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Drop of Power
BREE 495 - Design 3 Project

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Acknowledgements

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Abstract

This report investigates the use of rainwater as a power source for a micro hydroelectric system. The purpose of this design is to promote the development of these communities by providing a solution to safe and reliable lighting. Considering the importance of natural habitat, the traditional way-of-life, and the level of income in the targeted communities, environmental, social and economic constraints were established. NGOs in the Philippines were contacted in order to familiarize ourselves with the local needs and environment. Following this feedback the goal became to achieve a voltage of 5V and a current of 200mA to charge an Ni-mH battery that would be used to power a handheld light. The desired power was to be achieved using a 4m head and the only source of water being rain. Tests were then conducted using various prototypes of the system. The experimentation process allowed us to identify the ideal generator, turbine dimensions, and nozzle diameters. The most effective rainwater collection technique was found to be an umbrella catchment that would direct precipitation into the system's penstock and through a 4mm nozzle. The type of turbine that most adapted to the flow and water velocity in our system was found to be a Pelton wheel with a diameter of 280mm. Using a stepper motor as a generator, we achieved an output of 7.2V and 300mA and can charge two batteries at once.

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1. Introduction

This paper summarizes a study and experiment conducted to assess the feasibility of generating power from a hydroelectric system depending on collected rain water. Thorough research was conducted regarding the different potential methods of harvesting this natural resource and using it as a source of energy. The objective was to provide renewable energy to underserved regions in an innovative and sustainable manner. We distinguish ourselves from conventional hydro-electric systems as the project aims at using under-exploited resources.

Although the amount of people without access to electricity has been declining this past decade; going from 1.2 billion in 2010 to 759 million in 2019; this number still remains high (World Bank, 2021). Efforts in research and innovation in the renewable energy sector must be maintained to further attenuate this issue. We aimed at creating a system that would be as accessible as possible, in terms of cost and simplicity of the design, installation and maintenance. If implemented in communities in need of electricity, this system has the potential to improve the living conditions of users, increase autonomy and resilience of the community. Although the amount of power such a system can generate is not as high as that of conventional micro-hydroelectric turbines, we found it to be sufficient to have a light on for two hours everyday. This is already a large step forward in underserved communities, and would allow people to perform tasks that might otherwise not be possible in the evenings. It has the potential to not only improve access to education and safety, but also to improve the community's overall resilience.

Such a system is highly dependent on the amount of rainwater available in an area, therefore only countries with high precipitation were considered. We contacted organizations in the locations of interest to get more familiar with local issues we were to take into consideration when doing our design. In building our prototype and testing for different designs, we made sure to keep all these aspects in mind, and ensured our final design would be adaptable and suitable in the targeted communities.

2. Identification of need

Despite the increasing globalization and spreading of affordable energy, many areas in the world still lack access to reliable power grids. Consequently, populations in these regions are highly dependent on off-grid systems for their electricity consumption. As these are often remote and underdeveloped areas, these alternatives must be financially accessible, socially acceptable and respectful of the environment. In this context, the use of low power-output systems would make a

significant difference towards improving education, safety, as well as community development and empowerment.

With this challenge in mind, we contacted Non-Governmental Organizations (NGOs) developing hydroelectricity projects in these regions to benefit from their expertise. We exchanged with two of them, Yamog and CREST, both based in the Philippines, who informed us that 14 million people had no access to electricity in the Philippines, where they are based. They explained that part of the population uses solar energy for their needs, but could not completely rely on it due to the dark skies from high levels of precipitation. This helped us formulate our objective to design a renewable energy system for residential use, particularly, a hydroelectric setup powered by rainwater. This would provide a means of energy production complementary to solar panels, generating electricity by rotation of a turbine and generator. Such a design could be implemented in various underserved communities areas around the world experiencing high precipitation.

Energy poverty is an important obstacle to the development of isolated and underserved regions. In Southeast Asia, despite electrification rates having reached 91% in developing countries in 2019, many islands and rural areas still do not have reliable access to electricity (Shyu, 2022). The communities living in such places would be among the ones to benefit from a durable and sustainable system such as ours. Indeed it has been shown that energy poverty was directly correlated to income poverty, and that a larger share in renewable energy production could help reduce that issue (Tundys et al., 2021).

Engineering challenges include achieving a high efficiency to balance the small energy production per rain event, storing the energy, and using accessible devices and materials. An application for this project is to power lights at night in underserved areas of high-precipitation regions. Having access to a light source after dark for reading and other activities would help promote quality and equality of education in these areas. Indeed, studies conducted in a variety of developing countries have shown that reliable access to electricity contributed to higher literacy rates, with lighting as one of the main factors (UNDESA, 2014). This is inscribed in the global objective to ensure inclusive and equitable education for all, as stated by the Fourth Sustainable Development Goal set by the United Nations for 2030. Moreover, our system would provide a safer and sustainable alternative to the current popular light sources in these regions, that includes kerosene lamps and fire. These can present risks to human health through the release of smoke and volatile compounds, and should therefore be avoided when providing light to children for instance. Providing access to a rainwater-powered electrical light, even for a few hours a day, would already significantly increase the safety and development of the targeted communities.

3. Problem definition

The following mission statement was established as a guideline for the design process:

“Provide a universal rainwater powered generator to improve resilience in underserved high-precipitation regions.”

Indeed, after talking to NGOs such as Yamog and CREST, it became clear that providing electricity to underserved communities would make a significant difference. We made that our first success criteria for the project as it defined our vision: to enhance access to renewable energy in high-precipitation regions. A direct application for this project is to power lights after dark, helping to improve the literacy rate. We aim to gather the power necessary to activate a light for 2 hours every day, during half of the year. This will be done by creating a simple and highly adaptable design; Figure 1 is a sample setup amongst others. We aim to thoroughly address the environmental, social and economical impacts of our project using the principles and frameworks for life cycle assessments described in the ISO/TR Standard No. 14040 (2006).

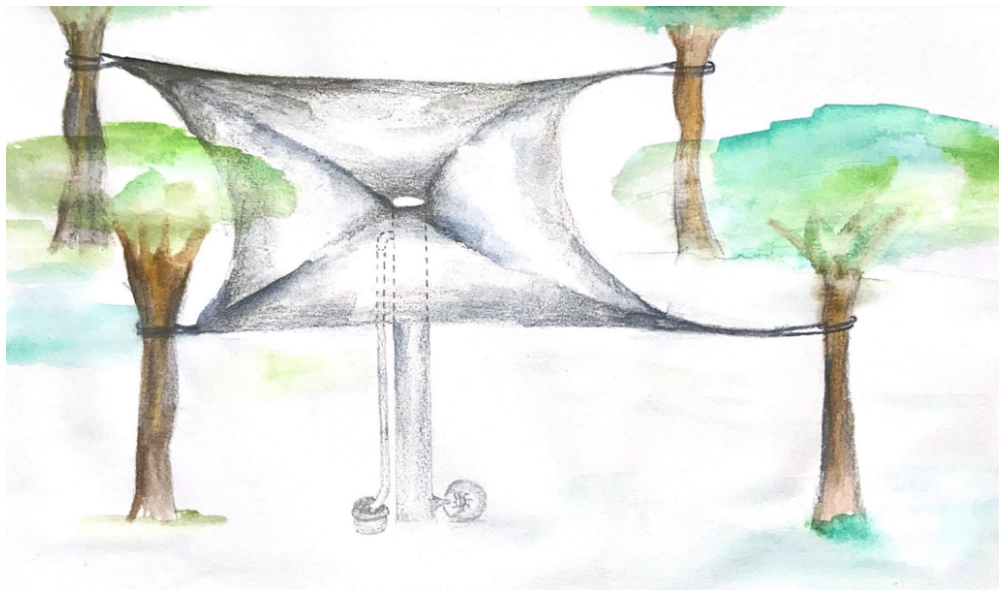


Figure 1. Sample design sketch of the system.

4. Review of literature

This project is made up of several sub-assemblies that need to have the best performance. To achieve our objective, we have conducted in-depth research in several fields of study to evaluate all possible solutions. This was first done to estimate the amount of rainfall we could expect in our targeted regions, followed by different ways to capture it. We then went on to evaluate ways to temporarily store the water in a penstock and release it through a nozzle. Next, several turbine designs

were looked into to harness mechanical energy. This will eventually be converted to electrical energy by a generator and stored in a battery.

4.1 Micro-hydro projects

With a large number of people living in areas where it is difficult to extend the electrical network, renewable energy is a suitable solution in providing clean and accessible energy (López-González, 2018). Prior to the 21st century, diesel was the most widespread option for rural electrification in developing countries (López-González, 2019), this has now been replaced by biofuels. Although biogas is considered a more sustainable alternative, there are great inefficiencies in the production and use of this traditional energy source in the developing world, and policies are lacking to encourage afforestation and people (through education, training, and services) to use this energy in a more environmentally and human health friendly manner (Barnes & Floor, 1996). However, newer, more sustainable, and sometimes cheaper technologies such as micro-hydroelectric power plants are being explored and implemented all around the world. They represent a suitable solution in reducing poverty by improving access to cleaner and more affordable electricity, as well as mitigating the impacts of climate change (López-González, 2019).

In Venezuela, the potential of MHP is approximately 4400MW. This renewable energy has been expanding in the country because of a strong need to save fossil energy resources and avoid pollution in regions with fragile ecosystems and environments. Differing from the type of micro-hydroelectric project *Drop of Power* investigates; in Venezuela, the source of water and power stems from local rivers and basins. In regions such as Kavanayen, where the territory contains highly fragile ecosystems, the closest village is 40.8 km away and the closest town is 210 km away, micro-hydroelectric power has provided 100% of the houses with electricity since 1957. This encompasses 300 households, 1200 beneficiaries using a Francis Turbine. It has been working for the past 60 years and has been generating an average of 210,818 kWh/year, however, in 1994 the original turbine was replaced due to wear. Engineers provided the topographic surveys, instructions, and designs. The construction was carried out by the local indigenous population (López-González, 2019). Other micro-hydroelectric projects are spread out across the country, benefitting in total 5150 people in small towns and remote villages.

Nepal is a country which has a large amount of water resources, and a potential to generate 83,000 megawatts (MW) through hydropower. Despite this, only 37% of its population has access to electricity. The country has received support from donor agencies, such as the United Nations Development program (UNDP), the Asian Development Bank (ADB), the World Bank and many others (Gippner, 2013). More emphasis has been brought to smaller scale renewable energy projects, mainly on the implementation of various micro-hydroelectricity units, through the UNDP's rural energy development program (REDP), (UNDP, 2011). Since its inception, the REDP has installed 295 micro-hydroelectricity plants across the country. The REDP has adopted a community-based approach

in which it promotes both male and female members of the community to engage in local governance. These are key ingredients in ensuring the long-term sustainability of each project, as well as scaling up for rural energy systems. Studies, such as the one carried out by Gippner (2013) have evaluated the success and impact of various REDP projects across the country, relying on field research and interviews as a primary source of data, as the literature on such projects is not very prominent. It was found that communities with micro hydroelectric schemes could benefit from 100 W per household (enough to charge 3 light bulbs for approximately 3 hours).

Several studies have been undertaken around the world to assess the feasibility of generating hydroelectricity from rain. A research project undertaken by the department of Physics and Astronomy at the University of Leicester was used to assess how much energy could be transferred from rainfall to power a 60W light bulb. A drainpipe of 6 inches in diameter was attached to one of the University's physics buildings, whose roof was used as the catchment area. The total head used was 11m, and the average rainfall was 620 mm per year. Physical tests were focused on the water catchment and the penstock, and the rest of the calculations were hypothetical and based on research (turbine, nozzle, generator ...). The results proved that waiting for the pipe to be filled to a head of 1m and then releasing the water would be sufficient to light a 60W light-bulb non-stop for almost a month (Carvalho, 2019).

Another project undertaken by Khandaker et al. (2021) in Bhutan also assesses the feasibility of harvesting rainwater for power generation. It looks into storing rainwater to produce electricity from high rise residential buildings. The building used for this study was 20 m high and had a catchment area of 905m² which would accumulate 15,000 liters of rainwater. The Phuentsholing region (Bhutan) received an annual rainfall of 24mm/day. Pelton and cross-flow turbines were explored in this study, and they found that water falling at a rate of 7.789L/s from a height of 16 meters could provide 339 watt-hour of electrical energy.

Despite some studies and research, few examples have been found of micro-hydroelectricity being generated from rainwater harvesting. The examples explored around the world rely on the access to nearby rivers, streams, or basins. However, with the growing threat of climate change, these methods might not be viable in the long term. The Government of Nepal published a National Adaptation program of Action (NAPA) to climate change. In it, several vulnerabilities assessed are relevant in the expansion of the micro hydroelectricity industry in the country. A reduction in snow cover, and glaciers in the Himalayas will lead to unpredictable river flows, which will ultimately impact the operation of run-of-river hydropower plants (Gippner, 2013). In addition, landslides and sedimentation will become a rising issue. This all further underlines the point that using rainwater, an under-exploited resource, will have varying advantages in the future.

4.2 Precipitation in Areas of interest

Initially, this project contained uncertainties due to the variability of rainfall, which is why we decided to target high precipitation areas, thus providing a higher and more reliable power output. That said, we also want to serve the greater portion of the underserved communities that could benefit from our system. We had this conversation with Reido Panaligan from CREST, and started looking into the rainfall data from underserved regions in the Pacific highlands of the Philippines. These areas receive between 1800 and 2500 millimeters of rain per year according to the Philippine Atmospheric, Geophysical and Astronomical Services Administration (2021). These are values that can be found in similar regions around the globe, such as in Equatorial Africa and South America as seen in Figure 2. To put these numbers into perspective, deserts receive less than 10 mm per year and Cherrapunji in India holds the record for surpassing 24000 mm in 1974 (Starkel et al., 2002). In Montreal, one can expect 864 mm of annual precipitation (Environment Canada, 2021).

