Technische Universität Graz
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3D Printed Pico Hydropower Stations – Conception and Application Possibilities

Master´s thesis

by

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Graz, on May 2017

Master´s thesis mentor:

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I assure that, until now I have not presented this thesis, not domestically nor internationally (to an evaluator) in any form as an examination paper.

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Abstract

The following master´s thesis will provide a basic knowledge and know how on the planning and designing of pico hydropower plants. as well as a small overview of the water and energy economy for 3D printed power plants will be given.

At first, there will be an overview of the basics of hydropower, explaining how to produce electricity by using running water, as later the basic components of hydropower systems will be explained including their importance and function for a functioning pico hydropower system.

The main part of the thesis will revolve around planning and designing of a pico hydropower system, complete with hydrodynamic calculations and designing parameters. After the theoretical explanation the thesis goes on to provide a real laboratory test that was performed in the hydro-laboratory at the Graz University of Technology. The laboratory test was executed in order to prove that the uprising technology of 3D printing can be used for producing turbine components for the purpose of pico hydroelectric power production and compete with the conventional production methods. Here a complete designing process behind a functioning prototype, starting with the concept and finishing with a 3D printed prototype will be provided. The laboratory works are explained in detail as also documented with photographs to help with a better visualization of the testing. Results of every measuring series are interpreted and commented on.

The last part of the thesis will provide basic information on the world and EU water and energy economy. In addition an overview of the current pico hydropower research and implementation will be investigated as the vision and application possibilities for the 3D printed hydropower plants will be presented.

Kurzfassung

Die folgende Masterarbeit wird ein Basis-Wissen zur Verfügung stellen, wie ein Pico-Wasserkraftwerk geplant und entworfen sein kann. Sowie ein kurzer Überblick über die Wasser- und Energiewirtschaft für 3D Druckkraftwerke wird gegeben.

Erstens wird sich ein Überblick von den Grundlagen von Wasserkraft geben und wie man Elektrizität mit fließendem Wasser produzieren kann. Später werden die Grundkomponenten von Wasserkraftanlagen erklärt, einschließlich ihre Bedeutung und Funktion für ein funktionierendes Pico-Wasserkraftsystem.

Hauptteil dieser Arbeit wird sich um die Planung und Gestaltung von einem Pico-Wasserkraftsystem drehen, dazu gehören hydrodynamische Berechnungen und Design-Parameter. Nach der Erklärung von dem theoretischen Teil, bietet die Masterarbeit eine echte Labor-Untersuchung, die in dem Wasserlabor von der technischen Universität Graz durchgeführt wurde. Der Labortest wurde durchgeführt, um zu beweisen, dass die Aufstandstechnologie von 3D drucken für Herstellung von Turbinenkomponenten genutzt werden kann, die dann für Zwecke des Pico-Wasserkraftsystem dienen und konkurriert mit den konventionellen Herstellungsmethoden. Komplettes Designprozess hinter einem funktionierenden Prototyp ist beschrieben, beginnend mit dem Anfangskonzept und endend mit einem 3D gedruckter Prototyp. Die Laborversuche sind detailliert erläutert und mit Fotos dokumentiert, um ein besseren Visualisierung vom Versuch zu bekommen.

Der letzte Teil von der Arbeit befasst sich mit grundlegenden Informationen über die Welt und EU-Wasser- und Energiewirtschaft. Darüber hinaus gibt es ein Überblick über die untersuchte aktuelle Pico-Wasserkraftforschung und Realisierung. Die Vision und Anwendungsmöglichkeiten für den ausgedruckten 3D Pico-Wasserkraftwerk werden am Ende der Arbeit vorgestellt.

Contents

1 Pico hydropower overview

Pico Hydropower works on the same principle as all of the other high performance large hydro power plants. The main difference with the pico hydropower plants is that the word pico implies the overall output of the power plant to be set between 0 and 5 kilowatts of electric power. As in comparison to the large power plants, which can put out up to several Gigawatts of electric power. The categories for sizing the power plants are not exactly defined, but the table below (Table 1) shows the most widely accepted categories:

Table 1: Categorization of hydro power plants by power output
(Source: https://www.renewablesfirst.co.ukTable 2/hydropower/hydropower-learning-centre/what-is-the-difference-between-micro-mini-and-small-hydro/)

Hydro category	Power range
Pico	0 kW - 5 kW
Micro	5 kW – 100 kW
Mini	100 kW – 1 MW
Small	1 MW – 10 MW
Medium	10 MW – 100 MW
Large	100 MW +

Chapter 1 will contain information about:

- **Basic principles of hydropower:** Will provide information of the basic natural conditions that are needed and come into a count while constructing the hydropower system
- **Basic components:** The parts of the conventional hydro system will be explained, complete with their function.
- **System control:** How to control the electrical output of the power plant

1.1 Basic principles of hydropower

Hydropower comes from two natural types of energy. The first one is the potential energy, which is later transformed into the second type known as kinetic energy. With the help of the turbine the kinetic energy gets converted into the rotational energy, as finally with the generator into electric energy. The most important thing to keep in mind is that neither of these energies can be created, rather they can only be transformed from one type into another. The problem we face during the transformation is that some of the energy will get lost in form of friction and heat. Therefore, we are limited in how much energy we can convert from water to electricity. At this point, the term efficiency comes into the consideration as in how much energy can be transformed. The better the design of the hydropower system and components inside of it, the better the efficiency will be as well as the overall result. Since many unconventional terms were used, a close explanation of their meaning will be provided [3a][1c].

Figure 1-1: Waterfall Veliki Šumik (Pohorje-Slovenia) *(Source; http://www.geago.si/sl/pois/14903/slap-veliki-sumik: 2017)*

Potential Energy is the gravitational energy, which an object possesses while dependent on its mass and the distance by which it is distant from another object. In a hydropower plant system the object containing potential energy is water and the distance is the vertical distance between the water level at the intake and the turbine. This vertical distance is called HEAD and is one of the two most important things in hydropower. The potential energy is calculated with the equation below (1); [2c]:

$$E_p = m * g * H \tag{1}$$

Where:

E_p [Joule] → Potential energy

g [m/s²] → Gravity acceleration

m [kg] → Mass

H [m] → Head (vertical distance)

This equation shows that the higher the head the more energy is available. If the vertical drop between the turbine and the intake (head) is doubled, the amount of the energy also doubles.

Kinetic energy is the energy that the mass (water) possesses due to its motion. Water that flows from the intake to the turbine is losing its potential energy but gaining on kinetic energy. The kinetic energy is at its maximum when the potential energy is at its minimum. Therefore, we get the biggest kinetic energy at the turbine. The turbine then transforms the kinetic energy into mechanical or rotational energy. This process will be explained in the subchapter (1.2.4) where a variety of different turbine options is provided. The kinetic energy is calculated with the following equation (2): [3c]

$$E_k = \frac{m * v^2}{2} \tag{2}$$

Where:

E_k [Joule] → Kinetic energy

v [m/s] → velocity of the water

m [kg] → Mass

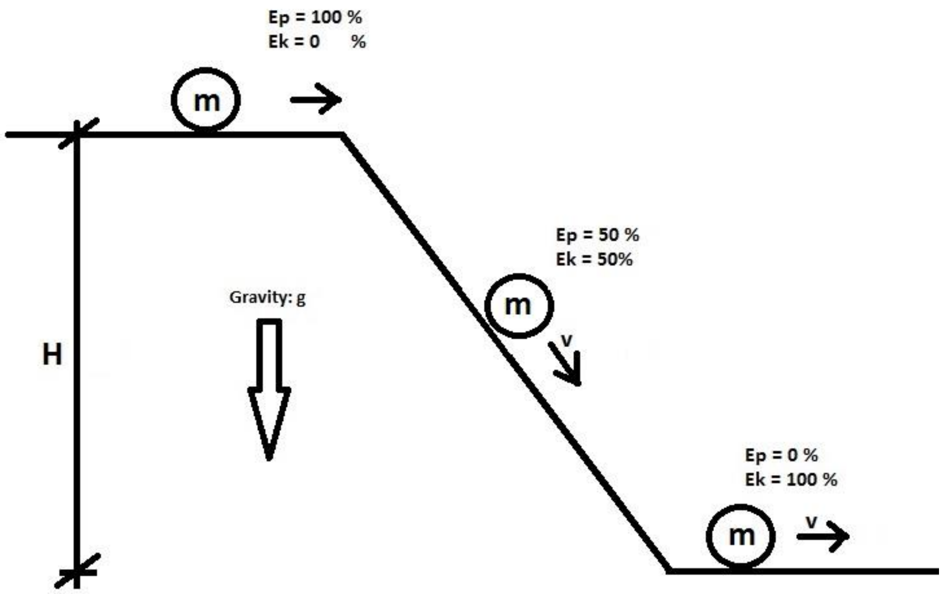

Figure 1-2: *Relation between the Potential and Kinetic energy.*

Figure 1-2 is showing an object, that has a maximum potential energy and minimum kinetic energy when the vertical distance equals H. As the object moves down and the vertical distance is equal to H/2 the potential energy is equal to kinetic energy. On the bottom where the vertical distance equals to H=0 is the potential energy t its minimum and the kinetic energy is at its maximum

Both of the equation consist of a parameter m (mass). The mass is determent by the density of the object containing the energy and can be calculated with the following equation (3): [2a]

$$\rho = \frac{m}{V} \tag{3}$$

Where:

ρ [kg/m³] → Density (Water 1000 kg/m³)
V [m³] → Volume
m [kg] → Mass

In the equation (3) above a new parameter is included, which is the quantity of water that we have to our disposal (Volume). The quantity or volume of the water running through the pipeline at a given time lap gives the second most important thing in the hydropower system and this water quantity per time unit is known as FLOW. Flow can be expressed by two different equations (4a ; 4b):

$$Q = \frac{V}{t} \quad \text{or} \quad Q = v * A \qquad (4a\ ;\ 4b)$$

Where:

Q [m³/s] → Flow
V [m³] → Volume
t [s] → Time
v [m/s] → Velocity
A [m²] → Area (of the pipeline cross-section)

These equations (4a ; 4b) give the overview of the parameters that are used while planning the hydropower system. A detailed explanation of them will be presented later in the subchapter (3.1) where a hydrodynamic calculation of head and flow complete with hydraulic loses will be shown.

For the overview is enough to know that the head and flow are the most important parameters needed for constructing a hydropower plant. These two components determine the design of the components that are going to be used and the overall electric power outcome of the system. In the chapter (2) the insitu measurement options of head and flow will be shown. To reweave:

- **HEAD** is the vertical distance between the water intake and turbine (Figure 1-3) and is the pressure available for the electrical production. It can be expressed in meters (m) or pressure units of Pascal (PA). [1c]

- **FLOW** is the quantity of the water passing through the turbine on the base of a second of time. It is expressed in Volume usually cubic meters or liters per second (m³/s) or (l/s). [1c]

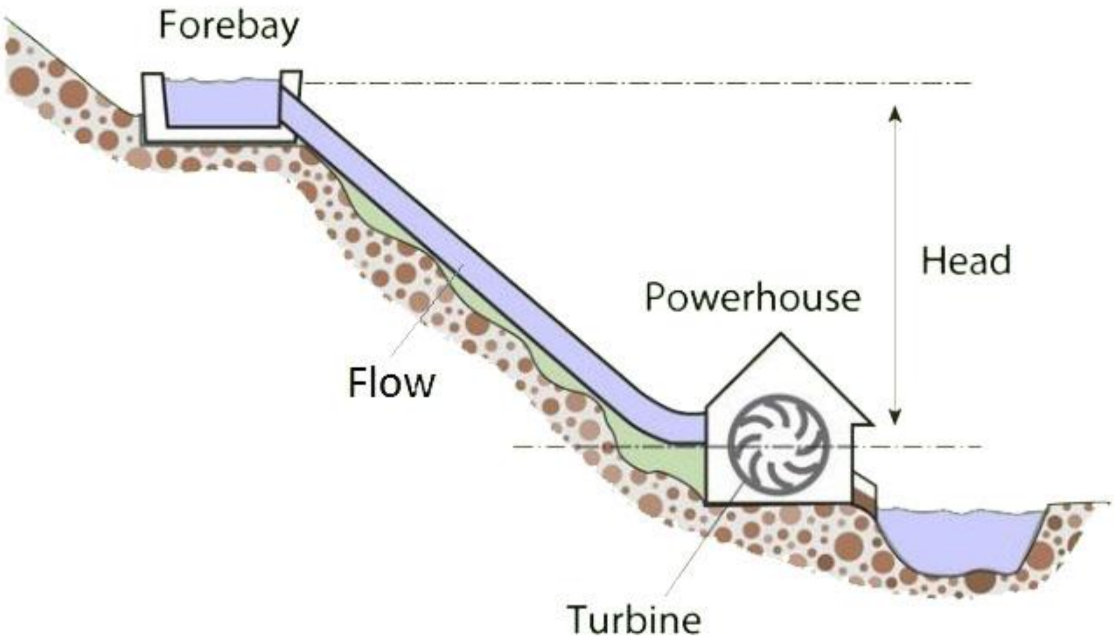

Figure 1-3: Scheme of a Hydro system with demonstration of Head and Flow
(Source; https://energy.gov/energysaver/planning-microhydropower-system; 2016)

While considering these two parameters a certain loss of energy has to be taken into a count as mentioned before, some amount of energy will transform into friction and heat. With head we lose some pressure as water flows through the pipeline. The pressure gets lost because of the friction in the pipe and therefore we get a net head which is the pressure that will be available at the turbine while the system is operating. As for the flow, the loses occur because the water quantity in the stream, from which we take the water, differs according to the time of year and rain conditions. Therefore the balance between the extreme values has to be found in order to get the design flow, which is the maximum flow for which the system is built. This is done in order to ensure a steady production of the electricity throughout the year. [1c]

As stated only net Head and design Flow data can be used to actually design a hydro system, and components that are necessary for it to work. If these data is wrong the whole system will not work efficiently, so it is very important to get them right as they are the base for every hydro power project no matter big or small. [1c]

Another term that was already mentioned was efficiency. Efficiency is how much water power is actually being transformed into electric power. As observed with the difference between Head and net Head is clear that all the way we are losing energy. The most basic formula for calculating our outcome or net power is: [1c]

Net Power [W] = Gross Power [W] * Efficiency [%]

And this formula shows hat the higher the efficiency is the more power we can produce and less gets lost in the system. Efficiency is affected by every component in the system. The fact that loss of power at every step cannot be changed but it can be optimized with good design while considering the natural given resources on the site. [1c]

1.2 Basic components

A hydro power station consists out of many components that must interact with one and other. The goal of this interaction is to let water in on one end and get electricity out on the other end. In this subchapter (1.2), the basic components are going to be explained, including their function, which are necessary for reaching the mentioned goal. Every hydropower system must consist of following components: [1c]

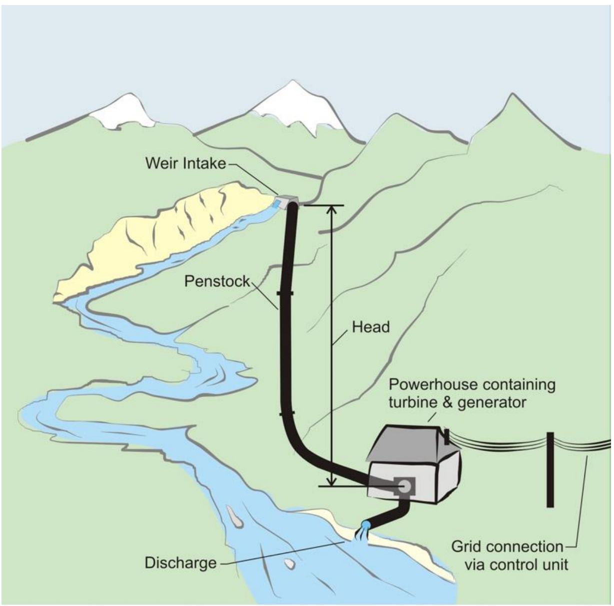

Figure 1-4: A scheme of basic components needed for Pico hydro power plants
(Source: http://snowdoniahydro.com/micro-hydro/, 2014)

1.2.1 Intake

Intake is in the case of pico hydropower systems the component that provides a small pool of water from which the turbine is fed. For the creation of this pool a small dam can be built to help stable the water surface and divert the water into the pipeline. While building the dam caution has to be used in order not to disturb the wild life in the eco system. Dams are considered as cross structures,

Figure 1-5: Intake with a weir to ensure the head for a small hydropower plant. *(Source; https://www.treehugger.com/clean-technology/is-hydropower-really-a-clean-power-source.html ; 2017)*

which means that they are constructed perpendicular to the stream flow (Figure 1-5). While building such structures the stream of the flowing water is blocked. Therefore, the living organisms cannot move freely up and down the stream anymore. Such actions can have major affect on the eco system. Out of this reason the type of the dam has to be carefully chosen based on the wildlife in the stream. Another possible solution is to provide the wildlife an extra passage so the organisms in the water are free to move around the dam. At big projects where the dam is also used to gain head needed for the turbines the fish path is constructed so that the fishes living in the river have a possibility to get on the upper streamside of the dam. When constructing the intake the depth of the pool has to be considered. Meaning how deep the pool needs to be so that an air free water flow in the pipeline can be ensured. Air in the pipeline will cause major problems to the turbine due to the unsteady flow conditions and also dramatically lower efficiency. [1c] [3a]

The second important function of the intake besides providing head is to stop debris and sediment that moves along with the water flow (Figure 1-6). Such floating impurities like lives, brunches or dirt and sediment particles can cause problems to the turbine if they enter the pipeline. Sediment particles cause abrasive wear on the turbine blades due to the small rocks hitting them with high speed and the lives can wrap around the impeller of the turbine and cause it to stop completely. The large debris can be stopped by using screens on the inflow, as for the sediment, it is wise to build a deep enough pool so the water can come down and let it settle on the bottom dues preventing the sediments to enter the pipeline.[1c] [3a]

Figure 1-6: Intake system with self-cleaning screen
(Source; [1c])

1.2.2 Pipeline or diversion channel

Figure 1-7: Intake, Penstock, Powerhouse *(Source; https://energypedia.info/wiki/Hydro_Power_Basics:2017)*

Pipeline or diversion channel is the component that guides the water from the intake into the powerhouse, where the Turbine is connected on the end. In literature you can also find the term penstock being used to describe the pipeline. Usually there are two different ways to transport water from the intake to the turbine. One is an enclosed pipeline and the other one is an open diversion channel. The benefits of the pipeline lie mainly in the enclosure, which creates head pressure in combination with an increasing vertical drop. If we are using a diverted open water channel to transport the water this energy dissipates as it flows down the hill. The disadvantage of the pipeline is the friction that accurse when the water is passing through the pipe. In case of large friction, a considerable los on efficiency occurs and we cannot produce maximum amount of power even if the pipeline is able to transport all of the designed water quantity to the turbine. Things that affect friction are pipe diameter, length, and routing. There are specific guidelines that tell us how to choose the right type of the pipe for the designed flow so we do not lower our efficiency of the power plant to significantly.[3a][1c]

