2022

Implementation and Usage of Low-cost Turbines for Power Generation in Water Networks

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Recommended Citation

Ortiz Osornio, L. J. (2022). Implementation and usage of low-cost turbines for power generation in water networks [Master’s alternative plan paper, Minnesota State University, Mankato]. Cornerstone: A Collection of Scholarly and Creative Works for Minnesota State University, Mankato. https://cornerstone.lib.mnsu.edu/etds/1181/

Implementation and Usage of Low-cost Turbines for Power Generation in water networks

By

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An Alternate plan paper (APP) Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

In

Manufacturing Engineering Technology

Minnesota State University, Mankato

Mankato, Minnesota

May, 2022

March 24th 2022

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This Alternate plan paper (APP) has been examined and approved by the following members of the student's committee.

Advisor

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Abstract

The following APP is part of an investigation and development, carried out to design, and implement a hydroelectric turbine of horizontal axis, in order to generate electrical energy in rural areas, utilizing existing infrastructure or natural waterways such as irrigation canals, piping, rivers and streams. Every industrialized country, as well as, most of the developing nations, have a stake in agriculture and thus access to the infrastructure required for irrigation purposes. Artificial irrigation canals offer advantages such as a clean continuous flow, with the possibility of flow regulation: this together with their vast availability as agricultural infrastructure constitute the main motivation for the application sought with the results of this APP. It is thus established that the problem at hand is selecting an appropriate design in order to overcome some of the needs of rural populations and an effort to promote the use of renewable energies in order to lower cost in electrical bills as well as a reduction in carbon emissions produced by conventional power plants. Among the availability of different sources on turbines, the horizontal axis turbines types were selected. This type of turbine is relevant to the geometric and hydraulic characteristics and challenges of irrigation canals, as well as its easy construction and transport. The work methodology used is aimed at describing the geometric and hydraulic characteristics of irrigation canals, the engineering principles that govern the operation of hydraulic turbines and the fundamental characteristics of energy conversion to the generation of electrical energy. In the prototype design process, the main variables, hydraulic dimensioning, selection of geometric parameters and mechanical principles are identified. The prototype has the main purpose as test equipment for purposes of measurement and evaluation of design and operation parameters. The most important manufacturing procedures are highlighted, taking into account locally available materials and manufacturing facilities. In the same way, test results carried out are shown with discussions, conclusions and recommendations for improvements.

I.-Introduction

For as long as we can remember, mankind has been able to harness the power of nature to solve problems and challenges that were endemic to their surroundings. Utilizing complex engineering devices, man was able utilize the power of rivers and streams to facilitate labor in aspects such as milling grain and sawing timber, thus freeing him to peruse more challenging endeavors and thus achieving more and more technological advances.

One of the greatest challenges of the 21st century is to mitigate the impact of long-term climate change and the emission of greenhouse gases. According to the latest IPCC report, in order to avoid an increment in global temperature of 1C, conventional power plants need to reduce their carbon emissions by an estimate of 80% by the year 2050. Renewable energy technologies such hydroelectric, wind or solar, contribute significantly to the reduction oh GHG emissions and to the security of energy supply outside of a conventional power grid. In comparison with conventional coal power plants, hydropower prevents the emission of about three GT CO2, per year, or about 9% of global annual Co2 emissions. (Goldstein, R., & Smith. W., 2002)

The following APP work, proposes the use and exploration of hydroelectric energy for the purposes of electrical power self-generation by private individuals in either distant regions where a power grid is non-existent or rural areas due to its ease of variety, flexibility in scales and sizes. For this reason, several prototypes of hydrokinetic turbines will be explored, their pros and cons, which in the end which will benefit users who do not have access to a nearby electrical network by utilizing existing pluvial resources. This type of technology takes advantage of the flow and the speed of a waterway, being either a river or canal, therefore the kinetic energy converts hydraulic energy into mechanical energy. This technology has an additional advantage to the present proposal that is, its lower environmental impact. This type of infrastructure does not alter the flow of natural water sources as it occurs in large-scale artificial systems on the planet such as dams or artificial reservoirs. The development of this prototype will encourage research into the potential for hydroelectric generation in the numerous artificial canals existing in around the globe. Hydroelectric power is often attributed as one of the cheapest sources of renewable energy, as the initial investment is far less of those required by wind and solar, and has a long lifespan with very low maintenance input.

II.-Objectives

2.1.-General Objective

Study and Possible implementation of a Horizontal Axis turbine for the purpose of electrical power self-generation, utilizing either irrigation infrastructure or natural waterways.