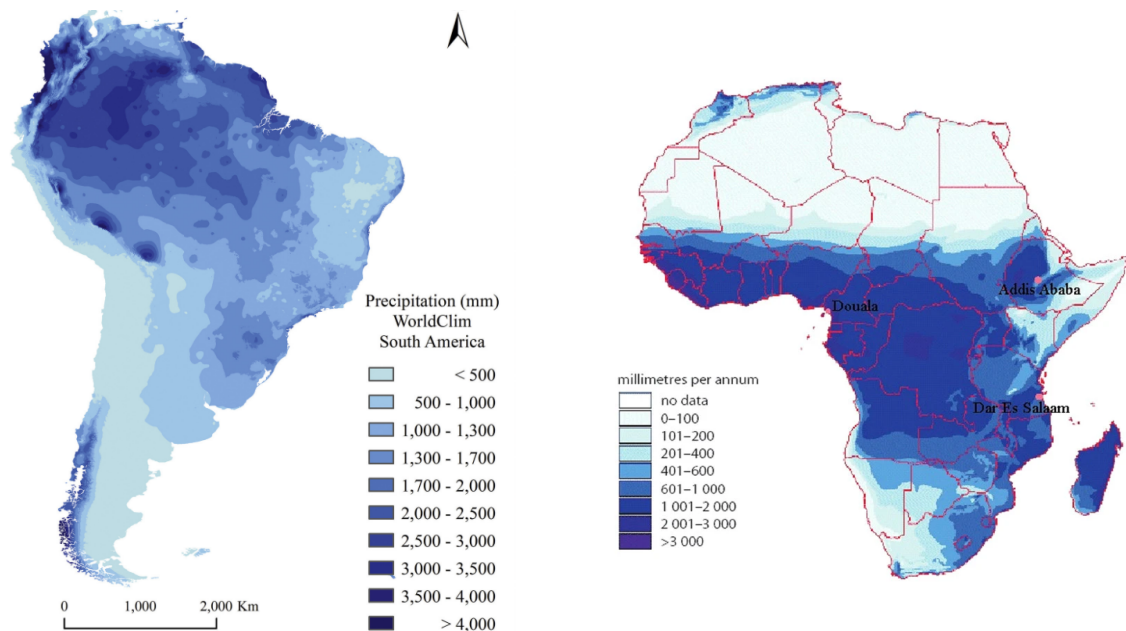


Figure 2. Annual rainfall in millimeters, in Africa, and South America (Paola et al., 2014; Riquetti et al., 2020).

Worldwide, many underserved communities experience high precipitation. In fact, Bangladesh is ranked tenth in average annual precipitation depth with 2666 mm; and has 31.4% of its population living under \$1 a day (Index Mundi, 2014; Zeller et al., 2006). Similarly, parts of Uganda receive up to 2200 mm of rainfall per year; while 32.36% of the population is ‘very poor’ (Uganda National Meteorological Authority, 2021 ; Zeller et al., 2006). Similar cases can be made for countries of Southeast Asia. Indeed, remote rural areas in archipelagos such as Indonesia and the Philippines do not have access to electricity while the rest of the country is connected. There are also energy-poor countries such as Myanmar, Cambodia, and Laos, where most of the population is not connected to

the grid (Stewart-Wilson, 2016). As a consequence, popular light sources in these regions are kerosene lamps and fires that generate volatile compounds which can be of serious health concern. That said, in the case of Southeast Asia these countries all have wet seasons, and archipelagos can have intense rain events as they are near the Pacific Ocean.

To better understand what we were working with, we examined rainfall data from three different continents: Asia, Africa, and South America. The Weather Atlas (2021) compiles climate data from all countries which were taken into account for the calculations seen in Appendix A. This includes cities from the Philippines (Aurora, Irosin, Davao (Figure 3)), India (Pathanamthitta, Neriamangalam), Bangladesh (Sylhet), Guyana (Georgetown), Colombia (Cartago), Uganda (Mbale), and Cameroon (Yaounde).

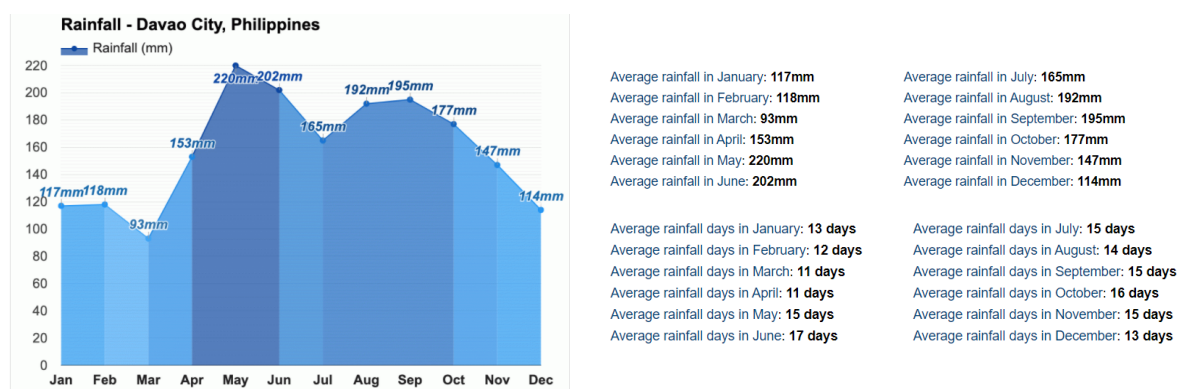


Figure 3. Average rainfall and rainfall days for Davao City, Philippines (PAGASA, 2021).

It was agreed that using the average rainfall in an area was not the best approach as it is sensitive to extreme values. We are looking at regions that have both high and low rainfall periods, due to weather patterns like typhoons in the case of the Philippines. To increase the power output of our system, we want to be able to capture these intense rainfall events, as any overflow is considered a loss. Therefore a penstock will be necessary to accommodate for larger storms and act as a buffer.

To determine an estimated daily precipitation, we have used our best engineering judgment to elaborate the following method. We divided the monthly rainfall data by the number of rainy days within that month, to obtain the average milliliters per rainy day within a given month. These values were ranked, and the 9th highest value was chosen to represent that region (Table 1). By performing this calculation for underserved regions in 10 countries across 3 continents, we obtained an average of 8,80 millimeters per rainy day. This means that our system should be designed to operate at this rate, and as seen in Table 1, other months have similar values. Calculations for all areas mentioned above can be found in Appendix A. For the months where precipitation is lower, it will just take more than one day to run the turbine. We believe emphasizing on the rainier months will benefit the community to a greater extent. Indeed, rain will cause people to spend more time indoors, and demand for artificial lighting is expected to be higher. In contrast, months without rain are bright and sunny.

Table 1. Precipitation data with the selection method applied for Davao, Pathanamthitta, and Mbale.

Philippines 1893 mm/yr	Davao	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	117	118	93	153	220	202	165	192	195	177	147	114
	Rainy days	13	12	11	11	15	17	15	14	15	16	15	13
	mm/day	9,00	9,83	8,45	13,91	14,67	11,88	11,00	13,71	13,00	11,06	9,80	8,77
	Rank	3	5	1	11	12	8	6	10	9	7	4	2
Kerala 1549 mm/yr	Pathanamthitta	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	9	15	70	135	163	235	188	196	123	208	149	58
	Rainy days	8	8	20,3	28,2	28,4	27,8	26,6	26,2	23,3	25,4	23,3	17,3
	mm/day	1,13	1,88	3,45	4,79	5,74	8,45	7,07	7,48	5,28	8,19	6,39	3,35
	Rank	1	2	4	5	7	12	9	10	6	11	8	3
Uganda 2204 mm/yr	Mbale	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	42	46	136	261	319	218	195	248	199	240	176	124
	Rainy days	11,1	12,1	21,3	28	30,4	29,6	30,6	30,8	29,1	29,3	27,5	21,4
	mm/day	3,78	3,80	6,38	9,32	10,49	7,36	6,37	8,05	6,84	8,19	6,40	5,79
	Rank	1	2	5	11	12	8	4	9	7	10	6	3

Another key component to remember is that different rain events have different intensities. Rainfall intensity is measured in millimeters per hour and can be found based on different storm return periods on an Intensity - Duration - Frequency (IDF) Curve (Figure 4). The most intense rainfalls do not occur as often, and common return periods are 2, 5, 10, 20, 50, and 100 years (Ratnasingam and Wikramanayake, 2014). To achieve a reliable output on a yearly basis, planning for a 5 year storm is not relevant in our case. When comparing the different IDF curves, a rainfall duration of 10 hours appeared most reasonable. That said, according to the Sixth Assessment Report from the IPCC (2021), rainfall intensity is expected to increase as climate changes. Indeed, daily extreme precipitation events will likely intensify by about 7% for every 1°C that global temperature rises. That said, it is already not uncommon for places like India to experience up to 3 days of continuous rain (Rakhecha & Soman, 1994).

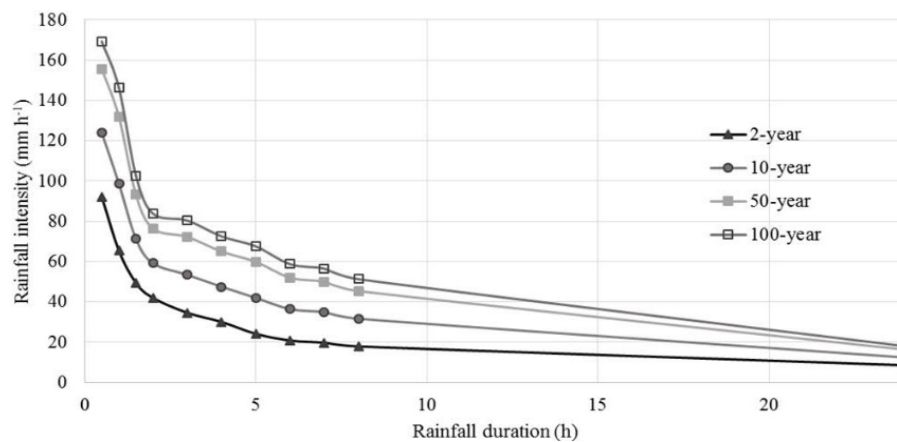


Figure 4. Rainfall IDF Curve from the Philippines (Duka, 2018).

4.3 Rainwater Harvesting

Rainwater harvesting can be done in various ways. Water can be collected directly from precipitation or it can be collected by condensing fog, pumping underground water and redirecting

water channels (Netherlands Water Partnership, 2007)(Worm and van Hattum, 2006)(South Pacific Applied Geoscience Commission, 2004). In the planning of a water catchment, one has to account for available space, usage of water, and amount of water available (Worm and van Hattum, 2006). The amount of water available is calculated in section 4.1.1 and our water usage was determined in the experimental part of the project. The amount of space available for a catchment was determined by discussing with local NGOs and observing local landscape.

Pacey and Cullis (1986) also give additional information on the design considerations of a catchment:

The population size our system is providing water to:

In our case, we are not predicting the amount of people using the two Ni-Mh batteries (see section 4.8) but rather the amount of energy we want to produce. It's a system that is more useful to a single person but that can benefit many at the same time (e.g. lighting).

The average daily consumption of the population:

If we consider our system to be mainly used for lighting, the sun sets in the Philippines at 17h30 on average (Weather Atlas, 2021)). We can roughly estimate that the lighting is going to be used for around 2 to 4 hours when it is dark.

The losses through leakage and evaporation:

Evaporation losses can happen if the opening of the water catchment is constantly opened and exposed to the sun. Potential leakage can happen in the piping if damaged or in the storage or catchment if the material used is not properly waterproofed.

The relevant data of the rainfall:

As previously mentioned, our average precipitation volume, its intensity and occurrence were calculated in section 4.2 and taken into account in our design.

When taking into account the local environmental conditions, it is important to point out the lack of gutter infrastructure and water channeling structures. Vukovic (2021) proposes a few solutions regarding rainwater harvesting without the said infrastructures. One relevant method is the use of suspended impermeable tarps or hard surfaces to collect precipitation directly and channel it to a storage tank, as seen in Figures 5 and 6.



Figure 5. Butterfly water catchment system (Vuković, 2021).



Figure 6. Umbrella water catchment system (Vuković, 2021).

The umbrella water catchment is a laid out impermeable textile that is stretched from each corner. It can be fixed to the ground and anchored at different points to trees or other natural features. The main advantage is the fact that it's suspended at a certain height and offers a good hydraulic head potential. This type of design can be vulnerable to high winds. The butterfly water catchment directs the water down the middle crease and discharges it at one of the extremities. It is a sturdy alternative to an umbrella catchment since it's usually built with rigid materials. However, its significant weight can pose a safety hazard. Both roofless structures do not include a first flush diverter (Sustainable Sanitation and Water Management Toolbox, n.d.) (Figure 7). It is a contraption that traps the first flow of water containing debris accumulated in the catchment and allows the clean water to flow. This can be implemented to the final design depending on the available material. In our case we can use the advantages that each system presents. For example, we would prefer a light structure made of a tarp, but it would be safer to have the water flow along a crease and be discharged away from the under the catchment directly. Its size will be discussed later depending on our needs.

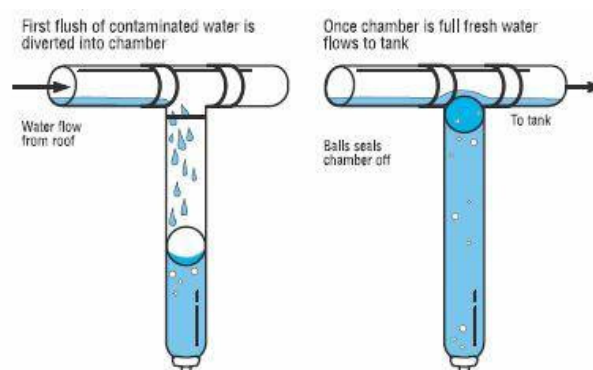


Figure 7. First flush diverter (Puchard, n.d.).

4.4 Penstock

This section is focused around the Penstock of our system, an enclosed pipe used to direct the water harvested in the catchment surface, through the nozzle and onto the turbine. Thorough research was conducted regarding the different materials available and best suited for these components of our design, as well as their respective properties. A water release system was used to let the water flow onto the turbine once the desired head was reached. After exploring several options, including siphons and floaters; a simple mechanical valve was finally chosen.

