 6.1.3 Conveyor Belt Motor Model

When it came to selecting a gear motor for the conveyor belts, we wanted to make sure that the gear box would decrease the motor’s output rpm to our desired speed. We wanted the conveyor belt to move slow enough that the icon would not simply zip across once started. Our prototype performance goal quantified that as the race lasting $\leq$ 1 minute long. In order to achieve this, we used the following model to select the gear motor that had a gear ratio that would give us our desired speed. We calculated the desired velocity of the belt using Eq. 6 the equation below [7].

$$x = vt$$  \hspace{1cm} (6)

where $x$ is the length of the belt (in), $v$ is linear velocity (in/s), and $t$ is time (s). The length of the belt was measured to be 33in and the time is 60s. Therefore, the speed of the conveyor belt must be traveling 0.55 in/s or faster.

Next, we used Eq. 7 below to find the angular velocity, $\omega$ (rad/s), of the roller shaft that is coupled to the motor [8].

$$\omega = \frac{v}{r}$$  \hspace{1cm} (7)

The radius of the roller is $r$ (in). A diagram of the conveyor belt can be seen in Fig. 33 below. Our roller radius was measured to be $r = 0.5312$ in. Using the equation above, the angular velocity
was calculated to be 1.035 rad/s. Converting that to rpm, the necessary rpm of the motor output shaft is 9.886 rpm.

Figure 33: Diagram of conveyor belt and roller

Based off of these calculations, we purchased the gear motor with the highest gear ratio, 499:1. This gear motor had a no-load speed of 11 rpm and it was the lowest speed available. While it is faster than our calculated 9.886 rpm, we figured it would be a good choice since our calculations didn’t account for friction or the load of the conveyor belt. Now that it is assembled with the purchased gear motor, we safety meet our goal of $\leq 1$ minute.

6.2 Design for Safety

Below are potential hazards that are associated with our prototype.

6.2.1 Risk #1: Rotating Elements

**Description:** A piece from the wind turbine, water mill, etc. falls off and hits user. A foreign object such as long hair or loose clothing gets caught in rotating element.

**Severity:** Critical

**Probability:** Likely

**Mitigating Steps:** Tightly secure all rotating elements in the device and recommending that users pull back long hair or clothing.

6.2.2 Risk #2: Water Leak

**Description:** The water supply for the mill and/or the mill itself leaks water causing electrical malfunctions with the motors or slipping hazards.

**Severity:** Critical

**Probability:** Likely

**Mitigating Steps:** Enclosing the water space, incorporating splash guards, and creating waterproof housing for electrical components.

6.2.3 Risk #3: Pinched Fingers

**Description:** A user gets their finger or any object stuck in a pinch point on the device.

**Severity:** Marginal

**Probability:** Seldom

**Mitigating Steps:** Provide warnings of potential pinch points.
6.2.4 Risk #4: Conveyor Belt

**Description:** The track of the conveyor belt slips off or breaks due to use hindering game performance.

**Severity:** Negligible

**Probability:** Frequent

**Mitigating Steps:** Replace elastic conveyor belt bands with toothed timing belt.

6.2.5 Risk #5: Loose Pieces

**Description:** A piece such as a screw or bolt becomes loose and a child swallows it and chokes.

**Severity:** Catastrophic

**Probability:** Unlikely

**Mitigating Steps:** Ensure that all pieces are tightly fastened to prevent any small parts from coming loose.

6.2.6 Heat Map

Using these risks and their severity and probability, the heat map in Fig. 34 was created.

![Heat Map of Risks](image)

According to the heat map, our highest priority risk is a water leak. This risk is fairly easy to occur risk and it could ruin the electrical system, shock users or cause someone to slip. Since this will be our highest priority, we will take extreme care to contain the water and shelter all electrical
systems from the environment. Our next priority would be rotating elements, loose pieces and the conveyer belt. They are all in the yellow section of the heat map and could cause damage but not to the same degree as a water leak. Our lowest priority risk is pinched finger because our prototype, by design, has relatively few pinch points. That would make getting something pinched possible but a little hard.