2.2 Specific Objectives

- Determine the geometric characteristics of the average irrigation canal
- Review the most common and accessible types of horizontal axle hydroelectric turbines
- CAD design of a basic turbine
- Generator Selection adequate enough for the selected turbine
- Estimate cost of prototype
- Construction of prototype if possible
- Field test

III.-Theoretical Framework

3.1 Hydrokinetic turbines

A Hydrokinetic or hydroelectric turbine is a motor device that is responsible for transforming kinetic energy into potential energy. It takes energy from a fluid, usually water, transforming it into rotational energy, without interrupting the natural flow of water. This movement mobilizes the machine or an electrical generator so that the rotating mechanical energy becomes electrical energy. Hydroelectric turbines are the fundamental piece of a hydroelectric power plant. However, they represent a great disadvantage regarding the low energy output compared to conventional hydroelectric plants, implying, at least, that their economic feasibility must be studied on a household level.

Horizontal Axis water turbines (HAWT's) have their axis of rotation parallel to the direction of the current, using propeller-type helixes. Various arrangements of this type of turbines shown in Figure 1.

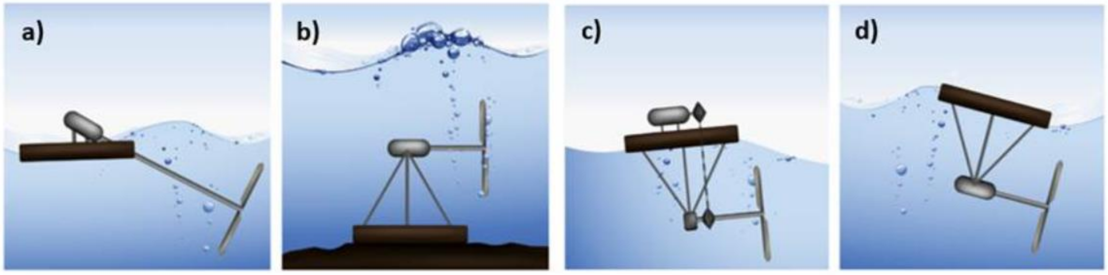

Figure 1: Axial flow hydrokinetic turbines with: a) inclined axis, b) rigid mooring, c) non-submerged generator and d) submerged generator

The inclined axis turbine (Figure 1a) is used in small rivers, while the other arrangements (Figure 1b, Figure 1c and Figure 1d) are mainly implemented for energy extraction in oceans. In horizontal-axis axial-flow hydrokinetic turbines, the fluid's kinetic energy is transferred in only one stage, resulting in higher rotational speeds than cross- or transverse-flow.

The energy stored in a stream of water is directly proportional to the density of the fluid, in the cross-sectional area, and the velocity of the fluid. Therefore, when comparing THCs with speeds of the order of 1.75 and 2.25 m/s, and wind turbines with speeds between 11 and 13 m/s, there is a great difference in terms of the potential for electricity generation, because the density of the Water is 832 times greater than that of air at normal conditions of temperature and pressure. In any case, it is important to indicate that the fluid that passes through the turbine does not deliver all its energy. In fact, a power coefficient has been defined that indicates the amount of kinetic energy that can be extracted from the flow and converted into mechanical energy in the turbine shaft, and whose maximum value, equal to 59.3%, is known as the limit.

As stated before, a turbine is a device designed to convert the kinetic energy of a waterway, to rotational energy, which in return produces electrical power. When the fluid makes contact with the turbine blades, it pushes the blades or helixes and makes them rotate, harnessing kinetic energy (energy of flow) and converting it into mechanical energy. Kinetic energy is harnessed the more pressure in the flow of water.

3.2 Canal geometry

When talking about irrigation infrastructure, when it comes to canals, the flow of water in a conduit can be open flow or pipe flow. Although these two classes infrastructure are similar in many respects, they differ in that canals have a free surface on which the liquid is in contact with the atmosphere. On the other hand, the flow in pipes can be full pipe (working under pressure) or partially filled, just like a canal. Despite the similarity between these two types of flow, it is much more difficult to solve flow problems in open channels than in pressure pipes. Flow conditions in open channels are complicated by the fact that the position of the free surface can change with time and space (taking environmental and weather conditions for instance) and because depth of flow, discharge, and the slopes of the channel bottom and surface are interdependent. Both cases will be explored in this APP.