The most commonly used materials for micro-hydro schemes are Polyvinyl chloride (PVC), Mild steel and High Density Polyethylene (HDPE)(The Pacific Power Association, 2020). According to the literature, it was found that PVC was the best suited material for our project. Indeed, it is a light material, easy to repair, and not very expensive. Because of the material's high insulation properties and resistance to wear and damage, it is commonly used in the construction industry. As a result scrap pieces of this material are more likely to be found around the world and should be compatible with our system. Another advantage of using this material for our project is that PVC pipes are available in a variety of diameters, meaning their dimensions can be adapted according to the location and water catchment area used. Finally, the manufacturing process of PVC is also highly efficient, as all the scrap material is reused (Alsabri & Al-Ghamdi, 2020).

The water release system is used to control the outflow rate of the water exiting the penstock onto the turbine. In order to choose the best design, it was important to keep in mind that the power generated by the system is proportional to the head of the water in the penstock. The best option for our design was to use a mechanical valve that would allow us to control the outflow manually once the appropriate head was achieved.

Several options were explored to connect another PVC pipe to the penstock to make this one longer, as well as methods to properly fit the valve to the penstock. These included solvent cement, and gasket rings such as a Rieber. After doing an analysis of each, and assessing the available options, a push-fit alternative seemed to be the best solution. These are easy to use, do not require any particular skill or dangerous solvents. They have an internal structure that allows them to create a watertight seal once pushed in a pipe, and can be removed when pulled out, and then repositioned as needed (American Society of Plumbing Engineers, 2020).

4.5 Nozzle

The nozzle is one of the most important parts of our system, as it directs the water stored in the penstock onto the turbine that will rotate the power-generating device. Nozzles are used to modify flow characteristics such as rate, direction, velocity and pressure in order to maximize the efficiency of the reaction between the fluid and other system components (Patrick and Guelph, 2012). In the case of our system, the purpose of the nozzle is to ensure optimal rotation of the turbine by meeting speed

and torque requirements, while maintaining appropriate flow for as long as possible. These characteristics of the flow depend on the number and design of the nozzles used, as well as on the flow rate and velocity of the water exiting the nozzles. Figure 8 shows the design of a typical adjustable nozzle.

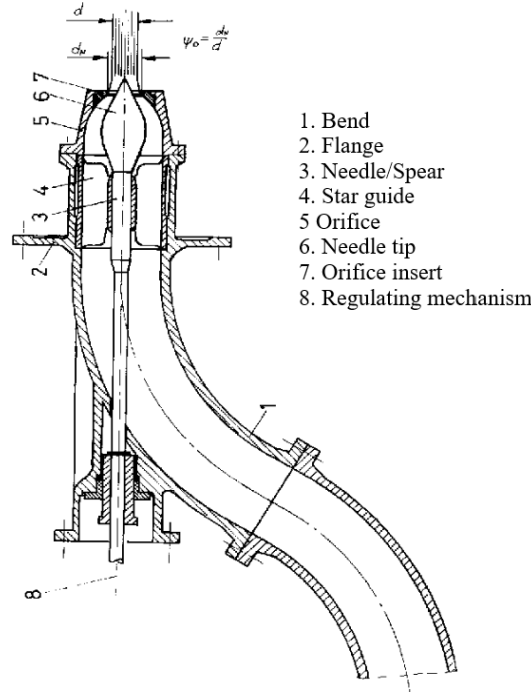


Figure 8. Schematic of typical adjustable nozzle design (Eisenring, 1991).

Large-scale hydroelectric systems often include several jet nozzles, all contributing to the rotation of a single turbine. Provided sufficient inflow rate is available, this will significantly improve the efficiency of the system, and minimize turbine erosion by reducing velocity through each nozzle (Chaurette, 2008). Turbines with a horizontal rotation axis are generally built with one or two nozzles directed on them, while turbines with a vertical rotation axis can be built with up to six jets (Eisenring, 1991).

The flow rate and velocity of the water exiting the nozzles in a micro hydro system are related by the following equation:

$$Q = A * V * N$$

Where:

$$Q = \text{flow rate (m}^3/\text{s)}$$

$$A = \text{water jet area (m}^2\text{)}$$

$$V = \text{water jet velocity (m}^2/\text{s)}$$

$$N = \text{number of jet nozzles}$$

With: $A = d^2 * \frac{\pi}{4}$

Where: d = jet diameter (m)

And: $V = K_N * V_N = K_N * \sqrt{2 * g * H}$

Where:

$K_N = \text{nozzle velocity coefficient } (0.95 < K_N < 0.99)$

$V_N = \text{absolute water velocity entering the main nozzle pipe (m/s)}$

$g = \text{gravitational constant } (9.81 \text{ m/s}^2)$

$H = \text{net hydraulic head at nozzle (m)}$

As it can be seen in the equation above, the nozzle velocity coefficient K_N must be maximized in order to obtain optimal jet velocity at the exit of the nozzle. The value of K_N is influenced by energy losses through friction and turbulence through the pipe, the nozzle itself, and at their connection. This is why the nozzle and pipe should have as few bends as possible, with largest radii allowable, and flow contraction (variation of pipe diameter) should be limited. Using smooth and round edges for the nozzle would also help maximize K_N , reducing the gap between the nozzle and the jet diameters, and therefore increasing torque on the turbine.

4.6 Pelton Turbine

The first form of hydraulic power was achieved through a water wheel in ancient Greece. Later, the invention of electric generators and the increasing need for power encouraged the development of optimized turbines for specific conditions. For example, in the nineteenth century, the Pelton turbine was designed to be efficient with low flow rates of rivers and relatively high heads. Other turbines like the kaplan turbine were adapted to low heads of inland watersheds (Dixon and Hall, 2014).

The power delivered by a turbine can be calculated using the following equation. Head is the mechanical energy per unit weight of water available for the system based on the elevation of the system and the pressure at the outlet (Dorji et al., 2021; Holton et al., 2003).

$$P_m = \rho * g * H * Q$$

Where :

$P_m = \text{gross potential power of the turbine (W)}$

$\rho = \text{density of water (Kg/m}^3\text{)}$

$g = \text{gravitational acceleration constant (m/s}^2\text{)}$

$H = \text{head (m)}$

$Q = \text{flow rate, or the volume of water displaced per unit of time (m}^3\text{/s)}$

Pelton turbines, as seen in Figure 9, are the most popular form of impulse turbines in the smaller hydro-electricity project (Kholifah et al., 2018). It is specially adapted to high head elevation and low flow rates. The main challenge of implementing a pelton turbine is the design of the buckets and their manufacturing. The precise dimensions and curvature of each bucket requires specialized equipment and good knowledge of the subject to produce successfully.

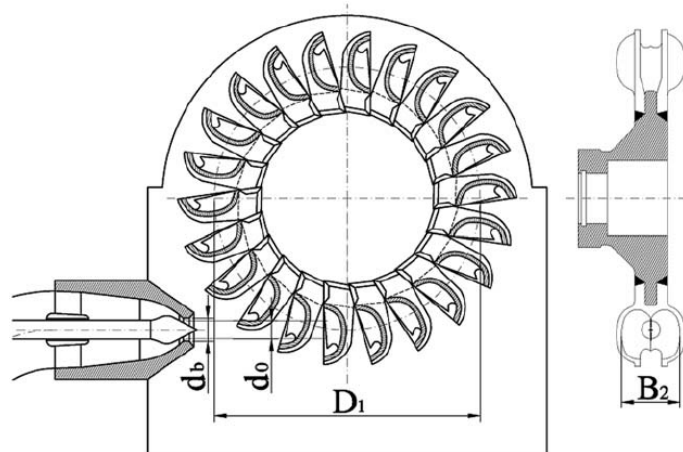


Figure 9. Schematic view of the single jet Pelton turbine (Rossetti et al., 2014).

Kholifah et al. (2018) tested the efficiency of Pelton turbines for low heads and different nozzle diameters. Their test parameters are shown below in Table 2.

Table 2. Flow rate for different parameters (Kholifah et al., 2018).

Flow rate(m^3/s)				
<i>Nozzle (mm)</i> <i>Head (m)</i>	5	7	9	11
3,6	$0,38 \times 10^{-3}$	$0,5 \times 10^{-3}$	$0,85 \times 10^{-3}$	$0,97 \times 10^{-3}$
4,6	$0,41 \times 10^{-3}$	$0,53 \times 10^{-3}$	$0,88 \times 10^{-3}$	1×10^{-3}

The Pelton wheel itself was designed using the specifications shown in Table 3.

Table 3. Original Pelton turbine design specifications (Kholifah et al., 2018).

Specifications	Values
Diameter of Bucket	70 mm
Number of Buckets	22
Runner Diameter	D 300 mm
Shaft Diameter	20 mm
Diameter of Casing	1320 mm
Pulley Transmission Ratio	1 : 2
Material Bucket	<i>Stainless steel</i>
Generator	A permanent magnet AC generator capacity of 200 watts

It was designed to predict an optimal jet diameter range between 7 and 9 mm. In fact, the power generated was increasing with increasing jet diameter until it reached a threshold at 9 mm. Power generated dropped at 11mm. This illustrates the fact that an increasing flow rate will produce more torque and therefore more current up until the jet velocity drops too much, reducing rpm speed and therefore voltage produced.

As it can be seen in Figure 10, voltage drops with rpm drop at a nozzle of 11mm.

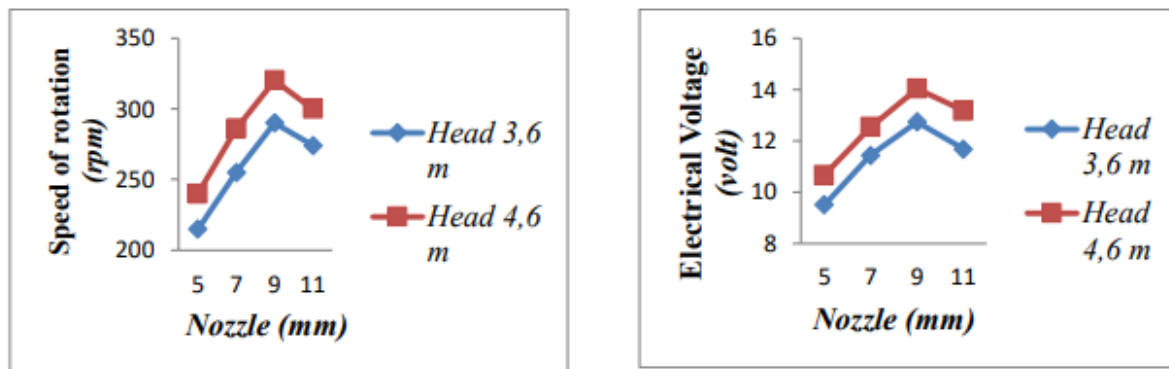


Figure 10 . Variation of rpm and voltage depending on the nozzle diameter (Kholifah et al., 2018).

A page in Eisenring (1991) effectively summarizes all parameters and calculations necessary to design a turbine (Appendix B). These formulas were first used to obtain theoretical values for the geometry of our turbine. However, the scale of our project as well as our means of construction do not translate well to the normal calculations of a pelton turbine.

The challenging part of the design is modeling the turbine's bucket. The geometry of each subpart can highly influence the torque obtained in the end and therefore the current. Rosseti et al (2014) characterized the contribution of each subpart of the buckets to the torque of the turbine. The key takeaway in our case is the overall shape of the bucket including the top notch that allows the jet to pass (Figure 11).

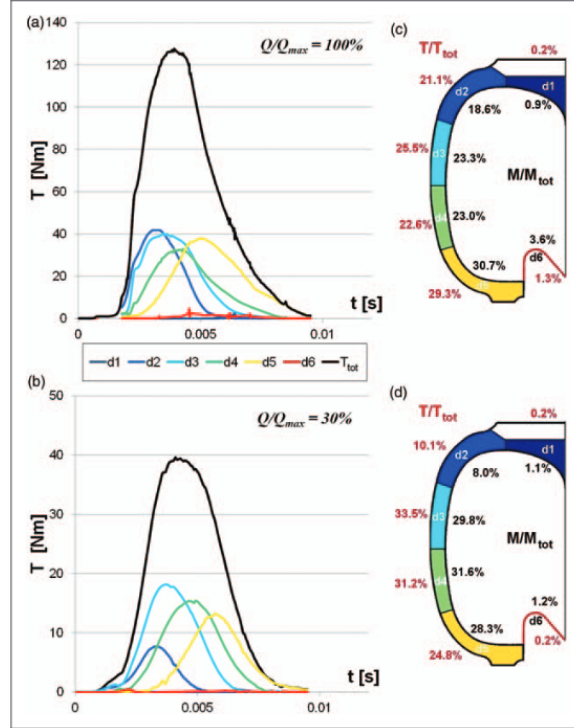


Figure 11. Contributions of the different bucket discharging areas to the total bucket torque (Rossetti et al., 2014).

Presently, most pelton wheel designs are made with the help of computational modeling. This is done to obtain the geometrical parameters that give optimal results without having to go through the complex machining of many pelton turbines. Nigussie et al. (2017), modeled a pelton turbine for a specific site in Ethiopia. After characterizing their potential head and flow rate depending on field studies, they were able to obtain a theoretical diameter for their turbine as well as bucket geometry. A 3D model of three half buckets was made and by assuming symmetry and constant results for a complete wheel, modeled the flow of water on the buckets. These assumptions allowed them to save on computational costs and obtained the following model (Figure 12) (Nigussie et al., 2017).

