RUTGERS UNIVERSITY MARINE ENERGY COLLEGIATE COMPETITION 2024

BUSINESS PLAN, TECHNICAL DESIGN, AND BUILD AND TEST FINAL SUBMISSION

Prepared by:
Team Captain: Katherine Moreira, *Electrical Engineering Major, Computer Science Minor*
Team Secretary: Krista Chempiel, *Civil Engineering Major*
Engineering Lead: Kaetana DeGiovanni, *Mechanical Engineering Major*
Marine Science Lead: Zachary Soricelli*, Mechanical Engineering Major, Oceanography Minor*
Business and Marketing Lead: Rylie Gantz, *Mechanical Engineering Major, Sustainability Minor*
Team Member: Parie K. Patel, *Civil Engineering Major*
Team Member: Christopher T. Cafiero, *Mechanical Engineering Major*
Team Member: Paul Alves*, Animal Science Major*

Faculty Advisors:
Prof. Onur Bilgen, *Associate Professor, Mechanical and Aerospace Engineering*
Dr. Gregory Methon, *Postdoctoral Research Associate, Mechanical and Aerospace Engineering*

School of Engineering
Rutgers University – New Brunswick
Piscataway, NJ 08854, USA

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EXECUTIVE SUMMARY

The project created by RUPower, the Rutgers University Maring Energy Collegiate Competition (MECC) team, aims to address the pressing need for sustainable energy solutions in underserved communities with access to riverine resources. The ultimate goal is to develop a riverine hydrokinetic turbine capable of supplying electricity at low-cost. Our project is structured into three phases: the Business Plan, Technical Design, and Build and Test.

For the Business Plan, the objectives are clear: recognize market potential, determine possible infrastructural and financial outcomes when increasing scale, and realize opportunities for social connection and consideration. This challenge lays the foundation for understanding the chosen *Blue Economy Market* of "Community-scale Isolated Power Systems." This includes a four-step plan for market entry: 1. Community Engagement, 2. Site Assessment, 3. Customized Solutions, and 4. Installation & Training. Main revenue and expense streams were identified as well with sales, installation, and licensing as revenue and research, manufacturing, and marketing deemed as expenses. Lastly, interviews with professionals in industry assisted in gaining perspective on the logistics surrounding introducing a hydro turbine to market. The stakeholder perspective emphasized a multidisciplinary approach with discussion on wildlife considerations and advice on marketing strategy. Ultimately, at scale, it was determined that the overall cost of the turbine would be around $73,500 which considers the cost of development, installation, and maintenance.

The Technical Design objectives included optimizing efficiency of the harnessed river kinetic energy, refine turbine performance, and ensure reliability in various flow conditions. Technical development began with researching industry standards such as Kaplan and Francis type turbines for inspiration. The project finalized into a vertical-axis kinetic reaction turbine for its ability to operation under increased variability in flow conditions when compared to horizontal-axis, and being able to produce energy in no-head circumstances, purely utilizing the river current. Before building, the design process involved hand-sketching and creating a comprehensive CAD model to lay out the "revolving door" turbine design. The rotor's blade angle sits at 105° with respect to the positive x-axis which balances between efficiently capturing the kinetic energy of the river, and taking considerations of drag or turbulence into account.

The Build and Test challenge focused on the materials, fabrication, and testing of the hydrokinetic turbine, and validating the turbine response under various environmental conditions. The rotor and guiding vanes are created with 3D-printed PLA plastic for the prototype, the metal plate attached to the generator and the interior acrylic plates were machined, and all other components were adapted to the design. In experimentation, six environmental factors are tested: flow speed, wake and wash, turbulence, bridge piers, orientation, and marine debris. The tests are conducted in a combination of facilities including a wind tunnel for initial understanding of turbine efficiency, a water flume to simulate river conditions, and a water tank for marine debris testing.

Being our first year in the MECC, the team accumulated many valuable insights such as time management, the design process, and experiment development. It is knowledge that each member has earned and are lessons RUPower hopes to share with future teams.

BUSINESS PLAN

Authors: *Rylie Gantz and Parie K. Patel*

I. Concept Overview

The need for energy continues to increase due to population growth, development, and modernization of the world. As renewable energies start to become more reliable, our dependence on fossil fuels and nonrenewable sources needs to deplete. Hydroelectric power has proven to be a reliable renewable source of energy by harnessing the movement of water to generate electricity. River turbines are one example of hydroelectric power which relies on the current in a river, converting kinetic energy into electrical energy.

Renewable energy can be a very practical solution for the power needs of small communities that may be more remote and off the grid. If the resources required to continuously generate this power are low cost, then power becomes more assessable. Providing continuous energy to these communities will directly impact their living standards promoting economic development. Economic development benefits the community and its industries which can include agriculture, small-scale businesses, and possibly ecotourism. The RU Power team has a mission to ensure everyone has access to reliable and affordable electricity. Riverine turbines can create a sustainable source of energy for small communities that are within a reasonable distance to a river.

II. Market Opportunity

With an increasing awareness of climate change, various measures are taken to reduce the need to burn fossil fuels. There is a growing demand for renewable energy sources, especially those requiring minimal effort to set up and operate. Small communities, particularly in rural areas, heavily rely on burning fossil fuels for energy which is imported. Renewable energies, like river turbines, can provide these communities with energy independence. By harnessing the resources that are locally available to them it can provide a convivence factor ultimately creating a more sustainable solution. The IEA estimated that one gigaton of carbon dioxide emissions come from grid losses, equal to almost 3% of current global energy-related CO2 emissions (de Faria). Small-scale communities can help reduce those losses through contributing to the grid by generating and sharing energy, which overall enhances energy efficiency.

The market for river turbines is very small, however it has been experiencing steady growth. In recent years due to its increasing awareness. Comparing these to other renewable energy sources like wind, solar, and biomass, harnessing the power of water provides a more reliable and predictable output. However, each technology has its own strengths and limitations. Given the correct environment and conditions, a river turbine could change a small community’s life. Therefore, it is ideal to set customers up for success. If a river turbine is not a proper solution to implement in a certain community, then it is best not to proceed.

Many contributing factors need to be considered to determine a price for our concept. These factors include direct and indirect investments. Direct investments include cost of material, assembly, transportation, and construction. Indirect investments include long-term costs like operating costs, predictions of when materials may fail and require maintenance, and cost of labor. These costs will differ in value depending on the current project being considered. A location where there is a clear foundation to construct the turbine is going to require less startup investment than a location where land needs to be cleared or moved. Therefore, the best way to provide an accurate price for the concept would be a preliminary assessment. However, an accurate estimation of direct costs and some indirect costs can be modeled which is detailed in Business Model/Pricing.

Customer perspectives on the value of the concept will differ. Small communities tend to be more rural and remote. Individuals in the agricultural industry tend to be more aware of climate change and the steps required to work against it. When working within the Blue Economy of micro-grid communities the government plays a huge role. Financial incentives can be a tool to promote the concept of river turbines. One obstacle in itself is overcoming the lack of awareness of marine energy, which financial incentives can help speed up. These incentives include government grants, tax credits, feed-in tariffs, and performance incentives. The correct time to use incentives depends on the current state of the project.

The value proposition should be considered from the customer~~s~~’' perspective. It is crucial to successfully introduce and promote river turbine technology. The emphasis on energy independence is one key aspect that can be appealing to customers. Especially considering areas where there are frequent power outages. Community development is another important aspect to apply. Introducing a river turbine stimulates jobs, economic development, and community empowerment. Building a compelling value proposition that aligns with the customer’s perspective has a meaningful impact on achieving market success.

III. Problem Statement

When analyzing the market opportunity for river turbines in small communities a few different challenges that a rise. The challenges can be organized into three major obstacles: environmental and regulatory challenges, infrastructure and financial hurdles, and social considerations.

Environmental and regulatory challenges include the need for thorough environmental impact assessments. River turbines directly interfere with surrounding plants and wildlife. The current of a river plays a huge role in fish population and their migration patterns. River turbines, unlike solar and wind energy, are completely submerged in rivers. Therefore, considering all the environmental factors is crucial to conserve all surrounding nature. Obtaining permits and regulatory approvals is a huge obstacle prior to the construction of the project itself.

Infrastructure and financial hurdles are especially a challenge in the Blue Economy of small communities due to the limited financial resources. High costs associated with building infrastructure like transmission lines and grid connections are financial concerns. Securing funding will most likely require creative approaches and partnerships to attract investments.

Social considerations involve the public’s perception of river turbines. It heavily influences the success of the project. The appearance of wind turbines and how they affect landscapes is a very relevant issue. River turbines may also draw opinions from the community regarding affecting river appearance and landscape. However, unlike wind turbines located out in the sea, river turbines have the benefit of being out of sight of the common eye.

IV. Proposed Solution Overview

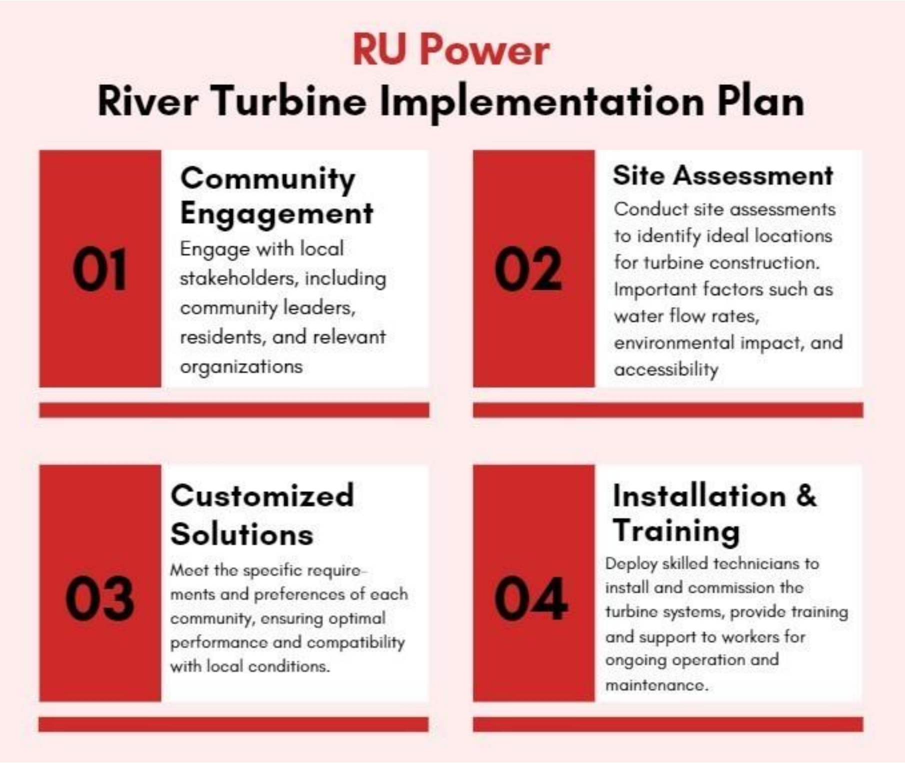
We propose the development and deployment of river turbine solutions specifically for the energy needs of small communities. Our river turbine solutions consist of compact and simply designed to be installed in rivers, streams, or canals.

Pollution can reduce biodiversity within water ecosystems and could drive certain species to extinction. River pollution encompasses various concerns such as nutrient imbalances, undesired salinity in freshwater environments, litter, and microplastic contamination. These challenges elevate the risk of diminished access to clean freshwater and heighten the possibility of water systems becoming breeding grounds for disease-carrying organisms. Thus, a pollution monitoring system will only serve to complement the community-scale river turbine.

Table 1: The three key figures of our turbine geared towards remote communities.

Compact and Reliable Design	Ease of installation	Low Environmental Impact
Our river turbines cater to the energy needs of the small community. It is also built with materials that are durable and able to withstand intense weather conditions and temperatures.	The river turbine has a relatively simple design which makes the manufacturing and installation process require limited technical expertise.	Turbine generates energy with minimal carbon emissions. We also have taken time in the technical design process to consider a pollution monitoring system and its implementation.