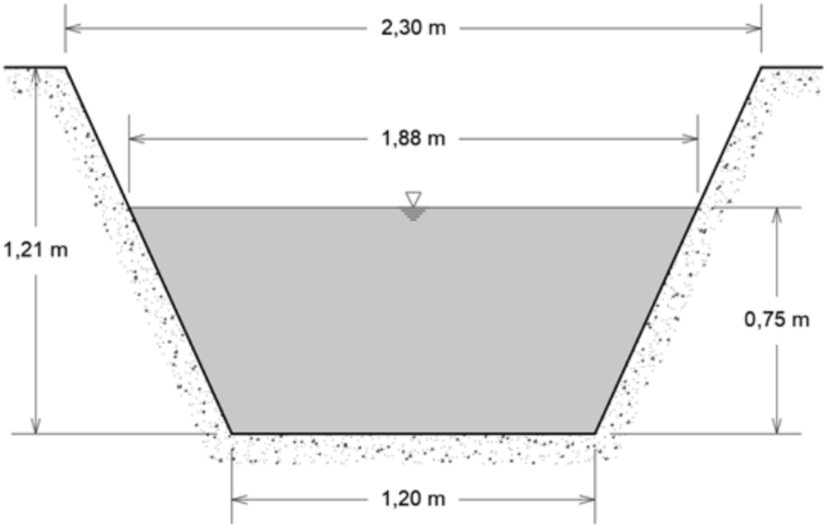

Fig 2. Cross section view of average canal

3.3 Flow Calculation

Taking into consideration the assumption that for a turbine to work with minimum input, the average water velocity must be around 4m/s

$$V_l = \frac{4m}{s}$$

- Calculating the geometric area of the trapezoid (A m^2) in the canal *(note: the area of calculation can change depending on the design of the canal)*

$$\mathrm{A} = \frac{1.88 + 1.20}{2} \times 0.75 = 1.155m^2$$

- Flow calculation (m^3/s)

$$Q_c = AV_L = 1.155m^2 \times 4m^{3/}s \;\; = 4.62\, m^3/s$$

Therefore, in this proposed scenario, the flow of the canal is approx. 4620 l/s., which of course can be subject to change due to weather conditions or, management of the main gate. Again this is just to set an example of flow calculation, but the design of the canal, the average flow of the stream are subject to change depending on the environmental and terrain conditions.

3.4 Supplied Power

The power supplied by a hydrokinetic turbine depends on the volume swept by the blade and, therefore, the length and number of blades. The theoretic kinetic energy of water, due to the mass of water in motion is given by the following equation

$$\mathrm{EC} = \frac{1}{2} \times \rho \times \mathrm{A} \times \mathrm{v}^3 \text{ [Joules] } o \; [W] \qquad (1)$$

However, in a real scenario, it is not possible to extract all the available power from a free-flowing stream for two reasons:

- In order for water to cede all its kinetic energy, it would have to come to a complete stop, which in reality is not desirable at all; one might be able to reduce flow but not stopping entirely.
- Second, in every energy transformation process, there will be limitations and losses such as drag forces, friction, incorrect

Thus, the addition of a constant to represent the conversion efficiency of the river flow in power in the axis of the turbine, the previous equation (1) writes as follows:

$$\mathrm{EC} = \frac{1}{2} \times \rho \times \mathrm{A} \times \mathrm{v}^3 \times C_p \qquad (2)$$

Where $C_p$is the power coefficient? In this APP, a C_p will be used based in relevant field data of other literature relevant to the subject.

3.5 What affects power supply?

There are three main factors that affect the power output of a turbine shaft:

a) Water current velocity

   Susceptible to either environmental, design or operational factors

b) Rotor Area

   The power of the turbine shaft is directly proportional to the area rotor sweep.

c) Power Coefficient

   Power output is directly proportional to the power coefficient according to expression (2). It is currently impossible to extract all of the potential energy available in the flow of water, as it must continue to flow through the rotor, so that the cycle is allowed to repeat turning the turbine and therefore the water must still have some kinetic energy moving away from the blade.

   “It can be shown that the maximum coefficient of power (Cp. max.) is 0.59 for a machine that operates on lift forces such as a propeller or a rotor Darrieus. The value of 0.33 for a machine that operates on forces drag such as a waterwheel floating on a free stream flow. From the previous statement, it can be seen that in order to obtain the maximum output power on the shaft, we should use the most efficient rotor available, and set it to a higher current speed that can be found” (Silva Guevara,2017)

3.4 Energy Transformation process

The following figures are a representation of the process undergone by the kinetic energy of water from the moment it enters the system, provides mechanical movement to the turbine, which in turns moves a generator that provides electrical output until the water resumes its normal course of flow.