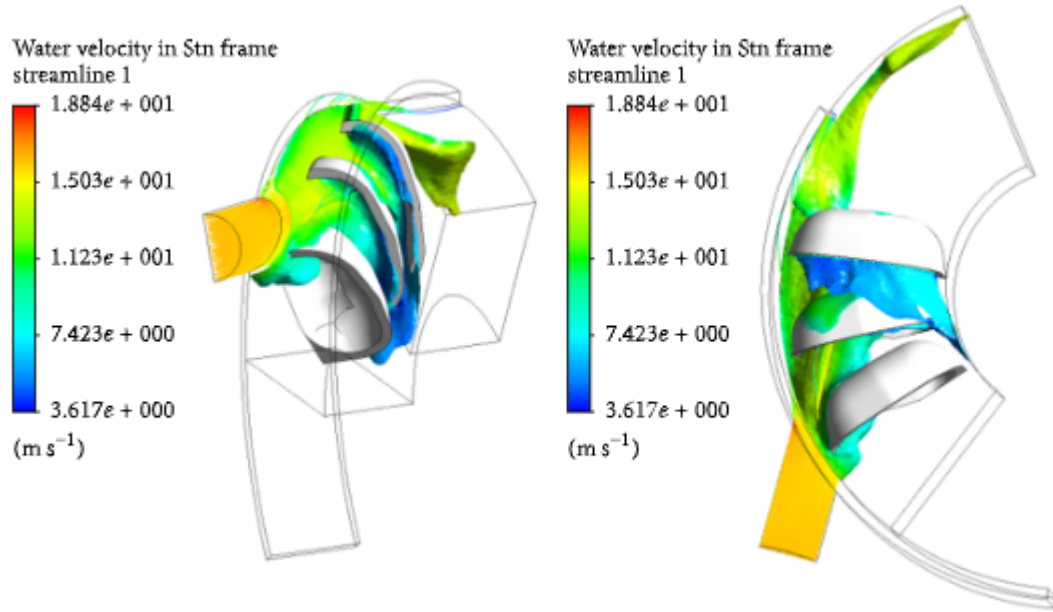


Figure 12. Characterization of flow on three half-buckets (Nigussie et al., 2017).

4.7 Stepper motor

A stepper motor is a type of electrical motor, commonly found on fused deposition modeling 3D printers and computerized numerical control machines. Its name comes from the fact that it divides each full rotation between a finite number of angular steps. This type of motor is advantageous for use as a power generator since it is able to achieve a high voltage at a low rotational speed (Stepper Motors, 2017).

A model of stepper motor was donated to our group by the M3D Club for the purpose of building our prototype. The specification sheet of this motor can be seen on Figure 13. Based on the rated current and holding torque specified in this sheet, we were able to determine the torque-to-current conversion coefficient of the motor. This allowed us to then determine the torque requirement for our targeted current (200mA), and the associated necessary nozzle diameter, as shown in Tables 6, 7, and 8.

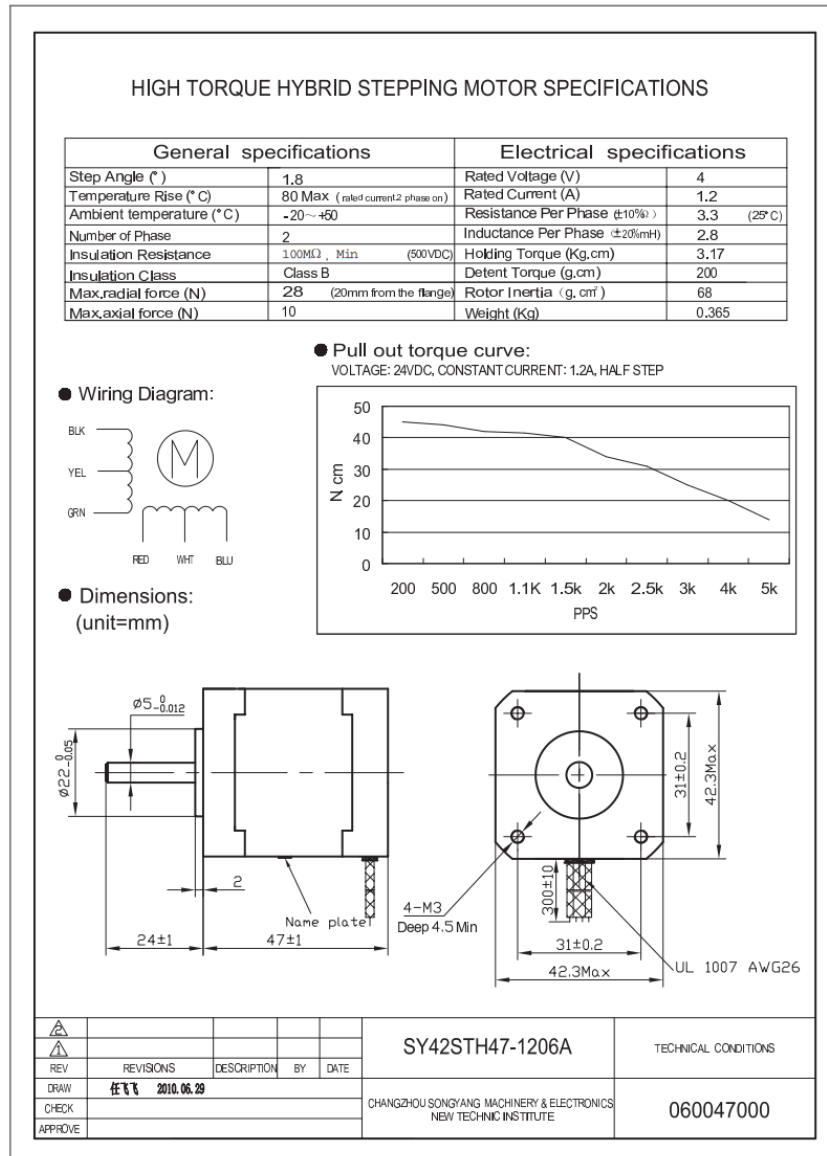


Figure 13. Specification sheets of stepper motor.

4.8 Battery

We aim to gather the power necessary to activate a light source for 2 hours every day, during half of the year. The simplest way to achieve this is through commercially available flashlights that can be powered with AA batteries.

According to the literature, it appeared that precharged Nickel-Metal Hydride (Ni-MH) batteries best suit our project. Indeed, they are cheap and much less toxic than Nickel-Cadmium batteries and are very similar to typical alkaline batteries whether it be the shape or nominal voltage (Kuchhal and Sharma, 2019). When operated safely, 1.2V Ni-MH batteries can be used in moderate to high intensity devices like headlamps and GPS. The most critical point is at a high state of charge where the charge current must be limited to avoid overcharge resulting in damage (Jossen et al., 2004). The safest way to charge these devices is through “trickle charging”, meaning without

exceeding 10% of the charge capacity. According to the manufacturer's specifications, the self discharge rate of standard Ni-MH batteries is around 30-40% per month, whereas pre-charged ones can retain up to 75% of charge after 1 year of storage. Precharged Ni-MH batteries can also handle more charging cycles than standard ones and come in AA and AAA formats (REI, 2021 and Maha Energy, 2021). The battery chosen for this project was the Eneloop AA Nickel Metal Hydride which specifications are listed in Table 4 below.

Table 4. Eneloop NiMH battery specifications (Sanyo, 2006).

Product	AA Nickel Metal Hydride Battery
Model Number	HR-3UTG 
Nominal Voltage	1.2V
Nominal Capacity ^{*8}	2000mAh
Rated Capacity ^{*9}	1900mAh
Dimensions	14.35 mm (diameter) X 50.4 mm (height)
Weight	Approximately 27g

Having chosen the battery that best fits our project, the electrical circuit could be elaborated. To apply the safest option, we would need to provide a maximum of 10% of the charge capacity, meaning 200mA to charge a 2000mAh AA battery. Furthermore, a 2V LED should be included in series to the 1.2V battery, to indicate when current is produced. This yields a minimum voltage requirement of 3.2V to charge one battery. Thus, we can use a 3.3V voltage regulator that will require 5V to function properly considering dropout voltage. Lastly, a resistor must be added to limit the current and can be computed using the following equation: $R = V/I = 3.2/0.200 = 16 \Omega$. The following Figure 14 shows the electrical circuit past the rectifier and voltage regulator.

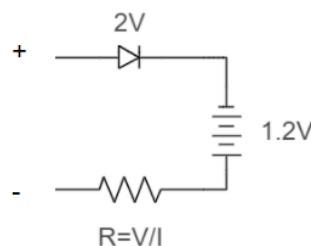


Figure 14. Preliminary circuit to charge a single Ni-MH battery.

As a result of the trickle charging, the battery will take longer to reach full capacity. This is not necessarily a problem as we know that, although limited by the trickle charging, overcharging can damage the cell. Like most batteries, Ni-MH batteries can be used even if they are not at full capacity. The time necessary to achieve full charge for a AA, 2000 mAh, can be estimated by the following calculation: $2Ah/0.2A = 10 \text{ hours}$.

5. Materials & Methods

In the case of the prototype building, a 4m head was used for testing. Components of the design were chosen based on needs, accessibility to materials, sustainability, durability, cost, and safety. The materials and components were purchased progressively from various sources, including Amazon, Canadian Tire, Rona, and Mcaster-Carr. In addition, some elements were borrowed from professors to reduce costs, and the overall environmental impact of our prototype building.

5.1 Manufacturing & 3D printing

The simplest way to manufacture our prototypes was through 3D printing. Indeed, given the innovative nature of our design, this technique allowed us to build custom prototypes with complex shapes, and precise dimensions. This is particularly true given the design of the Pelton buckets. In addition, Yamog has a 3D printer in their workshop meaning once they receive the file, they can easily print and recreate the system. We were accompanied by the Macdonald Manufacturing Modeling & Design (M3D) Club on McGill's Macdonald Campus which kindly made their machines available. This allowed us to iterate rapidly and print a design once we had completed it on AutoCAD.

As we were printing our own designs, we had the liberty to focus on the material properties that were of interest to us. In fact, we decided to use biobased polylactic acid (PLA) filament throughout this design project as it would be enough to perform our test, but most importantly it is easy to print and biodegradable. Although PLA filament is cheap (\$0.03/g), it is good practice to keep material costs and printing time to a minimum. This was another advantage of printing our own custom designs, as seen in Figures 15 and 16, material was only added where necessary. In addition it allowed us to design responsibly in a way that would allow the user to easily replace broken parts without having to discard the entire system.

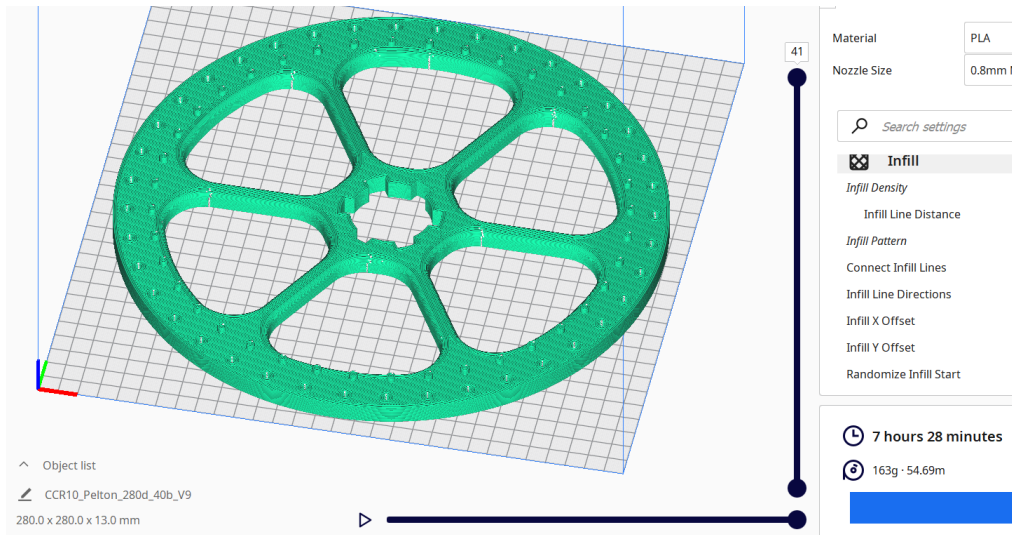


Figure 15. Mammoth turbine in the Cura slicer, indicating time and material estimates.

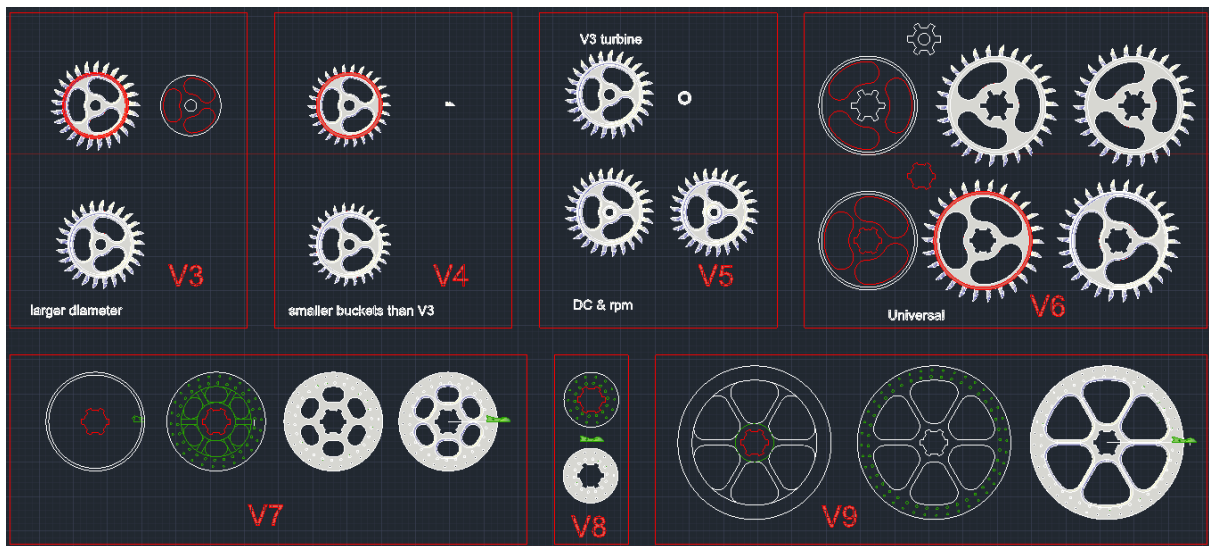


Figure 16. Screenshot from the AutoCAD file containing all the iterations of the turbine design.

The majority of the parts from our prototypes were custom designed and 3D printed. We quickly realized that printing the Pelton turbine in one piece was too much of a challenge and resulted in brittle buckets (Figure 17). As a result, buckets were printed separately (Section 5.4) and assembled to the turbine using a bolt and nut, and a protruding cylinder to reduce weight and prevent the latter from acting as a pivot (Figure 18). We also designed and printed our own nozzles (Figure 19), buckets (Figure 20), adaptor to link the generator, rotary encoder, and turbine (Figure 21), and holders to mount the generators to the prototype (Figure 22).



Figure 17. Pelton turbine as a single print.