### 6.3 Design for Manufacturing

Based on our current prototype and CAD model, a list of parts used in the creation of the Renewable Energy Demo is listed in table 3. A simplified model view is seen in figure 35 below.

![Figure 35: Project CAD Model](image_url)
Table 3: Number of parts in the project, including and excluding fasteners

<table>
<thead>
<tr>
<th>System</th>
<th>Item</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conveyor System (x3)</strong></td>
<td>Wood Planks (frame)†</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Exercise band</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roller</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Guide caps</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Roller Shaft</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Icon</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mount</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Wires</td>
<td>2</td>
</tr>
<tr>
<td><strong>Frame structure</strong></td>
<td>Base board</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Support stand</td>
<td>1</td>
</tr>
<tr>
<td><strong>Water System</strong></td>
<td>Water Jug</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Water Pump</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tube</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Nozzle</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Water Container</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Splash Guard</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Water Wheel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Water Wheel Shaft</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ball Bearings</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Generator</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Coupling</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Generator mount</td>
<td>1</td>
</tr>
<tr>
<td><strong>Wind</strong></td>
<td>turbine</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>generator</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Air pump</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Generator Mount</td>
<td>1</td>
</tr>
<tr>
<td><strong>Solar</strong></td>
<td>Hand Crank</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Generator</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Wires</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>LED light bulb</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LDR</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Transistor</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Resistor</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Battery</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Generator Mount</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Bread Board</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL ITEM COUNT WITHOUT FASTENERS:</strong></td>
<td></td>
<td>43</td>
</tr>
<tr>
<td><strong>Fasteners (Ball park estimate)</strong></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td><strong>TOTAL ITEM COUNT WITH FASTENERS:</strong></td>
<td></td>
<td>58</td>
</tr>
</tbody>
</table>

In terms of the Theoretical Number of Components (TNC), table 4 below has the simplified components. In order to reduce the number of components, all parts that acted as joinery and fasteners were removed. All parts listed are either: made of different materials, move relative to a
different part, and/or must be separate for repair. For different TNC are explained below as well as why they must be both separate and necessary.

1. Conveyor Shaft:

- The conveyor shafts in the conveyor belt system are TNC because they must be separate so that the conveyor belt can loop around the shaft’s axis of rotations. Additionally, the shaft must be removable in case the belt need to be replaced.

![Conveyor Shaft](image)

Figure 36: Conveyor Shaft

2. Water Wheel:

- The water wheel is a TNC because it is necessary to cause the generator in the hydroelectric system to turn and produce power. The water wheel can be built with an attached shaft of the same material, making only the wheel unit is necessary.

![Water Wheel + Shaft](image)

Figure 37: Water Wheel + Shaft

3. Air Pump:

- The air pump is a necessary theoretical component because it produces the "wind" necessary to move the wind turbine. It is also not connected to any other moving components of the demo, but it does cause movement and is of different material.

4. LED Light bulb:

- Although the LED light bulb is stationary/a fixed component, it is still considered as TNC because the material used for the LED must be different from it’s structure/joinery. The LED light must also be replaceable in case the bulb burns out.
### Table 4: Theoretical Number of Components (simplified)