We have developed a four-step procedure to implement our river turbines in small communities. First, it requires community engagement. We need to engage with local stakeholders to access energy needs and find support for the project. Section 6 discusses our relevant stakeholders in more detail. Next, we need to conduct site assessments. Working with the community, the goal is to identify the most suitable location to install the turbine. Then, after analyzing the specific needs of the community, we create a customized solution to ensure we meet all the needs of the company. Lastly, we install the turbine and develop a plan to ensure there is enough support for long-term operations. This four-step procedure is represented in a Figure 1 below.



RU Power

River Turbine Implementation Plan

01 Community Engagement
Engage with local stakeholders, including community leaders, residents, and relevant organizations

02 Site Assessment
Conduct site assessments to identify ideal locations for turbine construction. Important factors such as water flow rates, environmental impact, and accessibility

03 Customized Solutions
Meet the specific requirements and preferences of each community, ensuring optimal performance and compatibility with local conditions.

04 Installation & Training
Deploy skilled technicians to install and commission the turbine systems, provide training and support to workers for ongoing operation and maintenance.

Figure 1: Our plan to implement riverine turbines broken down into four specific steps.

Table 2: Four stages of turbine development.

Stages	Development and Operations
Proof of Concept	• Generation of various sketches • Interviews with industry and governmental professionals
Developing the System	• Simulations in SolidWorks, troubleshooting potential issues • Simulating riverine flow vectors and their interactions with the turbine • Finding different pollution monitoring sensors to attach and designing how it would fit with the turbine system
Testing	• 3D printing and purchasing materials • Assembling components • Testing in the wind tunnel lab • Testing in the fluid mechanics lab
Continuation Engineering	• Troubleshooting areas with poor efficiency • Slight remodeling for more stability

V. Impacts, Risks, and Opportunities

i. Socio-Economic Impact

Our project aims to make riverine energy more accessible to all communities – particularly rural communities. By generating energy in a sustainable manner and at a low cost, positive short-term effects are created as more people have access to electricity which increases social mobility.

ii. Ecological Impact

Hydroelectric systems can disrupt aquatic ecosystems as essentially you are inserting a foreign object into the body of water (in this case rivers). However, by creating a closed system, we prevent any sediment, aquatic flora, and fauna from entering the system and unintentionally becoming entangled or entrapped within it – thus minimizing the ecological impact.

iii. Upfront Project Risks

Dangers to turbine operation that were considered to be most likely are detailed below in Table 3.

Table 3: Project risks described by cause and rated for an estimated risk level.

Cause	Description/Mitigation	Estimated Risk Level 1-5*
Extreme Weather Conditions	Damage to the system due to extreme environmental conditions	4
Corrosion/Wear-and-Tear	Overall conditions that would lead to components needing repairment or replacement	3
Aquatic life interaction	Interaction of aquatic life and the system, leading to disruption for both the turbine and riverine ecosystem.	1
River flow variability	Using the Raritan River as the testing site – different seasons and watershed conditions can lead to variable river flows.	4

*Increasing levels of risk

VI. Business Model and Pricing

Our business model is structured to integrate river turbines into small, remote communities. The first aspect of the model is the value proposition. We plan to provide affordable and sustainable electricity solutions for these communities, especially those who currently rely on diesel engines and burning of expensive fossil fuels. We hope to offer reliable energy sources that overall reduce environmental impact through harnessing river current.

To tailor our market and turbines to better meet the needs of customers, we can divide the customer base into groups that share relatively similar characteristics. We have identified four main Customer Segments: small rural communities without reliable access to electric, off-grid communities located near rivers, small communities looking to implement renewable energy solutions, and development agencies focusing on community empowerment,

We can use various channels to deliver the turbine and its services to these different customer segments. The simplest channel is direct sales to community leaders or municipal authorities. Other channels could include partnering with local installers or energy cooperatives. Community engagement plays a huge role in developing channels. We could create an online presence and participate in local events to reach many different customers and spread awareness of our river turbine.

There are a few key aspects that are essential to consider in order to establish a successful business model. These include key resources, key activities, and key partnerships. Key resources refer to assets, capabilities, and infrastructure required to deliver our value and product to customers. Resources include river turbine technology, technical expertise required, partnerships with suppliers and energy companies, and reliable access to financing (which may be one of the more crucial resources). Key activities highlight the tasks that must be accomplished that we, RUPower, must accomplish to deliver value proposition to customers. We have identified four key activities, ranking in chronological order: marketing and sales efforts, site assessments, installation, and training. It's also vital to establish key partnerships with various individuals including government agencies, local contractors/electricians, and regulatory bodies and utilizes. These partnerships are key in receiving funding, maintaining affordable pricing, and permitting.

Main revenue streams and expenses can be seen in Table 4 below:

Table 4: Main revenue streams and expenses.

Main Revenue Streams	Main Expenses
Sales of river turbine systems	Research and development
Installation and training services	Manufacturing cost
Maintenance contracts	Marketing and sales expenses
Licensing or royalties	Installation/project management
Electricity sales	Ongoing maintenance

Collecting data and understanding key metrics can help identify overall performance. These metrics include the number of turbines installed, total revenue from sales and services, a customer satisfaction rating, the energy output, and performance of each turbine. The total environmental impact is another important metric to consider, which can be quantified in various ways. The simple business plan presented is modeled to provide energy solutions to small communities, placing emphasis on affordability, sustainability, and reliability.

By conducting interviews with industry and governmental professionals as part of the Community Connections submission, we were able to gain invaluable insights into our potential market and learned more about potential stakeholders.

Stakeholder 1:

Bill McShane

- Technology Manager at the Water Power Technologies Office (WPTO)
- Specializes in R&D engineering; he explores a machine's various control systems to determine which of those systems functions best for optimal energy
- Touched on the low cost and low risk of marine energy in terms of production and how emphasizing those attributes could effectively spread awareness

Stakeholder 2:

Joseph Ruggeri

- New Jersey Department of Environmental Protection (NJDEP)
- Civil engineer with a focus in flood mitigation
- Specializes in dam structures and has significant insight into environmental awareness
- Implements fish ladders and removes any concentrated sediment before releasing a dam

Stakeholder 3:

Mikaela Freeman

- Pacific Northwest National Laboratory (PNNL) Marine Science and Environmental Policy Analyst focusing on Marine Energy Outreach and Engagement
- Emphasized the importance of providing the public eye with a visual of our project, as that is what marine energy is lacking
- Being underwater, marine energy systems are a "mystery" to the general public and are therefore misunderstood

Stakeholder 4:

Ryan Coe

- Wave Energy and Fluid Dynamics Modeling Specialist conducting research under the Sandia National Laboratories' Water Power Technologies Program
- Discussed the challenges of deploying and maintaining marine energy technology
- a diversified renewable energy grid is essential for a chance at a sustainable future and should therefore be prioritized regardless of the challenges
- "The wind doesn't always blow, and the sun doesn't always shine."

VII. Financial Analysis

Analyzing the finances of implementing our river turbines in small communities can provide us with useful information and show us where costs lie. We can break down project expenses into three scopes which can be seen in Table 5. The first scope specifically looks at expenses for the turbine itself. Scope 2 highlights the process of installing the turbine into the river current. Finally, Scope 3 looks at more long-term costs following the installation process.

Table 5: Financial analysis broken into three main scopes.

Scope	Project Expenses	Cost/Unit
Scope 1	Turbine Materials	$5,000
	Turbine Manufacturing	$20,000
	Total	$30,000
Scope 2	Turbine Installation Materials	$10,000
	Project Management & Construction	$25,000
	Labor/Transportation	$3,000
	Total	$38,000
Scope 3	Maintenance	$2,500
	Labor/Training	$2,000
	Total	$5,500
Total		$73,500

Affordability is a major factor we consider when conducting a financial analysis, especially because our customer base is a small, remote community. There are various adjustments we can make to create a more affordable solution including choosing cheaper materials that are still durable in the same applications, as well as adjusting the size of the turbine to fit the needs of our customers.

VIII. Conclusions

The market opportunity for riverine turbines is steadily increasing, driven by the awareness of climate change and the need for sustainable solutions. Despite upfront project risks and costs, it can be seen that the socio-economic and environmental benefits outweigh the challenges. This has been emphasized through conversations with industry professionals who recognize this and have shared their insight on the market with a multidisciplinary lens. Through community engagement, customized solutions, and recognizing the needs and risks of each project, the implementation of the riverine turbine has the potential to empower communities to generate their own reliable power.

TECHNICAL DESIGN

Authors: *Kaetana DeGiovanni and Katherine Moreira*

I. Objective Statement

This technical design description develops the concept behind a vertical-axis riverine kinetic turbine to support renewable and clean energy efforts for isolated power systems in remote communities.

II. Background

Remote communities with a local river can utilize the stream's kinetic energy to support the people's electricity needs. The design is specifically designed to cater to these communities. When considering the development of a riverine turbine to generate electricity, two common systems to capture this energy are dam and run-of-the-river systems.

i. Dams and Run-of-the-River

Hydroelectric dams utilize potential energy in combination with kinetic energy to generate electricity. Although the energy is carbon-free from being with renewable energy, the construction of the dam structure is not. The actual concrete being utilized is developed with unclean methods of heating limestone and the construction of the dam itself tends to utilize unclean equipment. The presence of dams can affect water quality due to the sediments eroded from the interaction with the water flow. Dams change the ecosystem patterns, "Large dams change the ecosystems of the river upstream and downstream. Upstream organisms that relied on oxygenated inning water may suffer when their former habitat is now still, de-oxygenated water as flowing water has a higher oxygen content than still water. The food supply will change. Organisms that relied on those organisms may struggle." (Simpson). These ecosystems are permanently changed and the continued introduction of dam structures to different areas continues the cycle of changing ecological patterns due to human interference.

As awareness of environmental and social impact grows in this area, there is a shift towards smaller hydropower plants which interact directly with a river stream without a dam structure, deemed "run-of-the-river". Run-of-the-river systems are a preferred alternative due to their reduced environmental footprint and overall lower capital costs. "The derived uncertainties of climate change on [hydropower plants], especially on large ones that have an immense capital investment cost, together with the undoubtable environmental and social impacts of conventional hydroelectric dams at basin scale, have proclaimed small hydropower plants (SHPPs) and, particularly, the run-of-river (ROR) type as the new alternative." (Skoulikaris). With the future leaning towards more cost-effective and environmental solutions for obtaining electricity, the design outline in this report utilizes a run-of-the-river system approach.

ii. Turbine Axis

Another key consideration is the turbine orientation, with horizontal and vertical axes as the primary options. Horizontal axis turbines have blades which rotate on a horizontal axis parallel to water flow direction. Horizontal axis turbines tend to have higher efficiency than vertical axis turbines; however, horizontal turbines are less versatile due to having additional volume and having limited flexibility in the flow conditions.

Vertical axis turbines have blades that rotate on the vertical axis perpendicular to the water's flow direction. Vertical axis turbines can operate efficiently in a wider range of flow conditions than horizontal and cross-axis, including low-flow and turbulent conditions. Vertical axis turbines also have omnidirectional operation which can capture energy from water flow in any direction, providing greater flexibility and adaptability to changing flow patterns and site conditions. A key characteristic is also the simplicity of a typical vertical design, allowing for ease of installation and maintenance, also providing reliability due to fewer operational components. This can also be seen as a benefit depending on the environment of the turbine and is a great benefit for the manufacturability of the turbine.

An advantage taken heavily into consideration is the existence of traditional dam structures with integrated hydro systems meant to provide energy to the grid. This turbine deviates from this standard to consider remote communities which may not have ideal circumstances for these systems. A run-of-the-river, vertical axis turbine has advantages to benefit isolated populations.

iii. Reaction Turbines

The Francis turbine is a reaction turbine – the turbine generates power from the combined forces of pressure and moving water – with fixed runner blades where water is introduced just above the runner and causes rotation in medium to high-head cases (130 to 2,000 ft) (WPTO). The Francis turbine was initially taken into consideration on account of its wide-spread usage in the hydropower market. The turbine has a high efficiency and flexibility from its capacity to accommodate a broad spectrum of head heights. However, our design aims for a lower head application than is capable of the Francis turbine and was not pursued further.