Figure 18. Buckets mounted on the big turbine.

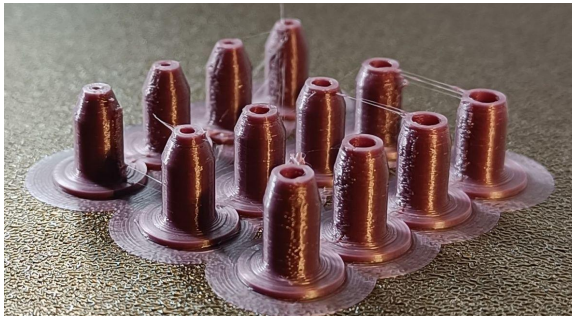


Figure 19. Nozzles of different sizes.

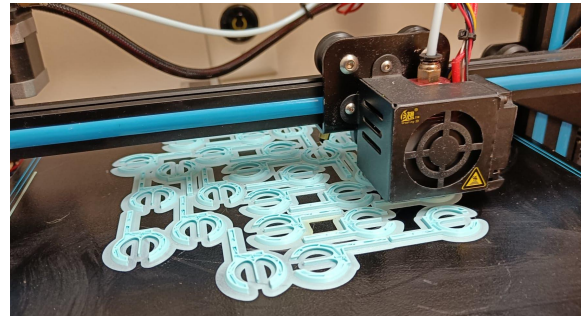


Figure 20. Buckets being printed.



Figure 21. Adaptor from DC to encoder.

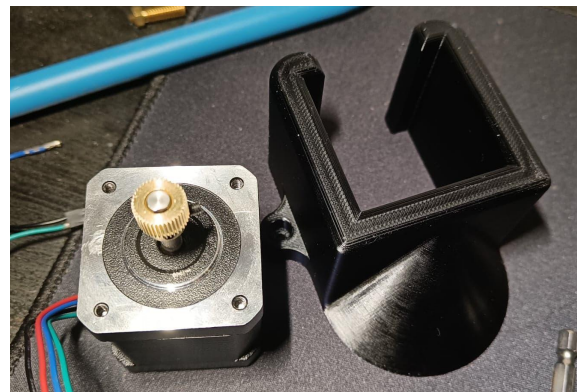


Figure 22. Stepper motor mount.

5.2 Penstock

The focus of prototype testing was not on the duration of rotation of the turbine, but rather on optimizing the design to generate the most power in the shortest possible time. It was therefore decided to limit ourselves to a $\frac{1}{2}$ "x20' PVC flexible tube. Since the head influences the pressure and velocity at the exit of the nozzle, the data collected with our thin tube is applicable to a standard, thicker penstock. Indeed, the size of the penstock will only impact the amount of water stored, and

hence how long the turbine will rotate for. The penstock was set up at a 4m head and was fully filled using 800 mL of water.

A push-fit valve was purchased and pressfitted to the PVC pipe. It is an Aqua-Dynamic ball valve made of lead-free brass as seen in Figure 23. It has a $\frac{1}{2}$ " push-fit end, and a $\frac{1}{4}$ " outside diameter compression end, and is suitable to join PVC tubing. In addition, it meets the NSF/ANSI 372 lead-free standard (NSF International, n.d.). The valve has the advantage of being dismantled at the exit in order to change the nozzle for one of a different diameter.



Figure 23. Push-fit Aqua-Dynamic ball valve with included 4mm-diameter brass nozzle.

5.3 Nozzle

An important part of our prototype testing process was to test our assembly for several nozzle diameters. The outlet of the valve shown on Figure 23 was an M6 male thread, therefore an M6 female threaded nozzle fitting was purchased, with a 4mm-diameter brass nozzle included. After seeing how efficient the provided 4mm nozzle was, we used its design as the model for our various nozzle iterations. Nozzles with diameters varying from 1.2mm to 3.4mm were first designed as seen in Figure 24, then 3D printed. The goal was to study the variation in electric generation between the theoretical nozzle diameter found last semester (1.2mm) and the diameter of the nozzle provided (4mm). These original nozzle designs underwent a number of modifications after the beginning of the prototype testing.

One of the first alterations made was to reduce the length of the nozzles, so that they would be protected by the nozzle fitting, therefore reducing risks of damage. We also realized that higher nozzle diameters yielded better electrical values, and therefore decided to only test nozzles between 3mm- and 6 mm-diameters. Finally, the performances of three alternative nozzle designs were tested using a COMSOL simulation, in order to establish the fluid velocity profile in different nozzle geometries for the same inlet velocity (see Section 6).

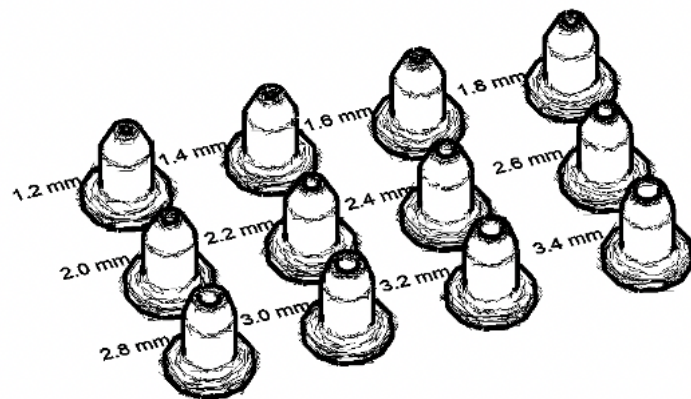
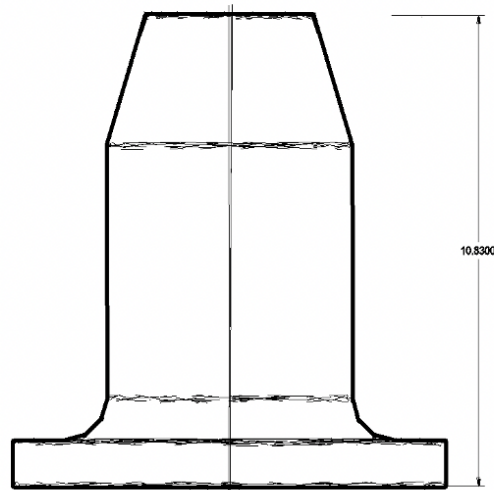


Figure 24. 3D printed Nozzles sketch from AutoCAD.

5.4 Turbine

Dimensions of the turbine influence the rotational speed (rpm) and the torque obtained. The rpm of the turbine is directly related to the voltage produced by the generator, while the torque applied is related to the current generated. In fact, the rpm is inversely proportional to the diameter of the turbine.

$$\text{Speed in rpm} = \text{Linear speed} / \text{circumference of the wheel}$$

The torque is proportional to the diameter of the turbine but can also be influenced by the force produced by the water jet. With the formula being the following:

$$\tau = rF \sin \theta$$

With:

τ = torque

r = radius

θ = angle between the applied force and the radius of the wheel

In order to know what is more efficient for our system, we printed out three turbines at 100mm, 180mm and 280mm, seen in Figures 25, 26, 27 respectively. Our diameter was chosen depending on the capacity of the 3D printing bed; 280mm was the biggest diameter possible, and we downscaled it twice. This way, we'll be able to know if we benefit more from having a bigger diameter and (increasing the torque) or reducing the dimensions (increasing the rpm). Rpm and torque are important parameters to control. In fact, torque directly influences current generated, while rpm influences voltage.

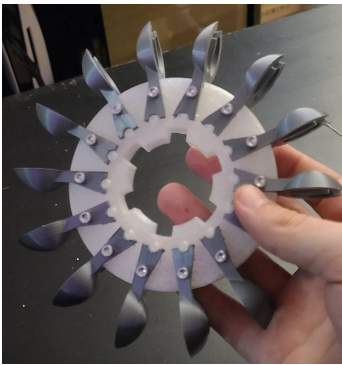


Figure 25. 100mm diameter

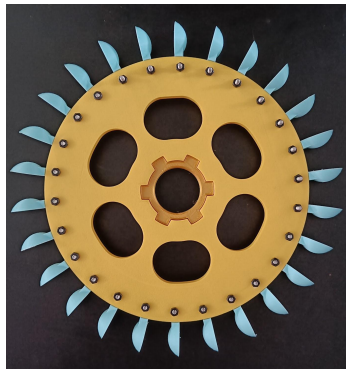


Figure 26. 180mm diameter

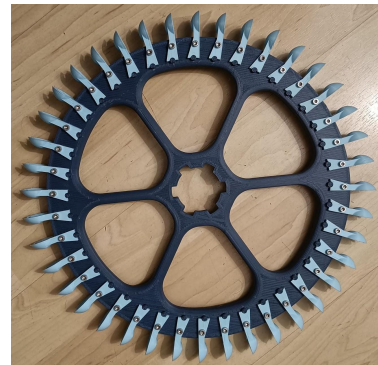


Figure 27. 280mm diameter

Following this approach, we had two sets of buckets. These were designed following the general shapes of pelton wheel buckets. However, some compromises in the shape were made to increase durability of the buckets and ease to 3D print. It allowed us to know what approximate scale was the best for our system. The dimensions are seen in Figure 28 and Figure 29, and the buckets are seen in Figure 30.



Figure 28. Dimensions of small buckets

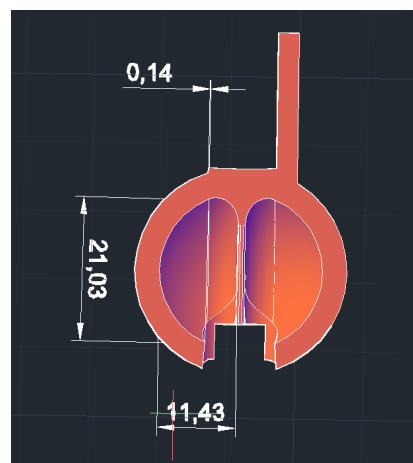


Figure 29. Dimensions of big buckets

Small Bucket:

Depth: 0.11mm

Half-Width: 9.14mm

Half-Length: 16.82mm

Big Buckets:

Depth: 0.14mm

Half-Width: 11.43mm

Half-Length: 21.03mm



Figure 30. Two different sizes of buckets

We were able to find 3D models of Pelton wheel buckets that were used in past experiments. However, the numerous tests that we needed and versatility needed in terms of changing bucket dimensions made it better to have buckets that can be consistently printed without errors. This form of buckets, see on Figure 31, can be used to further improve our system in the future.

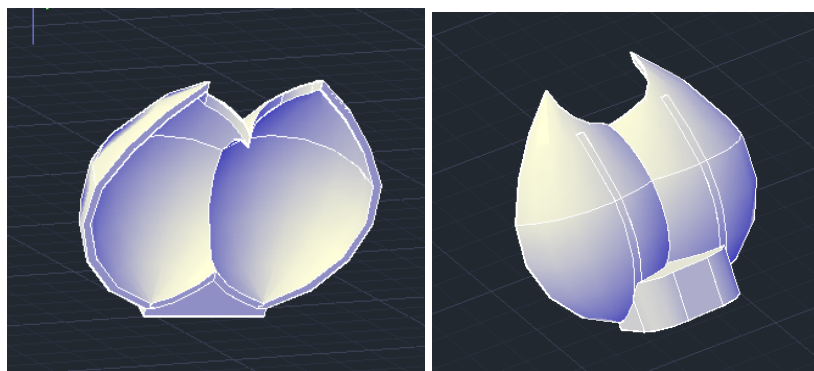


Figure 31. 3D model of ideal bucket shape.

The turbine itself was mounted on a shaft that had adapted insertion holes at the two ends, one of them being an adapter to our generator shaft while the other was on a free rotating shaft for stabilization. The shaft and mount in question can be seen in Figure 32 and Figure 33:



Figure 32. Mounting of the turbine

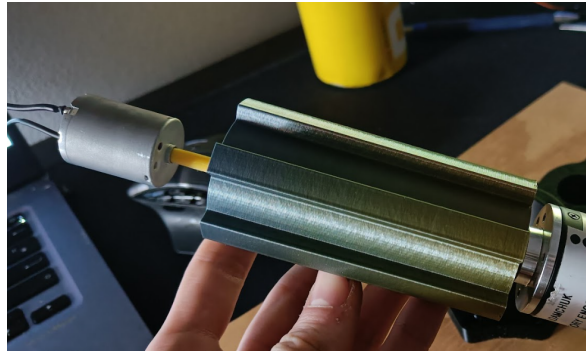


Figure 33. Shaft mounted on the DC motor

When following Appendix B formulas to calculate the geometry of our turbine we obtained realistic projected speeds of 265 rpm for the 279mm turbine. However, the dimensions of the bucket were unrealistic with a width of 2 mm and a depth of 0,8mm. These are however numbers that can be slightly increased and tested for in order to improve bucket design.

5.5 Electric circuit

This section is dedicated to the electrical components required to safely convert mechanical energy from a generator to chemical energy, via electrical energy. When used as generators, stepper motors are a source of alternating current (AC) which must be converted to direct current (DC) to charge a battery (Figure 34). Thus, the electric circuit requires rectifiers that were soldered in parallel to maximize the current output. Capacitors were added across the rectifiers to smooth out the flow and act as a buffer. To protect the LED and batteries in the circuit, a voltage regulator is required, it will dissipate excess voltage as heat. To operate properly, voltage regulators typically have a drop out voltage of 2V. Lastly, a resistor must be added to limit the current, and the circuit returns to the negative terminal of the rectifier. Follow what has been specified in Section 4.8 and evaluate whether a second battery can be charged at the same time (Figure 35).