<table>
<thead>
<tr>
<th>TNC</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Frame</td>
<td>2</td>
</tr>
<tr>
<td>Conveyor belt</td>
<td>1</td>
</tr>
<tr>
<td>Conveyor Shaft</td>
<td>2</td>
</tr>
<tr>
<td>Icon</td>
<td>1</td>
</tr>
<tr>
<td>Motor</td>
<td>1</td>
</tr>
<tr>
<td>Wires</td>
<td>2</td>
</tr>
<tr>
<td>Stand Structure</td>
<td>1</td>
</tr>
<tr>
<td>Water Jug</td>
<td>1</td>
</tr>
<tr>
<td>Water Pump</td>
<td>1</td>
</tr>
<tr>
<td>Water Catcher Container</td>
<td>1</td>
</tr>
<tr>
<td>Water Wheel</td>
<td>1</td>
</tr>
<tr>
<td>Generator</td>
<td>1</td>
</tr>
<tr>
<td>Turbine</td>
<td>1</td>
</tr>
<tr>
<td>Generator</td>
<td>1</td>
</tr>
<tr>
<td>Air Pump</td>
<td>1</td>
</tr>
<tr>
<td>Hand Crank</td>
<td>1</td>
</tr>
<tr>
<td>Generator</td>
<td>1</td>
</tr>
<tr>
<td>Wires</td>
<td>1</td>
</tr>
<tr>
<td>LED light bulb</td>
<td>1</td>
</tr>
<tr>
<td>LDR</td>
<td>1</td>
</tr>
<tr>
<td>Transistor</td>
<td>1</td>
</tr>
<tr>
<td>Resistor</td>
<td>1</td>
</tr>
<tr>
<td>Battery</td>
<td>1</td>
</tr>
<tr>
<td>Breadboard</td>
<td>1</td>
</tr>
</tbody>
</table>

**Theoretical Number of Components:** 28

This Renewable Energy Demo is generally designed with the minimum number of components in mind. In terms of reducing the number components used, as listed in the TNC, that would entail altering the method of manufacturing. For example, the water wheel was laser cut/glued together and the watermill shaft is an aluminum rod, as seen in figure 37. The number of parts could be reduced by CNC-ing, cast molding, or 3D printing the part, however, that would make the piece more expensive. This is the same for other parts that could be reduced to one part. Additionally, it would be ideal to maintain separate parts so that there is an ease of maintenance for the demo.

### 6.4 Design for Usability

The following is an evaluation of how different physical impairments could affect the use of the renewable energy demo.

- **Vision Impairment:** This device incorporates colored icons that represent the moving player. If a user has a vision impairment such as colorblindness, they may have trouble identifying which racing icon is theirs while playing. In this case, it would be useful to make each icon a different shape so that it is not solely color dependent.

- **Hearing Impairment:** Our design does not explicitly have any auditory components other
than sounds naturally made by powering the mechanical components of the demo. As a result, there is a very unlikely chance of a user with a hearing impairment having difficulties operating the demo to its full extent.

- **Physical Impairment:** This device is very dependent of physical labor of the user, particularly to operate a hand crank, hand pump, and bellow. These motions can be taxing on someone that may have a disability such as arthritis or muscle weakness. So, we designed our demo to require the least amount of strength necessary to operate the components by incorporating supplementary power sources and increasing handle sizes.

- **Control Impairment:** Users with control impairments would not be heavily affected by operating our device, but may experience some inefficiencies. Attentiveness and alertness is desired when operating our demo since it is essentially a racing arcade game. So, if a user were to be distracted or fatigue while operating the game, they would likely not win the race.

## 7 Final Prototype

### 7.1 Overview

The final prototype of the Renewable Energy Demo consists of 3 hand crank stations. The first station is the hydroelectric station where a hand crank is used to power both a conveyor belt and a representative water wheel. The second station represents solar power. In this station, the hand crank generator is used to power a LED light that then shines on a LDR (light dependent resistor) circuit that then uses a 9V battery to power the solar conveyor belt. The third station is the wind energy station. At this station, a hand crank generator is used to power the wind turbine (to represent movement caused by wind power) and the conveyor belt that moves the icon.

