2024

Run-of-River Device for Hydropower from the Crum Creek

Paula Suder , '24

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Abstract

With the onset of climate change from excess carbon emissions, renewable energy sources, especially in the form of hydropower, can offer comparatively low-emission alternatives to conventionally used fossil fuels that may lessen the environmental effects of energy generation. Although most hydroelectric facilities utilize dams to store water and channel flow, diversion facilities, also called "run-of-river" facilities, operate utilizing a portion of the natural flow and eliminate the need for dams and their associated construction and environmental concerns. To design and construct a small-scale run-of-river device, an iterative design process was implemented over two prototypes, including spiral axial hydropower turbine design and component selection. The second prototype was created by adjusting the metrics of the spiral axial turbine and implementing the concepts of bevel gear pair theory and design. After assembly, the device was tested in the Crum Creek for its ability to generate power. The device generated a small but detectable amount of voltage and current, successfully producing power. By optimizing various components in future iterations, the device can more efficiently capture the energy of the Crum Creek's flow and yield greater power output. Additionally, future iterations can rework and scale the design to produce enough power for common everyday uses, such as powering a modern smartphone.

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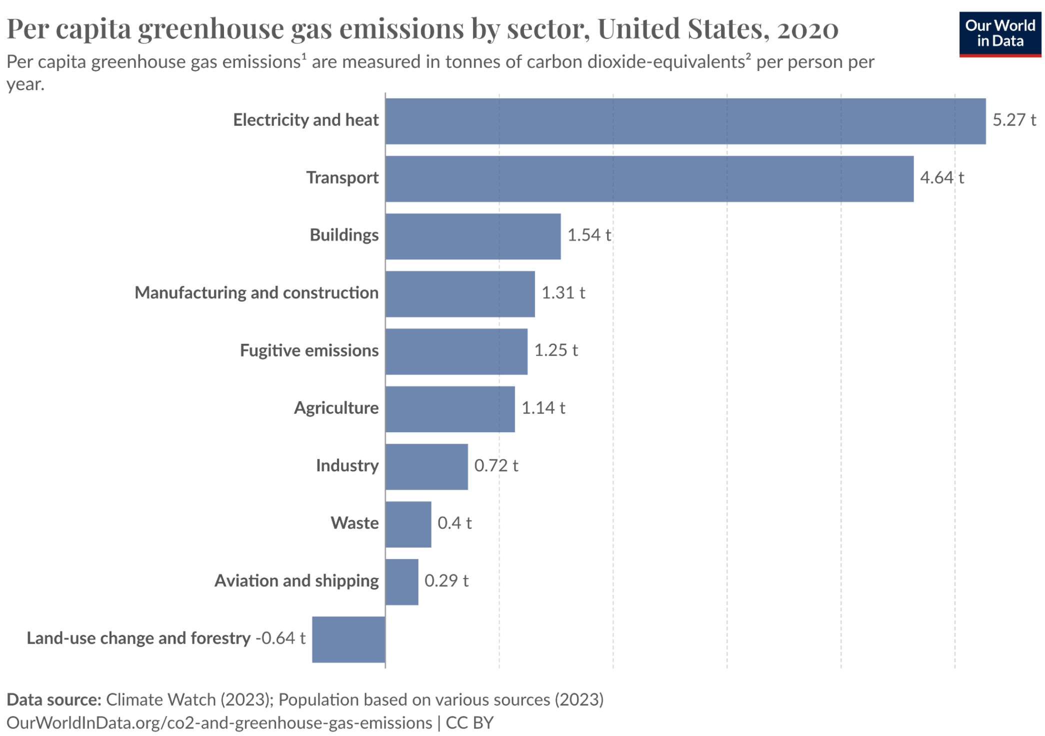
Acknowledgements

I would like to thank the following people for their impactful ideas, advice, and assistance throughout the development of my project. Thank you to Professor Carr Everbach for advising and mentoring me throughout the project, Cassy Burnett for helping me get the necessary materials, Mark Lohatepanont for teaching me how to 3D print and assisting me throughout the process, J. Johnson for helping me extensively in the machine shop, Michał Lach for their tutorial and contribution towards my turbine design process, and the user jimb15122 on Ultimaker Thingiverse for their “Bevel Gear Matched Pair Generator” and its contribution to my gear design process.

1 Introduction

Given its global scale, climate change is one of the most pressing concerns of the 21st century with excess greenhouse gas emissions like carbon dioxide, methane, and nitrous oxide increasing year by year. Greenhouse gasses, when emitted excessively, trap too much of the sun's heat radiating off the earth causing increasing global temperatures and other negative environmental effects such as extreme weather events, loss of natural plant and animal species, and human health risks. Although greenhouse gasses are emitted from energy usage by a variety of major sectors, one of the main sources of greenhouse gas emissions in the United States is the electricity and heat sector. According to data collected by Climate Watch in 2023, the electricity and heat sector produced 5.27 tonnes of greenhouse gas emissions per capita in 2020. Although this amount has decreased from previous years of electricity and heat production, the electricity and heat sector continues to emit the largest amount of greenhouse gasses per capita over all other sectors.