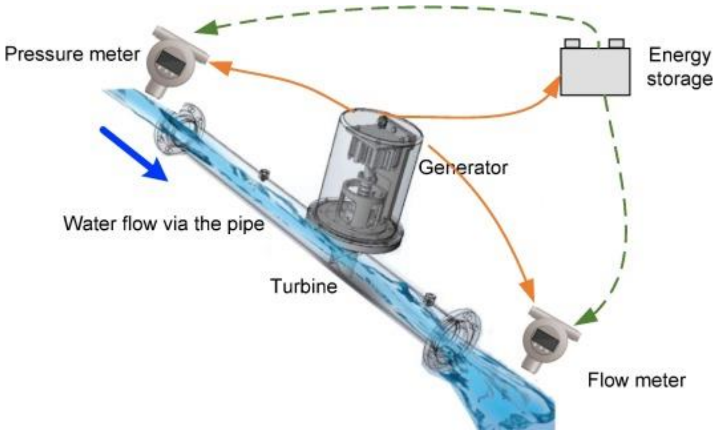

Fig 3. Power generation in a closed pipe system

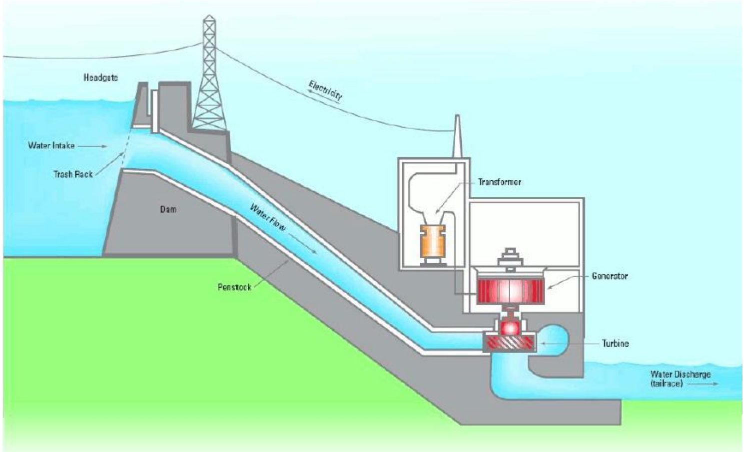

Fig 4. Power generation in an open channel system.

IV.-Methodology

4.1 Horizontal Axle Turbine Design

Although many types of turbines exist in the market, and its selection based upon the general technical characteristics of its hydric resource. Figure 5 shows a schematic view of the parts that compose most hydrokinetic turbine design.

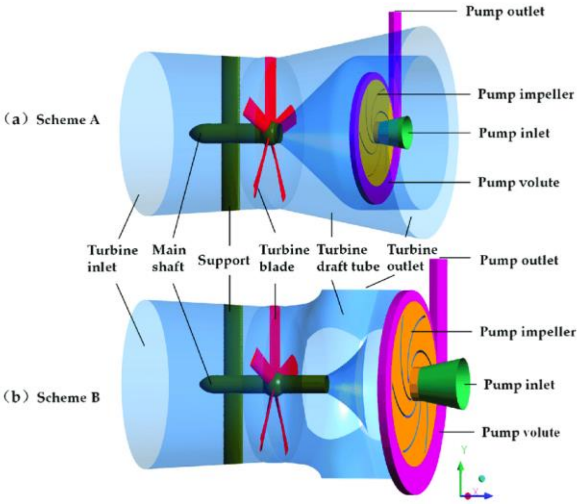

Fig 5. Schematic Design of river current water turbine

In average, a water turbine functions as follows: The water enters the impeller radially, to later change direction and exit parallel to the turbine's axis of rotation, that is, axially or in the direction of the axis. In this case, the water moves the impeller, not by direct blow, but by the reaction that causes, as it exists on the impeller. Following this provision, we are interested in having a large flow of water that pushes the water that enters the pipes or canal, so that it comes out with great force (pressure) and moves the impeller with greater force.

The height at which the water falls here is not very important because it does not hit the blades directly, what matters here is that we have a large flow of water pushing. Thus having to build infrastructure that makes use of gravity in order to accelerate the flow of water is not necessary, but neither is entirely discarded for its usefulness.