1.2.3 Powerhouse

Powerhouse is simply a building that indoors the turbine, generator, controls, and Batteries if they are being used to store the produced electricity (Figure 1-7 The building on the end of the penstock). Powerhouse design does not have any affect on the power production but it is crucial to ensure that it is built to all safety specifications as it contains dangerous and sensitive equipment. [1c]

1.2.4 Turbines

As already mentioned before in the basics of hydropower is known that the kinetic energy of the water is converted to the rotational energy in the turbine. This conversion happens in two fundamental and basically different mechanisms. One mechanism is when the water pressure applies the force on the face of the turbine runner blades and it decreases as it proceeds through the turbine. The turbines that work in such manner are known as the reaction turbines. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure. The water pressure is converted into kinetic energy before entering the runner. The kinetic energy is in the form of a high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines that operate in this way are called impulse turbines. As the water after striking the buckets falls into the tail water with little remaining energy, the casing can be light and serves the purpose of preventing splashing. [3a]

1.2.4.1 Impulse turbines

Pelton

Pelton turbines are impulse turbines where one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues through a nozzle with a needle (or spear) valve to control the flow (Figure 1-10). They are only used for relatively high heads. The axes of the nozzles are in the plane of the runner (Figure 1-9). To stop the turbine . e.g. when the turbine approaches the runaway speed due to load rejection-

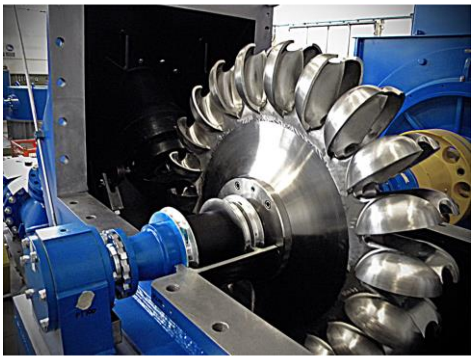

Figure 1-9: Pelton turbine runner
(Source; https://www.zeco.it/, 2012)

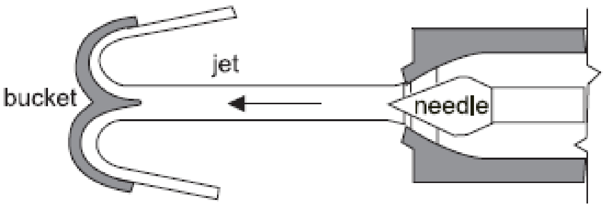

Figure 1-8: Water jet hitting the bucket
(Source; [3a])

the jet (see Figure 1-10) may be deflected by a plate so that it does not impinge on the buckets. In this way the needle valve can be closed very slowly, so that overpressure surge in the pipeline is kept to an acceptable minimum. Any kinetic energy leaving the runner is lost and so the buckets are designed to keep exit velocities to a minimum. The turbine casing only needs to protect the surroundings against water splashing and therefore can be very light. [3a]

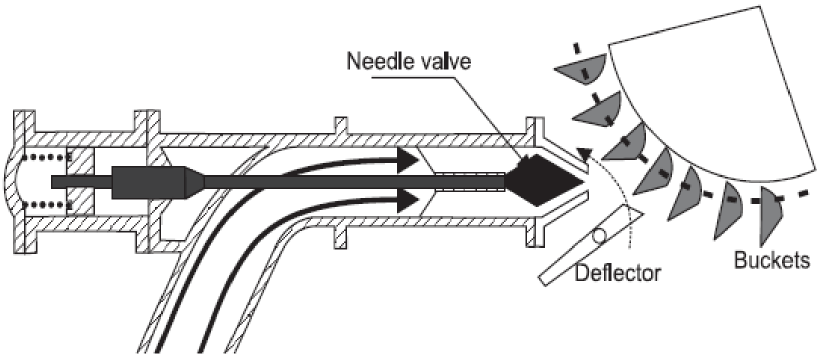

Figure 1-10: Needle valve can move left or right to control the flow. The deflector is used in case of emergency shutdown. *(Source: [3a])*

Turgo

The Turgo turbine can operate under a head in the range of 30-300 m. Like the Pelton it is an impulse turbine, but its buckets are shaped differently and the jet of water strikes the plane of its runner at an angle of 20º. Water enters the runner through one side of the runner disk and emerges from the other (Figure 1-12). (Compare this scheme with the one in Figure 1-9 corresponding to a Pelton turbine). Whereas the volume of water a Pelton turbine can admit is limited because the water leaving each bucket interferes with the adjacent ones, the Turgo runner does not present this problem. The resulting higher runner speed

Figure 1-12: Turgo turbine runner
(Source: http://www.tgvhydro.co.uk, 2016)

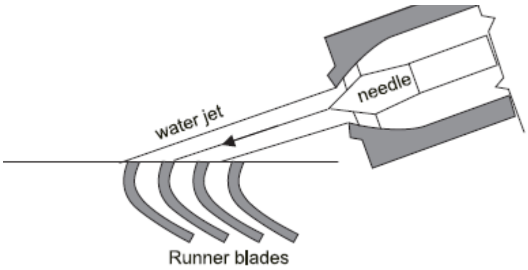

Figure 1-11: Eater jet hitting the runner blades
(Source: [3a])

of the Turgo makes direct coupling of turbine and generator more likely, improving its overall efficiency and decreasing maintenance cost. [3a]

Cross-flow

Figure 1-13: Banki-Michell turbine
(Source; http://www.temsan.gov.tr/banki.aspx, 2016

This impulse turbine, also known as Banki-Michell in remembrance of its inventors and Ossberger after a company (www.ossberger.de) which has been making it for more than 50 years, is used for a wide range of heads overlapping those of Kaplan, Francis and Pelton. It can operate with discharges between 0,02 m^3/s and 10 m^3/s and heads between 1 and 200 m. Water (Figure 1-13) enters the turbine, directed by one or more guide-vanes located in a transition piece upstream of the runner, and through the first stage of the runner which runs full with a small degree of reaction. Flow leaving the first stage attempt to crosses the open center of the turbine. As the flow enters the second stage, a compromise direction is achieved which causes significant shock losses. The runner is built from two or more parallel disks connected near their rims by a series of curved blades). Their efficiency lower than conventional turbines, but remains at practically the same level for a wide range of flows and heads (typically about 80%). [3a]

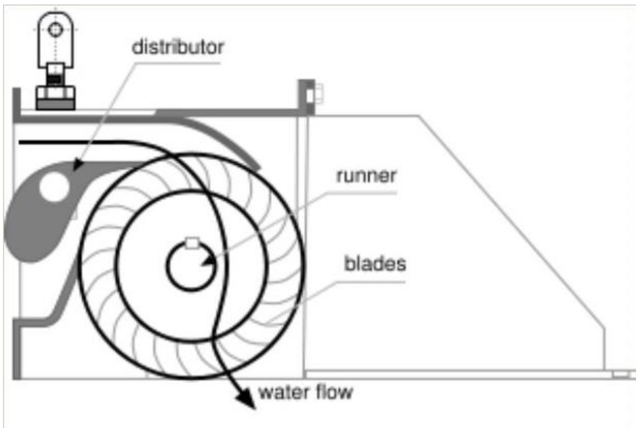

Figure 1-14: *Scheme of a* Banki-Michell turbine
(Source; [3a])

1.2.4.2 *Reaction turbines*

Francis

Figure 1-17: Horizontal axis Francis turbine
(Source: [3a])

Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In the high speed Francis the admission is always radial but the outlet is axial. Figure 1-17 shows a horizontal axis Francis turbine. The water proceeds through the turbine as if it was enclosed in a closed conduit pipe, moving from a fixed component, the distributor, to a moving one, the runner, without being at any time in contact with the atmosphere. Figure 1-19 shows a vertical section of a horizontal axis machine. The figure illustrates how the guide vanes, whose mission is to control the discharge going into the runner, rotate around their axes, by connecting rods attached to a large ring that synchronize the movement off all vanes. It should be emphasized that the size of the spiral casing contrasts with

Figure 1-16: Operating ring and attached links to operate the guide vanes
(Source; [3a])

Figure 1-15: *Scheme of the guide vanes movement*
(Source; [3a])

the lightness of a Pelton casing. In the Figure 1-15 the rotating ring and the attached links that operate the guide vanes can be seen. [3a]

Figure 1-16 schematically shows the adjustable vanes and their mechanism, both in open and closed position. As can be seen the wicket gates can be used to shut off the flow to the turbine in emergencies, although their use does not preclude the installation of a butterfly valve at the entrance to the turbine. [3a]

Francis turbines can be set in an open flume or attached to a penstock. For small heads and power open flumes are commonly employed. Steel spiral casings are used for higher heads, designing the casing so that the tangential velocity of the water is constant along the consecutive sections around the circumference. As shown in Figure 1-19 this implies a changing cross-sectional area of the casing. Figure 1-18 shows a Francis runner in perspective from the generator shaft end. Small runners are usually made in aluminum bronze castings. Large runners are fabricated from curved stainless steel plates, welded to a cast steel hub. In reaction turbines, to reduce the kinetic energy still remaining in the water leaving the runner a draft tube or diffuser stands between the turbine and the tail race. A well-designed draft tube allows, within certain limits, the turbine to be installed above the tail water elevation without losing any head. As the kinetic energy is proportional to the square of the velocity one of the draft tube objectives is to reduce the outlet velocity. An efficient draft tube would have a conical section but the angle cannot be too large, otherwise flow separation will occur. The optimum angle is 7º but to reduce the draft tube length, and therefore its cost, sometimes angles are increased up to 15º. Draft tubes are particularly important in high-speed turbines, where water leaves the runner at very high speeds. In horizontal axis machines the spiral casing must be well anchored in the foundation to prevent vibration that would reduce the range of discharges accepted by the turbine. [3a]

Figure 1-18: Francis runner
(Source; http://en.hydro-electricity.eu /references/?id=90, 2012)

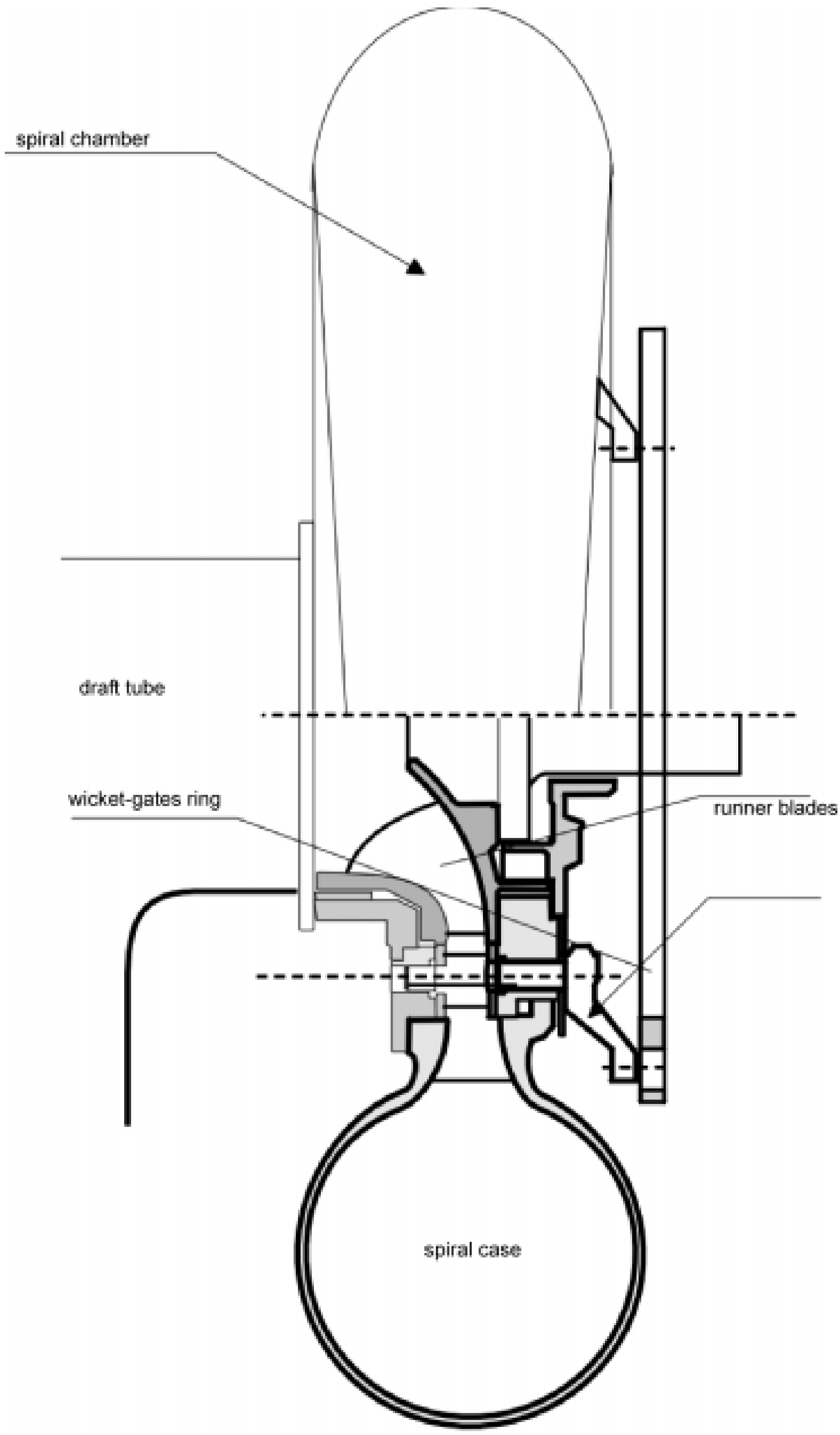

Figure 1-19: Axial cross-section of a horizontal Francis turbine
(Source; [3a])

Kaplan and propeller

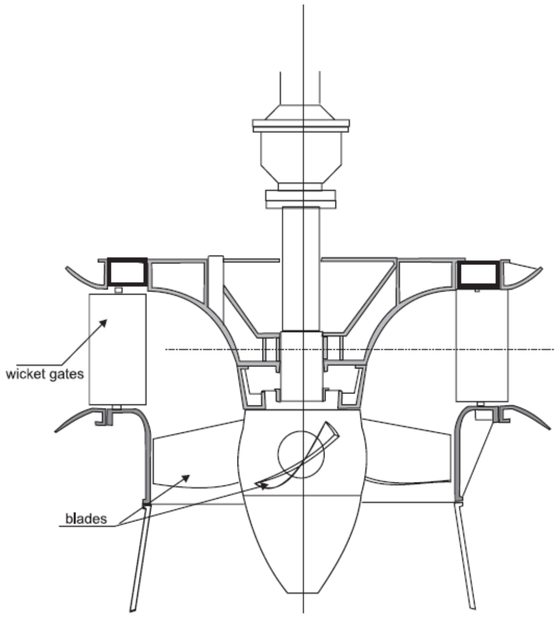

Figure 1-22: Vertical Kaplan turbine
(Source: [3a])

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads. The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide- vanes If both blades and guide-vanes are adjustable it is described as .double-regulated. If the guide-vanes are fixed it is single-regulated. Unregulated propeller turbines are used when both flow and head remain practically constant. The double-regulated Kaplan, illustrated in Figure 1-21 is a vertical axis machine with a scroll case and a radial wicket-gate configuration as shown in Figure 1-20. The flow enters radially inward and makes a right angle turn before entering the runner in an axial direction. The control system is designed so that the variation in blade angle is coupled with the guide-vanes setting in order to obtain the best efficiency over a wide range of flows. The blades can rotate with the turbine in operation, through links connected to a vertical rod sliding inside the hollow turbine axis. Bulb units are derived from Kaplan turbines, with the generator contained in a waterproofed bulb submerged in the flow. Figure 1-22 illustrates a turbine where the generator (and gearbox if required) cooled by pressurized air is lodged in the bulb. Only the electric cables, duly protected, leave the bulb. [3a]

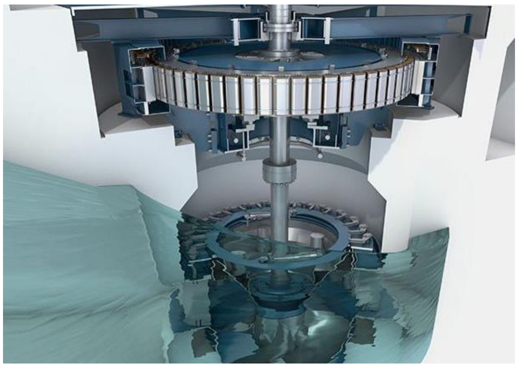

Figure 1-21: Vertical Kaplan turbine with generator and water flow
(Source; http://www.directindustry.com/industrial-manufacturer/turbine-66767.html, 2017)

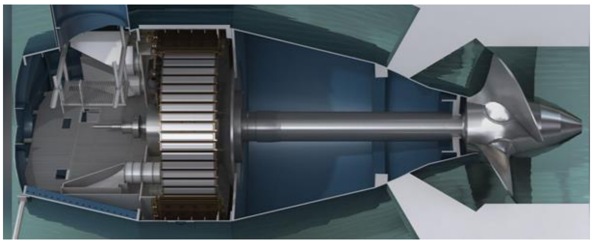

Figure 1-20: Kaplan bulb turbine with integrated generator
(Source; http://www.directindustry.com/industrial-manufacturer/turbine-66767.html, 2017)

1.2.4.3 Turbine selection criteria

The type, geometry and dimensions of the turbine will be fundamentally conditioned by the following criteria:

- Net head
- Design flow
- Rotational speed
- Cost

Net head

The gross head is the vertical distance, between the water surface level at the intake and at the tailrace for reaction turbines and the nozzle level for impulse turbines. Once the gross head is known, the net head can be computed by simply subtracting the losses along its path. The first criterion to take into account in the turbine's selection is the net head. Table 2 specifies for each turbine type its range of operating heads. The table shows some overlapping, so that for a certain head several types of turbines can be used. Turbine type Head range in meters [3a]

Table 2: Table of turbine models appropriate for corresponding head (*Source,* [3a])

Turbine type	Head range in meters [m]
Kaplan and Propeller	2 < H < 40
Michell-Banki	3 < H < 250
Francis	10 < H < 350
Turgo	30 < H < 300
Pelton	50 < H <1300

The selection is particularly critical in low-head schemes, where to be profitable large discharges must be handled. When contemplating schemes with a head between 2 and 5 m, and a discharge between 10 and 100 m³/s, runners with 1.6 . 3.2 meters diameter are required, coupled through a speed increaser to an asynchronous generator. The hydraulic conduits in general and water intakes in particular are very large and require very large civil works, with a cost that generally exceeds the cost of the electromechanical equipment. In order to reduce the overall cost (civil works plus equipment) and more specifically the cost of the civil works, several configurations, nowadays considered as classic, have been devised. To avoid an expensive civil work on the site a Kaplan turbine is used frequently. [3a]

Discharge

The design flow and net head determine the set of turbine types applicable to the site and the flow environment. Suitable turbines are those for which the given design flow and net head plot within the operational envelopes (Figure 1-23).