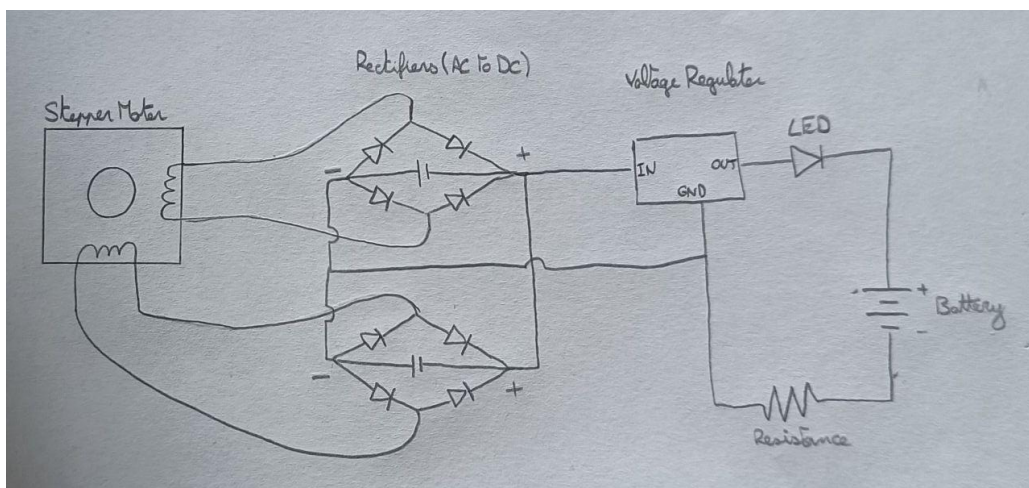


Figure 34. Electric circuit of a Stepper Motor charging batteries.

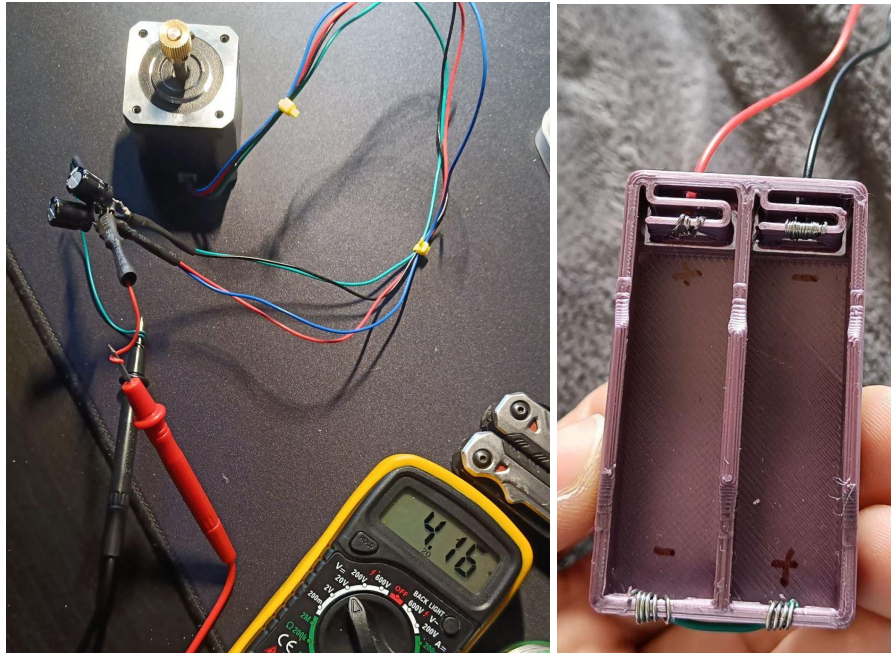


Figure 35. Rectifiers and capacitors in heat shrink and battery pack.

5.6 Set-up and Testing method

In order to test our system with several iterations of our turbine and nozzles, as well as with different generators, we chose a prototype assembly that we could easily interchange. Two sheets of plywood were used for structural integrity, and one of them was mounted with three types of generators, while the other was mounted with a rotary encoder (see Figure 32). Several models of an adapter were designed and 3D printed in order to hold the turbine and connect the shafts of the different generators with that of the encoder (see Figure 33). This set-up allowed us to easily switch our testing conditions, by interchanging adapters depending on the type of generator used, and aligning the encoder shaft with that of the appropriate generator. All three sizes of our turbine were designed to be mounted on all of our adapters, which also helped us reduce the cost of our prototype as much as possible (see Table 5).

We tested the resulting prototypes for several parameters: current and voltage generated, jet flow rate, and rotational speed. For all these tests, the procedure used was the same: a member of our group would pour water down a flexible PVC pipe from a 4m-height, in order to simulate the head from the top of the penstock. Another one would hold the valve and nozzle assembly at the end of the pipe and direct it onto the turbine. Finally, one or two members would record the results while ensuring proper operation of the prototype. Current and voltage measurements were taken using a standard multimeter, provided in an Arduino kit. Flow rate measurements were taken by recording the volume exiting our different nozzles in a fixed amount of time, then performing the proper calculations.

In an attempt to theoretically find the optimal design parameters for our design, we characterized the minimal rpm needed to produce 5V experimentally. This was done using

slowed-down video footage. The rpm was calculated once we got a constant reading of 5V, the generator was turned manually. Then we needed to find the minimal torque needed to achieve 200mA. In order to do that, we first looked at the specification sheet of the motor we used (Figure 13) (see section 4.7). Based on the holding torque and desired current, as well as the formula for electric torque (Figure 36) we were able to find our needed torque. From there, we applied the formula of mechanical torque (Figure 37) and found the needed force to produce this torque depending on the turbine diameter. Once the needed force was calculated, we found the outlet area needed to keep the projected pressure of 40 kPa. Through these theoretical computations we found an approximate ideal nozzle diameter to produce the needed torque. The results of these experiments are showcased in the next section.

$$\tau = k_t * I$$

$$k_t = \text{a constant}$$

$$\tau = \text{torque}$$

Figure 36. Electric torque formula (stackexchange.com)

$$\tau = rF \sin \theta$$

$$r = \text{radius}$$

$$F = \text{Force applied}$$

$$\theta = \text{angle of force from the vector normal to the radius}$$

Figure 37. Mechanical torque formula (www.physics.uoguelph.ca)

Table 5. Total cost of system prototype.

Component	Price (CAD)
Tube ½"x20'	\$9,69
Faucet	\$19,99
3D Printed Nozzle	\$0,03
3D Printed Turbine	\$4,89
Buckets	\$2,22
Nuts & Bolts	\$2,01
Adaptor	\$1,50
Stepper motor	\$18,99
Diodes & capacitors	\$1,50
TOTAL	\$60,82

6. Results

Before conducting the tests with the complete prototype, we approximated the ideal nozzle diameter to achieve a 200 mA current and a 5V voltage. The steps followed to find those numbers are described in section 5.6, to achieve the necessary torque of 0,08 N*m. The results obtained can be seen in the following tables (6,7,8):

<i>Determining the torque constant</i>	
T (holding)	0,48 N*m
I	1,2 A
k _t	0,4 N*m/A
<i>Determining target torque</i>	
k _t	0,4 N*m/A
I (target)	0,2 A
T	0,08 N*m
<i>Determining Force on buckets</i>	
T	0,08 N*m
r	0,152 m
F	0,53 N
<i>Determining area on which water pressure must be exerted</i>	
F	0,53 N
P	40000 Pa
A	0,000013 m ²
<i>Determining nozzle diameter</i>	
A	0,000013 m ²
d	4,09 mm

Table 6. Ideal nozzle for
280mm turbine

<i>Determining the torque constant</i>	
T (holding)	0,48 N*m
I	1,2 A
k _t	0,4 N*m/A
<i>Determining target torque</i>	
k _t	0,4 N*m/A
I (target)	0,2 A
T	0,08 N*m
<i>Determining Force on buckets</i>	
T	0,08 N*m
r	0,102 m
F	0,78 N
<i>Determining area on which water pressure must be exerted</i>	
F	0,78 N
P	40000 Pa
A	0,000020 m ²
<i>Determining nozzle diameter</i>	
A	0,000020 m ²
d	5,00 mm

Table 7. Ideal nozzle for
180mm turbine

<i>Determining the torque constant</i>	
T (holding)	0,48 N*m
I	1,2 A
k _t	0,4 N*m/A
<i>Determining target torque</i>	
k _t	0,4 N*m/A
I (target)	0,2 A
T	0,08 N*m
<i>Determining Force on buckets</i>	
T	0,08 N*m
r	0,062 m
F	1,29 N
<i>Determining area on which water pressure must be exerted</i>	
F	1,29 N
P	40000 Pa
A	0,000032 m ²
<i>Determining nozzle diameter</i>	
A	0,000032 m ²
d	6,41 mm

Table 8. Ideal nozzle for
100mm turbine

The raw results of our tests as well as the deduced values are shown below. Our first step was identifying the best generator. After testing both generators with a 4mm nozzle, we decided to further push our experimentation with the stepper motor as this yielded better results. Then, in order to identify the best bucket for each configuration, we tested the two sizes for the same turbine and nozzle diameter. The last step was to identify the best nozzle diameter for the chosen configurations. All tests were performed with a 4.0m head.

Table 9. DC motor raw results with the 180mm turbine and small buckets.

Nozzle Diameter (mm)	Max Voltage (V)	Max Current (mA)
1,2	1,00	15
1,4	1,58	17
1,6	1,80	25
1,8	1,76	25
2	2,05	30
4	2,40	34

Table 10. DC motor raw results with the 100mm turbine and big buckets.

Nozzle Diameter (mm)	Max Voltage (V)	Max Current (mA)	rpm
1,6	2,0	22	360
1,8	2,3	26	315
2,0	2,6	25	420
2,2	2,9	36	420

Tables 11 and 12 show the obtained results for the tests using a stepper motor and the two bucket sizes for the 180 and 280mm turbines. This was done after seeing that the 100mm turbine is not operational with the stepper motor, since not enough torque is produced to turn it. Also, only the small buckets were tested on the mammoth turbine since we were consistently getting better results with these.

Table 11. Results for the big turbine and small buckets

Nozzle Diameter (mm)	Max Voltage (V)	Max Current (mA)	Max Power (W)
3,00	5,40	48,20	0,26
3,20	6,15	62,40	0,38
3,40	7,40	78,60	0,58
3,60	7,53	86,30	0,65
3,80	7,40	95,80	0,71
4,00	7,41	142,50	1,06
5,00	10,70	192,50	2,06
6,00	11,00	370,00	4,07

Table 12. Results for the big turbine and big buckets.

Nozzle Diameter (mm)	Max Voltage (V)	Max Current (mA)	Max Power (W)
3,00	3,50	28,90	0,10
3,20	4,15	41,20	0,17
3,40	5,05	69,90	0,35
3,60	5,15	54,90	0,28
3,80	5,63	69,70	0,39
4,00	11,60	350,00	4,06
5,00	10,00	180,00	1,80
6,00	10,00	300,00	3,00

Table 13. Results for the mammoth turbine and small buckets

Nozzle Diameter (mm)	Max Voltage (V)	Max Current (mA)	Max Power (W)
3,00	5,00	106,00	0,53
3,20	3,60	88,00	0,32
3,40	6,47	180,00	1,16
3,60	4,30	82,00	0,35
3,80	6,60	192,00	1,27
4,00	7,20	300,00	2,16
5,00	6,90	290,00	2,00
6,00	7,90	220,00	1,74

Once the results of the stepper motor were obtained, the efficiency of each performance was calculated, as well as its difference to the target power to generate of 1W. These can be seen in table 14:

Table 14. Stepper motor, small buckets, mammoth and big turbine

Nozzle diameter (mm)	Power (W) 180mm turbine	Efficiency (%)	difference from needed efficiency for 1W of Power	Power (W) 279mm turbine	Efficiency (%)	difference from needed efficiency for 1W of Power
3	0,1	5,7	50,9	0,5	30,0	26,6
3,2	0,2	7,6	36,7	0,3	14,0	30,2
3,4	0,4	19,6	35,8	1,2	64,5	-9,1
3,6	0,3	13,2	33,6	0,4	16,5	30,3
3,8	0,4	15,6	24,2	1,3	50,5	-10,6
4	4,1	74,2	-55,9	2,2	39,5	-21,2
5	1,8	32,3	-14,4	2,0	35,9	-18,0
6	3,0	48,1	-32,1	1,7	27,9	-11,8

Finally once we found our optimal nozzle diameter we created various theoretical scenarios with different catchment areas and Penstock areas. This allowed us to find the best and most usable configuration of our system. A theoretical scenario using a 3.4 mm nozzle was judged realistic with slight improvement to our system. In fact, with a 279mm turbine, we are very close to our target power. Table 15 showcase these scenarios:

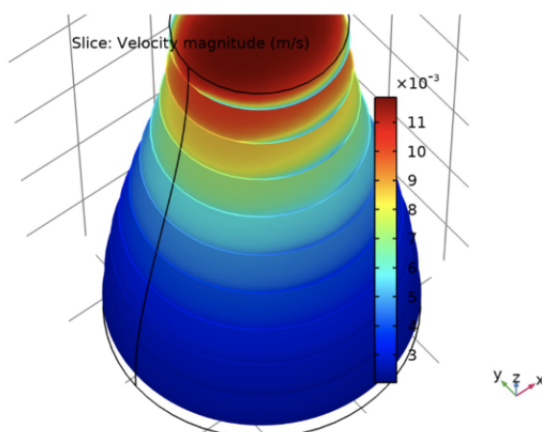
Table 15. Potential penstock and water catchment surface sizes and their corresponding fill and discharge time

Initial design

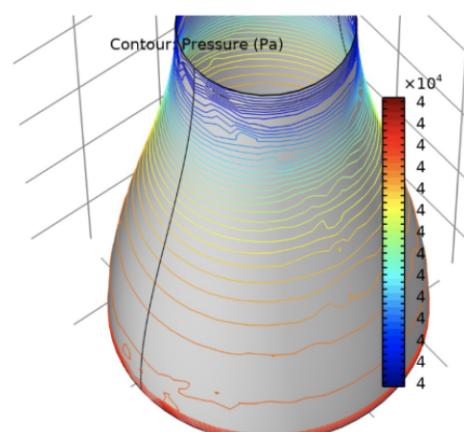
		<table><tr><td>Precipitation (m/10h)</td><td>0,0088</td></tr><tr><td>Precipitation (m/h)</td><td>0,00088</td></tr><tr><td>Catchment area (m2)</td><td>25</td></tr><tr><td>Precipitation volume (m3/h)</td><td>0,022</td></tr><tr><td>Precipitation volume (m3/min)</td><td>0,0004</td></tr><tr><td>Penstock height (m)</td><td>4</td></tr><tr><td>Penstock diameter (in)</td><td>3,042</td></tr><tr><td>Penstock diamter (m)</td><td>0,077</td></tr><tr><td>Penstock volume (m3)</td><td>0,019</td></tr><tr><td>Penstock fill time (min)</td><td>51</td></tr><tr><td>Nozzle size (mm)</td><td>4</td></tr><tr><td>Outflow rate (m3/s)</td><td>0,000139</td></tr><tr><td>Outflow rate (m3/min)</td><td>0,008364</td></tr><tr><td>Discharge time (min)</td><td>2,3</td></tr></table>	Precipitation (m/10h)	0,0088	Precipitation (m/h)	0,00088	Catchment area (m2)	25	Precipitation volume (m3/h)	0,022	Precipitation volume (m3/min)	0,0004	Penstock height (m)	4	Penstock diameter (in)	3,042	Penstock diamter (m)	0,077	Penstock volume (m3)	0,019	Penstock fill time (min)	51	Nozzle size (mm)	4	Outflow rate (m3/s)	0,000139	Outflow rate (m3/min)	0,008364	Discharge time (min)	2,3																												
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Smaller Nozzle (3.4mm)		Smaller nozzle (3mm)																																																								