The incidence of the water and the direction of rotation of the impeller coincide at the point where the impact of water on the blades occurs and thus most of the kinetic energy with which the water reaches the turbine is used for its rotation. The pressure energy that the water has at its entrance, being directly directed to the impeller, is completely converted into kinetic energy (movement) in the impeller and the shaft, which in turn converts this mechanical motion into electrical current via a generator. In the end, the water pressure at the inlet and outlet is the same, thus negating a potential environmental impact on the surrounding environment

Horizontal axis turbines are an excellent solution for projects with high and medium heads and flow with strong variation.

4.2 Commercial Design

4.2.1 Whirlpool power turbine.

At the top of the spectrum regarding turbines for power generation in water in rural areas, we find Belgian company Turbulent, with its Whirlpool power turbine. The whirlpool turbine uses small streams or waterfalls to harness energy. Turbulent develops areas near the water source and constructs a concrete channel and basin. A generator and turbine goes inside the basin. Afterwards a river wall is lifted, so some of the water will pour into the basin getting the turbine functional. According to the company, the turbine possess a single moving part, thus expanding its operational lifespan alongside its concrete infrastructure which makes it operational for at least 100 years. It also possesses a self-cleaning screen that captures debris.

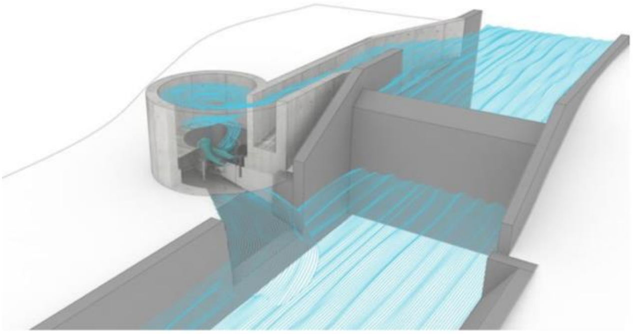

Fig 6.Turbulent turbine setup diagram

The company claims in a video that hydropower has become less sustainable over time, with high-pressure turbines and dams, and their goal is to make the energy source sustainable again. Unlike large dams, their low-pressure turbine requires a height difference of roughly five feet to function effectively.

Tested in rivers throughout Belgium, the device can be scaled up to generate 15, 30, and 100 kilowatts. However according to the company website, infrastructure such as this requires a large investment of $60,000

Micro-hydro power projects using vortex turbines around the globe include:

- 600 kW of continuous energy injected into the grid in Taiwan with a network of turbines along the Annong River.
- A 13 kW turbine providing power for 700 students and staff at the Green School in Bali, Indonesia.
- A 5.5 kW turbine providing electricity to a wastewater treatment plant in Versailles, France.
- 120 kW to 150 kW of continuous energy for 3,000 people in a remote part of Mindanao, Philippines.

Fig 7. Turbulent river wall infrastructure

4.2.2 Sumino Portable Power Generation

Sumino Co. located in Gifu Japan, developed a highly portable water turbine capable of working in shallow moving water. It is able to produce around 10W with a flow of 10L/sec and a head of 0.1m. With a weight of around 17.5 Kg, it is able to be highly portable; however, currently it is only able to light about two street lamps.

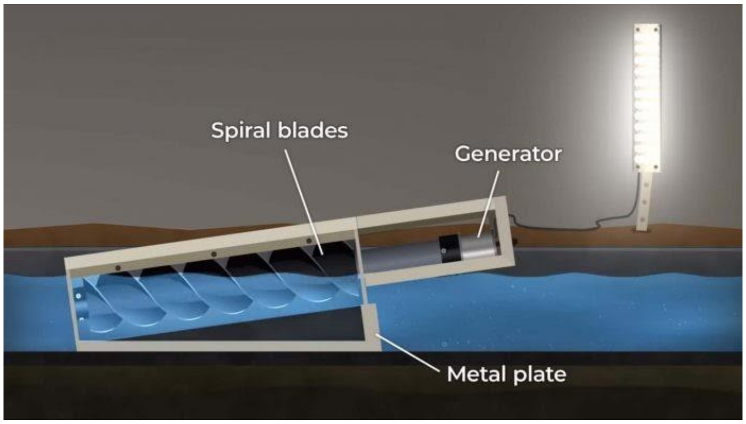

Fig 8. Sumino turbine design

Another model, weighting about 250 Kg is available, however, it requires a flow of approximately 100 L/sec, but is able to power a small household with its power output of about 500W. As the whole structure of this watermill is open-type and simple, works such as assembly, installation, cleaning, and maintenance can be completed with ease. Besides, the water screw design prevents the unit to be clogged with floating substances or dusts.