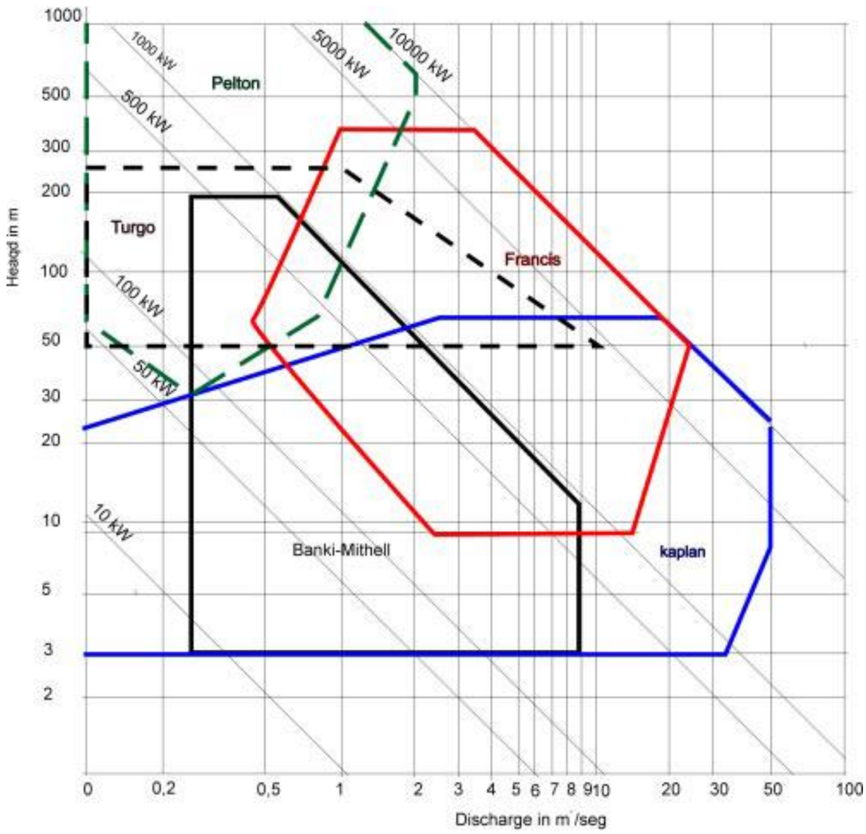

Figure 1-23: Envelopes of turbine models appropriate for specific head and flow conditions *(Source; [3a])*

A point defined as above by the flow and the head will usually plot within several of these envelopes. All of those turbines are appropriate for the job, and it will be necessary to compute installed power and electricity output against costs before taking a decision. It should be remembered that the envelopes vary from manufacturer to manufacturer and they should be considered only as a guide. [3a]

Specific speed

The specific speed constitutes a reliable criterion for the selection of the turbine, without any doubt more precise than the conventional enveloping curves, just mentioned. If we wish to produce electricity in a scheme with 100-m net head, using a 800 kW turbine directly coupled to a standard 1500-rpm generator we should begin by computing the specific speed n_s with the help of the following equation (5): [3a]

$$n_s = \frac{n * \sqrt{P}}{H^{1,25}} \tag{5}$$

Where:

n_s [m/s]	→	Flow
n [rpm]	→	Rotational speed
H [m]	→	Net head
P [W]	→	Power

With this specific speed the only possible selection is a Francis turbine. Otherwise if we accept the possibility of using a speed increaser with a ratio up to 1:3, the turbine itself could turn from 500 to 1500 rpm, corresponding respectively to specific speeds of 45 and 134. In those conditions it could be possible to select, in addition to the Francis, a Turgo, a cross-flow or a 2 jet Pelton. The spectrum of appropriate turbines has been considerably enlarged by the presence of the speed increaser. If we intend to install a 1500 kW turbine in a 400 m head scheme, directly coupled to a 1000 rpm generator, we will begin computing the specific speed, which indicates as the only option a 1 jet Pelton. [3a]

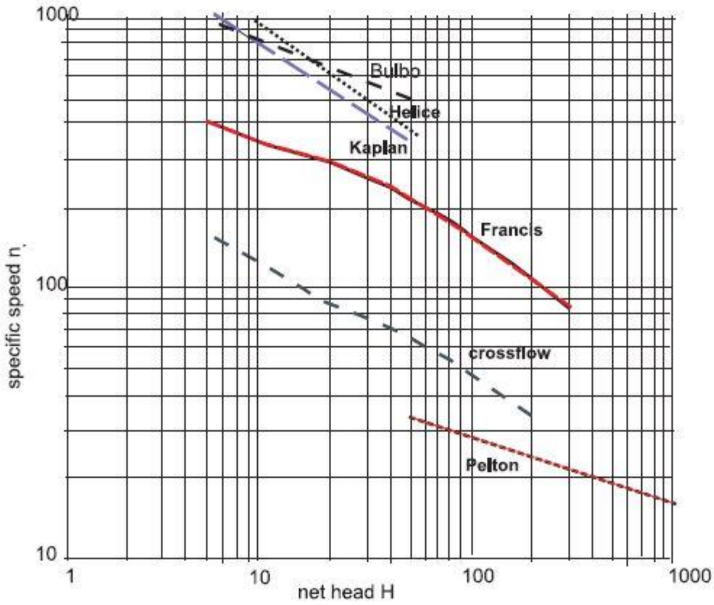

Figure 1-24: Criteria for turbine selection based on the specific speed *(Source; [3a])*

1.2.5 Drive system

Drive system is the medium component that connects the turbine and the generator. It is responsible to allow the turbine to rotate at its optimum RPM as the Generator at its optimal RPM. Meaning that if the turbine and the generator cannot be designed in such way that they can be connected with a 1:1 coupling a gear system is needed. Such gear systems provide a solution that the efficiency of the rotational energy transfer is high although some energy again gets lost due to the friction. The possibilities of the drive systems are many. Most popular are belts as they are cheaper than other solutions but they have lover lifespan and require more maintenance in comparison to gears. While considering the gear systems the solution with the planetary gearbox is preferable as they have the possibility to increase the turbines RPM for up to 50 and more times. In conclusion a balance between the costs, lifespan and efficiency has to be found while choosing the right drive system for the Pico power plant. [1c]

Figure 1-25: Belt drive system connecting the turbine left (blue) with the generator right (red) *(Source; http://www.pme-bandung.com, 2012)*

1.2.6 Generator

Generator converts the rotational power from the turbine into electric power. While talking about the generator we have to know that each generator has its own efficiency, which is different of the efficiency of the turbine. In a sense the turbine efficiency is the amount of transformed water power that turns the generator. The amount of electric power will then be determined by the generator efficiency itself. Modern generators are well build and they do have a fairly high efficiency rates. While constructing Pico power plants is wise to use the DC generators as they will produce more electricity but since it is DC we would have to have some converters to transform it into AC current, as most of the appliances use AC current. As if our site is a little bigger we can use the AC generators but we have to be careful on the electrical frequency. Most household items run on 50 Hz or 60 Hz frequency, so in the case that our generator spins too fast and produces higher frequency we have to set some current controlling system before using the energy provided by the generator. [1c]

Figure 1-26: Small Generator with integrated planetary gear box *(Source; http://www.lmagency.biz/contents/en-uk/p72.html, 2016)*

1.3 System control

When it comes to controlling the output electricity we have a variety of options. The system has to be controlled as the water flow will be changing over the year and the usage of the electric power is constantly changing. Such small power plants cannot produce enough power to run all electronic devices in one modern home, but they can be used to power some of the appliances such as water heaters, room heaters, charging stations etc. [1c]

While choosing the generator we have to be careful on a few designing conditions. The most important once are the Torque you need for producing the desired electrical energy while all of the produced power is being used and the RPM of the generator shaft, required to produce such power. The torque that the turbine produces, let us say 20 Nm, will stay the same, but the torque required by the generator to turn the magnets inside will change depending on the electrical load that the connected devices are producing. [1c]

For example we connect a water heater, E-bike charging station, refrigerator, washing machine and a backup battery to the system. If the generator requires the same 20 Nm to produce 5kW of electric power while all of this devices are switched on everything runs smoothly. Although when we take the bike for a ride we disconnect one of the power loads. Such switching off, of the loads will cause a drop in the torque from the electromagnetic field in the generator. As the turbine would not slow down the generator will start to turn faster. Due to the higher RPM the generator can start to overheat and “freewheel” and such actions can cause damage to the generator. We can maintain a steady consumption manually as we disconnect one device and connect some other device that use the same amount of power. The same thing can happen the other way around. In the dry seasons the water flow in your stream will be smaller dues causing a drop in the flow that runs the turbine. As the flow drops the turbine slows down and the torque that the turbine produces will drop. This will have an effect on the generator slowing down and the voltage that the generator is producing will also drop. In this case we are required to switch off one device in order to compensate the drop in the water flow. [1c]

As it is clear such electric power control is manually almost impossible. To ensure a steady electric power conditions an electric governor is required. The governor is a device that constantly monitors the voltage and the frequency on the output of the generator, so when the demand for the electric power drops as one of the power consumers is turned off it will automatically apply a load equivalent to the power consumption drop to ensure that the generator does not start to

Figure 1-27: Electronic load governor *(Source;[1c])*

rotate too fast (Figure 1-27). Such governors are very popular in Pico hydro systems because they are cost effective. [1c]

A more advanced approach is a load management system. Such system cannot only apply the load in case of the power consumption drop while something gets switched off, it can prioritize and direct the power from one device onto another. It can connect many different loads which are all connected in a prioritized series. As in previous example the devices are not used all the time but they consume the power at different rates at different times. If the washing machine is not running the system will divert the power to the filling of the backup battery and the water heater, but when the refrigerator turns on it consumes a lot of power but only for a short period of time so the power for the water heater and the battery will get distorted while the fridge runs and immediately restored when the fridge shuts down. Such compensating and prioritizing of the consumers is a good way to insure that we use the most power out of our system and also insure that all of the devices have the energy when they need it. [1c]

Figure 1-28: Load management system
(Source; http://www.prepayment-meter.com/sale-7647754-amr-ami-load-management-three-phase-power-meter-smart-wireless-electricity-meter.html 2016)

In some cases we also have the opportunity to connect our Hydropower system to the grid. Such connection will allow us to provide the grid with the energy that we are producing but not using. Seeing how the production of the electric power would stay more or less the same through the day, is our consumption on the other hand very different. For example a modern household has an average consumption of 10 kW at peak times. Our hydropower system is capable of producing 5 kW on average. It is clear that the remaining 5 kW would have to be supplied by the utility grid. At Night the consumption drops to 2 kW while the system is still providing the installed 5kW. In this case we can supply the utility grid with 3 kW of electric power. In conclusion the time when we do not use all of the produced power we supply the grid and on the time when our system cannot cope with the amount of the consumed electricity we cover the lack with the power from the grid. Such connections make a lot of sense but we have to confirm with the local authorities and grid control what kind of connection and parts we need, as the terms and conditions very from region to region and cannot be explained in advance. [1c]

Figure 1-29: Electric power grid
(Source; http://www.pennenergy.com/articles/pennenergy/2013/04/usda-loan-helps-georgia-improve-its-smart-grid.html, 2013)

Emergency shutdown

It is a very useful system to have on your hydro system as the rapid changes in the system could cause damage to the generator or the turbine rotor. For example a short circuit on the electric wiring could cause the electric overload or if it flips the bracer, a sudden drop in electric load. Such actions can have damaging consequences on the generator so it is wise to build in an emergency shutdown system. Such systems are mainly used to divert or cut the water flow to the turbine. As the water flow is cut the rotor of the turbine stops rotating and the whole system comes to a stop. The system for shutdown depends on the type of the turbine. If we are using the high flow turbines we have to stop the system slowly as the rapid interruption of flow could be damaging to your pipeline. [1c]

To clarify a rapid stop of the flow would cause pressure build-up in the pipeline as the water still has the inertia to move down the pipe. Since the pipeline is closed due to the shutdown system it has nowhere to go so the energy is transformed into pressure. In extreme cases this pressure can cause that the pipe bursts. On the big projects in the case of high pressure power plants where the head pressure is used to produce high Power they avoid such problems by building surge tanks. The surge tank reduces the pressure build-up by making room for the surge wave in case of sudden closure of the pipeline. The surge tank allows the wave to heighten the water level inside of it, dues dissipates its energy and revealing the pressure in the pipeline. Also it shortens the distance that the surge wave has to travel and allowing that this actions happen quicker. When we use jet nozzles to power our turbine as common in Pelton turbines the emergency shot down system is less complicated as we can simply divert the nozzle from the turbine and this would not change the pressure conditions in the pipeline dramatically. [1c]

2 Planning of the pico hydropower plant

The chapter 1 Pico/Micro hydropower overview gave as an idea how the Hydropower system works and a brief information on what do we need to consider while designing such systems. Since every site where we want to construct a hydropower system is different, we are going to take a look at different methods on how to measure the data we need for the designing process later and how to estimate how much power we can produce in combination with the conditions that are provided on the site. [1c]

2.1 Measuring the head and flow conditions

As already mentioned before the most important parameters that we need for the hydropower system are head and flow. These two parameters determine everything in the system from the pipeline diameter, turbine design, to the generator. All estimations from power production and costs would be pointless before we know these two parameters. [1c]

2.1.1 Head measurements

As already mentioned before, Head is the vertical distance between the intake and the turbine. This difference in height elevation creates pressure on the bottom end, which is then used to power the turbine. Following equation (6) will provide a better understanding of the relation between the distance and pressure. [1c]

$$1\ meter\ of\ head = 9{,}807\ kilo\ Pascal \tag{6}$$

The equation explains that for each meter of the height difference between the intake and the turbine we get 9, 8 kPA of pressure at the turbine. There are several methods that we can use to measure head on site. It is also wise to use more methods at one site so that we can determine head with better accuracy. Accuracy is key for a good design of the system, so we can design the components in order to get the most power for lower costs. The fastest way would be measuring the head with a GPS altimeter but they tend to be low in accuracy. Therefore we are going to look at two methods that are sufficient to provide good results. [1c]

2.1.1.1 Method 1: Differential leveling

For such measuring we use two rods which are basically the vertically supported measuring tapes. The second thing we need is the leveling instrument which we use to read the elevation between two points where the rods are placed. It is essential that all three things are perfectly level to ensure an accurate measurements. To run the complete measurement we place one rod on the intake position and the other one a few meters (depending on the leveling instrument) downstream in a straight line. The instrument is then placed in the middle of the rods and the height difference is calculated. Then we move the first rod downstream while the second one stays in place with the Instrument between them and calculate the difference in height again. We repeat the process until we get to the point where our turbine will be placed. When we reach the turbine point we sum up all of the measured height differences and we will get the total vertical elevation or head in meters, from which we can calculate the pressure using the equation (6) above. We can also perform the measurements in the other direction as shown in Figure 2-1. [12c]

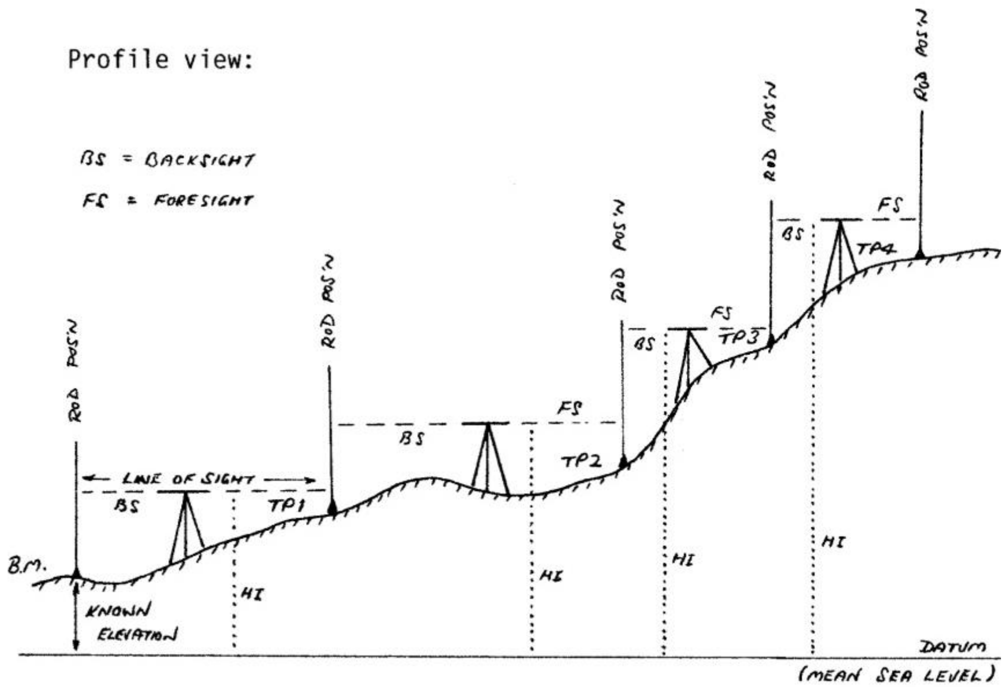

Figure 2-1: Scheme of measuring process for measuring the vertical distance between two points. *(Source; http://surveying.structural-analyser.com/surveys/survey04/, 2013)*

2.1.1.2 Method 2: Water pressure measurement

We can also do it the other way around by measuring the pressure and calculating the vertical distance. For this method we need a garden hose or if the distance is bigger we can use more of them connected, but the connections have to be waterproof and a pressure gage. We run the hose from the pint of intake to the point of where the turbine will be installed. At the end point we install the pressure gage which will give us the reading of the pressure in the hose. When everything is set we fill the hose with water and make sure that no air bubbles are trapped inside of it. When the hose is full we read the pressure on the gage and using the formula above we calculate the head in meters. While choosing the pressure gage we have to make sure that it is a quality one since they can have a major affect on the accuracy if they are not calibrated properly. Also we have to use the gage for which the measurements we take will be in the middle of its range. Meaning that if our measurement is going to be somewhere between 70-100 kPa we cannot use the gage that has a range of measuring between 0 – 1000 kPa. For such measurements is better to use the one which ranges from 0 – 200 kPa to ensure better accuracy of our measurements. In case that we cannot measure the total head from the intake to the turbine in one go due to the hose being too short, we can do it in segments like with the differential leveling but the room for error is in this case much bigger. [1c]