1. Greenhouse gas emissions: A greenhouse gas (GHG) is a gas that causes the atmosphere to warm by absorbing and emitting radiant energy. Greenhouse gases absorb radiation that is radiated by Earth, preventing this heat from escaping to space. Carbon dioxide (CO_2) is the most well-known greenhouse gas, but there are others including methane, nitrous oxide, and in fact, water vapor. Human-made emissions of greenhouse gases from fossil fuels, industry, and agriculture are the leading cause of global climate change. Greenhouse gas emissions measure the total amount of all greenhouse gases that are emitted. These are often quantified in carbon dioxide equivalents (CO_2eq) which take account of the amount of warming that each molecule of different gases creates.

2. Carbon dioxide equivalents (CO_2eq): Carbon dioxide is the most important greenhouse gas, but not the only one. To capture all greenhouse gas emissions, researchers express them in "carbon dioxide equivalents" (CO_2eq). This takes all greenhouse gases into account, not just CO_2. To express all greenhouse gases in carbon dioxide equivalents (CO_2eq), each one is weighted by its global warming potential (GWP) value. GWP measures the amount of warming a gas creates compared to CO_2. CO_2 is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. Carbon dioxide equivalents are calculated for each gas by multiplying the mass of emissions of a specific greenhouse gas by its GWP factor. This warming can be stated over different timescales. To calculate CO_2eq over 100 years, we'd multiply each gas by its GWP over a 100-year timescale (GWP100). Total greenhouse gas emissions – measured in CO_2eq – are then calculated by summing each gas' CO_2eq value.

Fig. 1

1.1 Background

Historically, the United States has produced heat and electricity using fossil fuels like coal, natural gas, and petroleum, all of which produce a significant amount of carbon dioxide when combusted. Alternatives to fossil fuels, such as nuclear and renewable energy, make up a comparatively smaller portion of heat and electricity generation than fossil fuels in the United States, contributing about 18.2% and 21.5% in 2022 respectively. Although not nearly as commonly implemented, these alternative sources have been increasingly favored as sources for heat and electricity because they emit much less greenhouse gas emissions, especially carbon dioxide, for the same amount of energy production as their fossil fuel counterparts. Although more favorable in terms of their reduced greenhouse gas emissions, nuclear and renewable energy still pose unique issues that can cause negative impacts in other regards. For example, nuclear power requires a lot of energy for mining and processing uranium ore and constructing the power plant itself. Additionally, the process of creating nuclear energy is highly radioactive, creating radioactive wastes, human worker health risks, and the potential for an extremely damaging environmental disaster from a nuclear meltdown. Renewables, on the other hand, can be inconsistent depending on weather conditions, costly to initialize and maintain, take up a lot of space, and not produce energy as efficiently as fossil fuels.

1.2 Hydroelectric Power Generation

Hydropower, a type of renewable energy that creates energy from water flow, is currently the largest source of renewable energy in the electricity sector. There are multiple types of facilities that produce hydropower, each of which implement similar but varying processes of capturing the energy of water flow. A pumped storage facility works by pumping water from a lower to higher elevated reservoir to store electricity from other energy sources, and then releasing the water back to a lower elevation onto a turbine when electricity is needed. The most common type of hydroelectric plants in the United States are impoundment facilities, which use dams to slow and store river water in a reservoir and release the flow of the reservoir through a turbine to spin a generator and generate electricity. As of 2020, there are more than 90,000 dams in the US, a majority of which are used for stock and farm ponds, flood control, and irrigation, and about 2,300 to produce power.

Fig. 2

The third type of hydroelectric plants are diversion facilities, also known as a "run-of-river" facility. Run-of-river facilities produce energy by channeling a portion of the natural flow of a river or other waterway caused by a decreasing bed elevation. This portion, channeled by a canal or penstock, is directed through a turbine to generate energy and then released back into the original waterway. Unlike impoundment facilities, diversion facilities often do not require the use of dams which can negatively impact the environment by slowing or blocking river flow and altering the surrounding environment, posing a threat to the survival of the natural plant and animal life. Although only a small percentage of dams are used for electricity generation, they still noticeably impact the environment of the most essential rivers around the country.