Fig 9. Example of portability design

Because this product does not require large waterways or pressure tubes for installation and there are not many component parts, this product is cost-effective compared to another hydraulic generation units. However, larger shipping costs and custom tariffs make this design not feasible to use outside japan.

4.3 Prototype Design

After reviewing a couple of commercial examples, a prototype can be designed based on the two major disadvantages of the previous models. Prototype has to be cheap to install and has to be manufactured locally, in order to avoid shipping expenses and tariffs, thus the most viable option is to 3D print the design of the turbine and assemble using low cost materials like PVC and timber.

Since the proposed turbine prototype is experimental, and still in the testing phase it was proposed to select as a prototype the model presented in figure 10.

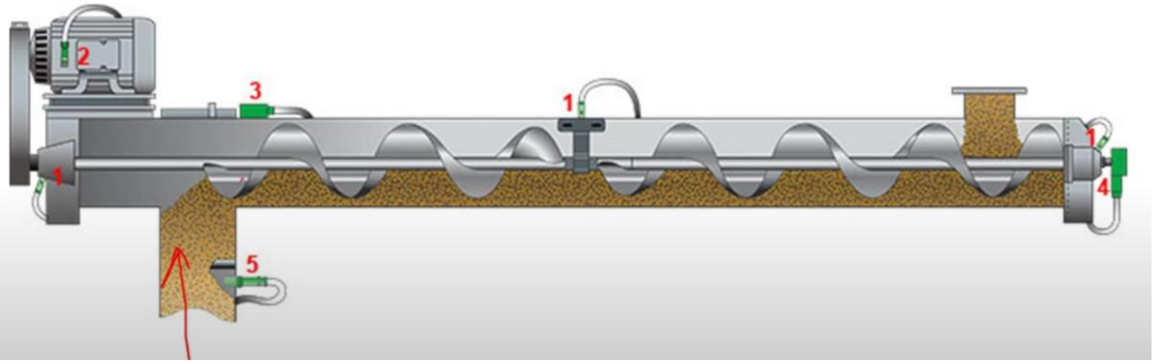

Fig 10. Proposed Design

Thus, the objective design is advantage of the kinetic energy of the water of a canal, which was designed and dimensioned above, or a natural stream or river without infrastructure or minimal impact to the environment. The geometric design characteristics of the proposed prototype can be seen in Figure 11,.

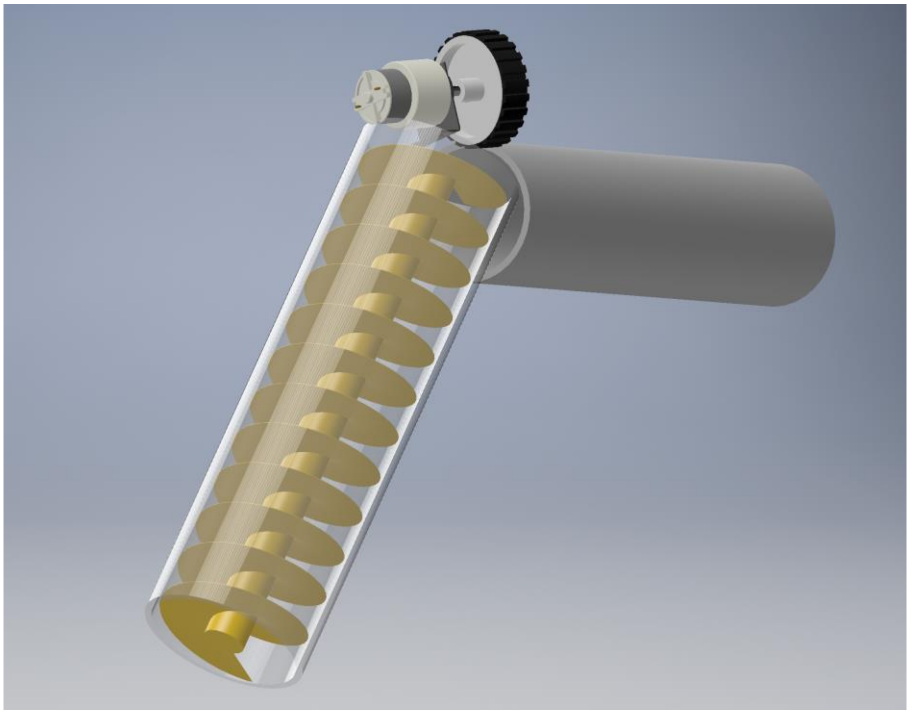

Fig 11. Rendered image of prototype design

The final proposed designs consists of a water screw that can be scaled to the desired length, for this proposed case, its length is 2m long. The protective cover was designed to be a polycarbonate cylinder of 50 cm diameter. While the feeding tube consists of a 30 cm diameter PVC pipe. The generator selected for this job is to be a salvaged car alternator.