The Kaplan turbine is also a reaction turbine where both the blades and the wicket gates are adjustable for a wider range of operation (WPTO). Kaplan is very efficient in variable flow conditions and requires minimal head to operate as expected, also has less blades than most other turbine standards (ClubTechnical). Due to these characteristics of the Kaplan turbine, it was the inspiration for the initial designs developed throughout the team's design exploration as these features match well with the blue economy market.

The Francis and Kaplan turbines were studied in the design development process. However, RUPower later focused on a kinetic turbine – also a reaction turbine – which generates electricity purely from the kinetic energy present in the river flow rather than potential energy from the head (WPTO). The generation of electricity in no-head conditions was the primary driver for this change in our design. As no-head conditions are optimal for the performance of turbine, it can ideally be placed wherever it is needed and meet the most demand.

III. Design Exploration

The RUPower team worked together to discuss a multitude of varying ideas for our turbine, and through an iterative design process, adjusted the designs over time. The team's original designs were inspired by a Kaplan turbine with high efficiency for low-head applications such as a river environment. The guiding vanes of this design were originally intended to house a pollution monitoring system to assess the river conditions. A standard Kaplan turbine in shown in Figure 2.

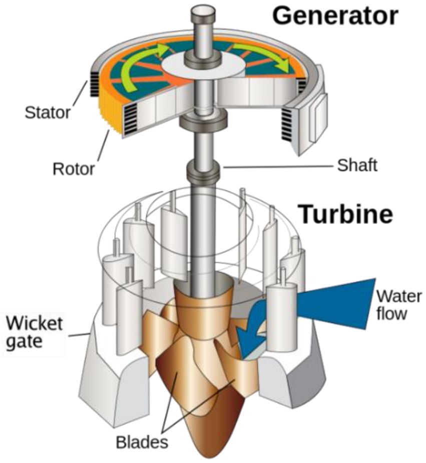


Figure 2: The team originally took inspiration from Kaplan turbine. (Source: Linquip)

Figures 3, 4, and 5 show the initial designs proposed for the team's Kaplan-inspired turbine. It was intended that these designs would also include a penstock pipe to direct the water flow over the runner blades to induce rotation. The turbine's testing environment is the wind tunnel at Rutgers University, which has dimensions of 20" x 28". However, the testing space was limited to about 8" x 8" to prevent the wind tunnel boundaries from interfering with the tests. Due to this space limitation, the team had to reconsider this addition of a penstock device to control the water flow. After being scaled down, Figure 5 was the primary design inspiration moving forward.

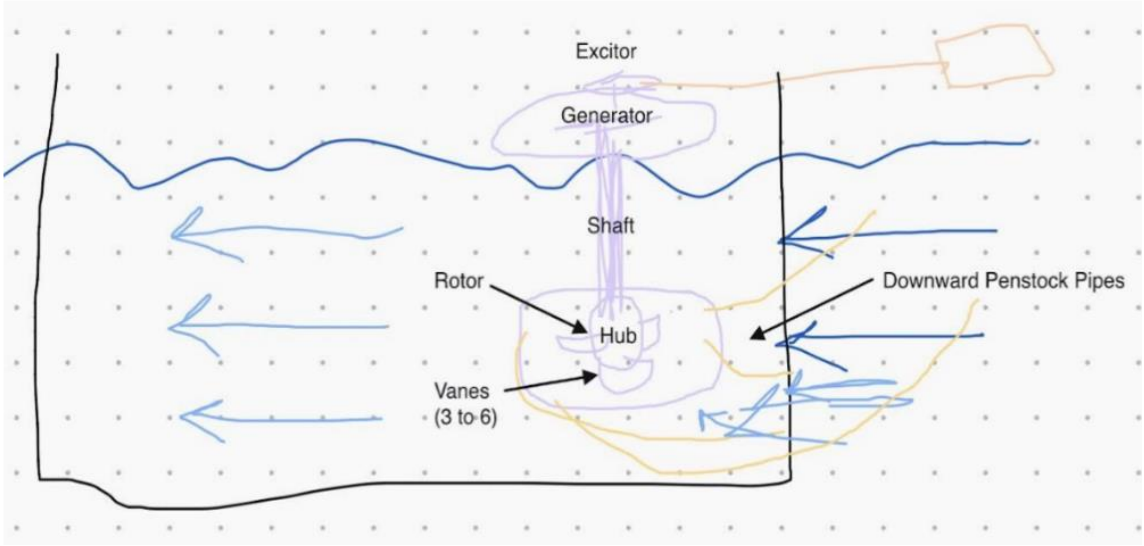


Figure 3: Initial turbine sketch based on Kaplan turbine.

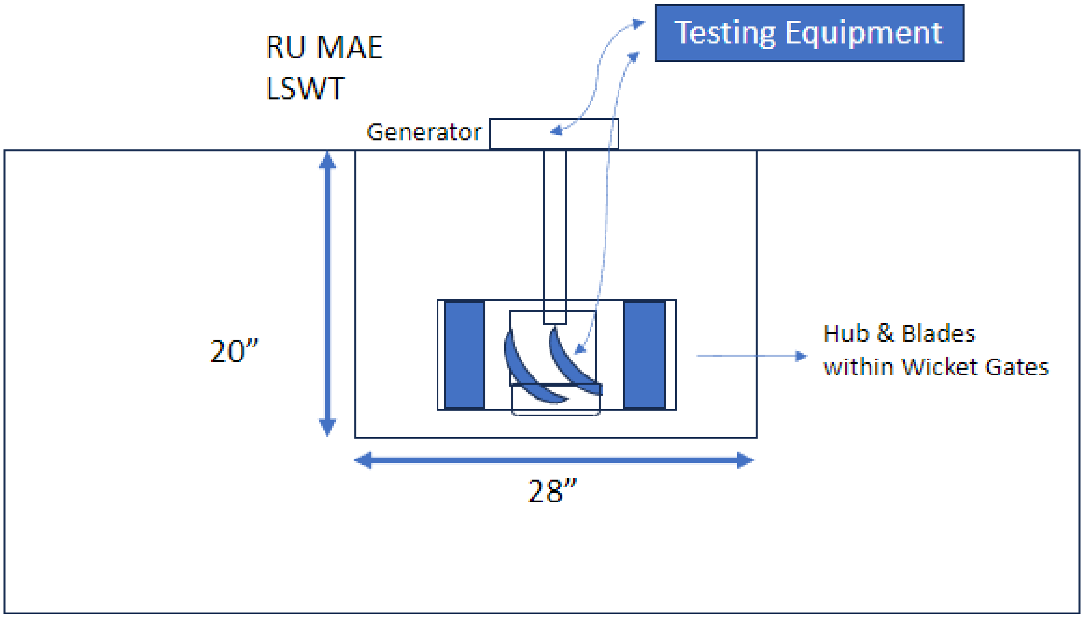


Figure 4: Initial consideration for testing setup in the wind tunnel.

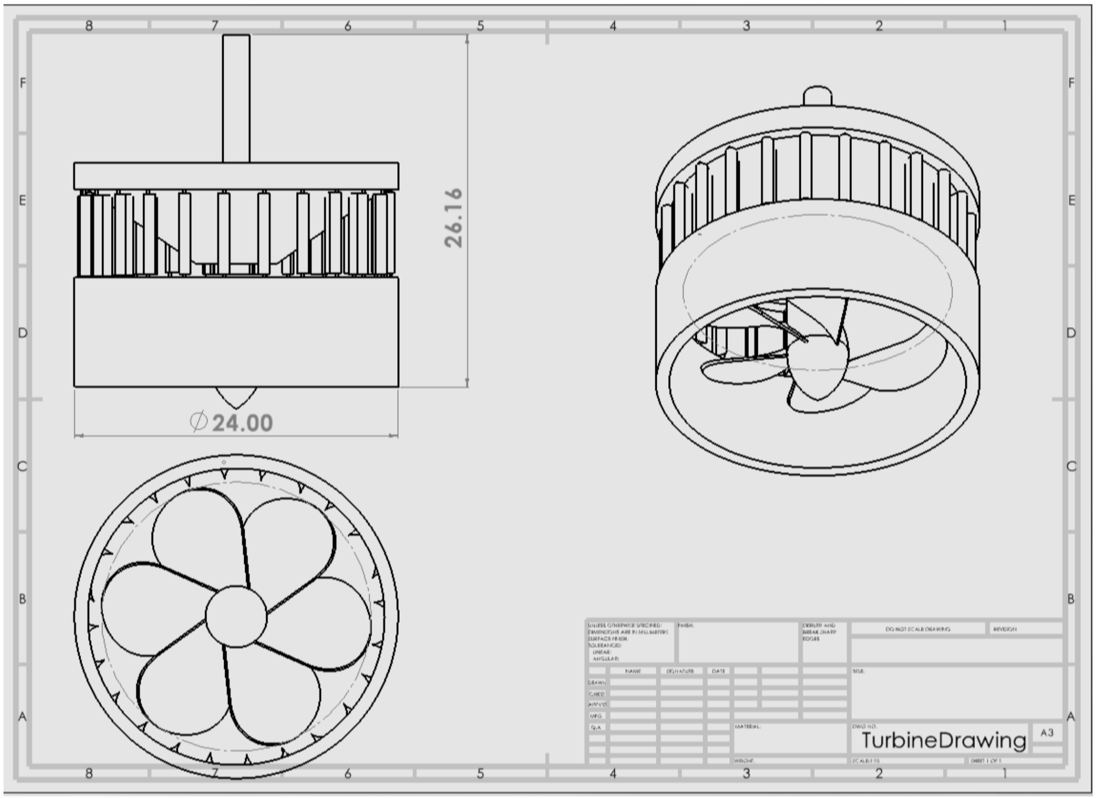


Figure 5: Proposed turbine assembly design engineering drawing, based on Kaplan turbine without a penstock pipe.

Kaplan turbines typically have adjustable guiding vanes and rotor blades which change angle depending on the water flow across the turbine. We adjusted our SolidWorks model to allow for this movement. To allow for the adjustment of the blades, the hub shaft sat on a plate raised and lowered by the rotor blades based on their angle. The blades were attached to hinged bearings allowing for this up and down motion as seen in Figure 6.

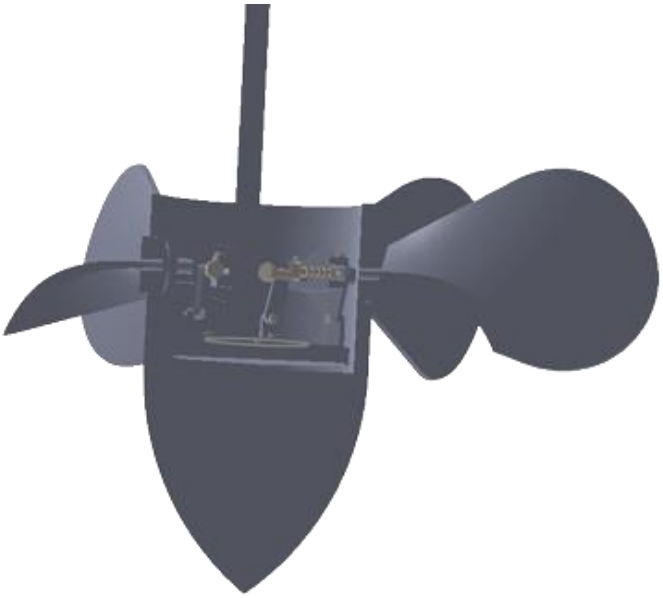


Figure 6: This design allows for movement of the rotors to adjust the blade angle depending on the flow.

Design changes occurred once the team realized we would not have the capacity to add a penstock pipe or any tubing to force a downward flow over the rotor. With the above designs, the introduction of downward flow would not be enough to have a favored output, and the flow had potential to go through the guiding vanes and not hit the rotor. Due to this, it was decided to move the guiding vanes to be level with the rotor as seen in Figure 7. In addition, we omitted the concept of adjustable guiding vanes and rotor blades due to the small size of the turbine and the materials we had access to and the difficulty it would add to the building process. The final rotor was 3D-printed as one solid part.