1.3 Motivation

As abundant environmental features, rivers and other waterways have the potential to produce a large amount of hydroelectric power that can help replace the need for fossil fuels. Despite its potential, not only does hydroelectric power comprise a small portion of electricity generation in the United States, but commonly uses dams which take a significant amount of time, resources, and energy to construct, and disrupt the environment of the river or waterway it uses. My motivation for my project is to create a system of hydropower production that does not block or impede the flow of a waterway, causing minimal disruptions to the environment. To achieve this, I decided to design and build a small-scale “run-of-river” device that is portable enough to transfer to and from a waterway. My system relies on the main concept behind run-of-river systems, which is channeling a portion of a waterway to generate electricity instead of blocking the water flow and causing environmental disruptions like dam systems. My overall goal for this project is to design and produce the system’s components, build a transportable device, and record its performance in a waterway.

2 Theory

2.1 Axial Hydropower Turbines

In order to generate electricity from water flow, hydropower systems use hydro turbines to capture the kinetic energy of the flow as mechanical energy to power a generator. In essence, the force of the flow onto the submerged portion of the turbine creates a torque, causing it to spin and harness the water's kinetic energy as mechanical energy. There are several types of commonly used hydro turbines, including the Francis, Kaplan, and Pelton turbines, each of which best suit different waterway conditions. Another category of hydro turbines are axial flow turbines whose axes are oriented horizontally parallel to the flow, such as a spiral axial turbine that floats horizontally atop the flow surface with continuous, spiraling blades.

- In slow and shallow conditions akin to the Crum Creek, spiral axial turbines have multiple advantages over other types of axial turbines, such as the conventional 3-bladed axial turbine

- The various parameters of a spiral axial turbine such as spiral diameter, pitch angle, blade thickness, and angle relative to the flow all impact its ability to spin.

- The direction of the spiral matters - clockwise turbines will spin one direction while counterclockwise turbines will spin the opposite direction

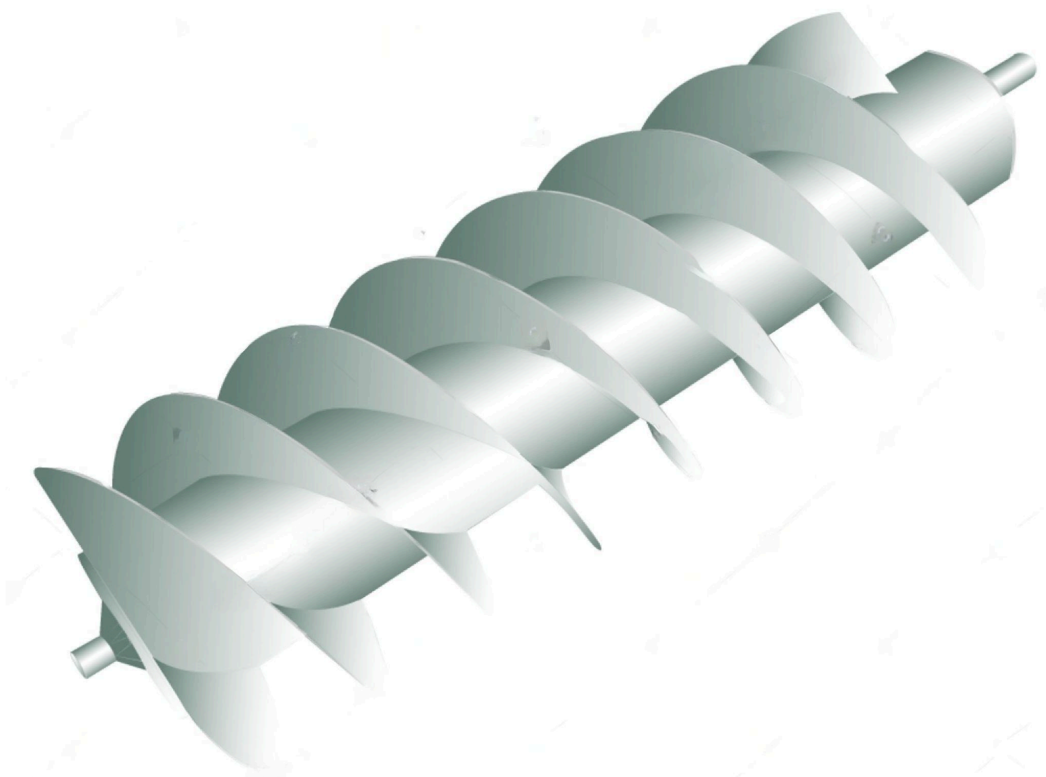
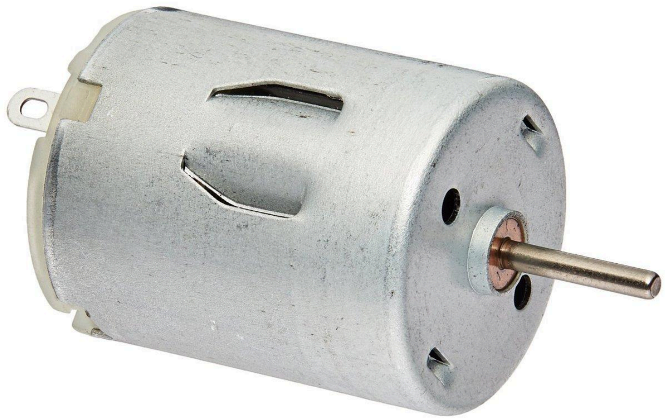