2.1.2 Flow measurements

There are quite a few different methods on how to measure the flow in the stream. We are going to cover some of them to get an idea of how does the measuring of the flow in the stream works. While measuring the flow in the stream we have to consider that the flow of the water is highly dependent on the time of year. The flow is bigger in the wet seasons when there is a lot of rainfall (spring, fall) and the flow is low in the dry seasons (summer, winter). Therefore we have to take the flow measurements at different times of year, so that we can get an approximation of an average flow in the stream. We also have to take into a count that the ecosystem around the stream, (birds, fishes and other organisms) depend on the water so we cannot use all of the available water for the power production. We have to design our hydropower system in a way that we do not disturb the ecosystem in the area. [1c][3a]

2.1.2.1 Method 1: Float

We find a section of the stream that is fairly straight so the depth and width of the stream is more or less consistent. On such sections we would get more accurate readings of the flow. The first step is to place a board across the stream and divide it in equal sections let us say 50 cm. at this marks we measure the depths of the stream getting a rough cross section of the stream. [1c]

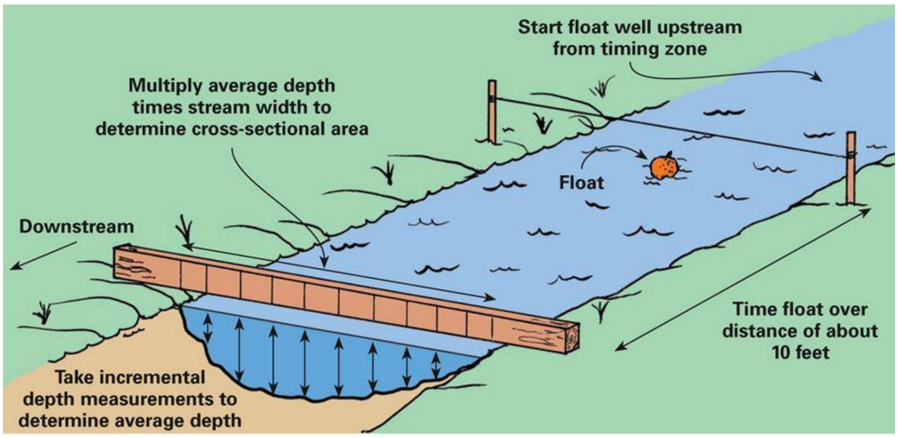

Figure 2-2: Scheme of the measuring process with float method
(Source; https://www.homepower.com/articles/microhydro-power/design-installation/intro-hydropower-part-2, 2017)

We calculate the areas of the sections and adding them up to get the complete area of the stream cross section. When we have that we have to measure the velocity at which the water moves through the cross section we measured the area at. The simple way to measure velocity is to place a floating body upstream and measure the time it needs to float a known distance with the stop watch. When we have the area and the velocity we can easily calculate the flow using the (4b) maintained before in the chapter (1.1). After calculating the flow we have to multiply the result with a coefficient of 0.8 to account for the friction as the water moves much faster on the surface as on the bottom of the stream. There are a lot of modern instruments that are capable of measuring the area of the cross sections and the speed of water from a stream such as laser sensors or ultrasonic emitters. Such devices are extremely accurate but on the other side very expensive. [1c]

2.1.2.2 Method 2: Measuring weir

For this method is required that we construct a weir across the stream. At the upper level of the weir we leave an opening where the water can run through. The opening has a specific area which helps us to eliminate the stream bead unevenness that we neglected in the method 1. A few meters upstream we place a measuring rod. The beginning of the measuring scale and the bottom of the weir outlet have to be perfectly leveled. Depending on the form of the weir opening, it being rectangular or triangle, we can use different formulas to calculate the flow for different water elevations that we measure on the rod. This method is one of the most reliable, but it requires the stream to be disrupted for a longer period of time. [1c]

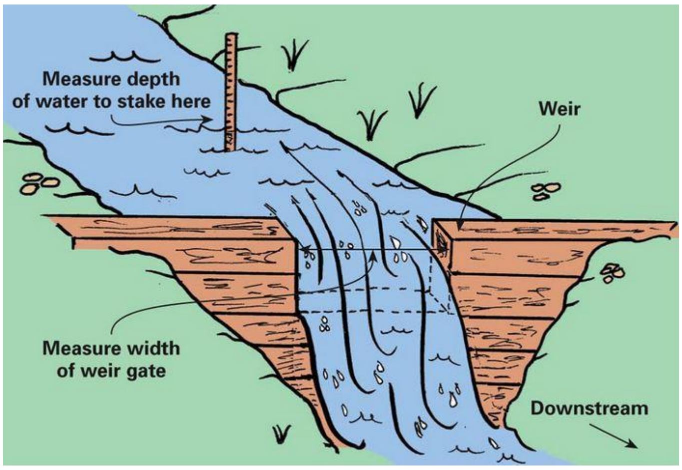

Figure 2-3: Scheme of the measuring weir method
(Source; https://www.homepower.com/articles/microhydro-power/design-installation/intro-hydropower-part-2, 2017)

A good example of such weir measurements is a Thompson weir which is also regularly used at big hydro structures to measure seepage water that runs under the construction. The Thompson weir has a triangle opening, meaning that the opening is widening linear from the bottom to the top. When we measure the water heights on the upstream side of the weir we then use the following formula (7) to calculate the flow. [4b]

$$Q = \frac{8}{15} * \mu * \sqrt{2 * g} * \tan\alpha * h^{\frac{5}{2}} \tag{7}$$

Where:

Q [m³/s] → Flow

g [m/s²] → Gravity acceleration

α [°] → Angle of the opening on one side

H [m] → Measured water level

µ → Coefficient compensating for friction ≈0.8

With this method we can easily measure the flow throughout the whole year and make a record of the changes that are happening in our stream over time. [4b]

2.1.2.3 Method 3: Dissolving tracers method

For this method we have to use calibrated measuring probes. For tracers we use NaCl or salt which we throw in the water a few meters upstream from the cross section that we are measuring with the probes. The concentration of the salt that we use is known and is used for the calculation. As the tracer then dissolves in the water and the stream caries the tracer cloud downstream and pass our measuring cross section where the probes are installed. The probes then measure the differences in the concentration of tracer and automatically calcu-

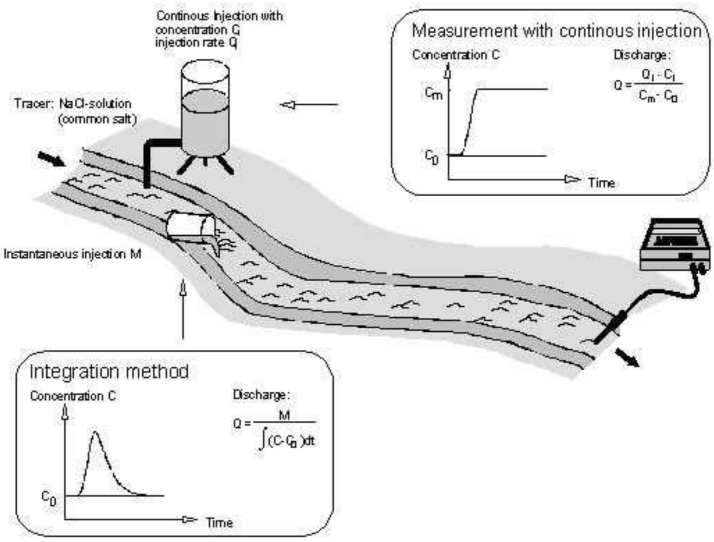

Figure 2-4: Scheme of the tracer flow measuring method
(Source; http://www.logotronic.at/produkte-2/qtrace-abflussmesssystem/93-121.htm, 2017)

lating the flow using the integral (8):

$$Q = \frac{M}{\int (c_t - c_0)} dt \tag{8}$$

Where:

M	→	Volume times concentration
c_0	→	Initial concentration
c_t	→	Concentration at given time
Q	→	Flow

For this method we have to estimate the amount of salt that we are going to use and the section on which we are doing the measurements. This method is also reliable and is perfect to be used on small streams.[2d]

2.1.2.4 Method 4: Measuring with ultrasound

There is also a variety of devices that can be percussed for measuring the flow using ultrasound waves. The probes are equipped with senders, which send out an ultrasonic wave and receivers to detect the reflected ultrasound. The ultrasound emitted from the senders is reflected from the small particles that are moving along with the flowing water. As the reflected sound is received the device calculates its velocity. If the cross-section area where we do the velocity measurements is known we can easily calculate the flow using the equation (4b). There are two possible methods for measuring with ultrasound one is ADCP (Acoustic Doppler Current Profile) and the other one is ADV (Acoustic Doppler Velocimeter). This methods are quick and very reliable but the downside is the expensive equipment. [2d]

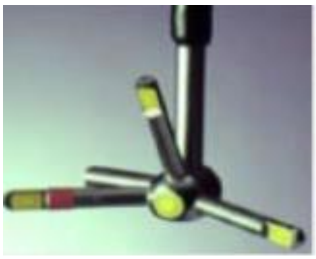

Figure 2-6: Son Tek Argonau ADCP instrument (left), Vectrino probe (right) (Source: [2d])

When we are doing our measurements we also have to be aware of the conditions surrounding us, meaning we will get a much higher readings if we do the measurements after a heavy rainfall. Although the higher flow translates in more power it is wise to design the system for an average flow reading as it will be much more cost effective then to design it to the maximum reading that we calculated. The flow measurements are done correctly when they are done for a period of one year. Every stream has a wet and dry season, meaning that in the summer the water flow will be much smaller as in the springtime. When the measurements are complete the graph as in (Figure 2-5) should be drawn, so that the correct design flow can be chosen. For the river in the Figure below a design flow of roughly 100 – 130 m³/s can be assumed as this flow will be available for the most of the year.

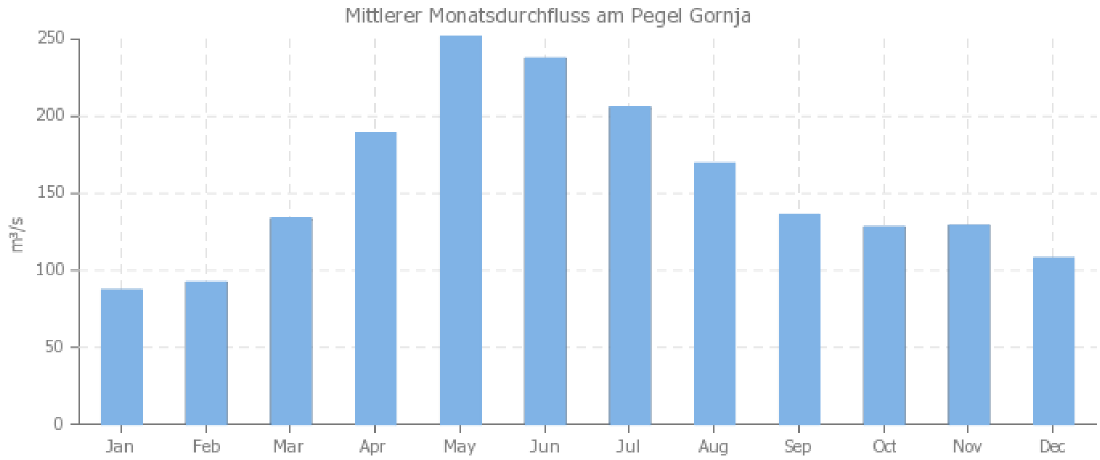

Figure 2-7: The average monthly flow for one year on river Mur, showing the peak in spring *(Source; http://www.faltboot.org/wiki/index.php/Mur, 2017)*

2.2 Calculating the Power supply

When we get the measurements of our site we can proceed to a rough estimation of the power we are going to produce so that we can choose the generator. As we know from previous chapter we are losing energy in every component of our system so we have to compensate our calculations for this in our calculations [1c]

The available power can be calculated very easily with the following formula (9):

$$P = H * Q * \rho * g \tag{9}$$

Where:

P [W]	→	Power
ρ [kg/m³]	→	Water density
H [m]	→	Head
Q [m³/s]	→	Flow
g [m/s²]	→	Gravity acceleration

The calculated power is in Watt units and is the value of the power we have available for our system. From this formula we can conclude that the head and flow are having a linear effect on the power, meaning if we double the head the power doubles and same with the flow. [1c]

To evaluate the power we are going to get on the turbine we have to compensate for the flow changes and the pipeline friction. To compensate the flow conditions we have to determine our design flow. The design flow is the maximum flow for which the system is designed and is the flow that will appear in the stream for the most of the year. All of the detailed calculations will be provided in the chapter (3.1).

3 Concept for a pico hydropower plant system

For this project we have decided to simulate a stream that has low inclination of the bed see Figure 3-1. Based on this conditions the hydro system will be provided with low head and low flow. The second thing that we were looking for was, to avoid constructing a dam with a weir, to disrupt the water flow for the purpose of gaining head. This decision was based on the fact that such constructions interfere with the ecosystem as we learned in the previous chapter. In addition, construction of a dam requires a lot of civil work and therefore it is too expensive considering that a pico-turbine will not produce a high amount of power. A few solutions are possible for such construction of the hydro system.

Figure 3-1: Stream Podgrajščica (Vransko; Slovenia)

1. Placing the intake, a long way upstream to ensure the head needed for running the turbine with enough power to turn the generator at required rpm. Such construction can be designed in two ways:
   - With an open diversion channel which is then connected to the pipeline that runs water to the turbine
   - A long pipeline that runs from the intake to the turbine.

The benefits of open water channel solution are the low friction loses which get bigger with the length of the pipeline. On the other hand, the debris such as lives and branches that should be cleaned at the intake can fall into water if it is in an open channel so another cleaning solution must be installed before the turbine.

2. Placing stones along the cross-section of the streambed to slowly rise the bed to required height so that the eco system stays intact and the needed head is supplied for the turbine.

This solution can be more expensive as the first one but we get less interference with the flow in the system. Further, the study of the stream behavior such as sediment transport has to be performed in case of changing the natural course of the streambed.

Another aim of this paper is to associate pico hydropower with the new uprising technologies. Based on that, will the turbine chosen and designed for the project be constructed using the technology of 3D printing. Even so, as the dimensions of the turbine are small, it can easily be printed with a conventional 3D printer.

As the full-scale model was not possible to recreate in the laboratory from Graz University of Technology, a small-scale model was built for the purpose of proving that the concept of a 3D printed turbine is possible and functional in sense of producing electric power.

3.1 Selecting the hydropower system

For the small-scale project in the laboratory, a hydro system was constructed to fit the specifications that were provided from the turbine design, which we will get into later on. The first idea was to simulate the conditions that would occur in a natural given stream. For such simulation a glass channel would be used and the turbine would be placed inside. As it would be optimal to test such hydro system it would be difficult to do the measurements. Another problem that we had to get into was the regulation of the flow in the channel. A problem was that the flow measuring device connected to the channel was not capable to provide a small enough flow needed for the simulation. After the discussion with the laboratory manager, we decided to simulate the conditions outside the channel and construct a system only to feed the turbine similar to the one in Figure 1-7.

Hydrodynamic calculation of hydraulic loses

As it was mentioned in the first chapter (1.2) a detailed calculation of hydrodynamics will be provided. In hydrodynamics we basically differentiate between two different types of calculations. First is the hydrodynamics in an open stream and the second is the hydrodynamics in the enclosed pipe. As the experiment is designed to use a pipeline to feed the turbine from the intake, only the hydrodynamics in an enclosed pipe will be considered.

First of it has to be clear how the formula for hydrodynamic calculations in the pipe is formed. In the first chapter was sad that the whole system revolves around transforming energy. In addition to that, the Energy law is the start of hydrodynamics. [1a]

Energy law says: as any mass, also the fluid mass changes its state of motion only, if an outer force influences it. The forces such as Friction force, pressure force, elasticity force and other similar, such as gravitational pull force, or centrifugal force are designated as forces of mass that can be deviated from a force plain. All this forces must be in an equilibrium with one another at any time and any space of the moving fluid, which is the inertial fluid set against the changing moving state. This is written in the newton’s movement law: [1a]

$$F - m * \frac{dv}{dt} = 0 \tag{10}$$

Where:

F	→	The geometrical sum of all forces acting on the fluid mass
$-m * \frac{dv}{dt}$	→	Inertial or d’Alembert complementary force

Next is the equation of a moving water in a pipe while leaving out all of the hydraulic losses. In Figure 3-2 an enclosed pipe can be seen through which a

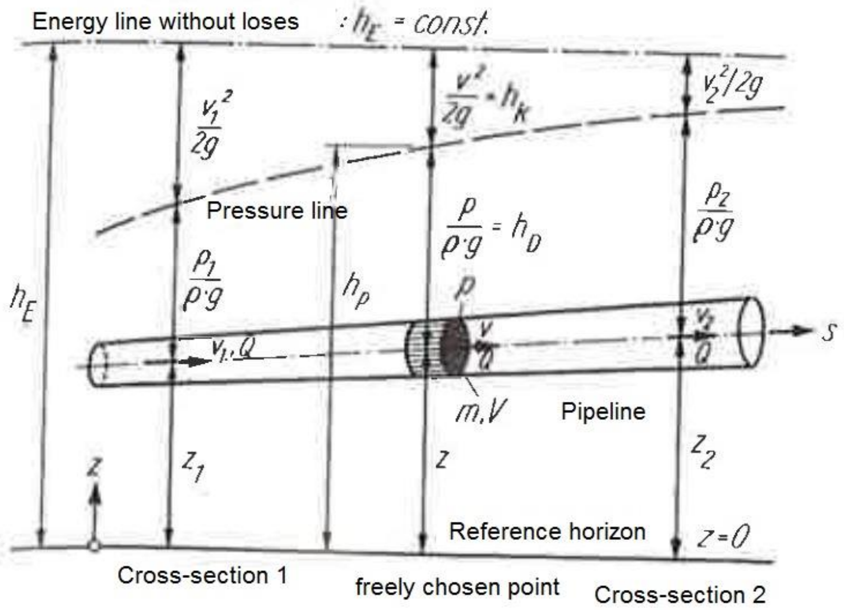

Figure 3-2: Sketch for Bernoulli equation, without hydraulic loses
(Source; [1a])

moving fluid is passing. It explains the force equilibrium that was summed up by the mathematician Bernoulli in its Bernoulli equation. Note that this example is for a fluid without considering the friction.[1a]

In a straight pipe which lies on a height level z from a freely chosen starting horizon level, and possesses a constantly changing area A in the direction of the current s, moves a frictionless fluid with a changing velocity, due to the area changes, as the discharge Q stays constant. The mass of the fluid Fg=m*g is the carrier of the hydraulic Energy. The energies involved in the Figure 3-2 are: [1a]

- Positional energy = Fg*z=m*g*z
- Pressure energy = V*p=m*p/ρ
- Kinetic energy = m*v^2/2

The Energy can then be expressed as:

$$W = m * g * \left(z + \frac{p}{\rho * g} + \frac{v^2}{2 * g}\right) = Fg * \left(z + \frac{p}{\rho * g} + \frac{v^2}{2 * g}\right) \qquad (11)$$

The Bernoulli equation says: in case of the stationary flow of a frictionless fluid through an enclosed pipe, the summed energy height is h_e is composed of the surveying height z from a freely chosen horizon level(positional energy), pressure height h_D (pressure energy) and velocity height h_K (kinetic energy). In addition, it has to be the same in any given point of the system. [1a]

$$h_e = z_1 + \frac{p_1}{\rho * g} + \frac{v_1^2}{2 * g} = z_2 + \frac{p_2}{\rho * g} + \frac{v_2^2}{2 * g} \tag{12}$$

The equation (12) explains the behavior of a frictionless fluid. Although water is not frictionless, so we have to modify the equation to compensate for the loss of energy that gets lost due to friction. As mentioned before this energy dose not despair, but it is transformed into other forms. In the Figure 3-3 we can see the energy line drop compared to the Figure 3-2 as the loses are taken into a count. To satisfy this in a Bernoulli equation we have to write the equation (12) as: [1a]

$$h_e = z_1 + \frac{p_1}{\rho * g} + \frac{v_1^2}{2 * g} = z_2 + \frac{p_2}{\rho * g} + \frac{v_2^2}{2 * g} + h_r \tag{13}$$

h_r is the height of the friction loses.