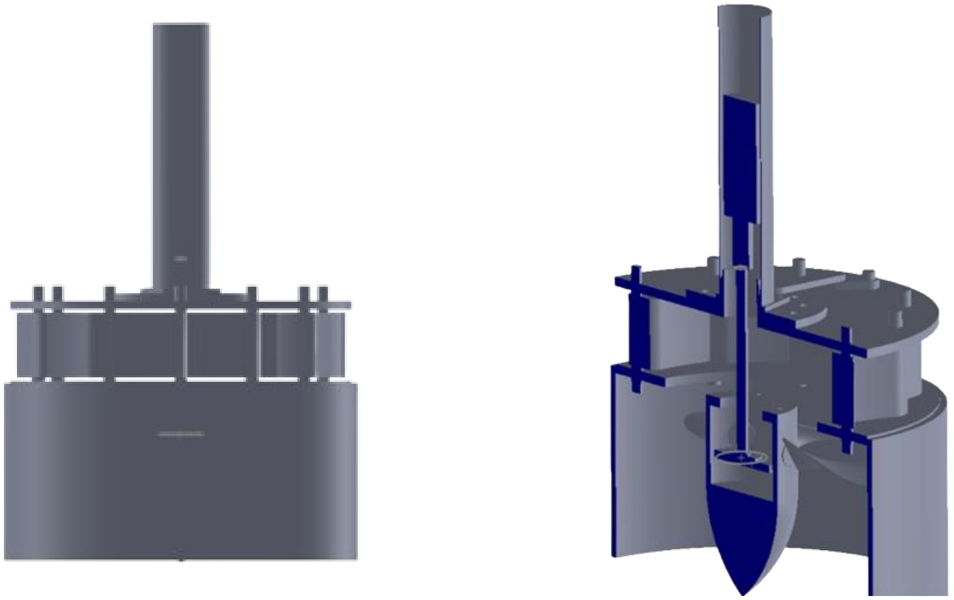


Figure 7: This design allows for the movement of the guiding vanes to control fluid flow.

As shown in Figure 8, the draft tube was adjusted to have an entry and outlet window for water to flow across the blades and guiding vanes were going to be secured externally. We also adjusted the rotor and hub design to print as one solid piece for ease of assembly, but it occurred to us how difficult printing this type of shape might be. We decided to keep this foundation and adjust our rotor slightly for the final design. Additionally, up until this point we had been intending to connect our 3D printed hub directly to the generator shaft to maintain the turbine's compact size, however we decided to include a center shaft in our final design for additional stability and prevent misalignment.

Figure 8: A design modification made to have guiding vanes level with rotor blades.

IV. Technical Design

Moving forward it was decided that our turbine would have a unique “revolving door” rotor design with guiding vanes fixed at 90 degrees to force flow over the large blades for easy rotation. The shape of the rotor and blades were adjusted so that it mimicked an angled revolving door shape. The new larger blades allowed fluid to flow completely over the rotor to induce maximum rotation. This design is a purely hydrokinetic turbine, not dependent on the potential energy from head difference.

i. Turbine Overview

The engineering drawing shown in Figure 9 is of the SolidWorks model of what would be the final design to be prototyped.

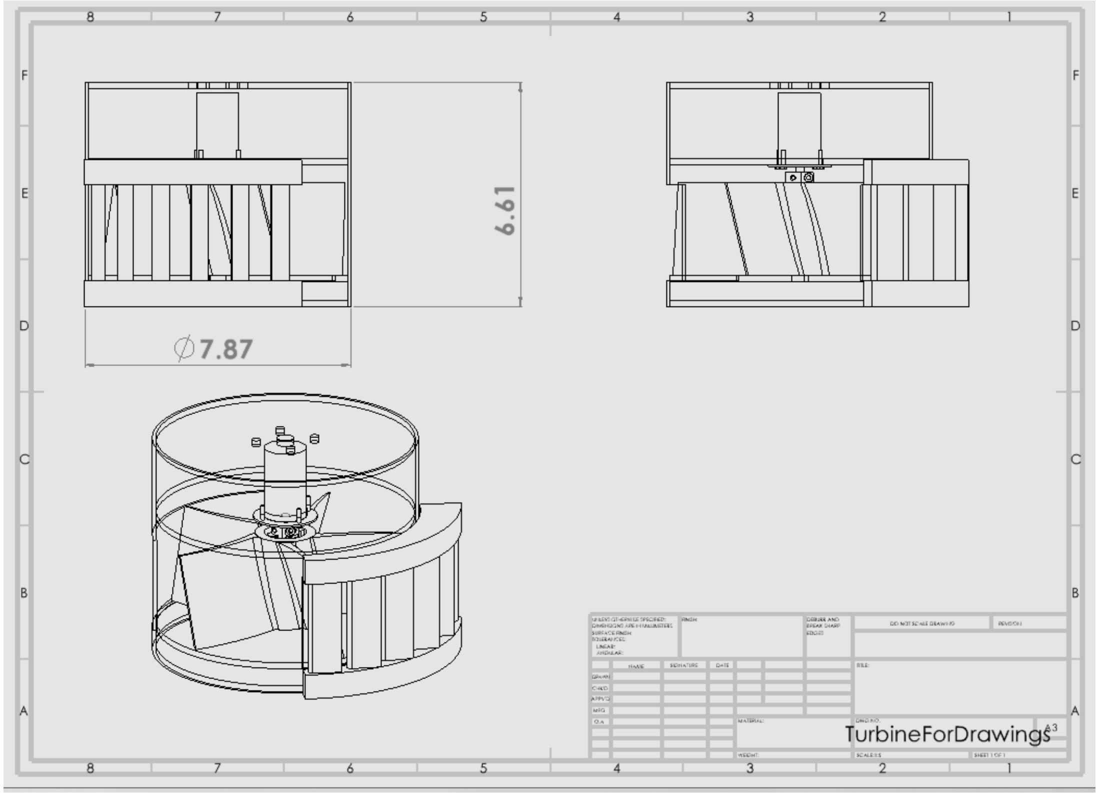


Figure 9: Engineering drawing of final turbine design.

In Figure 10, attached to the top plate is a flange-mounted shaft support, used to mount the device into a ½” rod in the wind tunnel for testing, and is not needed for the water testing zone. The final design features a PLA 3D printed rotor blade with a 1310 Series Hyper Hub attaching the generator to the internal rotor shaft and a 1309 Series Sonic Hub securing the shaft to the bottom of the rotor. The shaft is secured into the rotor with ball bearings to allow for easy rotation. The draft tube is a clear acrylic pipe fitted with four acrylic plates. The upper most plate holds the mounted shaft support; the next plate supports the generator and houses the electronic components and is watertight from the use of PVC glue. The plate below the rotors is fitted with a ball bearing to secure the shaft, and below is one additional plate to ensure that it is waterproof. A 3D printed set of guiding vanes is secured with the same glue on the outside of the draft tube.

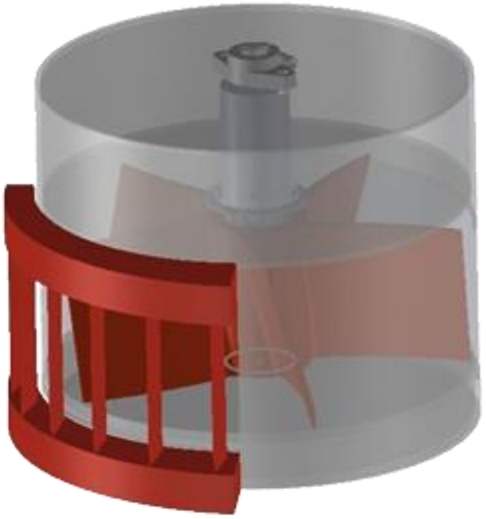


Figure 10: CAD model of final turbine design.

ii. Isolated Systems and Components

Electrical Subsystem

In the prototype, a permanent magnet DC motor of 24 VDC operates as a generator. The mechanical rotor of the turbine spins from the river current and transfers its rotational energy to the generator for electrical energy. The motor is standard in that the mechanical rotor connects to the generator shaft connected to the rotor. The rotor spins in the center of the electrical stator. There are four motor leads total, two are red & blue and are the output leads, blue is positive and red is negative. There are also yellow & green leads for a tachometer output which provide a series of pulses that approximate the supply voltage when measured on an AC voltmeter. For the small-scale model, there is no additional circuitry required to connect the turbine to the load other than the output leads due to the DC-to-DC connection.

At scale, a different approach would be applied as the application for the electricity would differ. A permanent magnetic synchronous motor would harness the power of magnetic fields created by spiral movement of the magnets within their core to convert kinetic energy to electricity. The utility of an AC synchronous generator with rectifier and bridging circuitry will allow the transfer of electricity for longer distance transmission. This integration is to ensure an efficient and reliable power supply to meet the energy needs of a community.

Mechanical Subsystem

A shaft was reintroduced to the final prototype to better support and reinforce the rotor. This addition was intended to increase durability to the 3D printed rotor to handle axial and radial loads during operation. The team added a ¼” stainless steel shaft which was cut to fit the length of the rotor, two ¼” ball bearings secured to the ½” inner rotor diameter, as well as two hubs to connect to the top and bottom of the shaft. This can be seen in Figure 11.

Figure 11: Design with generator directly connected to rotor hub (left). Design with a shaft and bearings connecting rotor and generator (right).

This design also features long runner blades as seen in Figure 12, with a large surface area to capture all the available flow, allowing for ease of rotation. Fluid flow is directed perpendicularly to the long, wide blade shape by the guiding vanes.

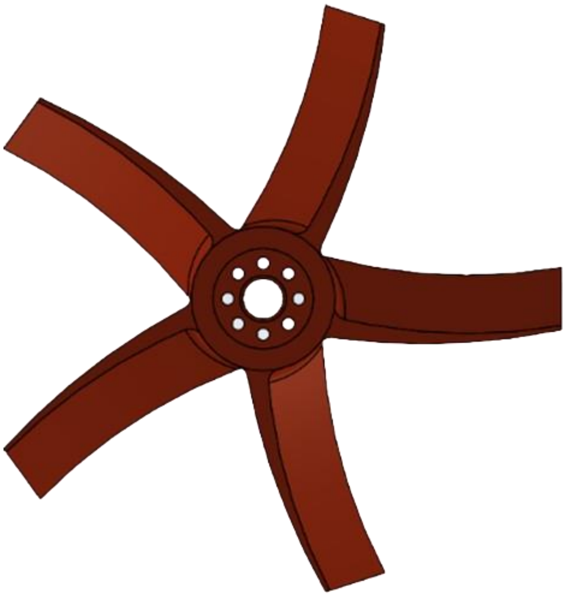


Figure 12: 3D-printed rotor with a ½" center hole for the ball bearings and shaft, as well as tapped holes for the screws of the connection hubs.

Water is being pushed over the rotor blades horizontally instead of vertically, requiring less force to rotate. This is assisted by the angle of the blades themselves at 105° with respect to the positive x-axis. The orientation is modeled below in Figure 13.

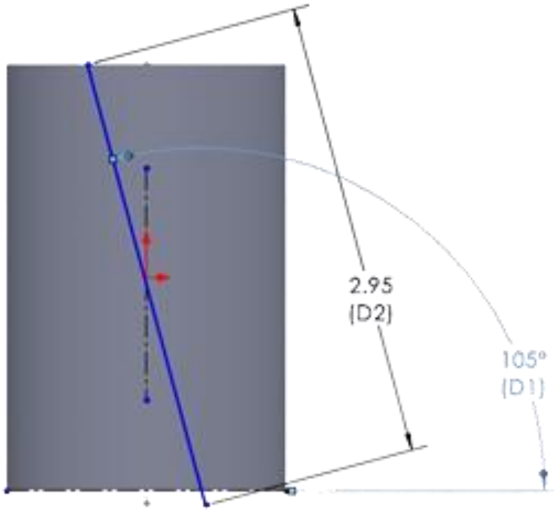


Figure 13: Turbine rotor has a blade angle of 105° or 75° with respect to the positive x-axis.

$$V_{flow} = \frac{Q}{A} \tag{1}$$

$$P_{in} = \rho g H Q \tag{2}$$

$$\tan(180° - \theta) = \frac{V_{flow}}{V_{whirl}} \tag{3}$$

$$P_{out} = \rho g (V_{whirl})^2 \tag{4}$$

$$\eta_{runner} = \frac{P_{in}}{P_{out}} \tag{5}$$

$$P_{in} = \frac{1}{2}\rho A v^3 \tag{6}$$

The equations 1 through 6 describe a reaction turbine's flow parameters and how they impact the output power and turbine efficiency (Azad). The flow velocity V Flow refers to the incoming river velocity. The input power to the turbine comes from the fluid flow where ρ is the density of water in lb/ft^3, g is gravity in ft/s^2, H is head in ft, and Q is the flow rate calculated from equation 1. The optimal blade angle can be found experimentally depending on known flow parameters. In equation, 3 vWhirl is the tangential velocity as it enters the turbine runner and can be calculated for varying blade angles. The output power, as seen in equation 4, depends on this tangential component of the velocity, as it generates the rotor rotation.