Precipitation (m/10h)	0,0088	Precipitation (m/10h)	0,0088
Precipitation (m/h)	0,00088	Precipitation (m/h)	0,00088
Catchment area (m2)	25	Catchment area (m2)	25
Precipitation volume (m3/h)	0,022	Precipitation volume (m3/h)	0,022
Precipitation volume (m3/min)	0,0004	Precipitation volume (m3/min)	0,0004
Penstock height (m)	4	Penstock height (m)	4
Penstock diameter (in)	3,042	Penstock diameter (in)	3,042
Penstock diameter (m)	0,077	Penstock diameter (m)	0,077
Penstock volume (m3)	0,019	Penstock volume (m3)	0,019
Penstock fill time (min)	51	Penstock fill time (min)	51
Nozzle size (mm)	3.4	Nozzle size (mm)	3
Outflow rate (m3/s)	0,000046	Outflow rate (m3/s)	0,000045
Outflow rate (m3/min)	0,002760	Outflow rate (m3/min)	0,002700
Discharge time (min)	7,8	Discharge time (min)	8,0

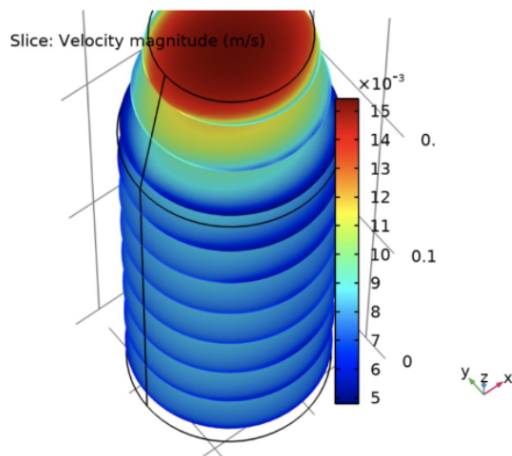
A computational model was made in COMSOL Multiphysics and used to assess the impact of three different nozzle geometries on the velocity of a water jet going through them. It is not possible to directly measure the change in velocity across the nozzle without a simulation. Although it is feasible to measure the speed at the exit of the nozzle using the outflow rate, it is important to see how the geometry affects the speed of water flowing throughout it to design the best nozzle for the system. A computational model provides a precise visualization of the flow through each geometry. Although the values from the simulation do not reflect the actual velocity of the jet, the simulation shows that geometry of nozzle *b* yields the highest jet velocity amongst all three. Figure 38. Velocity and pressure profiles of several nozzle designs in COMSOL.



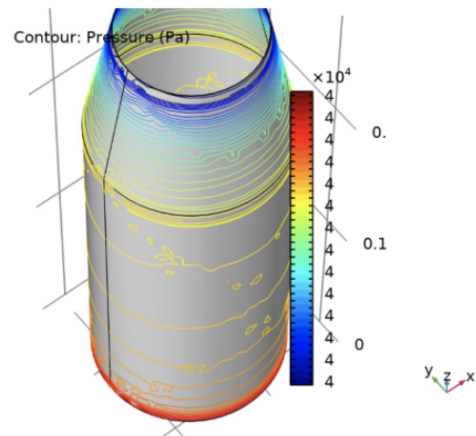
Nozzle A. Velocity Magnitude (m/s)



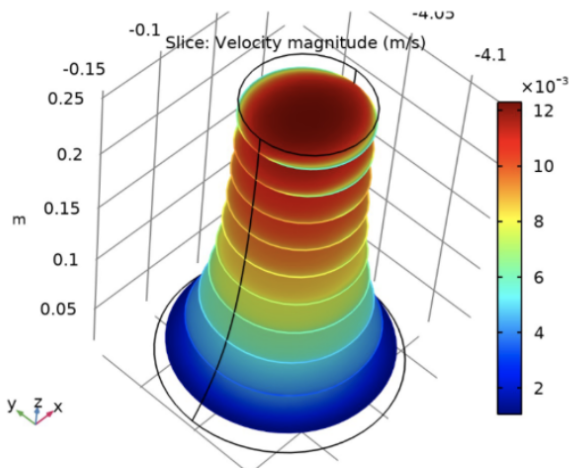
Nozzle A. Pressure (Pa)



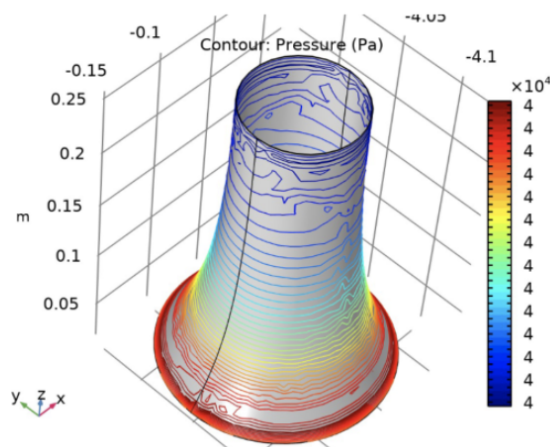
Nozzle B. Velocity Magnitude (m/s)



Nozzle B. Pressure (Pa)



Nozzle C. Velocity Magnitude (m/s)



Nozzle C. Pressure (Pa)

7. Discussion

7.1 Final Design

Throughout the testing process, we noticed that nozzles with larger diameters would have stronger jets, increasing the torque and speed of rotation of the turbine. This went against what we had anticipated; based on the literature, the smaller the nozzle, the stronger the jet. The three nozzles that yielded the best results for our mammoth turbine were those with 4mm, 5mm, and 6mm in diameter. Interestingly, from diameters of 3mm to 4mm, the power generated shows an overall increasing trend

despite two outliers (3.2mm and 3.6mm). However for nozzles beyond 4mm, these values begin to decrease.

Results have proven that the stepper motor yielded the best results. Indeed, our brushless DC motor did not meet the voltage and current requirements, with the greatest values recorded being with our big turbine, generating 2.9V and 36.6mA. We therefore quickly decided to switch for another, more performant motor. Voltage is directly related to the speed of rotation of the turbine, and current is directly related to the torque. When we were not achieving our desired output, we looked into ways to increase the torque and speed of rotation of the turbine, whether that was by changing our motor, our turbine and its buckets, or our nozzle.

The outflow rate from the nozzles of different diameters were measured and used to assess different options for the sizes of water catchments and penstocks, while maintaining the head constant (4m). Using a 4mm nozzle, a catchment area of 25m² and a standard PVC penstock with a 3 inch diameter (Pvcfittingsonline, 2021) the penstock would be filled in 51min before the valve could be opened. Once opened, the discharge time would be 2min18s. Since the battery requires 10-12 hours in order to be fully charged, this set-up would be long, requiring multiple interventions. Increasing the water catchment area to 50 m² would have the advantage of decreasing the penstock fill-time to 26 minutes, while maintaining the discharge time at 2min30s, which would decrease the overall time taken to charge the battery but still require multiple interventions. However, if the penstock size is increased to a 6 inch diameter standard PVC pipe (Pvcfittingsonline, 2021), the filling and discharge time become 3h21min and 9 min12 s respectively, requiring fewer interventions.

A larger nozzle means a greater outflow rate, therefore if one wants to increase the discharge time, and hence the time during which the turbine would be turning, they must decrease the nozzle diameter. Using a smaller nozzle, for example a 3.4mm nozzle, the discharge time may be increased. For the same set-up (25m² and 3" PVC pipe) the discharge time would be 7min48s. Although the 3.4mm nozzle only generated 180mA of current, this could be improved to meet the 200mA requirement, and would have the advantage of decreasing the outflow rate. It is important to note, however, that the design should be adapted appropriately based on the available catchments and penstocks in the regions of interest, and such decisions are out of our control.

Regarding the turbines, smaller buckets yielded better results than larger buckets. Indeed, when testing for the 180mm diameter turbine, the highest current generated was 370mA with the small buckets, and 350mA with the big buckets. Therefore, only small buckets were used for the tests with the 280mm diameter turbine. The results have shown that the highest power output was achieved using the big turbine of diameter 180mm with 26 buckets, a 4mm nozzle, a 4m head and the stepper motor. The maximum voltage and current generated with this setup were 11.6V and 350mA respectively. However, in the context of this project, we are not looking to achieve such high values, and doing so might in fact be detrimental to the system. Indeed, excess voltage will be lost as heat

within the voltage regulator. Therefore, the Mammoth turbine ($d=280\text{mm}$) is the best design, producing 7.2V and 300mA, when using a 4mm nozzle to direct the jet, a 4m head and the stepper motor. This is closer to the necessary amount of power required (5V and 200mA) to activate a light for 2 hours every day, during half of the year.

7.2 Applications

One of the main goals of this project was to create a design that would be highly adaptable for different locations, and available water catchment options. The prototype building and testing method was mainly focused on achieving our power output by changing the design of the turbine, nozzle and the available alternators and motors. The head was kept constant (4m) throughout all tests. It is therefore the end-user's responsibility to ensure that the catchment area and size of the penstock are suitable to harvest enough water to charge the battery in the time period and intervals that best suit them.

As previously mentioned, a larger penstock would mean a longer filling time, however this would also mean a longer discharge time, reducing the amount of interventions required to open and close the mechanical valve. A larger catchment would also have the advantage of decreasing the time taken to fill the penstock, however it may be intrusive as well as difficult to find in the targeted communities. If a tarp is used as a water catchment surface, this may harm the scenery, keep plants and local ecosystems in the shade, having the potential to negatively impact their growth.

An alternative that could be explored in certain locations, would be to use the landscape to set up the penstock and water catchment. Water could be harvested at the top of a mountain or hill, the penstock could be longer, have a larger volume while still providing the 4m head necessary for the system to function. This would increase the amount of water that could be stored, and therefore the discharge time.

7.2.1 Environmental considerations

Throughout the design process, and the prototype building, we have had to keep in mind several environmental, social and economical considerations if the system were to be implemented. Producing renewable energy with minimal impact on the surrounding environment was the principal environmental criteria for our design. We ensured to consider several other factors which included limiting the generation of greenhouse gasses in the production and implementation of the system by choosing materials that were widely available such as PVC, thereby reducing transportation. These materials were carefully chosen, keeping in mind that we wanted to avoid introducing toxic compounds to the site. It was important to design a system that was as low tech as possible in order to make the repair process simple and prevent discarding the entire system.

This impact may be direct or indirect, and the location should be carefully selected based on the feedback of qualified professionals and locals in the regions of interest. There are three criteria that must be taken into consideration when selecting the site; it must have no constant flowing body of water rendering our design obsolete, a high amount of precipitation, and a solution to achieving a high head. Finally, a location with open canopy would be best suited, as branches and leaves may clog the inlet of water and damage the system or decrease its performance.

Further environmental considerations include dealing with runoff water caused by the overflow and outflow through our system, which may cause chronic flooding in the local community. The choice and disposal of materials as well as the growing issues related to climate change are also very important factors to keep in mind. As we are collecting precipitation, a large water catchment may cause localized drought if the water is not passing through the covered location. It is therefore important to ensure that the system is not in the way of important vegetation and agricultural fields. That being said, it may also provide shelter for members of the community during rain events.

The materials used for the design parts of our prototype were carefully chosen, based on environmental, economical and social constraints. For example our 3D printed materials were made of biodegradable PLA. We have also used rechargeable batteries as opposed to single use ones, further reducing the overall impact of our system. Although most materials were chosen making sure they would be widely available, it may not be possible to source some of them locally and importing them from elsewhere may lead to greenhouse gas emissions. That said, the entire operation may become carbon neutral as the electricity produced by our system is renewable. An important aspect of the project is informing the local population, and consumers of the potential dangers of this material if incorrectly disposed of, and provide them with the relevant knowledge on recycling practices. Regarding the issue associated with transportation, the distances covered in shipping should be as small as possible. Finally, if the project is implemented, re-purposing of local waste and building materials should be implemented when adequate.

7.2.2 Social considerations

Our project aims to help specific communities. As mentioned, these communities live in mountainous regions with no access to flowing water, in a tropical climate. This makes their social dynamics singular and worth adapting our system to. By furnishing a system that can produce energy we are inevitably creating an opportunity for inequalities to form locally and conflicts to arise. Therefore, a fair distribution of the governance and energy furnished has to be done. The most efficient way of doing that, is to directly work with the locals and allow them to organise themselves following their own needs. For example, if we provide a single micro-hydro system, we are only powering a AA battery for a big community. The people involved in that community will be the ones that can identify what is the most urgent use of that energy.

Local governance is a key aspect of our project. One of our main goals was to increase the resilience of these isolated communities, or in other words, their ability to thrive without depending on constant foreign supply. Therefore, the locals need the technical knowledge and leadership skills to organize their power supply system, manage it and maintain it. The local NGOs (Yamog and CREST) we interviewed both stated that a main step of their project was the formation of individuals from the communities benefiting from their help. The formation would consist of involving the interested stakeholders in the construction of the project, educating them on the different technical aspects of it and the necessary maintenance to be made. Then, the locals would elect internally people in charge of maintaining, inspecting and organizing the whole system.

If we follow this strategy we are avoiding the creation of dependency of these communities on external help. We will be furnishing a solution as well as the necessary knowledge needed to recreate the system independently. Our strategy of 3D-printing most of the components allows us to transfer physical components virtually and make them accessible technically whenever it's needed. According to CREST the local organizations involved with the isolated communities often have access to a 3D-printer, and it's a piece of technology that is becoming more and more affordable.