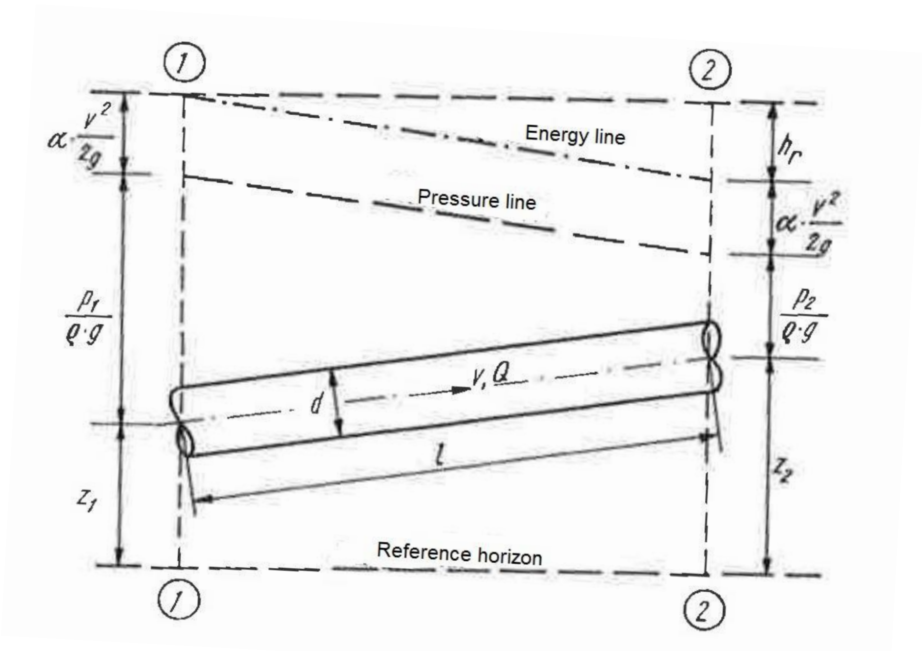

Figure 3-3: Energy height on two cross-sections of the pipeline *(Source [1a])*

In a pipe there are two possible ways for a fluid to flow through. One is the laminar and the other the turbulent flow. Figure 3-4 is showing a velocity distribution of the fluid in both cases. The Laminar flow is very rear and in a laminar flow, the stream filaments are parallel to one another which means if there is a bump in the pipe which distorts the flow it will cause the flow to get turbulent but it will even out after a while. As for the turbulent flow, it stays turbulent after the distortion. Considering the mathematical- and physical alliances of the fluid we can calculate the Reynolds number Re (named after Osborne Reynolds)

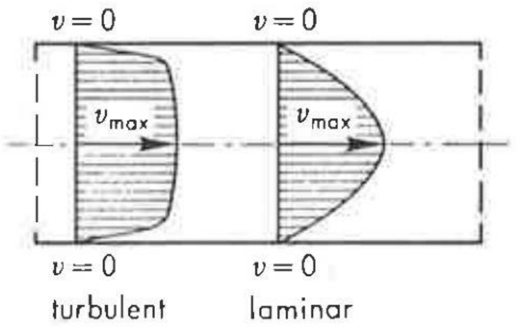

Figure 3-4: Velocity distribution in the Pipeline *(Source, [2a])*

The Reynolds number consists of: [1a] [2a]

$$Re = \frac{v * d}{\vartheta} \tag{14}$$

Where:

Re	→	Reynolds number
v [m/s]	→	Velocity
d [m]	→	Pipe diameter
ϑ [m²/s]	→	Kinetic viscosity

The kinetic viscosity in fluids is dependent on the temperature the viscosity is changing in relation to changes in temperature. [2a]

A number of laboratory tests showed that, if the Re < 2320 the flow in the pipe will be laminar and if Re > 2320 the flow will be turbulent. Based on this conclusion the Re= 2320 is also known as Re_{krit}. [2a]

The equation for the energy line incline is as follows (15):

$$I_E = h_r = \lambda * \frac{v^2}{2 * g} * \frac{L}{d} \tag{15}$$

Where:

λ → Friction coefficient

L [m] → Length of pipe

d [m] → Pipe diameter

The friction coefficient λ is dependent on the type of flow in the pipe. For the laminar flow it is dependent only on the Reynolds number Re and the equation (16a) for that is as follows: [2a]

$$\lambda = \frac{64}{Re} \tag{16a}$$

As for the turbulent flow Re > 2320there are three ranges to differ between:

Smooth range where all of the unevenness of the pipe are under the thin border layer, the λ depends only from Re: [2a]

$$\frac{1}{\sqrt{\lambda}} = -2 * log\left[\frac{2.51}{Re\sqrt{\lambda}}\right] \tag{16b}$$

Rough range where the unevenness are sticking out of the thin border layer, the λ depends on the relative roughness of the pipe k_S [m] the table of roughness coefficients for different materials is provided in Table 3 below. [2a]

Table 3: Table of absolute roughness coefficient ks
(Source: http://www.engineeringtoolbox.com/surface-roughness-ventilation-ducts-d_209.html, 2017)

Surface	**Absolute Roughness - *k***
	(10^{-3} m)
Copper, Lead, Brass, Aluminum (new)	0.001 - 0.002
PVC and Plastic Pipes	0.0015 - 0.007
Epoxy, Vinyl Ester and Isophthalic pipe	0.005
Stainless steel	0.0015
Steel commercial pipe	0.045 - 0.09
Stretched steel	0.015

Weld steel	0.045
Galvanized steel	0.15
Rusted steel (corrosion)	0.15 - 4
New cast iron	0.25 - 0.8
Worn cast iron	0.8 - 1.5
Rusty cast iron	1.5 - 2.5
Sheet or asphalted cast iron	0.01 - 0.015
Smoothed cement	0.3
Ordinary concrete	0.3 - 1
Coarse concrete	0.3 - 5
Well planed wood	0.18 - 0.9
Ordinary wood	5

$$\frac{1}{\sqrt{\lambda}} = -2 * log\left[\frac{\frac{k_s}{d}}{3.71}\right] \tag{16c}$$

Transitional range where the unevenness penetrate the border layer only partially, the λ is dependent on Re and k_S. [2a]

$$\frac{1}{\sqrt{\lambda}} = -2 * log\left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{\frac{k_s}{d}}{3.71}\right] \tag{16d}$$

When the formulas (13) and (15) are combined a complete Bernoulli equation between two points of the pipeline can be written as: [2a]

$$z_1 + \frac{p_1}{\rho * g} + \frac{v_1^2}{2 * g} = z_2 + \frac{p_2}{\rho * g} + \frac{v_2^2}{2 * g} * \left(1 + \lambda * \frac{L}{d}\right) \tag{17}$$

Friction coefficient λ can be calculated using the equations (16a to 16d) or they can be read out of the Moody diagram, which is presented in the Figure 3-5.

The explanation above is for a straight pipe with a constant diameter. There are a number of other energy loses that are involved in hydrodynamic systems, as the energy los in piping curves, inlet, screens and many more. The detailed information on how to calculate such energy loses are provided in literature for hydrodynamics for example [1a] [2a].

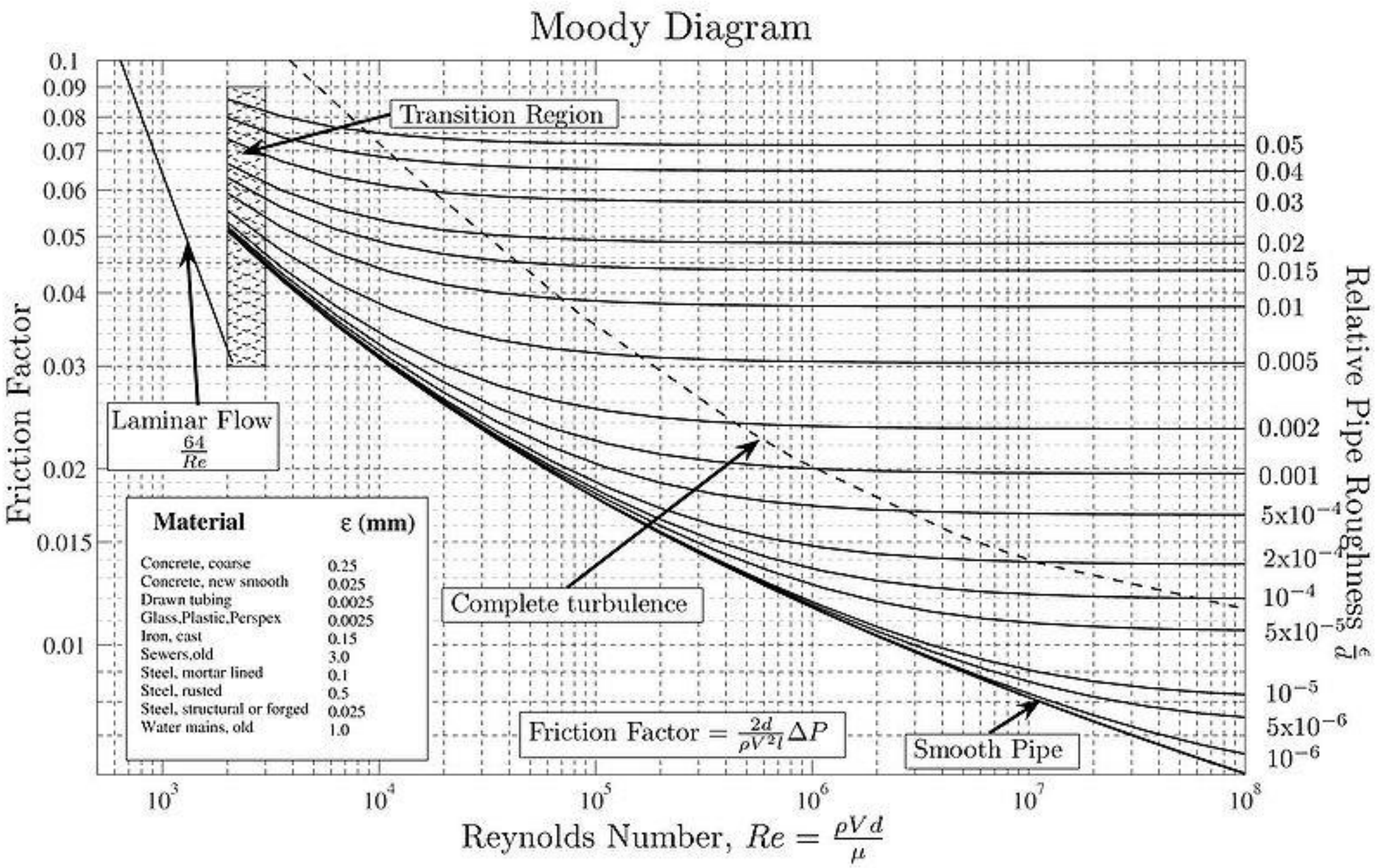

Figure 3-5: Moody Diagram for estimation of the Friction coefficient
(Source; http://en.academic.ru/dic.nsf/enwiki/9665240, 2015)

3.2 Selection of the turbine

As the stream conditions are, low head and low flow we decided to go for an Ossberger or Banki – Michell turbine. As we know from the chapter on the Turbines (1.3.4) is an impulse cross-flow turbine. In addition, if we look at the choosing criteria in (1.3.4.3) it is clear that this model of turbine will be the best option since this turbine is efficient in various load conditions as in low head and low flow.

Calculating the turbine parameters

For the calculation of the parameters the paper that was published in energies journal (April 2013) was used. As the paper [1b] proposes a two step design procedure should be followed while designing a cross-flow turbine:

The studies on the design of the Banki-Michell turbine were heavily based on laboratory tests and, more recently, on numerical simulations of single cases, but a theoretical framework for a fast sequential design of the turbine parameters is still missing. In the present paper a standard procedure is proposed for the design of a Banki-Michell turbine, based on two different steps. The first step is the design of the outer diameter of the impeller D_1 and of the blade attack angle β_1, for given water discharge Q and hydraulic head H, as well as of the nozzle profile. The maximum efficiency attainable in these conditions is derived from the Euler's equation for rotating machines and from the assumption of zero energy dissipation inside the nozzle. The other impeller parameters are estimated by testing single options by means of CFD analysis. The inner diameter D_2 is optimized by evaluating the efficiency of the turbine for different values of the diameter ratio D_2/D_1; the inner radius blade, the attack angle, the number of blades, their shape and the inner/outer diameter ratio are optimized starting from known literature results. Computations can be carried out in cases both of zero downstream pressure (where the air phase is present in the impeller case) and non-zero downstream pressure (where the impeller case is fully pressurized). The power P_t transferred from the current flow to the rotating system, according to the Euler's equation can be written in the following (18a) form: [1b]

$$P_t = \rho * Q * [(\vec{V}_1 * \vec{U}_1 - \vec{V}_2 * \vec{U}_2) + (\vec{V}_3 * \vec{U}_3 - \vec{V}_4 * \vec{U}_4)] \quad (18a)$$

Where:

V → particle velocity

U → velocity of the rotating reference system

Q → water discharge

ρ → Density

(see Figure 3-6). The underlying assumption is that there is a radial symmetry of the velocities along all the inlet and outlet arc of both the inner and outer impeller circumferences. This is, of course, a simplification of reality. The particles with low inlet velocity could not even enter the impeller, due to the centrifugal forces. [1b]

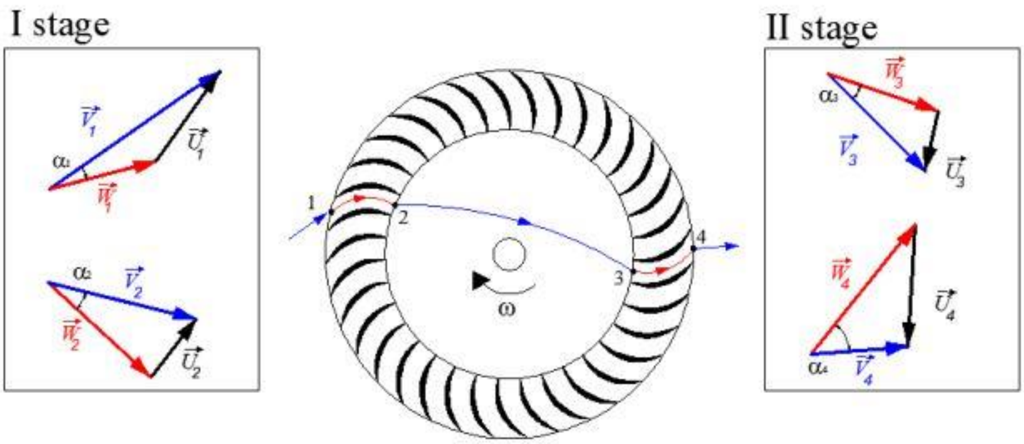

Figure 3-6: Points in the Euler´s equation *(Source; [1b])*

The power in Equation (18a) has four components, which we call P_1, P_2, P_3 and P_4. Assuming a β_2 blade angle equal to $\pi/2$, the sum of the second and third components is equal to:[1b]

$$P_2 + P_3 = \rho * Q * (-U_2^2 + U_3^2) = 0 \quad (18b)$$

because on the blade surface the component of the particle velocity in the direction of the reference system velocity is equal to the norm of the same velocity

($U_2 = U_3$). If a further assumption is made by neglecting the fourth power component P_4, and assuming that almost all the fluid energy has been either transferred or dissipated before leaving the impeller, the only component affecting the turbine efficiency remains the first one. Thus, Equation (18a) could be simplified and becomes: [1b]

$$P_t \cong \rho * Q * (\vec{V}_1 * \vec{U}_1) \tag{19}$$

Equation (19) holds if the norm V at point 1 (see Figure 3-6) is the same immediately inside and outside the impeller and the velocity continuity must also hold around the blade surface. Because a simplifying assumption is made that the velocity has radial symmetry at the impeller inlet, Equation (19) only holds if the norm U of the velocity of the reference system is equal to the component of the particle velocity V in the tangent direction minus the tangential component of the relative velocity W (see Figure 3-6). This implies the equality: [1b]

$$U_1 = V_1 * \cos(\alpha) - W_{1,t} \tag{20}$$

where $W_{1,t}$ is the tangential component of the relative velocity W. Thus, Equation (19) can be written as: [1b]

$$P_t = \rho * Q * V_1 * \cos(\alpha) * (V_1 * \cos(\alpha) - W_{1,t}) \tag{21}$$

All the energy of the entering flow can be either dissipated or transferred to the rotating system if: [1b]

$$W_{1,t} = \frac{V_1 * \cos(\alpha)}{2} \tag{22a}$$

and, in the ideal case of $\cos\alpha = 1$,

$$W_{1,t} = \frac{V_1}{2} \tag{22b}$$

Moreover, if we assume that the relative velocity *W* satisfies Equation (22a), we can see from Equation (21) that the efficiency of the turbine has an upper theoretical limit, given by the constraint: [1b]

$$\eta \leq \cos^2(\alpha) \tag{23}$$

as already found by Mockmore and Merryfield with a different procedure. [1b]