Fig. 3

2.2 DC Motors

Direct Current, or DC, motors are devices that convert an input of electrical energy from a source such as a battery into mechanical energy. They work by utilizing the Lorenz Law to create a force in the presence of a current which is specified by the voltage rating, a parameter describing the maximum voltage that can safely be applied to the motor. DC motors can also function as generators, inputting mechanical energy and outputting electricity. When the shaft is rotated by an external force such as a water flow, there is a voltage induced across the opposing terminals. In hydropower systems, a generator is able to input the mechanical energy generated by the spinning turbines and induce a voltage to produce power. The voltage induced by the generator is directly proportional to the speed of shaft rotation and increasing the rotational speed results in higher output voltages up to the voltage rating. One of the defining metrics of a generator, the efficiency, is the ratio between output and input power and characterizes how much energy into the generator is successfully converted to output energy and lost to the environment. While a higher voltage rating gives a generator the capacity to generate more electricity than a lower voltage rating, power generation is more efficient when the voltage rating is closer to the input voltage.



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2.3 Gear Pairs

In a simple hydropower configuration, gear pairs, or a set of gears with identically sized teeth allowing the gears to mesh, enable the mechanical energy generated by the turbine to be inputted into the generator. An important parameter of gear pairs is the gear ratio with a larger ratio implying a larger difference in the number of gear teeth and a smaller ratio implying less of a difference. When the gears are meshed together and begin to rotate, the smaller gear of the pair will spin faster relative to the larger gear based on the respective gear ratio. Given a fixed speed of the larger gear, the smaller gear can be designed based on the ratio between the speed of the turbine and the desired power output by reducing the amount of teeth on the smaller gear on the generator.

- While typical gears mesh at 180 degrees, bevel gears are a type of gear with conical teeth-bearing faces that enable a pair to mesh at a specified angle with the shafts of the gears intersecting.

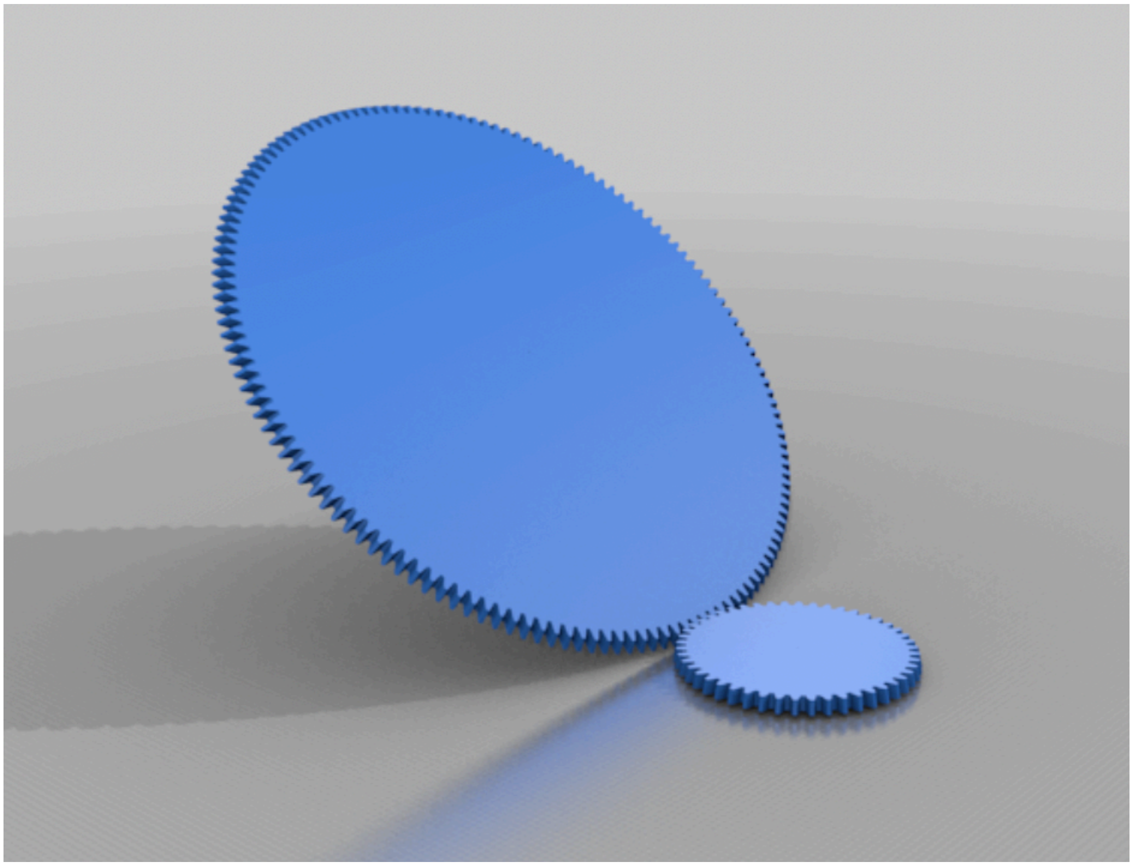


Fig. 5

3 Design and Construction

3.1 Overall Design Considerations

Implementing the theory explored above, my project produces power using a small-scale, run-of-river device demonstrated by the following schematic:

- Add figure of a labeled schematic of the device

The main requirement of my project is to design a portable, small-scale, run-of-river device that generates electricity from the kinetic energy of water flow and can be reconfigured and scaled in size to generate enough power for common everyday uses, such as charging a modern smartphone. Constrained by factors such as time and the ability to be constructed and transported by myself, I did not require my design to produce a specified power output, but rather aimed it towards successfully generating mechanical energy from the turbines and inducing a measurable voltage across the generator. My design intends to demonstrate small-scale run-of-river hydropower in a working prototype that can be scaled and reworked for more specific applications. In the process of designing hydropower systems, one must also consider the professional standards and codes that may govern the constraints of the overall design. Given the extremely small scale and lack of further optimization of my design, it can only produce a very small fraction of power produced by any commercial hydropower systems including Pico Hydropower, the smallest category of commercial hydroelectric power generation ranging from 100 Watts to under five kilowatts. Due to its very small scale, I was unable to find any professional standards or codes that could govern my design process.

3.2 Spiral Axial Turbine Design

My first step was to design the axial turbine that would capture the flow of the creek. One of my main requirements was that part of the turbine would float above the surface of the water it is placed in. To most efficiently model and generate a floating turbine prototype, I used AutoDesk Fusion to create a 3D model of my design and then 3D printed the model out of PLA using a Original Prusa i3 MK3S+ 3D printer. When designing my turbine prototypes, one of my largest constraints was the maximum print size allotted by the Original Prusa i3 MK3S+ 3D printer, which is 250 x 210 x 210 mm or 9.84 x 8.3 x 8.3 in. As a result, the turbine diameter was limited to a maximum size. To begin creating a preliminary turbine model, I initially designed a model with a 5-inch “plus sign” base to observe the effect of the number of blades on the spiral pattern. Due to the height and width printing limits of the Prusa printers, I had to stick to a relatively small spiral diameter and height for my model; So although I had to keep my spiral diameter within the limits, I printed the model in two segments and adhered them together to double the length and increase the water-receiving area without making it too long and hard to transport.