In terms of Health and safety, there are no major risks associated with our system. However, some aspects have to be considered carefully; the water catchment is a heavy object placed at significant height, the turbine is ideally not placed directly under by having the catchment in a butterfly shape (see section 4.3). Also, since we're dealing with electrical components, the batteries and capacitors have to be properly shielded from the splashing water.

7.2.3 Economic considerations

It was critical to create a design that would be accessible to the targeted communities. This was taken into consideration at every stage of our design process, from the conceptualization to the implementation. As previously stated, the choice of materials was crucial in this regard as the raw cost, ease of processing and transportation of the chosen components will all influence the final price of our product. These criteria led us to using 3D modeling and printing for the design and production of our custom parts (see section 5.1). The 3D printing technology is an accessible means of manufacturing that is spreading around the world, and is already being used by energy NGOs such as CREST and Yamog.

The implementation of our project would need to be substantially subsidized by local governments, considering it is still costly at its development stage. These subsidies could either be directly addressed to the targeted communities for the purchase of our system, or to NGOs as part of a campaign to make our product widely available in a specific region. In both cases, it is necessary that the end-users are directly involved in the implementation process, as they will later be in charge of operating and maintaining the system. Indeed, training communities to use and manage their

development tools is an effective way to improve local governance, and to maximize long-term economic benefits in the region.

Such a system also has the advantage of improving the economy of the community in which it is implemented by improving the education quality, raising literacy rates as well as the safety in the targeted regions. When applying this system in the locations of interest it is therefore important to ensure that the water catchment and penstock dimensions are adapted to power a portable light source for at least 2 hours a day, for half the year. This would allow members of the community, especially children, to have a longer access to light during the winter season, when days are shorter and solar energy is insufficient. Being able to complete educational and other developmental activities for a longer period of time every day would help bring long-term economic benefits to these areas.

7.3 Instructions for maintenance and safety

Finally, this system should be implemented in the safest, most durable and sustainable way possible, in order to maximize its efficiency and life cycle, as well as its usefulness to the local community. For that purpose, we provide a set of guidelines on how to use the system in the most efficient possible way. These guidelines apply to the final design as described in section 7.1, and can be adapted by the users depending on the system set-up they identify as being most adapted.

First, in order to avoid clogging the system with leaves or other debris that could make their way into the catchment during precipitation events, a filter should be installed at the inlet of the penstock. This filter should be checked regularly, especially after strong winds and heavy rains, and changed when necessary. If the penstock were to be installed on a hill slope and the water collected at the top, as mentioned in section 7.2, the filter used should be adapted to the type of debris found in this environment. Similarly, the inside of the penstock itself should also be drained and checked regularly for debris and potential sources of clogging that would reduce the efficiency of the system and increase wear. Finally, the valve and the nozzle should also be frequently checked to ensure that they allow for optimal jet flow.

It is also important to ensure that the turbine and the generator attached to it both rotate synchronously with as little friction as possible. The position of the turbine may have to be manually adjusted by the user to make sure its rotation is not obstructed by any structural component of the system. Furthermore, the connection between the turbine and the generator shaft should be frequently checked as well, as this part of our system can experience a lot of wear due to the fast rotation of the turbine.

Finally, the users of our system are to make sure that all electrical components are preserved from any external damage. They must be encased in a water-tight container connected to the generator in order to protect them from being splashed by water from the turbine. They should also be checked

regularly for any sign of “frying”, and replaced if necessary. Furthermore, for the system to operate properly, both batteries to be charged should be inserted in the allocated compartment when rotating the turbine.

The local community should designate one or more of their members to be in charge of operating and ensuring proper functioning of the system. Maintenance requirements being relatively low, this person would mainly be tasked with opening the system’s valve when the water level in the penstock has reached sufficient head. They would then close it when the head has dropped, allowing the penstock to recharge. This involvement of the local communities in the implementation and operation of the project is one of our main goals, and would help improve local governance and general knowledge about renewable energy production in the targeted areas.

8. Recommendations & Optimization

The testing we were able to do during the semester was not enough to pinpoint the optimal components for our projected head and flow rate. However, we were able to narrow down the range of possible dimensions to use for nozzle diameters, bucket sizes and turbine size. Also, we are confident in saying that an AC permanent magnet generator or a brushless generator are the best options for our system.

In order to improve our results and find the best possible configuration a few ameliorations are possible. Most of our efficiency was lost in the conversion of mechanical energy to electric energy. In order to get better energy conversion, a more fitted generator can be used. We considered constructing a custom brushless generator adapted to our system. However, the technical difficulty and the access to components made it very complex to achieve in the allotted time. The construction of a fitted generator can be a project in itself and greatly increase the power potential of our turbine.

Another loss of power was due to the geometry and material of our nozzle. Our single metal, custom-fitted nozzle of 4mm gives better results relative to the other nozzles independently of the jet diameter. Also we could observe less leaks at the end of the tube. We are confident that our nozzle shape is optimal, but it could be manufactured in stainless steel or lead and increase the jet speed even more.

The bucket shape can be optimized by printing the more accurate model. It is a more complex print that is not consistent and practical in real life applications. However, if the layers can be thickened and a more performant 3D printing system is used, the buckets could be printed more easily and ameliorate the conversion of kinetic energy to mechanical energy.

When considering the growing threats of climate change, it is important to have a system that will withstand intense weather events. Having a concrete foundation holding the penstock in place is therefore crucial, and should be thoroughly assessed when implementing such a design. This is

especially important considering that these storms are expected to become more and more frequent in the near future.

Finally a contraption can be built in order to keep the nozzle at a fixed known angle during further testing experiments. This will allow us to know the optimal jet angle for maximum rotational speed.

9. Conclusion

Our micro-hydro power prototype system sets the base for future micro-hydro projects of the same scale. The different tests we performed allowed us to find the potential power that can be obtained with a 4 m head and rainfall as our only source of water. Our results are effective at giving a range of values for the geometrical dimensions of the turbine and bucket, as well as the nozzle diameter to obtain 1W of power consistently and charge two Ni-mH batteries.

As some of these regions already make use of solar power for their energy needs, the proposed system provides an alternative electricity source during rain events, when the efficiency of solar panels is low. The proposed design has a minimal impact on the environment, during the production, construction and operation processes; it also needs to be socially acceptable, low-maintenance and safe to handle. Finally, it should be financially accessible and useful to the targeted communities, through the use of the most appropriate materials and technologies.

Future improvements for this project mainly includes optimizing the shape and material of the buckets and nozzle. Also, the system could be greatly improved with a custom-fitted generator. Finally, creating a concrete foundation to the structure will increase resilience in potential extreme weather conditions. It is crucial to keep in mind that when implementing this system in the regions of interest, several environmental, social and economical considerations must be taken into account to properly adapt the system to local conditions.

We successfully achieved our goal which was to provide a universal rain powered generator to improve the resilience of communities in underserved high-precipitation regions.

10. References

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11. Appendices

A. Estimated Rainfall calculations

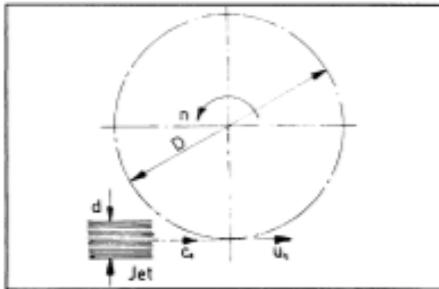
Appendix A - Screenshot from the spreadsheet in which daily rainfall was estimated in different locations, as per the method detailed in section 4.2.

Philippines 1234 mm/yr	Aurora	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	54	40	50	97	161	189	155	127	111	112	75	63
	Rainy days	18.8	15.8	20.2	23.7	28.4	27	25.3	25.8	26.1	25.8	22.5	20.4
	mm/day	2.87	2.53	2.48	4.09	5.67	7.00	6.13	4.92	4.25	4.34	3.33	3.09
	Rank	3	2	1	6	10	12	11	9	7	8	5	4
Philippines 1516 mm/yr	Irosin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	148	76	88	45	97	131	143	126	125	147	127	263
	Rainy days	22.8	17.7	20.5	17.3	20.8	23	25.3	20.6	22.1	23.1	23.9	23.5
	mm/day	6.49	4.29	4.29	2.60	4.71	5.70	5.65	6.12	5.66	6.36	5.31	11.19
	Rank	11	3	2	1	4	8	6	9	7	10	5	12
Philippines 1893 mm/yr	Davao	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	117	118	93	163	220	202	165	192	195	177	147	114
	Rainy days	13	12	11	11	15	17	15	14	15	16	15	13
	mm/day	9.00	9.83	8.45	13.91	14.67	11.88	11.00	13.71	13.00	11.08	9.80	8.77
	Rank	3	5	1	11	12	8	6	10	9	7	4	2
Kerala 1549 mm/yr	Pathanamthitta	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	9	15	70	135	163	235	188	196	123	208	149	58
	Rainy days	8	8	20.3	28.2	28.4	27.8	26.6	26.2	23.3	25.4	23.3	17.3
	mm/day	1.13	1.88	3.45	4.79	5.74	8.45	7.07	7.48	5.28	8.19	6.39	3.35
	Rank	1	2	4	5	7	12	9	10	6	11	8	3
Karnataka 1696 mm/yr	Neriamangalam	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	10	26	69	140	232	133	150	198	136	326	209	67
	Rainy days	6.3	6.9	15.8	24.9	28.5	27.6	27.3	27.8	24.6	26.6	22.8	17.5
	mm/day	1.59	3.77	4.37	5.62	8.14	4.82	5.49	7.12	5.53	12.26	9.17	3.83
	Rank	1	2	4	8	10	5	6	9	7	12	11	3
Bangladesh 1868 mm/yr	Sylhet	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	4	13	49	175	289	353	287	308	254	111	18	7
	Rainy days	2.4	3.4	11.3	21.3	26.8	29.3	29.3	30.2	28.5	18.3	4.8	2.5
	mm/day	1.67	3.82	4.34	8.22	10.78	12.05	9.80	10.20	8.91	6.07	3.75	2.80
	Rank	1	4	5	7	11	12	9	10	8	6	3	2
Uganda 2204 mm/yr	Mbale	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	42	46	136	261	319	218	195	248	199	240	176	124
	Rainy days	11.1	12.1	21.3	28	30.4	29.6	30.6	30.8	29.1	29.3	27.5	21.4
	mm/day	3.78	3.80	6.38	9.32	10.49	7.36	6.37	8.05	6.84	8.19	6.40	5.79
	Rank	1	2	5	11	12	8	4	9	7	10	6	3
Guyana 2260 mm/yr	Georgetown	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	185.2	88.5	111	140.5	285.5	327.7	268	201.4	97.5	107.2	185.9	261.9
	Rainy days	16	10	10	12	19	23	21	15	9	9	12	18
	mm/day	11.58	8.85	11.10	11.71	15.03	14.25	12.76	13.43	10.83	11.91	15.49	14.55
	Rank	4	1	3	5	11	9	7	8	2	6	12	10
Colombia 1699 mm/yr	Cartago	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	93	114	165	183	150	113	137	127	129	178	163	147
	Rainy days	22.1	21.1	25	25.9	24.8	22.8	23	21.6	23.2	28	26.9	24.2
	mm/day	4.21	5.40	6.60	7.07	6.05	4.96	5.96	5.88	5.56	6.36	6.06	6.07
	Rank	1	3	11	12	7	2	6	5	4	10	8	9
Cameroon 1540 mm/yr	Yaounde	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)	19	42.8	124.9	171.3	199.3	157.1	74.2	113.7	232.3	293.3	94.3	18.6
	Rainy days	3	4	12	14	17	14	11	12	20	23	11	3
	mm/day	6.33	10.70	10.41	12.24	11.72	11.22	6.75	9.48	11.62	12.75	8.57	6.20
	Rank	2	7	6	11	10	8	3	5	9	12	4	1

B. Mathematical formulas to calculate dimensions of Pelton turbines (Eisenrig, 1991)

Following are the necessary formulas for the design and the layout of micro Pelton turbines:

F1	$c_1 = k_c \sqrt{2gH_n}$	c_1 = absolute velocity of water jet [ms^{-1}] k_c = nozzle coefficient ($k_c = 0.96 \dots 0.98$) g = gravitational constant = $9.81 \text{ [ms}^{-2}\text{]}$ H_n = net head [m]
F2	$d = \sqrt{\frac{4Q}{\pi c_1}}$	d = optimal jet diameter [m] Q = water discharge [m^3s^{-1}]
F3	$u_1 = k_u \sqrt{2gH_n}$	u_1 = optimal peripheral velocity [ms^{-1}] (at the pitch circle diameter) k_u = coefficient ($k_u = 0.45 \dots 0.49$)
F4	$b = (2.5 \dots 3.2) d$	b = bucket width [m]
F5	$h = (2.1 \dots 2.7) d$	h = bucket height [m]
F6	$h_1 = (0 \dots 0.35) d$	h_1 = see illustration 14.
F7	$h_2 = (0.85 \dots 1.5) d$	h_2 = see illustration 14.
F8	$t = 0.9 d$	t = bucket depth [m]
F9	$D = \frac{60 u_1 i}{\pi n_o}$	D = pitch circle diameter (PCD) [m]
F10	$n_o = \frac{60 u_1 i}{\pi D}$	n_o = rotational speed of driven machine (RPM) [m] i = transmission ratio (RPM of driven machine / RPM of turbine) ($i=1$ if a generator is coupled directly)
F11	$a = 1.2 d$	a = width of bucket opening [m]
F12	$k = (0.1 \dots 0.17) D$	k = offset of bucket
F13	$z = \frac{D \pi}{2d}$	z = approximate number of buckets
F14	$D_a = D + 1.2 h$	D_a = outside diameter of runner [m]
F15	$P = Q H_n g \rho \eta \frac{1}{1000}$	P = power output [kW] η = efficiency ρ = density of water = $1000 \text{ [kg m}^{-3}\text{]}$



The parameters are explained in illustration 4, on the left side, and in illustration 14 (on page 21).

Illustration 4:
Fundamentals of the Free Jet Turbine