However, these equations differ slightly for our hydrokinetic turbine's unique rotor design. The turbine we have developed is used for no head applications, therefore equation 6 is used for power input from the flowing water. The cross-sectional area of the water flume is 1’ by 1.5’ and the height can be adjusted to test different flow velocities.

iii. Foundation

The foundation of many riverine turbines usually includes a draft tube and penstock pipe. A penstock pipe controls the flow of water to the entry of the turbine, they can span several feet long, or even spiral to create a flow vortex over the blades (EERE). A draft tube directs the flow at the outlet of the turbine and is primarily used to prevent backflow of water back into the turbine due to the pressure difference. These components are seen in large scale and run of the river applications (Testbook).

Our small-scale turbine’s foundation serves as the penstock pipe, draft tube, and rotor housing by directing flow over the rotor blades. This housing is constructed from clear acrylic piping with an inner diameter of 7.68” as well as entry and outlet dimensions of 5.57’’ by 2.83’’. Despite this housing missing crucial features of a traditional penstock pipe and draft tube, design choices in other areas of the turbine make it so these features are not necessary. The large rotor blades help to capture all the available water flow without having to divert it in various ways, and due to this design not utilizing potential energy from head differences, there is no concern for backflow.

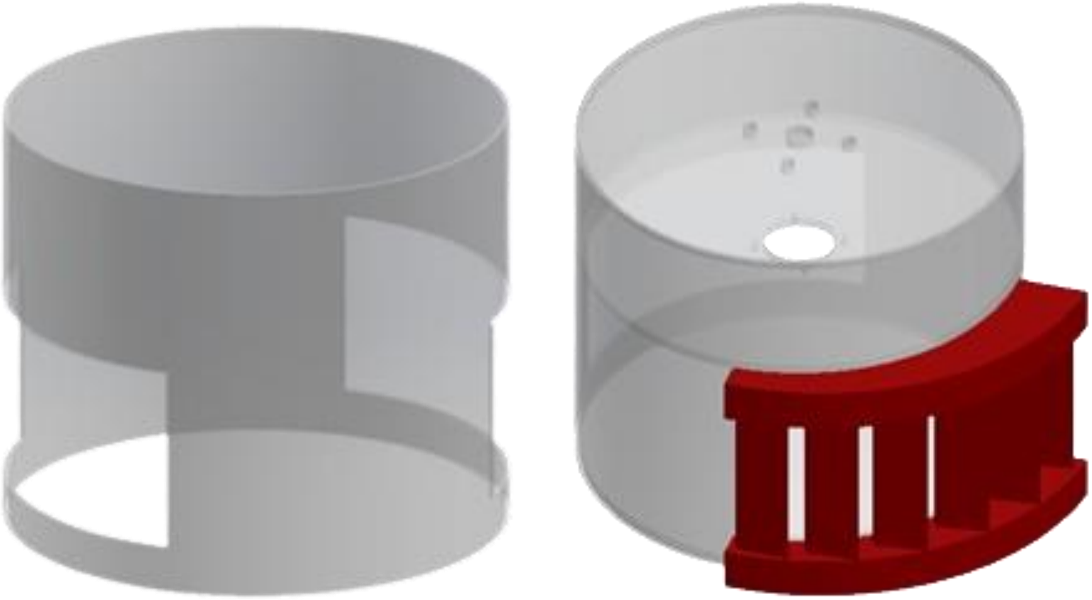


Figure 14: Turbine foundation (left) and the addition of fixed guiding vanes (right).

Both Francis and Kaplan turbine designs feature adjustable guiding vanes which aim to direct the water flow to the turbine rotor by adjusting the angle of the guide vanes to all have the same angle, this angle depends on the available water flow. The regulation of the guiding vanes is coordinated with the turbine blade’s angle for maximum efficiency. Guiding vanes are also designed to convert turbulent flow upstream into laminar flow at the turbine blades. Turbulent fluid flows pass through the guiding vanes to effectively harness the kinetic energy of the fluid.

Typically, these guiding vanes are arranged in a circular wicket gate around the turbine entrance's perimeter. However, due to the unique input and output windows, it was decided to position the guiding vanes directly in front of the entry window to the rotor. The guiding vanes are attached to the foundation with waterproof PVC glue. The guiding vanes on our design are completely stationary, directing flow to be perpendicular to the rotor blades to allow for maximum rotation of the turbine.

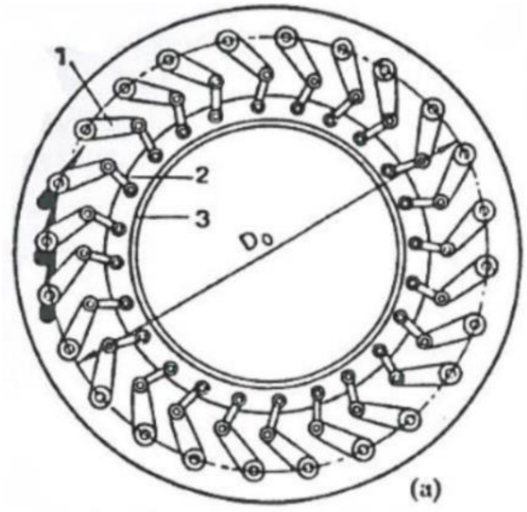


Figure 15: Guiding vane system on a regulating ring (3) with levers on the upper pivot point (1) and shackles and pull rods connecting the levers (2). (Source: Krivchenko, 4.1 Guide vane operating gear, 1993)

V. Community-Scale Isolated Power Systems

River turbines are pivotal in the blue economy market and especially relevant to communities along these rivers. Therefore, the RUPower Team has elected to concentrate on community-scale isolated power systems as our blue economy market. Our small-scale hydrokinetic turbine design is easy to install, and does not require the use of a dam, making it perfect for multiple types of rivers. The goal of this turbine's development is that a river community will have access to continuous and reliable electricity essential for improving living standards and local economic development. This economic development will directly benefit the community and its industries which can include agriculture, small-scale business, and possibly ecotourism. Furthermore, this river turbine would be resilient against the impacts of climate change as it will maintain its output of energy supply even as the flow patterns of the river vary due to changing conditions over time. A river turbine would help to reduce these effects of climate change by replacing harmful methods of obtaining power, such as fossil fuels.

VI. Pollution Monitoring

In addition to electricity, access to clean freshwater is a global necessity. The primary power production method currently used by these communities are diesel generators; however, the cost of fuel is higher for remote locations. Diesel fuel contributes to water pollution in and around these communities. Pollution may lead to a loss of a water ecosystem's biodiversity and may even contribute to the extinction of certain species. There are many different concerns about river pollution including nutrient imbalances, unwanted salinity in freshwater systems, garbage, and microplastic pollution. These issues increase the likelihood of compromised access to quality freshwater and increase the potential for water systems to become breeding grounds for disease-carrying organisms. In a commercial scale turbine of this kind, it would be beneficial to include a pollution monitoring system to assess water quality.

VII. Community Connections

To combat environmental issues prevalent in riverside communities, the RUPower Team initially hoped to incorporate pollution monitoring into the final prototype. The ability to monitor pollution and river conditions can help bring awareness to this issue in local communities. By having this information available publicly and easily accessible, it could motivate local community members to learn more about these issues thereby aligning with our community connections mission of improving “Marine Energy Perception.”

It was intended to mount sensors for pollution monitoring to the guiding vanes of our turbine design; however, due to size and material constraints, this could not be implemented in our prototype. There exist small electronic water quality monitoring devices such as total dissolved solids meters, or high accuracy pen-type pH testers, which could be implemented upon further research. The addition of a pollution monitoring system will benefit the local community through additional power generation with the added improvement of pollution monitoring. This will increase awareness of the issue and encourage a standard, or at least provide a foundation, for the continuous assessment of our waters.

Traditional hydropower setups operate at a much larger channel width and depth, causing interruption to marine ecosystems. However, vertical axis hydrokinetic turbines have been deemed minimally intrusive to local wildlife, by allowing aquatic life to pass around and through. Studies have examined the implications of these turbines on fish movements and behaviors, and findings demonstrate that turbine presence and operation do not prevent fish from passing around or through the turbine area (Müller). These turbines feature a more open design and low rotational speed, both assumed to reduce the risk of fish collision.

Upon completion of prototyping, we had the opportunity to speak with some possible end users of our device. We spoke with members of the Rutgers chapter of Engineers in Action (EIA), a college organization which builds bridges in remote communities across dangerous river crossings to connect these communities to schools, hospitals and overall make travel safer and more efficient. We decided to reach out to EIA due to their extensive work in remote communities, and to get their feedback on which regions would benefit from setting up community microgrids powered by hydrokinetic turbines.

The organization’s president described his experience working and living in Eswatini, Africa, a small country bordering South Africa. Eswatini is reliant on coal power, but has none of its own power plants; all their electricity comes from South Africa. Because of this, the country experiences stretches of prescribed blackouts. These communities would benefit from small-scale renewable energy systems to start during these blackouts. RUPower envisions a university organization, similar to EIA, whose goal is to bring reliable access to electricity to these isolated communities by installing a scaled-up version of our riverine turbine.

VIII. Conclusions

This project represents the prototype that the RUPower team designed and developed throughout the course of our first year in this competition. The technical report highlights the valuable insights gained through research and multiple design iterations as well as the prototyping process. The process involved careful consideration of various turbine routes, ultimately landing on the unique “revolving door” mechanical rotor design with fixed guiding vanes at its entry. A key element to the design is the mechanical subsystem which includes a stainless-steel shaft to the interior of the rotor to ensure durability and prevent misalignment. This also ensures reliable operation and minimizes the loss of output power. In addition, communication with organizations like Engineers in Action supported in emphasizing the importance in this type of technology becoming more available and accessible and identifying the types of suitable regions and operations of this turbine. In short, the technical design focuses on the development of a vertical-axis hydrokinetic turbine which caters to areas where traditional hydropower systems are not feasible, affordable, or environmentally sustainable.

BUILD AND TEST CHALLENGE

Authors: *Krista Chempiel, Christopher T. Cafiero, and Rylie Gantz*

I. Design Process

The design process of our hydrokinetic river turbine began with researching and understanding ways in which fluid flow can be optimized. Exploring the current market and developing an understanding of the various types of hydropower turbines was the very first step in the process. Grasping these different concepts knowing that our intentions were to build and test some type of device was an important reminder. We needed to set goals that put us in an environment to learn, challenged us, but where an end project could be produced. The process required us to think through the various resources Rutgers provided and how we could use them to our advantage.

After brainstorming, we created rough hand sketches to gauge each other's ideas and concepts. We collaborated and analyzed several different design ideas and eventually settled on one that proved to be the simplest, therefore assuring the turbine would perform a desired output. We took into consideration the role of water and the areas that needed to be sealed. A cylindrical shape with various plates worked well with protecting the blade and allowed for a sealed container for the generator and other electrical components to sit in. After selecting a generator that was suitable and could meet our needs, we began transforming our conceptual design into a physical design.

We differentiated the parts that would require fabrication and the parts that we could purchase. Using SolidWorks, we developed several different models which gave us a good understanding of what works and what does not work. At this stage of the design process, seeking feedback from various advisors was crucial to successfully developing the turbine. Once the CAD model was completed, we continued to the next step, by purchasing the necessary parts, fabricating some of the parts we purchased, and creating parts from materials we already had.