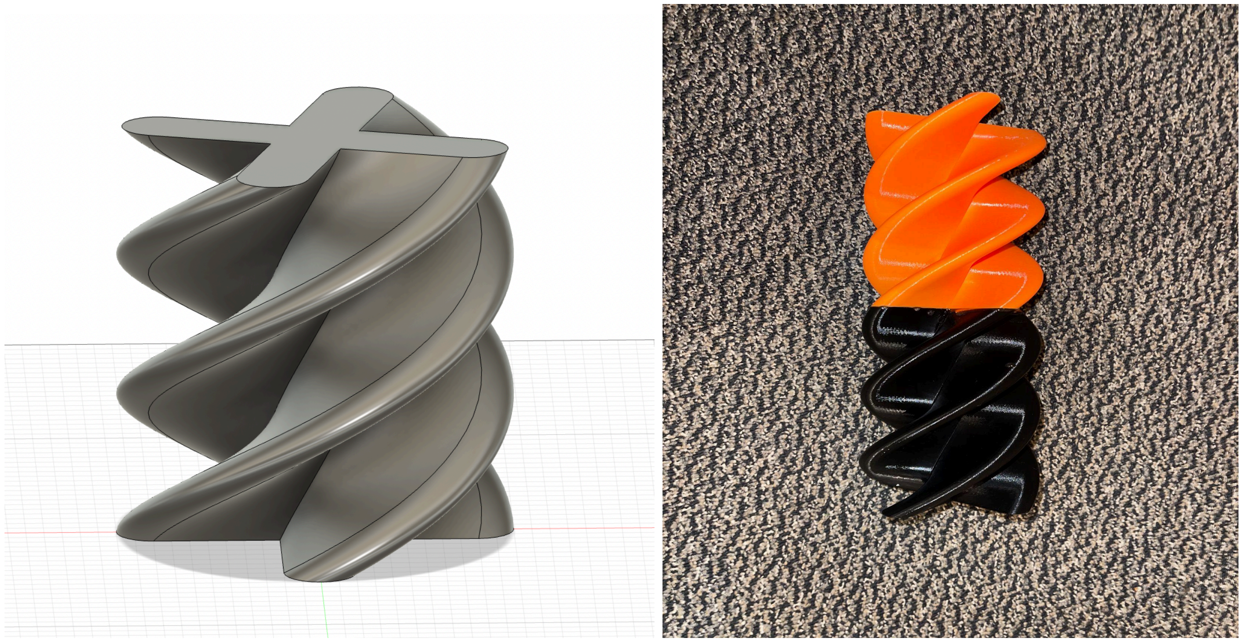
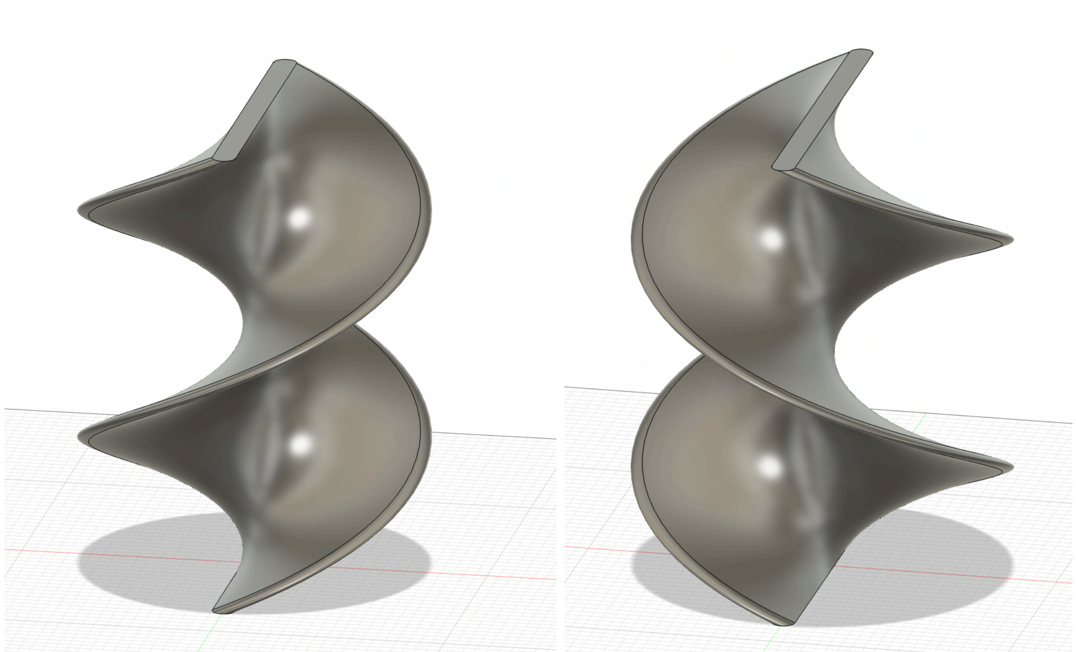


Fig. 6

My preliminary model set a baseline for my turbine design and highlighted necessary adjustments to certain spiral parameters. First, the blades of the "plus sign" base end up quite close together along the length of the spiral which is not ideal as this tightness makes it difficult for the flow to come in as much contact with the blades as possible. Second, the blades themselves ended up quite thick which is also not ideal because this bulk adds more material to the turbine while decreasing the water-receiving surface area due to creating a tighter spiral. Lastly, with my limited 3D modeling skills, I knew I wanted to stick to a model with a constant diameter along the length that I could easily alter and remodel so to increase the surface area in contact with the flow, I found the that the turbine would have to intersect the flow at an angle corresponding to the pitch angle of the spiral. Given that the spiral diameter is constrained by the Prusa i3 MK3S+ 3D printer dimensions, my next turbine prototype focused on maximizing the surface area of the turbine coming in contact with the flow to increase the force of the water on the turbine.

Next in my design process, I designed a second turbine model changing the metrics I discussed before. This time, I used a "minus sign" base that resulted in 2 blades instead of 4. I also increased the spiral diameter to the limit of the printer and cut the blade thickness in half to 0.5 inches to minimize the plastic I needed and increase the ratio of the surface area to overall volume as much as possible while maintaining structural integrity and durability. Additionally, Professor Everbach and I came up with the idea to create identical clockwise and counterclockwise models that could both sit at a 45 degree angle to the flow and converge at the front to power a generator. This configuration is more ideal than a single turbine because theoretically, the flow would apply an equal amount of force to either side of the device which helps keep the whole device balanced, making it easier to intersect the flow at the correct angle. On top of that, with the correct gear configuration, my design could combine the torque of the turbines to spin the generator twice as fast.