3.2.1 First Step: Design of Basic Parameters

The equations above even if obtained from a strong simplification of reality, highlight why the inlet velocity angle *α* is such an important design parameter. In addition, we will show in the following sections that its choice has a strong impact on the inlet width B and on the resulting structural stress. [1b]

Let us assume the water discharge *Q*, the hydraulic head *H* and the angular velocity ω to be input data of the problem and the design inlet discharge angle α to be taken from the literature experience. If we assume the optimal value of the relative tangent velocity to maintain the value calculated in Equation (22a), we can compute either the diameter D_1 or the *α* angle by substituting Equation (22a) in Equation (20). Assuming that $U = \omega * \frac{D_1}{2}$, we obtain: [1b]

$$\frac{V * cos(\alpha)}{2} = \omega * \frac{D_1}{2} \tag{24}$$

Equation (24) allows one to compute either the outer diameter D_1 starting from the *α* angle, or vice versa. Once both D_1 and the inlet velocity angle *α* are known, the blade β_1 angle can be calculated as the inverse of the tangent function, equal to the ratio between the velocity relative components, that is: [1b]

$$\beta_1 = arctan\left(\frac{V * \sin(\alpha)}{V * \cos(\alpha) - \omega * \frac{D_1}{2}}\right) \tag{25}$$

Observe that, when the angular velocity of the reference system ω is equal to half the velocity component in the tangent direction and condition (22a) is attained, the same optimal relationship between α and β as suggested by Mockmore and Merryfield. The main nozzle parameters are the following: the nozzle initial height S_0, its width B and the shape of the wall between its tip and the initial rectangular section with height S_0 (see Figure 3-7). [1b]

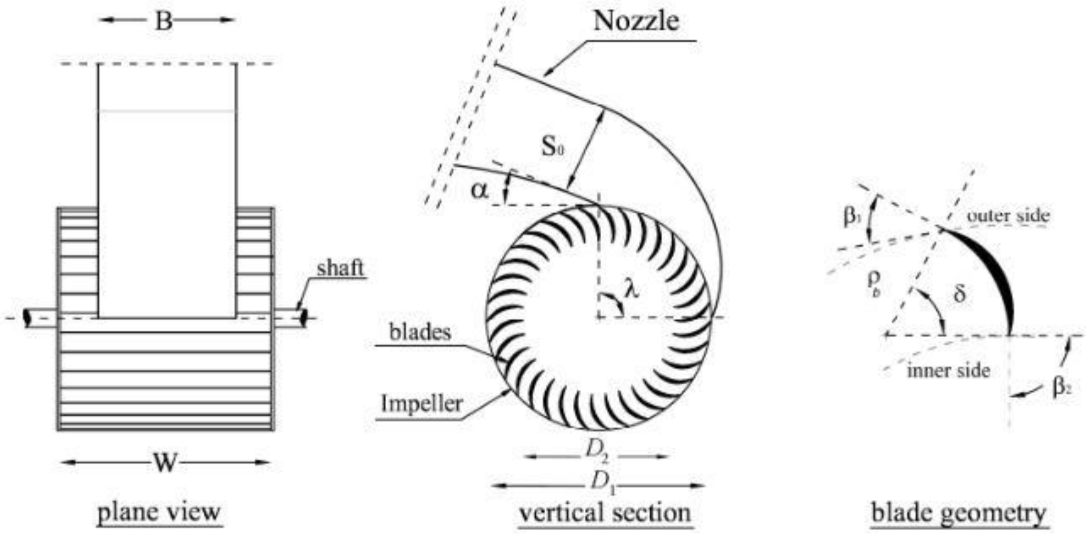

Figure 3-7: Geometricla parameters of a Cross-flow turbine *(Source [1b])*

The height S_0 is a function of the specific water discharge q (per unit width), and this can be directly calculated according to the continuity equation applied at the inlet of the impeller: [1b]

$$q = V * sin(\alpha) * \lambda * \frac{D_1}{2} \tag{26}$$

Mass conservation requires (see Figure 3-7):

$$\begin{cases} S_0 = \dfrac{q}{V} \\ B = \dfrac{Q}{q} \end{cases} \tag{27}$$

The lower (plane) wall of the initial nozzle forms an angle α with the tangent direction in the initial point of the impeller inlet arc. The same angle α is formed by the direction of the upper wall with the tangent direction at the tip of the nozzle. It is observed that the specific discharge *q* is proportional to *sin α* (26) and that the impeller width B is inversely proportional to *q* (27). The choice of the angle *α* and the outer diameter D_1 stems mainly from a balance between the search of a low angle *α* (and a high hydraulic efficiency according to (23) and the need to limit the width B of the nozzle resulting from Equation (27), because the blade length W (W > B) strongly affects the mechanical stress inside the same blades. Moreover, by reducing the angle *α*, the ratio between the free inlet surface of the impeller and the total inlet surface of the same impeller drops due to the enhanced effect of the blade thickness. The shape of the upper wall has been defined by adopting a linear relationship between the radius of curvature *r* and the angle *Θ*, that is the angle between the radial and the horizontal directions, as shown in Figure 3a. The linear variation of the upper wall of the nozzle is aimed to get an approximately constant angle *α* along the impeller inlet. The reason is that, assuming a constant angle *α* and a constant velocity norm *V* (that is to say neglecting energy dissipation) with such an upper wall profile, mass continuity is globally satisfied in each partial volume where the entering flux surface is proportional to the remaining arc length (see Figure 3b). In each partial volume depicted in Figure 3b, neglecting the transition zone between the no-slip velocity at the upper wall and the fully developed internal velocity, the entering and the leaving fluxes (q_e and q_l respectively) are equal to: [1b]

$$q_e = V * S_0 * \frac{\theta}{\lambda} \tag{28a}$$

$$q_l = q_e = (V * \sin(\alpha)) * \frac{D_1}{2} * \theta = V_r * \frac{D_1}{2} * \theta \tag{28b}$$

where V_r · is the radial velocity. According to this hypothesis the upper wall radius *r*(*Θ*) is equal to:

$$r(\theta) = K * \theta + \frac{D_1}{2} \tag{29}$$

where K is a constant. The radius r at the nozzle initial height S_o can be calculated as: [1b]

$$r_{(\lambda-\gamma)} = \frac{S_0 * \cos(\alpha) + \frac{D_1}{2}}{\cos(\gamma)} \tag{30}$$

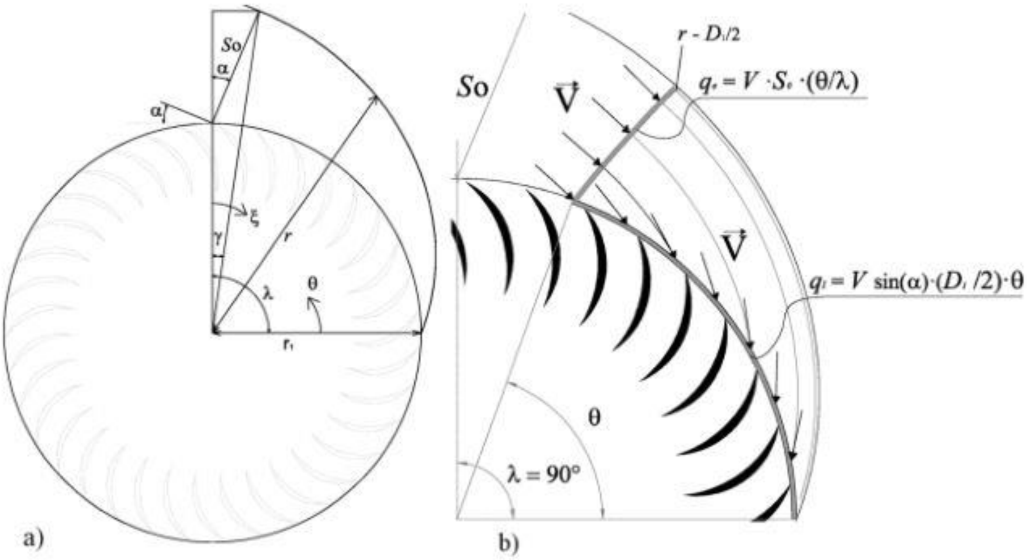

Figure 3-8: Nozzle upper wall shape: (a) geometric scheme; (b) entering and leaving water *(Source [1b])*

where

$$\gamma = \arctan\left(\frac{S_0 * sin(\alpha)}{S_0 * cos(\alpha) + \frac{D1}{2}}\right) \tag{31}$$

Equations (30) and (31) make it possible to calculate the constant K in Equation (29), as:

$$K = \frac{1}{\lambda - \gamma}\left[\frac{S_0 * cos(\alpha) + \frac{D_1}{2}}{cos(\gamma)} - \frac{D_1}{2}\right] \tag{32}$$

The hypothesis of a homogeneous attack angle along the impeller inlet will be further validated with reference to a specific case. [1b]

3.2.2 *Second Step: Impeller Parameters Optimization*

The variation in the diameter ratio D_2/D_1 affects the efficiency of the cross-flow turbine: an increment of the diameter ratio leads to a reduction in the blade radius, a reduction of the blade surfaces and a shorter distance for energy transfers. In order to select the optimal internal diameter D_2, a sensitivity analysis on the diameter ratio can be carried out by using a fluid dynamic investigation. As will be shown in the methodology testing, the sensitivity analysis often leads to a diameter ratio very close to the 0.68 literature value. [1b]

After the diameter ratio has been chosen, the geometry of the inner blade surface can easily be calculated. For simplicity, this surface is designed as part of a cylinder, whose axis is located at the intersection of the two directions orthogonal to the relative velocities at the inlet and at the outlet, as shown in Figure 3-9. The exit angle β_2 is set equal to 90° and the blade radius ρ_b computed as follows: [1b]

$$\rho_b = \frac{D_1}{4} * \left[1 - \left(\frac{D_2}{D_1}\right)^2\right] * cos(\beta_1)^{-1} \tag{33}$$

Using the trigonometry functions the δ can be calculated as follows:

$$c = \sqrt{\rho_b{}^2 + \left(\frac{D_1}{2}\right)^2 - 2 * \rho_b * \frac{D_1}{2} * \cos(\beta_1)} \tag{34}$$

When the c is implemented into formula below we get:

$$\delta = arccos\left(\frac{\frac{D_1}{2} - \rho_b - c^2}{-2 * \rho_b * c}\right) - \arcsin\left(\frac{\frac{D_2}{2}}{c}\right) \tag{35}$$

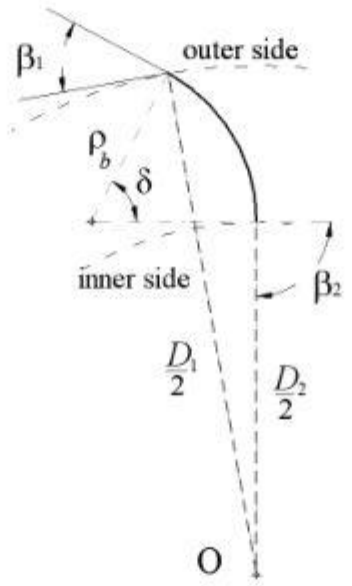

Figure 3-9: Blade geometry *(Source [1b])*

Other impeller parameters are the inlet angle, the shaft diameter, the number of blades and their thickness as function of the radius *r*. All these parameters must be selected according to a numerical fluid and structural dynamic investigation. In order to obtain an impeller with the maximum efficiency. The literature used in the paper suggests a ratio between the impeller width and the nozzle W/B=1.5, but the followed numerical computation shows that the ratio W/B=1 is much more efficient. For more detailed information on the calculation and complete numerical calculation see [1b].

3.3 Laboratory testing

The experiment was set to simulate the hydraulic system from the intake to the outlet from the turbine. The Intake and the turbine were connected with a pipeline (see Figure 3-10) which would be placed in a way that the system is pressurized, meaning that the pipe is fully submerged under the water level in the Intake pool, creating Head and therefore filled with water not allowing any air to be present. After constructing the hydraulic system the measurements would be taken to confirm the Theoretically calculated predictions of efficiency and power production.

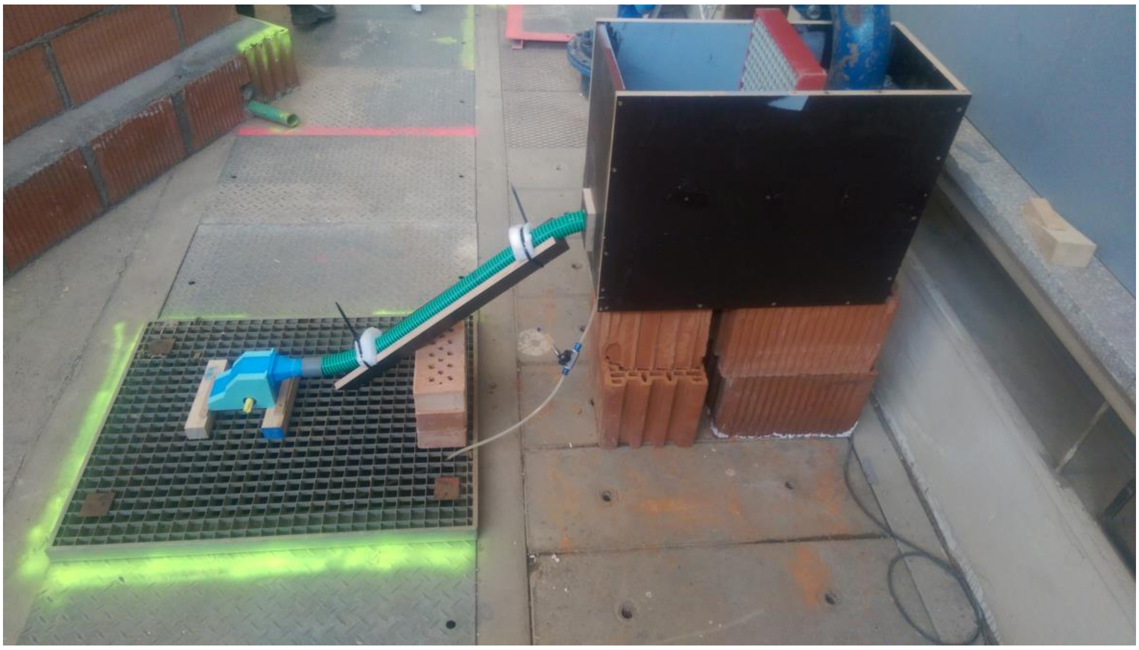

Figure 3-10: Intake pool on the right side and the 3D printed turbine on the left side connected with the pipeline

3.3.1 Precalculations and design

Considering the real system finding itself in the natural environment the first conditions are determent by the surroundings. The natural resources decide how much head and flow can be used for hydropower. This conditions give us the amount of total power that is available and out of that we can estimate using simple formula (9) and how much power we can produce with our system. Only when this conditions are known we can proceed with the designing and choosing parts that would be most efficient in the given case.

As it was the case in the laboratory, we could simulate any conditions possible so the question set for the experiment was. How large does the turbine have to be to power a simple dynamo used primary on bicycles, and if the technology of 3D printing is already suited enough to construct a working prototype as well as the real working turbine later on. The second question posed was if the 3D printed prototype could satisfy the proposed theoretical efficiency of approximately 80%.

Understanding that some simple parameters were set to provide guidelines on the design of the turbine and the hydraulic system. Starting with the electric power generation the research was carried out on the bicycle dynamos. As this products are intended for a wide commercial use the manufacturers do not provide the exact testing results of how much mechanical work has to be invested for corresponded electric power production. Researching the internet two sites [4c], [5c] were found which provided some rough information on the speed and power needed for the electric production see Figure 3-11 and 3-12.

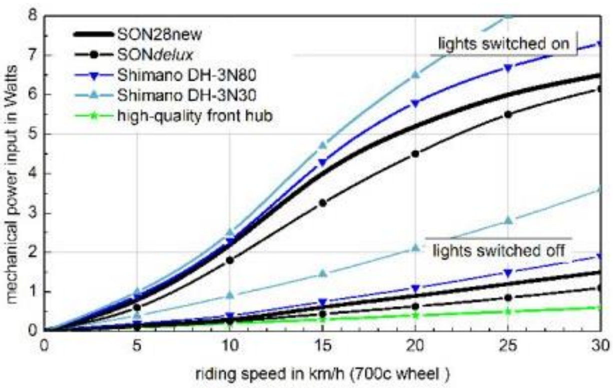

Figure 3-12: Diagram of HUB dynamo drag for specific power input and speed *(Source; [4c])*

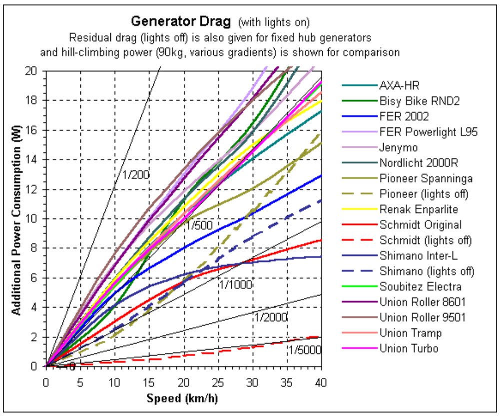

Figure 3-11: Diagram of BULB dynamo drag for specific power input and speed *(Source; [5c])*

Based on this diagrams it was decided that the Power of the turbine should be at least 14 W provided that a 1:1 coupling between the turbine and dynamo is being used. As to determine the speed an estimated speed of 350 RPM was set for the calculation.

Using the two-step calculation process explained in the chapter (3.2) an excel table was written for the purpose of calculating the turbine design parameters. The same excel table sheet was used for the hydrodynamic calculations of the pipeline system feeding the turbine. The set parameter was to use a 40mm plastic hose. After implementing the initial data (Table 4) in the excel table sheet it was an easy task to change the flow and head conditions in order to satisfy the power required for the generator.

Table 4: Input data

Attack angle α [°]	Rotational speed ω [RPM]	Pipe Diameter D_p [mm]	Power turbine P_t [W]
22	350	40	14

The only parameter that was changing was the Head according to the calculation formulas in the chapter (3.1) the velocity and the flow were automatically calculated using excel (Table 5).

Table 5: Result of Hydrodynamic calculation for the system before the turbine

Head [m]	Flow Q [l/s]	Velocity [m/s]
0.66	3.69	2.98

After obtaining the flow and head conditions the corresponding design parameters of the turbine were calculated automatically with excel. Results are provided in the Table 6.