4.4 Prototype construction and Assembly

In order to construct a working prototype, the water screw section had to be 3d printed in individual 50cm sections that where assembled afterwards via hinges, four sections were necessary and assembled within a polycarbonate case, and placed within a timber and aluminum frame, parallel to a water stream. Since the local homestead where the porotype was selected, did not had an irrigation system, the timber frame had to be adapted, however the original prototype of the turbine can be adapted within an irrigation canal regardless.

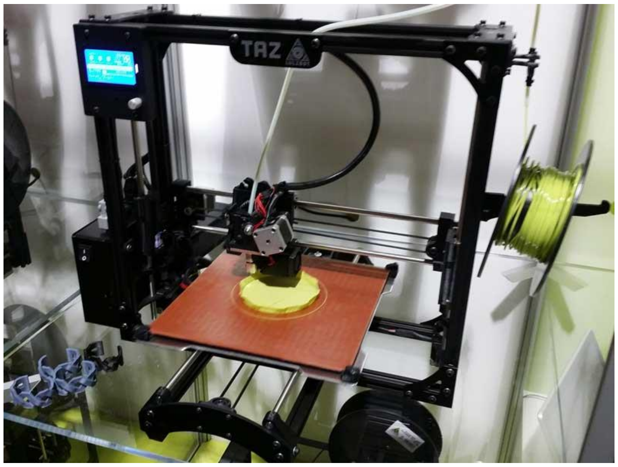

Fig 12. Water screw section print

A synchronous type electric generator was selected for its low cost of acquisition and maintenance, because it is an automotive alternator widely available in any scrapyard. This generator has the following specifications:

A power output of up to 700 Watts, synchronous speed of 1200 rpm, 6 poles and with a frequency of 60Hz.

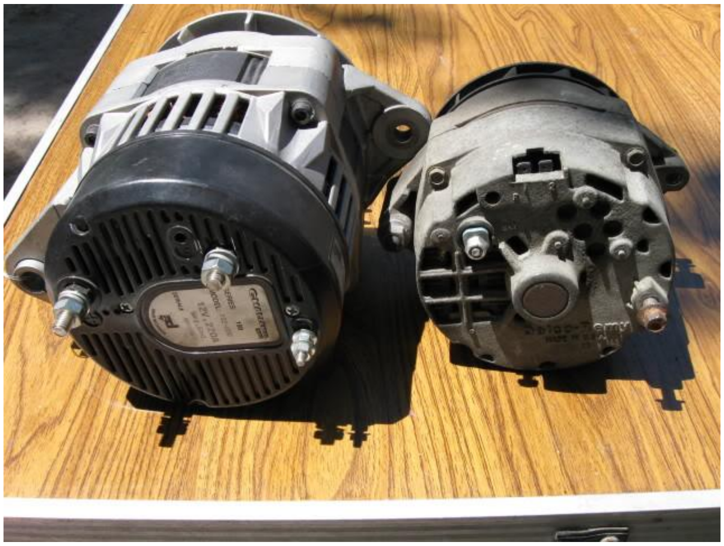

Fig 13. Alternator

After Assembly, a pipe structure was designed and implemented so that a fraction of water from the nearby stream could be diverted into the desired infrastructure.

Fig 14. Assembled Prototype 1

Fig 15. Assembled Prototype 2

In a basic description of functionality, the screw turns the alternator with the water provided by the PVC infrastructure. Water pressure is regulated with a small valve (pictured in red) this allows the motion of the screw to increase as desired output is needed. Coming out of the alternator, a cable goes to a power box where an inverter is housed.

4.5. - Costs

A referential budget was made for all the stages to carry out the implementation of the project; These are: design, and Assembly.

4.5.1.-Design

Due to the use of software with a student license and that, the resources and drive for the project have been for academic purposes, the design costs are nonexistent since they only cover stationery; transportation and travel expenses Therefore, the general costs of the APP project are based primarily on turbine manufacturing costs.