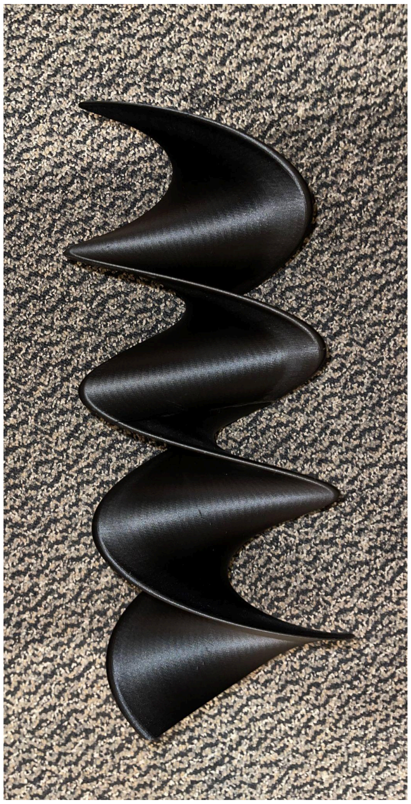
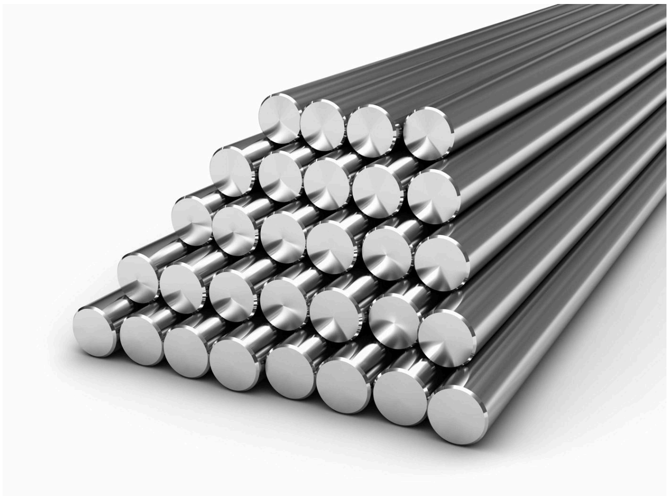


Fig. 7

3.3 Device Component Selection

The next aspect of the design process was the components I would need for the device. This included rods and bearings for the turbines to spin around and a motor that I use as a generator.

- Given its accessibility on consumer retailers such as Amazon, I purchased 2-mm stainless steel rods and corresponding bearings to serve as the axes of my turbines.



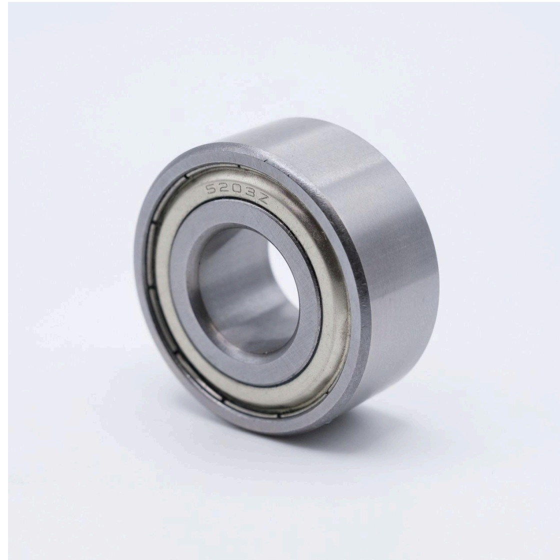


Fig. 8

I chose to use a small, standard motor on hand for this purpose which was 6 volts. The most important component to consider was the gears connecting the turbines to the motor. Considering the theory behind gear ratios, I knew that the motor gear would spin faster than the turbine gear relative to their ratio so I decided to design gears that would allow the motor to spin much faster than the turbine.

3.4 Bevel Gear Design

For my second prototype, I decided to use 3D printed bevel gears in order to allow the right- and left- handed turbines to both be at an angle to the flow and design a specific gear ratio and center hole diameter for the gear pairs. Given that my turbines would converge with each turbine 45 degrees to the center axis of the device, I designed bevel gears with teeth-bearing faces at 45 degrees to mesh teeth at 90 degrees. Keeping the diameter of the gear slightly smaller than the spiral diameter to impede the flow as little as possible, I created a 3:1 gear ratio with 144 to 48 teeth respectively. The idea is that the turbine gears would mesh with each other in the center to form a right angle and the motor gear would mesh with the turbine gear at 45 degrees driven by the combined torques of the turbines.

- To help generate my bevel gear design, I used the “Bevel Gear Matched Pair Generator” that creates a 3D bevel gear pair model based on the creator’s design and user-customized metrics and generates downloadable .stl files online for open-access 3D printing

- Add pictures of the printed bevel gears

3.5 Device Construction

Once I acquired all the main components needed for my second prototype, I created a detailed design sketch to help visualize the assembled device to-scale and allow me to make additions or adjustments before construction. The last component consideration was adding a frame to house the components of the device in one place and enabling portability while keeping the device floating when in water.