II. Fabrication

Our design required us to fabricate several components. The material of each component was selected based on its application and the resources available. First, we needed to create a part to attach the generator to the main structure of the turbine. We utilized the Rutgers machine shop to fabricate a plate and cut various precise holes that matched those of the generators created by the manufacturers. Because the plate was going to be placed close to the shaft, it needed to be relatively thin. Aluminum was the ideal material. The holes of the plate also needed to align with the acrylic plate, which is another component we fabricated. The outer structure of the turbine was composed of three main acrylic plates, two of which required us to adjust and drill into. We selected acrylic as the material for the plates that made up the turbine structure because it’s durable, light weight, waterproof, seals nicely with glue, and can be transparent. We used Rutgers Makerspace to cut out the plates from a purchased acrylic sheet, as well as the appropriate hole, using a CNN machine. The outer draft tube which the acrylic sheets were glued to was also fabricated from a large plastic tube that we purchased. Plastic was the ideal material, as it has a lot of similar drawing factors like acrylic. Using a Dremel, we cut the draft tube to the desired size and cut out the window like holes where current flows in and out. Figure 16 depicts examples of the necessary fabrication for this project.

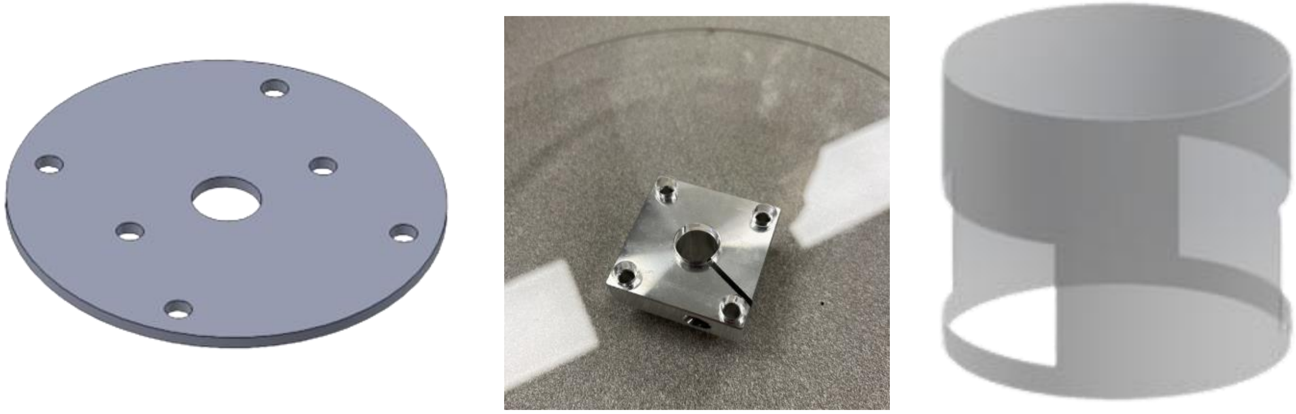


Figure 16: Fabricated metal plate CAD model (left); Attaching flange mount to top acrylic sheets (middle); Fabricated draft tube CAD model (right).

The largest and most complex component we fabricated was the turbine blade. Through various design ideas and developed CAD models, we ultimately created a blade shape that we knew could optimize the river current by having a large blade surface area. Because of the blade's smooth and complex shape, we opted to 3D print it. Using Rutgers Makerspace, we 3D printed a few different blades due to adjustments and errors created along the way. Once the blade was 3D printed, we tapped holes in the filament to screw in one of the metal clamps. We also 3D printed the gilding vanes with that attach to the front of the turbine window, angled parallel to the river flow. The rotor was printed in the Rutgers Makerspace, the 3D printer which can be seen in Figure 17.

Figure 17: Blade actively 3D-printing.

III. Assembly

The final assembly of the turbine required several steps. First, we ensured we had all our required parts and that they fit as expected. The CAD model that we developed in the design process was a key part of assembling the turbine. Throughout the fabrication process, we made sure a particular component would fit and was cut to the correct size by developing loose subassemblies. This allowed us to confirm that a fabricated part was going to work and did not need further adjustments prior to moving on and focusing on a new component. A few adjustments we needed to make include shaving down the generator shaft and redrilling holes in the metal plate due to errors just to name a few.

We began assembling the turbine starting with the generator. The metal plate screwed into the generator, which was bolted to the acrylic plate. The purchased coupling was clamped to the generator's shaft. A bearing was glued inside the blade, where an inner shaft slid into the center. The inner shaft was clamped to couples at the top and bottom of the blade. The top couple clamped the generators shaft and inner shaft and screw into the tapped threads in the blade. The bottom couple was bolted all the way through the blade and also clamped to the inner shaft in efforts of avoiding misalignment issues at high speeds. The acrylic sheets were glued to the correct height of the draft tube. The gliding vanes were glued to the front window of the tube. The last step was applying waterproof tape around the perimeter of the draft tube in the section that needed to be sealed. Overall, the simple design allowed for a quick and easy assembly. The main obstacles were ensuring all the parts fit as expected.

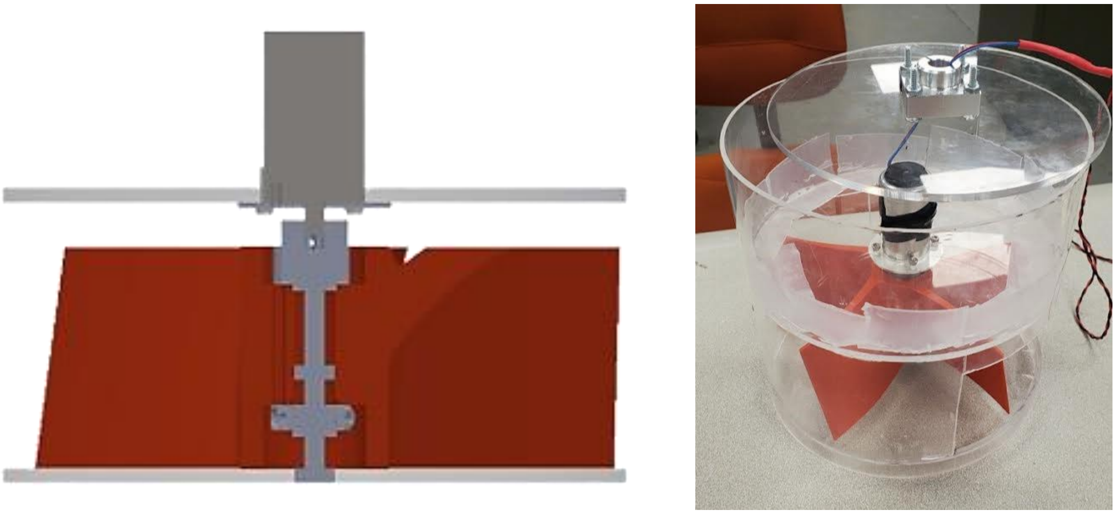


Figure 18: CAD model of assembly (left) and turbine assembly in progress (right).

IV. Bill of Materials

The Bill of Materials in Table 6 represents the components that make up the turbine. They do not include other parts we purchased that were not used to produce the end product. The materials that we already had in the lab are listed as N/A for the cost.

Table 6: Bill of Materials.

Component	Material	Purchased/Fabricated	Cost
Blade & Hub	3D printed filament	Fabricated	N/A
Guiding Vanes	3D printed filament	Fabricated	N/A
DC Motor	N/A	Purchased	N/A
Metal Plate	Aluminum	Fabricated	N/A
Acrylic Sheets	Acrylic	Fabricated	$44.00
Draft Tube	Plastic	Fabricated	$9.99
Ball Bearings	High Carbon Steel	Purchased	$4.38
1310 Series Hyper Hub (1/4" Bore)	Steel	Purchased	$7.99
1309 Series Sonic Hub (1/4" Bore)	Steel	Purchased	$6.99
Flange-Mounted Shaft Support	Aluminum	Purchased	$20.42
1/4" Shaft, 6" length	Stainless Steel	Purchased	$2.29
Bolts & Nuts (Pack)	Steel	Purchased	$39.99

V. Scaling Factors

Scaling is an important aspect of creating a prototype. The first scaling factor that was considered in our design was our constraints. These constraints were set by the size of our testing facilities – Rutgers University's wind tunnel and water flume. The test section of the wind tunnel is 28 in. wide by 20 in. high (71.12 cm wide by 50.8 cm high). To accurately simulate flow and reduce the effects due to boundary conditions, the turbine was only allowed to occupy a fraction of this test section. It was decided that the turbine should fit in an 8 in. by 8 in. by 8 in. (20.32 cm by 20.32 cm by 20.32 cm) box. The water flume has a test section that is 12 in. wide and 18 in. high (30.48 cm wide and 45.72 cm high). At the request of the managers of the water flume, we can only have a maximum water height of 12 in. (30.48 cm). Like the wind tunnel testing, it is crucial to minimize the effects of the boundaries by only utilizing a fraction of the test section. Given this constraint, it would be best to build a turbine with a maximum diameter of 3 in. (7.62 cm) For practical reasons, this could not be achieved. Ideally, the water flume would be at least 24 in. (60.96 cm) wide to accommodate our 8 in. (20.32 cm) diameter turbine.

There were also constraints for the turbine components since only certain sizes of shafts, generators, and couplers are commercially available. It was important to purchase these components to ensure the quality of our turbine. To stay within our budget, we wanted sizes that were on the smaller side since these components are typically cheaper. We thoroughly reviewed products that could potentially be used for the turbine and created a list to keep track of these parts. After the final sizing of the design was finished, the parts required for the design were purchased.

Components with unique geometries, like the blades, can be difficult to machine shop. To ensure the correct geometry and stay on schedule, these parts were 3D printed. The drawback of this is that the 3D printed parts were going to be made of plastic, which is a material that has lower tensile and compressive strength compared to steel and aluminum. This made the 3D printed components of the turbine vulnerable to breaking. To prevent this, these components were scaled so that it would be able to withstand the hydrostatic and hydrodynamic loading that it would be subjected to during the testing phase.

VI. Experimental Test Plan

i. Flow Velocity

Flow velocity is the rate at which a fluid moves through a particular area. The velocity of a fluid directly correlates with the amount of energy as shown in Equation 1, with EK representing the kinetic energy of the fluid :

$$E_K = \frac{1}{2} m u^2 \qquad (1)$$

Where m is the mass of the fluid (in kg), and u the velocity of the fluid (in m/s).

This equation can be reduced by dividing by the unit of volume, V, into Equation 2, with q being the dynamic (velocity) pressure,

$$q = \frac{1}{2} \rho u^2 \qquad (2)$$

Where ρ being the density of an incompressible fluid (kg/m^3).

An incompressible fluid being a fluid whose density remains constant, with water typically being referred as an incompressible fluid. (SimScale) The turbine is designed for marine use i.e. use in water, meaning it should be in a scenario of incompressible fluid flow while testing with flow velocity. An easy way to represent this is by using air flowing at a speed less than 0.3 Mach, as below that speed it will be acting as an incompressible fluid (SimScale). At standard conditions for air this is approximately 100 m/s or 335 ft/s, meaning we must operate below this speed.

To model our turbine, we will use a wind tunnel which is a system that the interaction of a fluid flowing through/over a device by having a fan sucking air past the device which remains static (Medium). At the opposite end there is usually a grid to kill any turbulence which removes an additional unnecessary variable in our experiment and ensures that our experiment better represents a laminar flow situation i.e. a flow situation where each particle follows a regular path. As stated, all wind tunnel experiments will be done at velocities below 0.3 Mach, so there is no compressible fluid simulation as that is unnecessary and complicates the experiment.