In the final design prototype, several kinks were still present within the system that did not allow the project to meet all performance goals. The first performance goal completed was met because all stations were able to complete a race in under a minute; 20 seconds for the hydro and wind stations and 40 seconds for the solar station. The second performance goal was partially met, 2 of the 3 conveyor belts were able to operate 5 times without manually resetting, however, the hydroelectric conveyor belt required manual adjustment after the second race. This malfunction is most likely stemmed from the construction of the conveyor belt. The last performance goal completed was each station being operated at less than 4 lbs, in this prototype, all hand cranks were operated with less than 1 lbs force.

### 7.2 Documentation

Below is a picture of the final prototype for the Amazing Renewable Race. Figure 38 shows the three stations to represent wind, hydro, and solar energy.
Below in Fig. 39, the 3D printed wind turbine is shown. The wind turbine is powered by the hand crank.
The hydro station can be seen in Fig. 40. The water wheel was made of laser cut acrylic.

Figure 40: Final Hydro Station

Figure 41 shows the final solar station where a solar panel is placed on top of the LDR circuit.

Figure 41: Final Solar Station
The breadboard operating the solar station can be seen in Fig. 42 below. The breadboard was covered by a 3D printed case.

Figure 42: Breadboard for Solar Station

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- Yes, the final prototype still aligns with the initial project description. The demo is a 3-player race suited for children that conveys the principles of renewable energy.

Was the project more or less difficult than expected?

- The project was much more difficult than expected as it was essentially three mini projects (hydro, wind, and solar) in one. Once each individual station was working, it was challenging to get them to work simultaneously while also powering the conveyor belts.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

- Although a lot of time was already spent on determining which motors to use for powering the demo, more time would have been useful to physically test and evaluate varying motors
to find the appropriate ones for the final prototype. More time could also have been spent refining the final prototype to further stabilize the foundation.

*Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?*

- The water station was significantly harder to build than the other components of the demo. Creating a stable coupling system between the water mill and the motor was tricky, but the most challenging part was finding the right water pressure to rotate the water mill and output an appropriate RPM to power the motor as well as the conveyor belt.

*In hindsight, was there another design concept that might have been more successful than the chosen concept?*

- A design concept that the team initially considered but didn’t follow through with was the process of charging up batteries with the renewable energy stations then releasing the player icons in a drag race style. This could have been a less time-consuming approach and avoided the issue of finding suitable motors.

### 8.2 Design Resources

*How did your group decide which codes and standards were most relevant? Did they influence your design concepts?*

- The team prioritized child safety in designing the demo, so codes and standards relevant to toys or other child products were considered in the final decisions.

*Was your group missing any critical information when it generated and evaluated concepts?*

- The group was not missing any critical information when evaluating concepts. However, the group did underestimate the difficulty to implement the concepts efficiently to produce the desired power output. If any critical information was missed, it would be the effect of friction and inefficiencies on the entire prototype.

*Were there additional engineering analyses that could have helped guide your design?*

- The team could have done more efficiency evaluations to determine how much usable energy would be produced given possible inputs.

*If you were able to redo the course, what would you have done differently the second time around?*

- A less challenging or smaller scope project would have likely been chosen.

*Given more time and money, what upgrades could be made to the working prototype?*

- Fastening and coupling systems would immediately be upgraded as some components of the final prototype are secured with tape and other temporary adhesives.

### 8.3 Team Organization

*Were team members’ skills complementary? Are there additional skills that would have benefited this project?*

- Yes, the skill set of all team members were extremely complementary as some were skilled in wind energy, design aesthetics, dynamics, and machinery. An additional skill that could have benefited the group is greater background knowledge of electrical principles for designing the solar and motor components of the demo.
Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

- If given more time, money, and other resources, the group would definitely be interested in continuing this project so that it would work as initially envisioned as well as other projects related to renewable energy.
Bibliography


[8] Quantities of Rotational Kinematics. URL: https://courses.lumenlearning.com/boundless-physics/chapter/quantities-of-rotational-kinematics/#:~:text=The%20greater%20the%20rotation%20angle,or%20%CF%89%20%.20Fr.