Table 6: Design parameters for the turbine construction

Parameter	Value	Description
D_1 [mm] =	75.391	Outer diameter of impeller
D_2 [mm] =	51.266	Inner diameter of impeller
β_1 [°]=	38.9	Tangential angle between the impeller and blade
S_0 [mm]=	22.18	Nozzle initial height
B [mm] =	55.80	Nozzle width
W [mm] =	55.80	Impeller width

K [-]=	14.8	Constant for nozzle radius calculation
ρ [mm] =	13.027	Blade radius
δ [°] =	61,5	Blade central angle
N_b =	35	Number of blades
λ [°] =	90	Inlet discharge angle
β_2[°]=	90	Angle between the blade and inner impeller diameter

Note that the calculation progress in the chapter (3.2) proposes to carry out a numerical investigation of the parameter in order for optimization. In this case the numerical investigation was not performed, only the numerical investigation of the example provided in the paper was studied and the conclusions were implemented in to the design.

Following the calculations was the designing of the turbine in Auto CAD 3D program according to the results obtained. The drown segments of the turbine were drawn in 2D format (Figure 3-13) and then extracted into printing format and set to be processed by the 3D printer.

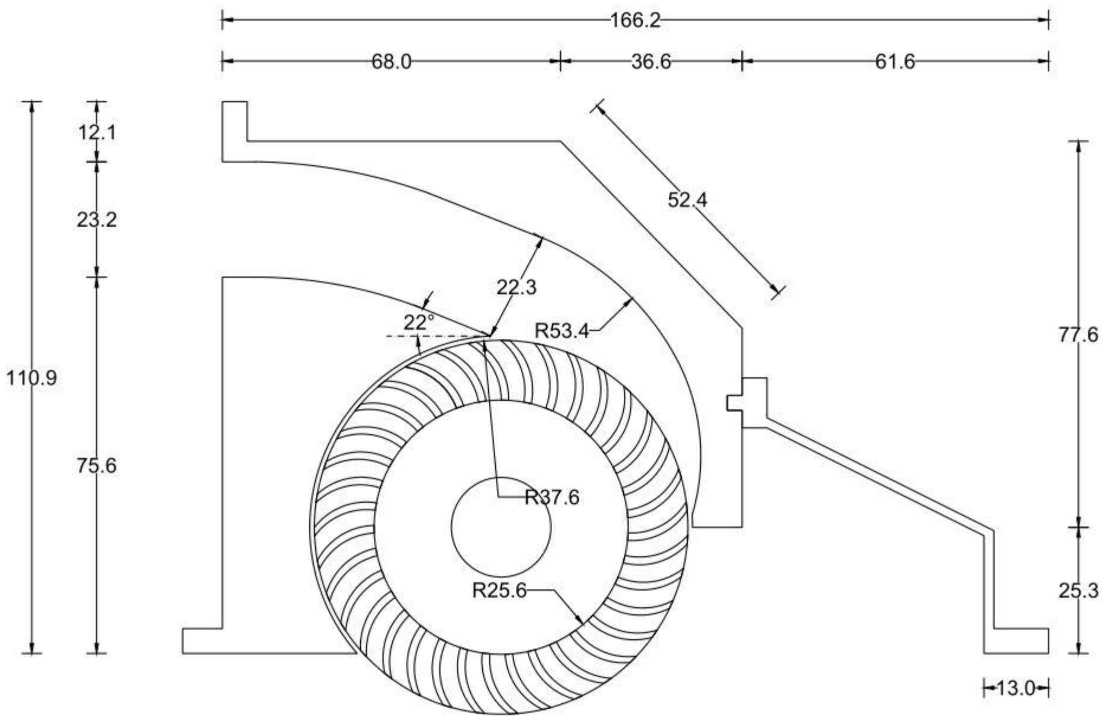

Figure 3-13: Design of the cross-section of the turbine according to the calculated parameters

First a cross-section was drawn according to the previously calculated parameters as seen in the Figure 3-13. The thickness and the housing was constructed after carefully inspecting the material properties and the already existing designs.

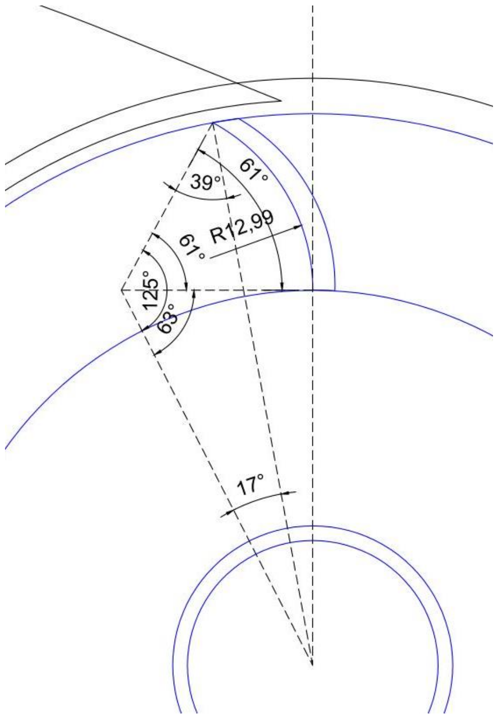

Figure 3-14: Design of the blades

Figure 3-14 is showing the designed blade for the turbine as seen in the chapter (3.2.1 Figure 3-9) one blade was designed and later multiplied 35 times to get the full circle of the runner as seen in the Figure 3-13.

After the cross-section the 3D model was extracted (Figure 3-15). While designing the investigation on the roller bearings had to be concluded. The specifications were later applied so that they would fit in the housing of the turbine. For the project the SKF bearings were chosen. They provided enough water resistance while not increasing the friction drag. This way more power can be transferred to the generator and not lost on friction.

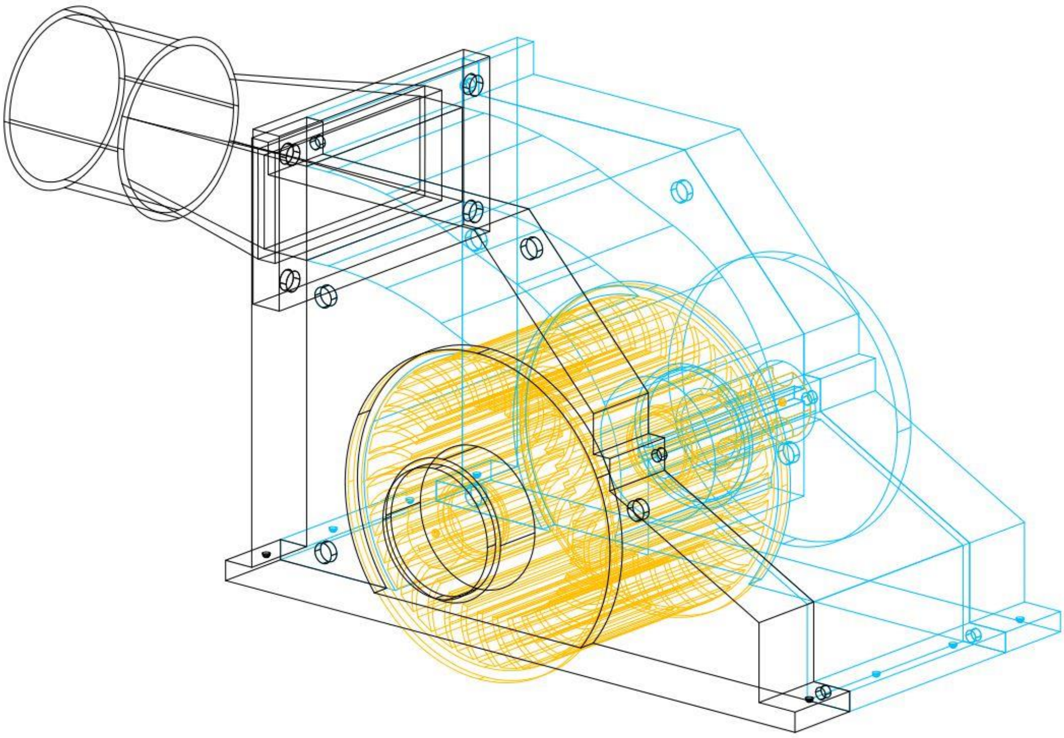

Figure 3-15: Turbine 3D design in Auto CAD 3D

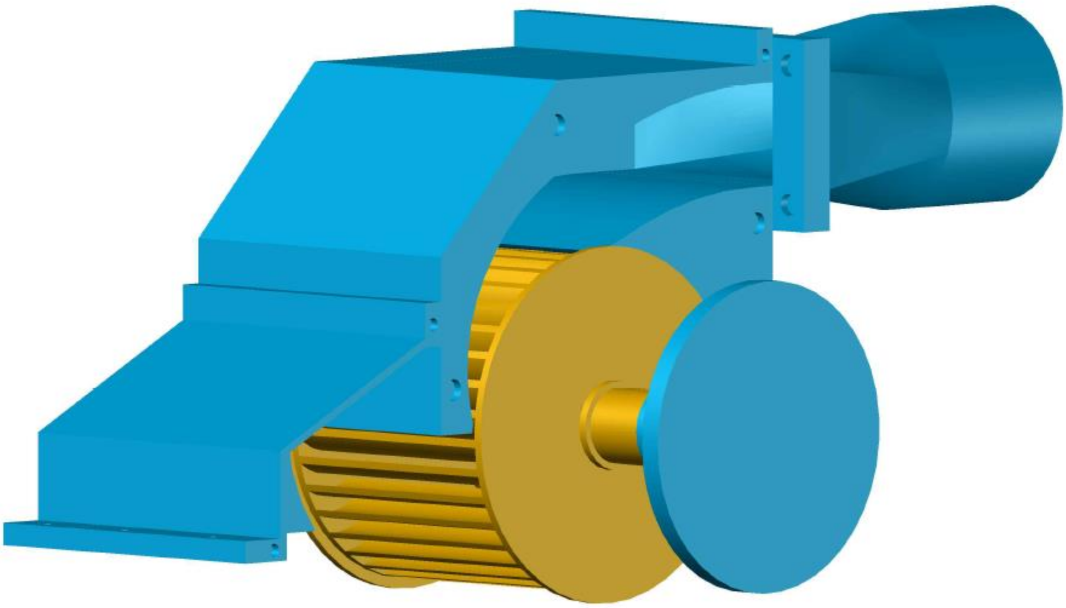

Figure 3-16: Turbine 3D design without right housing plate

3D Printing

A company in Slovenia, which is specialized in 3D printers, provided its knowhow and experience for choosing the right materials for the finished product. As there is a vast variety of optional printing materials such as metal, nylon, carbon fiber, and different plastic materials, it was decided to use the ABS (data sheet in appendix) plastic with 25 % infill in order to satisfy the water pressure conditions in the turbine, waterproofing while kipping the costs low.

The model was printed with the SheePAM 3D printer Figure 3-17. The printer uses the FDM (Fused Deposition Modeling) technique and has the possibility to print 390x180x200 mm models with the accuracy of 0.05 mm in the X- and Y-axis as 0.025mm in the Z-axis. It uses one nozzle head, which moves in the X- and Y-axis, as the base is moving in the Z-axis. The nozzle heats up the filament up to 290°C and can print with the maximum speed of 175 mm/s. The speed is dependent on the complexity of the model. The parts were printed in

Figure 3-17: SheePEM CNC and 3D printing machine, capable of Printing 3D models as engraving and milling (Source; [6c])

layers of 150 µm. [6c] In order to print The model had to be divided in parts so that the rotating bearings could be installed later on. The turbine was divided in 8 different parts (Figure 3-18) and later put together in the laboratory.

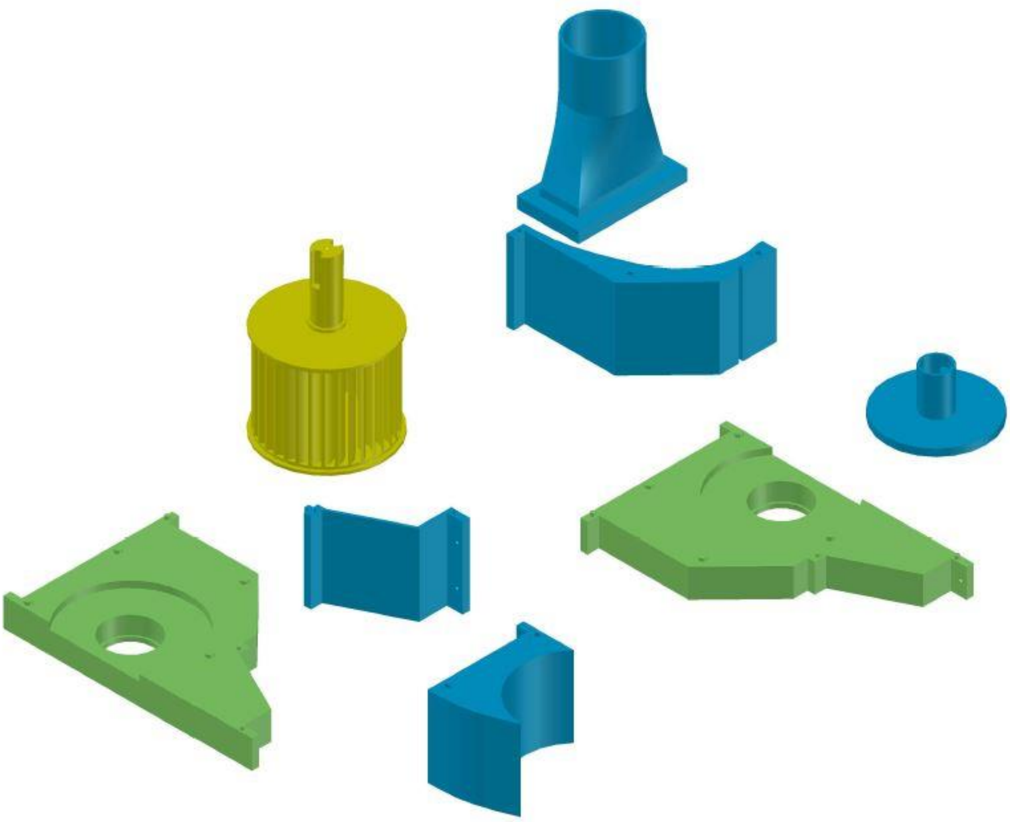

Figure 3-18: Turbine design divided in 8 parts for 3D printing preparation

The issue with the two axial moving head is that the circle shapes are hard to construct so an amount of post printing work is required. Also another problem with such printers is that they have to print additional supports as it was the case while printing the impeller (see Figure 3-19). The supporting structure has to be removed when the print is completed. Some other printers oppose such problems with rotating axis movements or dragging the model out of the pool of melted material, but these printers are still in the development phase and not available on the commer-

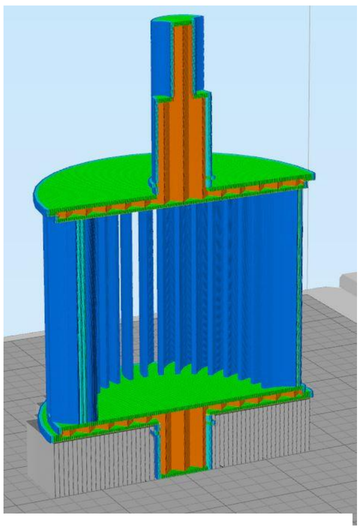

Figure 3-19: 3D printing preview with supports on the bottom in grey

cial market. The 3D technology is still in uprising but it has proven itself as a fast and light way to produce parts so it can be used for production of new, as for replacing the used or worn of parts in the turbine.

The other issue with the 3D printer is printing moving parts. In this case the problem were with the moving bearings of the impeller. Although they can be printed, there is the issue that they are not very useful as they produce a lot of drag while rotating. Therefor the conventional stainless steel rotating bearings were used in the model. The printing of supporting structures and the need of removing them as the low quality of printed bearings are the reasons why the model had to be printed in separate parts and not as one unit. The finished result is shown in the Figure 3-20.

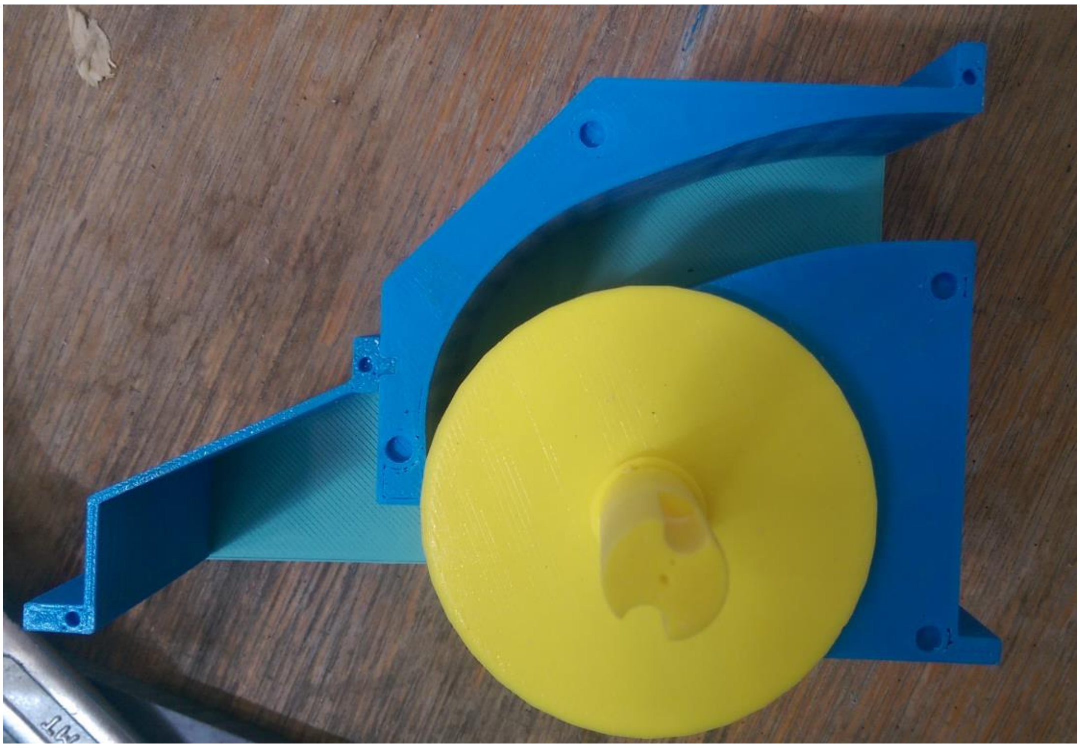

Figure 3-20: Printed 3D model of the Pico turbine

3.3.2 Laboratory works

First the Intake and the water supply had to be constructed. The intake pool was made from wood and placed on building bricks to insure the head for the turbine. The water supply line was fitted with the discharge measuring valve so that the inflow could be regulated. Between the inflow and outflow of the intake pool a screen was placed in order to come down the water horizon and ensure the level water surface.