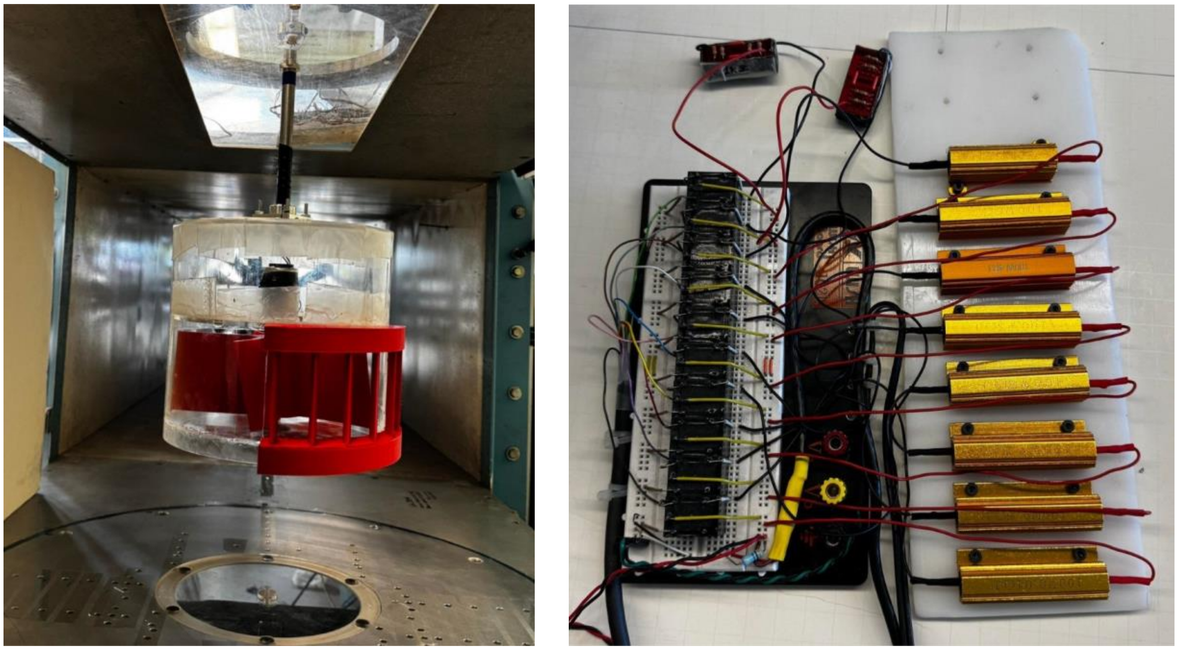


Figure 19: Turbine in wind tunnel (left) and resistance loads utilized to compute power output (right).

The next step is to calculate the coefficient of power, CP, this can be done by calculating the amount of electricity produced by the turbine which is shown in Equation (3) with V being the voltage produced by the turbine and A the amperage produced by the turbine, and then dividing by the total available energy which was shown above. After Equation (3) is used to find CP we can use Equation (4) to find the rated power output of a wind turbine, with r representing the blade length (Thundersaid Energy). This equation is similar to the equation to represent the rated power of a marine turbine, Equation (5) (Physics forum) Therefore to covert the rated power from our device acting as a wind turbine we should multiply our rated power from Equation (4) by two (2) and the ratio of the density of air to water which is 0.01293 (assuming ρ_{air} = 1.293 kg/m^3 and ρ_{water} = 1000 kg/m^3).

$$P = VA \tag{3}$$

$$P_{wind} = \frac{1}{2}\rho\pi r^2 u^3 C_P \tag{4}$$

$$P_{marine} = \frac{1}{2}\rho\pi r^2 u^3 C_P \tag{5}$$

Using the voltage and current values collected when wind blew through the turbine, we computed the power output using equation 3. Various resistor loads were used from 0.01Ω up to 1000Ω. The lowest resistance load of 0.01 provided the greatest power output, therefore the coefficient of power was computed using the power outputs of lowest resistance load.

Table 7: Flow velocities, wind power determined from wind tunnel testing, and the computed coefficients of power.

Flow Velocity [m/s]	Wind Power Output [W]	Coefficient of Power [%]
12	6.2308	19.65
14	5.9963	11.91
16	6.1127	8.13
18	6.1995	5.79

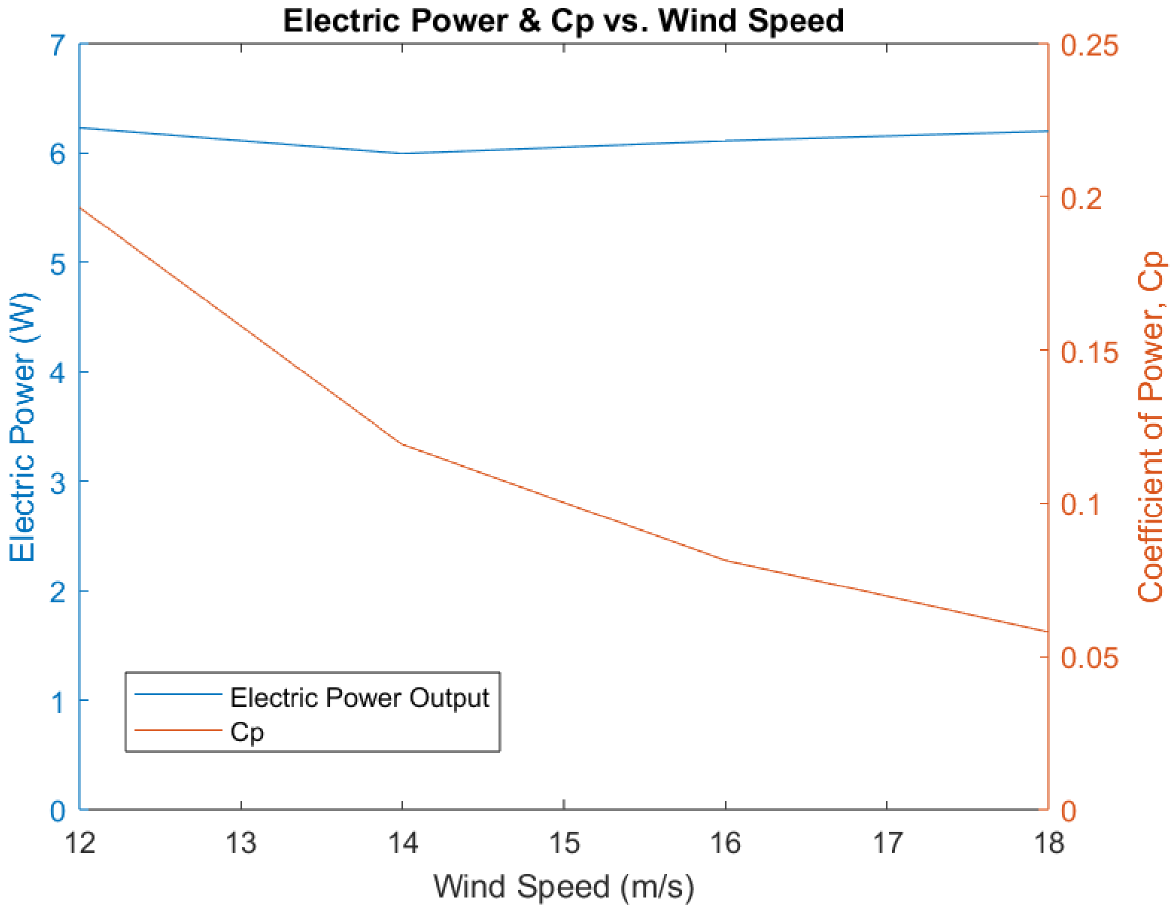


Figure 20: Electric output wind power and coefficient of power plotted versus wind speed.

ii. Man-Made Structures

Many rivers around the world have man-made structures to facilitate the function of human society and civilization. These structures can take the form of docks, pilings, or piers, with all these structures impeding the flow of the rivers they exist in. This causes the water to flow around the structure which creates turbulence as well as more water to go around the sides. This can theoretically cause a flow concentration to form when between two of these structures accelerating the water and creating more force.

These structures are largely round or an otherwise rounded shape to ensure the water doesn't create an excessive force and it simply goes around it. This being the case we used rounded plastic blades to simulate these structures in the fluids lab we were testing in. These were held in place by rocks, and the voltage and current out of the turbine was recorded at different set volume flow rates. This was then compared to the flow velocity test to see how it impacted performance.

iii. Turbulence

Every river in the world is largely uneven in its overall shape and bottom. This creates turbulence throughout the river, which creates uneven flow concentrations. This can affect any marine turbine present in a river as the turbulence should theoretically change the output of the turbine.

To test this, we simulated a field of rocks in front of the turbine which the water would flow over, creating turbulence. The voltage and current produced by the turbine were recorded at different set volume flow rates. This was then compared to the flow velocity test to see how it impacted performance.

iv. Wake and Wash

Wake and wash are the turbulence created by a vessel, such as a boat, when it moves through the water. Wake is the disturbance created by the vessel cutting through water, while wash is the turbulent area created by the vessel's propeller and the water rushing to fill the void behind the vessel. Due to our fluids lab's limited space, this was simulated using a small aquarium propeller to model the turbulence created by this scenario. The turbine was tested at different volume flow rates while this interference was created, with the voltage and current produced being recorded.

v. Marine Debris

Marine debris consists of objects carried through the water of a marine or riverine environment. This can be both natural, such as sticks, logs, or man-made, e.g. Styrofoam or other plastics. These objects can pose harm to marine power generation as they can get stuck and hamper the flow of water into the turbine. This was simulated by using our available fluids lab and placing a piece of flexible plastic, as well as later one of the pieces of plastic used to simulate the man-made structure. We recorded the effect on voltage and current generation, as well as qualitatively where the object got stuck or if it glanced off due to the geometry of our turbine. The tests where the objects were present were compared to one where there was no such impedance.

vi. Orientation

The turbine was designed to have the inflow of water come in through the guiding vanes, and the out flow come out the other end. In extreme real-world situations, the flow of a river of a river can be altered or fully reversed, such as by hurricanes or even large-scale earthquakes (Gabriel). To simulate the unlikely case of a river flow changing direction we decided to test inside the fluids lab the affect of water hitting our turbine at different angles, adjusting by 45° between data recordings. The voltage and current output were recorded and compared to the design case, with the water coming directly into the intake.

VII. Validation by Experiments

The preliminary testing in the wind tunnel was instrumental in verifying the quality of the prototype. When we were testing in the wind, we did not have to worry about water damaging the components of the turbine. This risk-averse decision made it possible to focus on the behavior of the turbine under certain wind speeds. Predictably, the flow speed is the most important factor that impacts power output. Through this, we were able to determine the wind speed that would cause the turbine to self-start. This wind speed was 12 m/s. The turbine was able to spin at wind speeds below this but only if the turbine was already spinning. This technique was also used to determine the wind speed that caused the turbine to vibrate too much. Vibration is a sign of instability, which would reduce power generation and, if the wind speed and vibration was too high, it may damage our turbine. The turbine began vibrating too much at wind speeds above 19 m/s. The results from this test can be seen in Figure 25. As wind and water are both fluids, testing in wind first allowed us to understand how our turbine will behave under certain flow speeds. Adjusting for the higher density of water, we can predict the self-starting speed and the speed that would cause too much vibration when testing our turbine in water.

We were able to successfully complete all six of our environmental testing objectives: flow speed, wake and wash, turbulence, (man-made structures) bridge piers, orientation, and marine debris. This was done by utilizing the water flume in Rutgers University's Urban and Coastal Water System Laboratory. To complete testing, raw measurements had to be recorded. For each of our six testing objectives, we recorded the flow rate. The water flume has settings to control the flow rate of the water and provides a reading for that flow rate by using a flow meter. This flow rate could allow us to calculate the flow velocity. Additionally, the water level upstream and downstream of the turbine was measured. This was measured in millimeters using a ruler. To gather data on the power output, a Fluke 287 True RMS Multimeter was used to record the voltage and electrical current. These measurements were recorded for all six testing objectives.

Some of our testing objectives required more measurements. These objectives include the experiments for wake and wash and bridge piers. In the wake and wash experiment, an AQUANEAT Circulation Pump, Aquarium Wave Maker, Fish Tank Powerhead Submersible Water Pump with Suction Cup (Small 480 GPH) was used to simulate a boat that was creating wake and wash. The distance between the wave maker device and the turbine was measured to be 205 mm. For the bridge piers experiments, the bridge piers were formed by using two turbine blades from a DIY Vertical Axis Wind Turbine Model Wind Power Generator, Three-Phase Permanent Magnet Generator Windmill Toy Night Light Making (Type A) and stabilized using rocks. The distance between the two bridge piers were measured to be 90 mm and 500 mm away from the turbine. It was important to take these measurements so the experiment could be replicated.