4.5.2. - Manufacturing and Assembly Costs

Just as the design process, the assembly of the prototype was in benefit of the homestead owner and the author of this APP, thus the costs can be negated. The following chart displays the sum of costs regarding the project:

Table 1. - Referential budget of materials used in the project

Quantity	Description	Value p/ unit	Total Value
4	Aluminum Profile square 1 ½ “	25	100
2	Aluminum Profile square 11 ½ “	35	70
6	80/20 Framing Extrusion Clear Anodize Aluminum	28.5	171
4	4 In. x 10 In. x 16 Ft. Douglas Fir Beams #2	150	600
1	Jm Eagle 1610 Pipe S&D PVC Sld 4X10BEL 16 FT	17.96	287.36
1	11in PVC valve profile 4x10BEL	15.35	15.35
1	12 in Polycarbonate 6xFEL 3FT	150	150
81	3/16 in Pin	0.5	40.5
1	Scrapyard alternator	50	50
1	Copper wire N14	2.75	2.75
1	DeWalt DXAEPI1000 Power Inverter	159	159
Total:			**1645.96**

V.-Results

The main result achieved by this work, is the design and implementation o f a hydrokinetic turbine from an engineering manufacturing and design process. Numerical Data is presented in order to calculate the main objective of this work, which is electrical power generation.

In order to determine the efficiency of the hydraulic water screw of the turbine, several tests with different levels of water flow were performed, regulating the main valve of the intake of this irrigation pipe of the present stream, in order to carry out the respective measurements.

The project at hand was installed 2.00 meters away from the main intake of water at the base of a small stream. The PVC pipe installed in such a way that a slight incline is present, given some gravitational push towards the intake of the water screw with a fluid velocity of 4m/s and approximately with a flow of 4.62 m^3/s.

For the analysis results, 10 measurements were performed at the intake of the water screw, where the voltage inverter was the final destination of the power generated by the alternator.

However, there is a natural variation of the flow of water that is shown thanks to various values of wheel speed (rpm) in each measurement that the pressure of the pipe and valve provided. Measurements are based on electrical power output.

The information collected is displayed in the following table.

Table 2. Preliminary results

Measurement	Speed (RPM)	Voltage	Current	Watts
1	1556	20.2	4.02	81.204
2	1100	12.15	3.09	37.5435
3	1200	12.98	3.69	47.8962
4	1234	13.28	3.85	51.128
5	1236	13.29	3.9	51.831
6	1214	13.08	3.3	43.164
7	1198	12.98	2.5	32.45
8	1189	12.6	2.33	29.358
9	1244	13.45	4.02	54.069
10	1212	13.15	4.02	52.863

The RPM measurements were provided by a tachometer, while the voltage, current and the power, were provided by the inverter itself.

Unfortunately, no more measurements were taken due to winter weather, as the homestead where the turbine is located, dwells in St. Peter, MN.

VI.-Conclusions

In conclusion, to this APP, it is shown that small communities, groups of farmers and other associations could implement self-power generation projects that are sustainable over time, to generate additional income and optimize the use of water resources.

The implementation of this type of project creates possibilities that benefit everyone involved in it , such as:

- Additional income generated from the sale of energy;
- Obliges the community to make better use of water resources, since it's a viable alternative to high cost of energy.
- The project shows the community to maintain its pluvial resources in an adequate way to benefit the proper functioning of the power plant.
- Mitigates the carbon footprint of conventional power plants

It is very important to mention that the developed project can be replicated, because it has a common feature, which is the presence of a network of canals with low slope and high flows, as well as small rivers and streams, as demonstrated by this project. This can boost the sector economically and energetically, generating income from energy sales, where the power grid is available, in the event that the project owner sells the energy same community or community partners, they can reduce energy costs and invest the saving in either their farming projects, or the turbines projects themselves. Thus, the development of similar projects is highly important, since it is a clean and renewable energy that is not currently exploited to its maximum effect.

once the investment has been determined, the estimation of prices, income and costs is carried out. Compared to the market options available and analyzed in this work, there is a significant reduction on initial capital, from $60,000 to $1,600, the main of objective of this APP is thus achieved, and the secondary objectives proposed in the beginning can be focused on. Although it is a profitable project, it is not comparable to other hydroelectric power plant projects that have return of investments close to 25%. A logical explanation being the high cost of the equipment of conventional power plants that have technology in development and that can still lower the prices of its equipment layout.

Therefore it is highly recommended further research into this topic and greater investment on the part of academic research on engineering students, so that projects such as these, become open source and accessible to a greater number of innovators worldwide.

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