- Add the device design sketch

The main requirements of the frame were to suspend the turbines horizontally at 45 degrees to each other, hold the device components as a cohesive unit, and float despite the added weight to the overall device.

- I decided to use wood as the frame material and used wood triangles to account for the angle of the turbines within the 3-sided rectangular frame. I also added a wood trapezoid to house the generator at the correct angle and height for its gear to mesh with the turbine gear

- After designing and assembling the pieces for the wooden frame, I was able to assemble the device following the guidance of my preliminary design sketch. The most critical aspect of the device construction was making sure the turbine gears were meshed securely at 90 degrees when measuring where the rods intersect the frame. I started by…

Fig. 9

To evaluate the ability of my design to harness the kinetic energy of water flow and generate electricity, I planned to test the device prototype in the Crum Creek.

- The Crum Creek spans miles and varies significantly in depth and width along its length, creating varying flow speeds at different locations. Since the Crum Creek has a slower flow and shallower depth than the rivers hydropower systems typically utilize, I chose a testing location that had a depth of at least two feet and relatively narrow channel creating a higher flow speed compared to other deep portions. This location of the Crum Creek also has a bridge built over the creek, allowing me to suspend my device into the water from above and monitor its performance.

- I measured the device's power output by attaching digital multimeters across the terminals of the generator to measure the output voltage and current, which are then used to calculate the power and evaluate its efficiency.

4 Results and Discussion

4.1 Device Results

- When testing my device in the Crum Creek, the turbines of my device successfully captured the kinetic energy of the flow and spun in opposite directions to converge at matching bevel gears, spinning the gear of the generator and inducing a detectable voltage. Based on the video footage, each turbine spun at approximately 0.416 revolutions per second, inducing a range of 50-80 mv across the generator and varying from 0 to 0.1 mA with 10 ohms of resistance. At 80 mv of voltage and 0.1 mA of current, my device generated a maximum of 0.008 mW of power.

4.2 Discussion

- The testing process was very short with only about a day of testing at one location, limiting the data on the results of my design, especially across varying flow conditions. My testing process was constrained by the lack of time left to complete the project…

- Although my device generated a very small amount of power, it was able to successfully generate a detectable amount of electricity from the flow of the creek. In that sense, my design met my requirement of prototyping a small-scale run-of-river device. On the other hand, it is difficult to determine if my design can be successfully built upon and scaled to produce more power on a small, transportable scale.

5 Suggestions for Future Improvements

5.1 Future Improvements for the Original Device

- In future iterations of the design, the performance of the device can be improved by optimizing the generator to fit the conditions and using a bigger gear ratio to create smaller gear with less teeth to make the gear smaller and allow it to spin faster

5.2 Improvements for Greater Application

One of the most important improvements that could be made for future iterations of the device is scaling up each component to create a system that resembles the original design but is able to generate upwards of 20 watts of electricity and power common devices like modern-day smartphones, almost exclusively of which are charged using power from electricity generated by fossil fuels. If I were to implement this improvement, I would first source a 15V-20V electric DC motor which I can use to generate up to 20 watts of power. Then, I would scale up the size of the axial hydro turbine designs according to my desired power output, keeping not only the estimated efficiency of the device in mind, but also the maximum power that the turbine can intercept which will be affected both by the scaling of the design and the velocity of the waterway. I would either construct the scaled turbine by hand using a different material than PLA as the Prusa i3 printer could not print a turbine of that size, or source a larger 3D printer that could accommodate the diameter of the turbine, allowing me to construct the full turbine from printing and adhering to each section. I would also source thicker stainless steel rods that will provide adequate support for the larger device components while connecting the turbine's gear to the bevel gear pair attached to the motor. To scale up each gear, I would first acquire new customized .stl files with the new larger rod thickness, then either scaling the gear using 3D printing software if a larger printer than the Prusa i3 is available, or constructing a larger version of the original design with the new center hole diameter by hand with a different material. The last aspect of the new device would be a scaled-up version of the protection chamber that is able to encompass the components of the enlarged device while remaining afloat.

6 References

- Currently a list of links, will be made a bibliography in APA format

- https://www.un.org/en/climatechange/science/causes-effects-climate-change
- https://www.thingiverse.com/thing:3682990
- https://ourworldindata.org/grapher/per-capita-ghg-sector
- https://www.americanrivers.org/threats-solutions/restoring-damaged-rivers/how-dams-damage-rivers/
- https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php#:~:text=The%20three%20major%20categories%20of,geothermal%2C%20and%20solar%20thermal%20energy.
- https://www.eia.gov/energyexplained/nuclear/nuclear-power-and-the-environment.php#:~:text=Nuclear%20energy%20produces%20radioactive%20waste,fuel%2C%20and%20other%20radioactive%20wastes.
- https://www.greenmatch.co.uk/blog/2021/09/advantages-and-disadvantages-of-renewable-energy