The raw data measured were the flow rate, upstream and downstream water level, voltage, and electrical current. These raw measurements were postprocessed to generate useful data that characterizes the device performance. The flow velocity was calculated using Equation (6) $V = \frac{Q}{A}$, where V is the flow velocity, Q is the flow rate, and A is the cross-sectional area. The the input power, which is generated by the water current, was calculated using Equation (5). The output power, which is the electrical power, is calculated using Equation (3). The coefficient of power was calculated using Equation (7) $C_p = \frac{P_{out}}{P_{in}}$, where P_{out} is the electrical output power and P_{in} is the input power from the flow velocity. The power output and the coefficient of power are the two most important metrics to determine the performance and efficiency of our design. These variables are dependent on the flow velocity.

The graph of electrical power output versus flow velocity can be found in Figure 26. This graph compares the different six different environmental conditions that our turbine was subjected to. As flow velocity has the biggest impact on power output, this will serve as our baseline scenario. The flow velocities used ranged from 0.15 m/s to 0.24 m/s. The flow rate was restricted to this small range since increasing the flow rate would have caused the water level to rise. As the generator chamber was not fully waterproof, we could not allow the water level to get too high. The maximum power output occurred during the marine debris test with the latex glove. The position of the glove caused the bottom portion of the guiding vanes section to be blocked, which increased the flow velocity through this section. Marine debris has a stochastic pattern, making it difficult to predict how it will impact power output. The orientation testing had the largest variation in power output. The turbine produced no power when the turbine was positioned 45, 90, 135, 225, and 270 degrees to the water flow. At 0, 180, and 315 degrees, the power output was 0.0313mW, 0.0185mW, and 0.0107mW, respectively. All the other testing objectives were conducted at 0 degrees. The test with higher turbulence consistently yielded higher power output. Wake and wash also had a higher power output compared to the flow velocity. The bridge pier experiment results were similar to the flow velocity experiment.

The graph of the power coefficient versus flow velocity can be found in Figure 27. The coefficient of power is the ratio of power output to power input and is a metric that measures the efficiency of a turbine. The maximum power coefficient was achieved in the marine debris experiment with a value of 0.00565. The higher turbulence experiment consistently yielded a higher power coefficient. The orientation testing had the largest variation in the power coefficient due to it producing no power when the turbine was positioned 45, 90, 135, 225, and 270 degrees to the water flow. At 0, 180, and 315 degrees, the power coefficient was 0.00135, 0.00079, and 0.00046, respectively. All the other testing objectives were conducted at 0 degrees. These values indicate that the turbine has poor efficiency. To assess the power coefficient more accurately, higher flow velocities should be used.

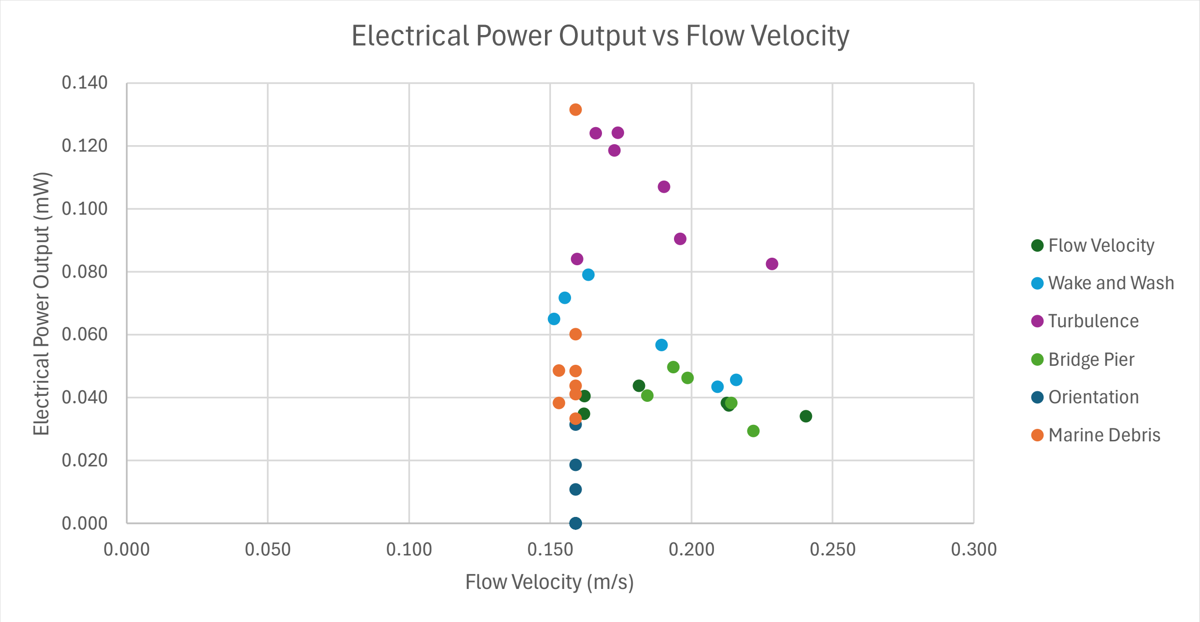


Figure 21: Electrical power output versus flow velocity in water flume testing.

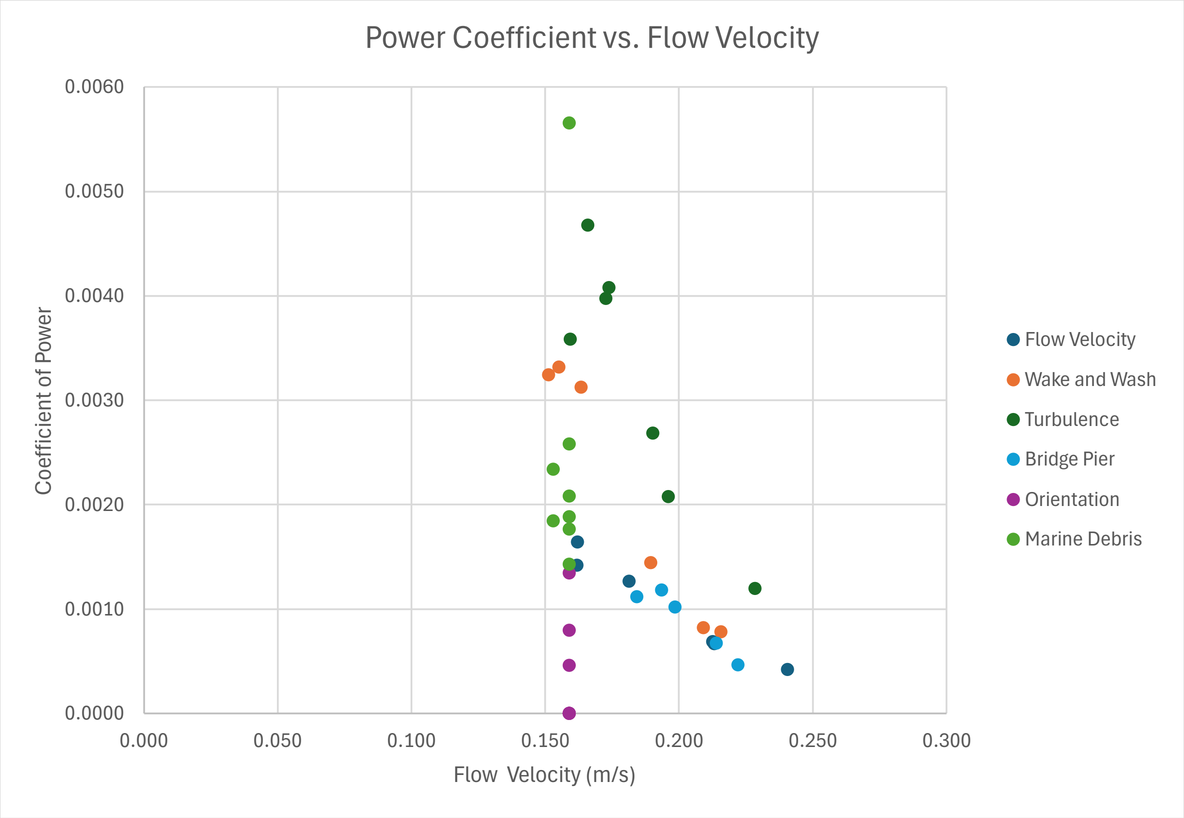


Figure 22: Power coefficient versus flow velocity in water flume testing.

VIII. Takeaways

Experimentation revealed areas where the turbine design worked well and where it could be improved. In the water flume, the mechanical rotor smoothly spun, indicating that friction was minimized throughout the system. This would primarily be due to the utilization of hydrophobic lubricant and an interior shaft for the mechanical rotor used to support the rotor on two ends and prevent loss due to generator-rotor misalignment. There arose an issue with the waterproofing methods of the turbine. Initial testing was done before placement of the turbine in the water flume and showed that small amounts of water were entering the system. A waterproofing sealant and tape were used around the exterior of the generator box; however, water still entered the system. As water entering in generator chamber could cause an electrical hazard, the decision was made to limit the water flow’s height. This restricted testable flow rates. For the future, it was advised to use additional waterproofing methods to test our turbine at higher flow rates and reveal the true power curve for this prototype.

While recording data, there would occasionally be instances where electrical voltage and current output would fluctuate. A pattern was noticed that when certain blades were closer to the entrance of the turbine, where the guiding vanes are, there was a slight decrease in speed. The blades may have had some imperfections during fabrication that should have been closely inspected. Any lack of symmetry in the blades may cause them to spin at inconsistent speeds. Additionally, adding one or two blades might help make our turbine more efficient. Further experimentation should be done with a turbine with six or seven blades to evaluate this.

The size of the water flume was not ideal for the size of our turbine. Our experiment was impacted by the boundary layer of the walls of the water flume. At the wall, the velocity would be 0 m/s. The farther away from the wall, the less the boundary affected the velocity. Ideally, we would want to be far enough away from the wall so that this boundary has a negligible impact on the velocity. The water flume used in our experiment was 12 in. wide and 18 in. high, while our turbine had an 8 in. diameter. Since our turbine took up so much space in the flume, the upstream water level was noticeably higher than the downstream water level. This turbine was designed to be powered by river currents and not the hydraulic head differential. To better assess the turbine for its intended applications, either we need to use a testing facility with a larger water flume, design and build our own water flume, or prototype a smaller turbine.

There are instruments and devices that could have been used to improve the preciseness and accuracy of our measurements. For the velocity, we used Equation (6) to calculate the flow velocity. This velocity assumes that that the velocity is the same at every cross-sectional area of the flume and this velocity is constant. This equation only computes the average velocity. To get more accurate flow velocity measurements, an acoustic doppler current profiler can be used. When selecting proper instrumentation, it is important that the expected measured values do not fall within the noise range of the instrumentation, as this can create errors in measurement.

There were additional testing objectives that we considered but were unable to complete due to lack of necessary instrumentation, restrictions on equipment usage, or time constraints. These would have included sediment transport, icy conditions, and stormy conditions with a high flow rate. We were not permitted to put sediment in the water flume due to fear of damaging the equipment. Similarly, the ice may recirculate through the pumping system of the flume and damage it. To complete these two future testing objectives, we should design and build our own water flume. We could not do storm-like conditions with a high flow rate since there was risk of leakage in the generator chamber and it would not be safe to complete this test. This test will evaluate the durability of our turbine so it would focus on any changes to geometry and orientation. If we could ensure the electrical components are safe from water exposure, then this testing objective could be completed.

IX. Conclusions

We developed a hydrokinetic turbine for river applications that would be capable of supplying low-cost electricity to small rural communities, when it is scaled up. To demonstrate our design, we fabricated a prototype of our turbine by using a combination of commercially available parts and 3D printed parts with unique geometries. We tested the quality of design and fabrication by using a wind tunnel and water flume. The water flume experiments can be improved by creating a smaller turbine or using a larger flume so that the boundaries have a negligible effect on our experiment and using instruments with more precision and accuracy. While we have met the requirements for the Marine Energy Collegiate Competition, there are a multitude of ways to improve the durability, efficiency, and experimental setups. Design is an iterative process and RUPower is committed to improving our concept for future competitions.

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