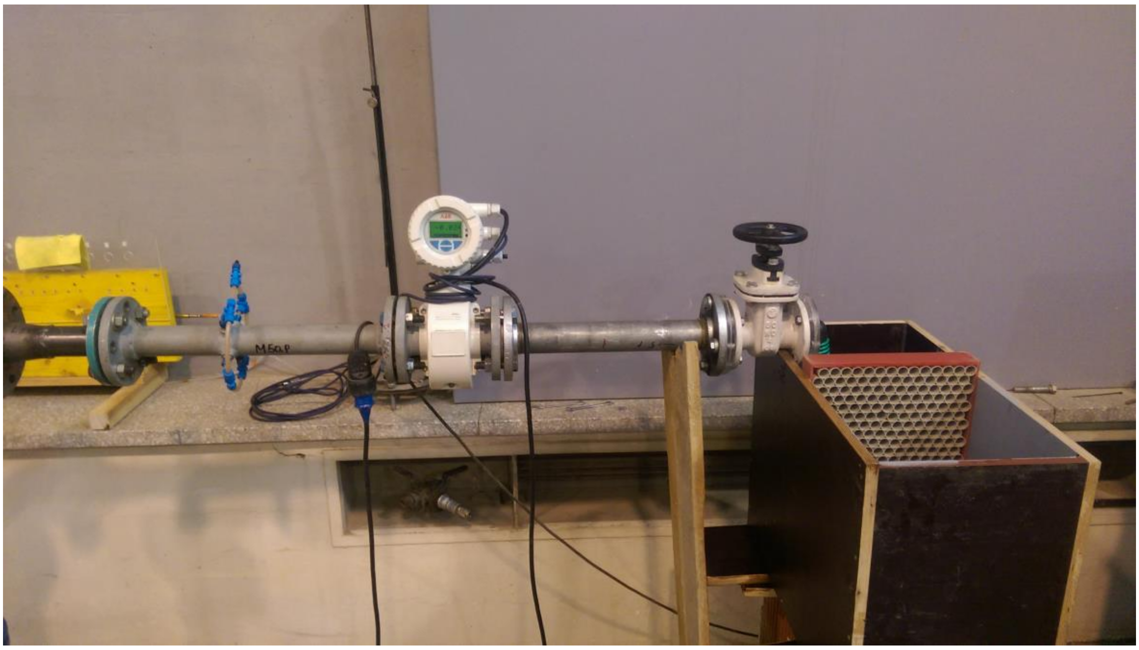

Figure 3-21: Inflow pipeline with discharge measuring equipment and turbine intake pool

The outflow of the intake pool was fitted with a 40mm diameter PVC hose. The hose was connecting the intake pool and the Turbine. It was also supported with building bricks so that it could not move while the water was flowing through. In addition the pipeline had to be straight so that there would not come to additional losses due to the curve in the pipeline. The pipeline between the intake and the Turbine was 82 cm long.

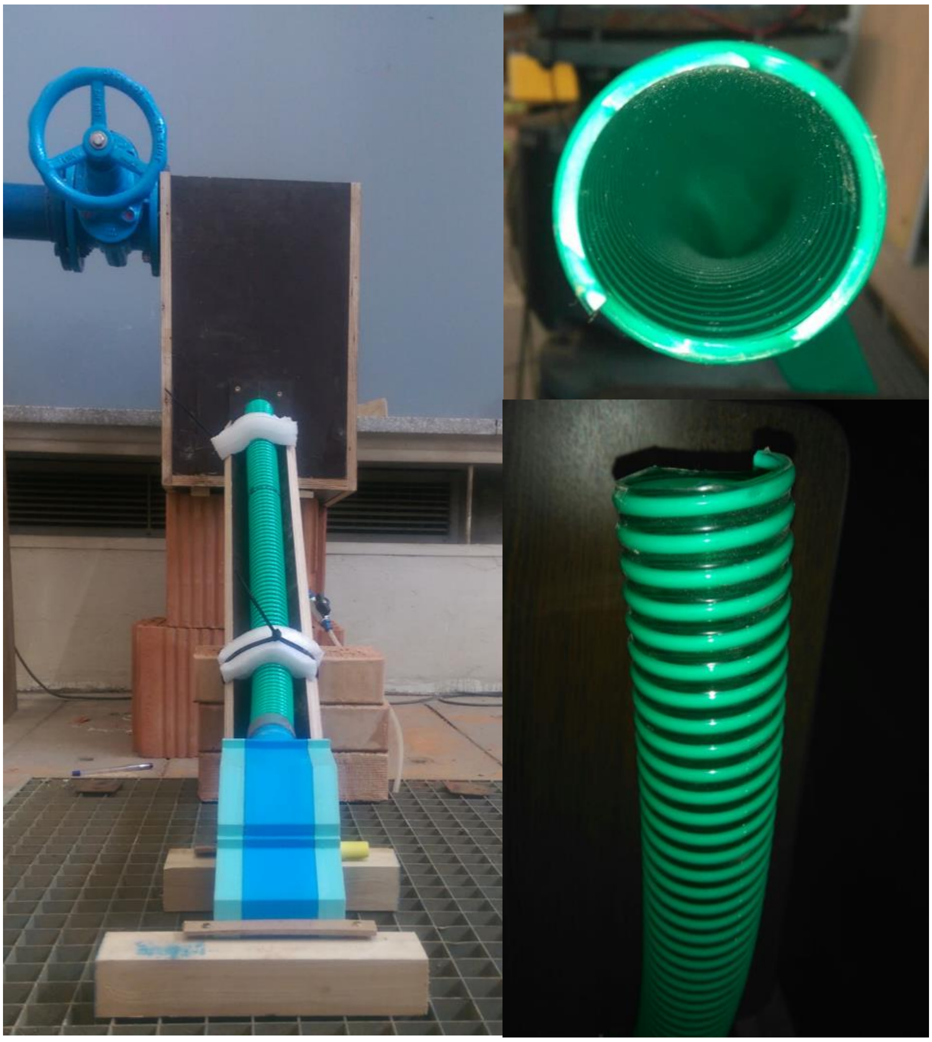

Figure 3-22: Pipeline connecting the intake with the turbine (left); Pipeline PVC cross-section and layout (right)

The printed parts of the turbine were then assembled. Some processing work had to be done to fit the roller bearings into the sides of the turbine housing Figure 3-23 is showing the printed parts before the assembly. The model was designed to be easy assembled in a specific order. First the roller bearings were inserted into the sides. Later the runner is placed into the one of the bearings. After the runner is in place the water guides and housing that prevents splashing of the water is mounted on the side containing the runner. The last piece of the assembly is the placement of the other side of the housing. The process and finished product are shown in Figure 3-24 to 3-26.

Figure 3-23: Turbine before the assembly; left and right sides of the housing in green, runner yellow and guide wanes in blue

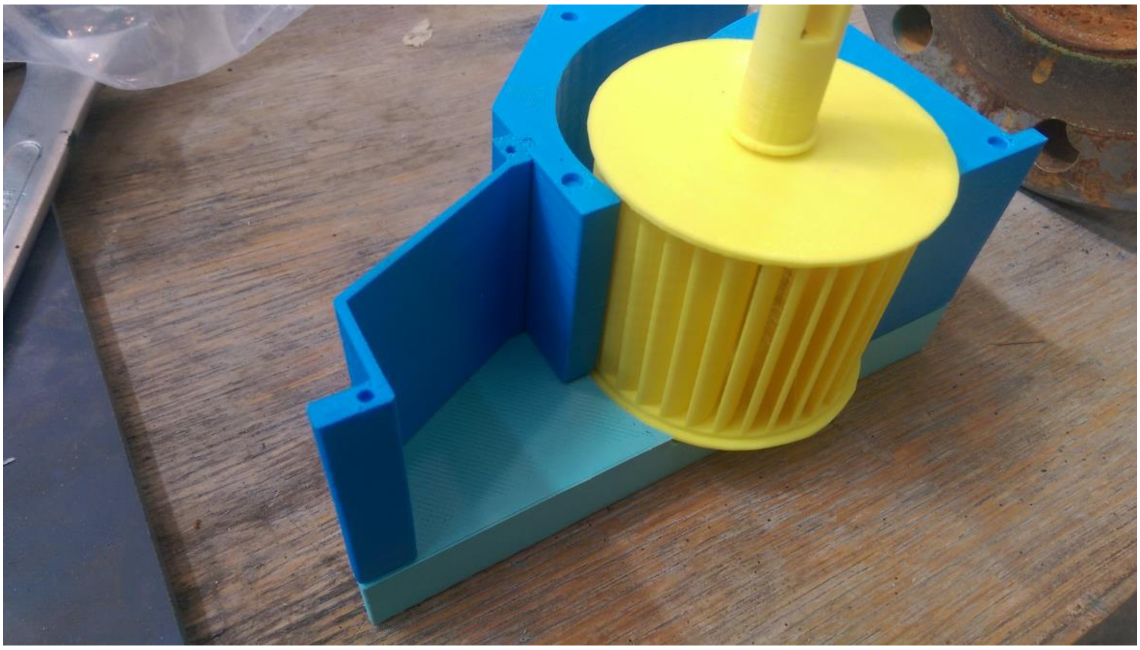

Figure 3-24: Assembly process; turbine without the left housing component

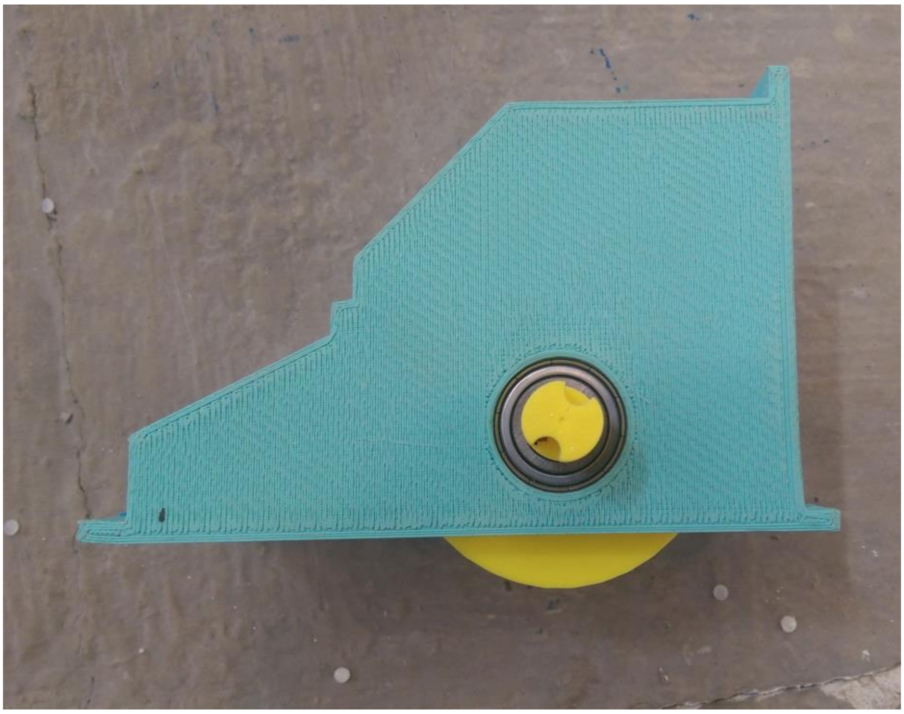

Figure 3-25: Side view of the assembled turbine, complete with metal roller bearings

Figure 3-26: Bottom view of the assembled turbine

The second task was mounting the turbine. It was mounted on 4 bolts so that the height adjustments and leveling were possible (see Figure 3-27). The turbine outlet was left so the water dropped straight down as it exited the turbine.

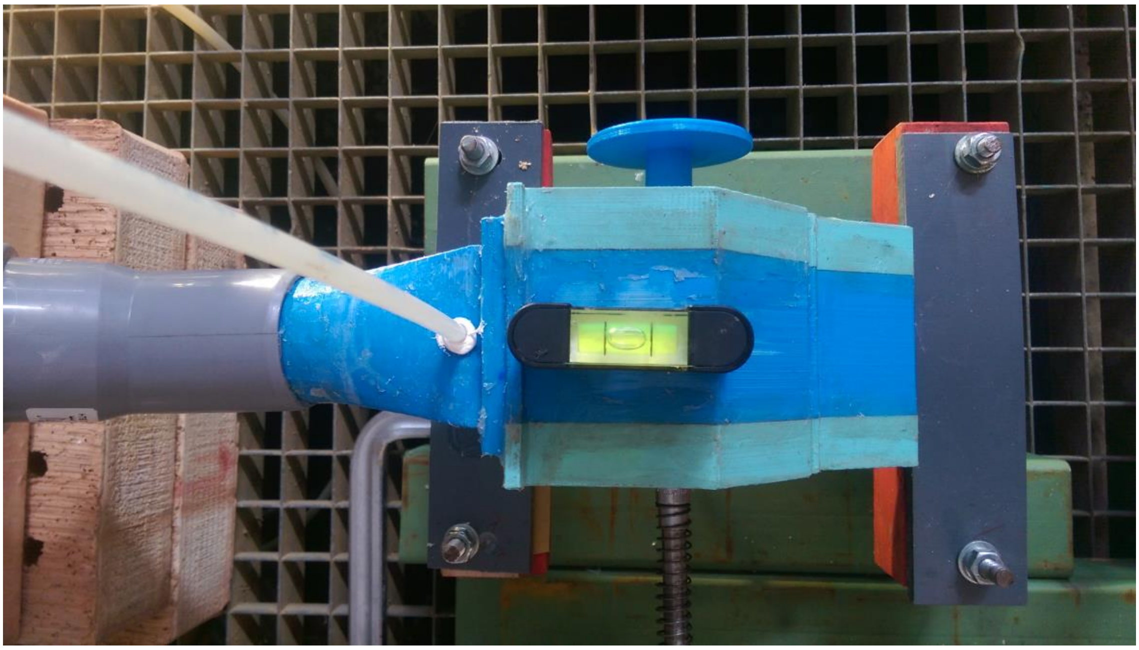

Figure 3-27: Mounted turbine on 4 bolts, the water gage showing that it is leveled. White tube on the top of the intake for the purpose of net head observation

Additionally a tube was mounted straight before the intake of the turbine so that the net head could be observed. This was mounted due to the lack of parameters concerning the PVC pipeline. The missing parameter was the roughens coefficient so the exact hydraulic loses of the pipeline was not possible to calculate. The tube can bee seen in the Figure 3-27.

3.3.3 Measuring and interpretation of results

The goal of the measuring was to determine how much power can the turbine produce in different conditions. The conditions were set through the opening of the valve on the inflow pipeline. The inflow pipeline was implemented with a ABB water flow measuring gage (Figure 3-28) and the water flow was set. As

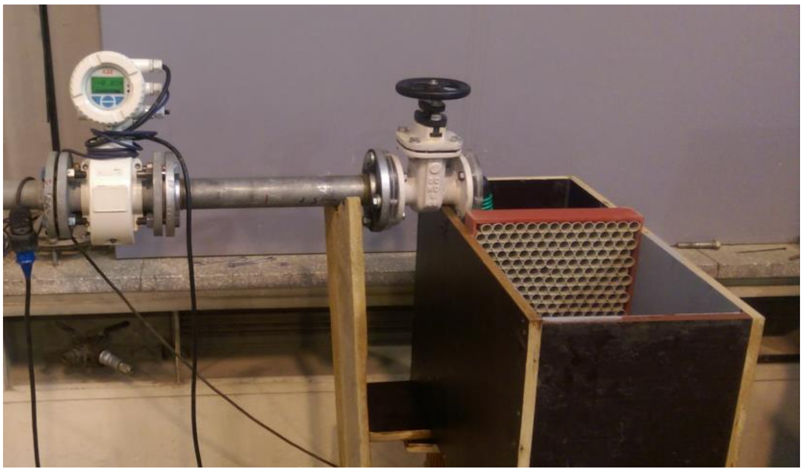

Figure 3-28: Inflow pipeline with integrated flow measuring gage from ABB

the turbine itself has no regulators and there were no valves in the pipeline between the intake and the turbine the law of stationary flow was in affect. Meaning that the amount of water flowing in the intake pool on one end, is the same to the amount of the water flowing out of the turbine on the other, while the water level in the intake pool stays stabile. The head was measured with a leveler and a measuring rod connected to the automatic handle (Figure 3-29), which uses electric impulses to detect when the rod is in contact with the water. This automatic handle ensures that the tip of the road stays on the water horizon at all times.

Figure 3-29: Measuring rod connected to the automatic handle for measuring the head

The difference in elevation of the water level and the turbine was measured with the leveler. The calculated difference was the gross head of the system.

For the measuring of power the Prony brake was constructed. The Prony brake caries its name after its inventor Gaspard de Prony and is used to measure the torque of a rotating shaft connected to the engine or in this case hydro turbine. This is the absorption type measuring equipment. The design of the Prony brake is very simple (see Figure 3-30). [7c]

Figure 3-30: Prony brake mounted on the rotating shaft of the turbine runner

The Prony brake consists of a lever that is clamped on the rotating shaft of the turbine using screws or bolts. The friction force between the lever and the shaft is then transferred through the lever on the other side where a weight scale is placed. The tighter the screws are the higher is the friction force. The affect that the higher friction has is that the shaft will turn slower but the transmitted force will be bigger. As if the screws were to be loosened the friction force would drop, meaning the drop in the transferred force on the weight scale but a rise in the rotations per minute. For calculating the torque we need two measured parameters. The weight scale gives us the transmitted force in Newton and the length of the liver gives us the distance of the force from the shaft. Multiplying these two parameters give us the torque in Newton meters (Nm). [7c]

There is a simple equation for calculating the power from torque. Torque is the amount of work that the turbine produces and the power is how fast can this work be produced. meaning if the turbine is capable to lift a 100 gram heavy weight (torque) is the power how fast can the turbine lift this weight. The formula for calculating torque into power is as follows:

$$P = \frac{2 * \pi * RPM}{60} * T \tag{36}$$

Where

P [W] → Power

RPM [-] → Revolution per minute

T [Nm] → Torque

For calculating the power speed is necessary. For measuring the speed a high-speed camera was used. The camera was placed by the turbine and the line on the shaft was drawn. The line was used to count the revolutions on the footage that the camera had taken (see Figure 3-32).

Figure 3-31: High-speed camera measuring the RPM of the turbine shaft.

The footage was taken in the speed of 3000 frames per second so that a detailed observation of the shaft revolutions could be made. The process was to take the time of how long does it take for the turbine to make one complete revolution and than multiply this figure to get the result of how many times does it turn in one minute.

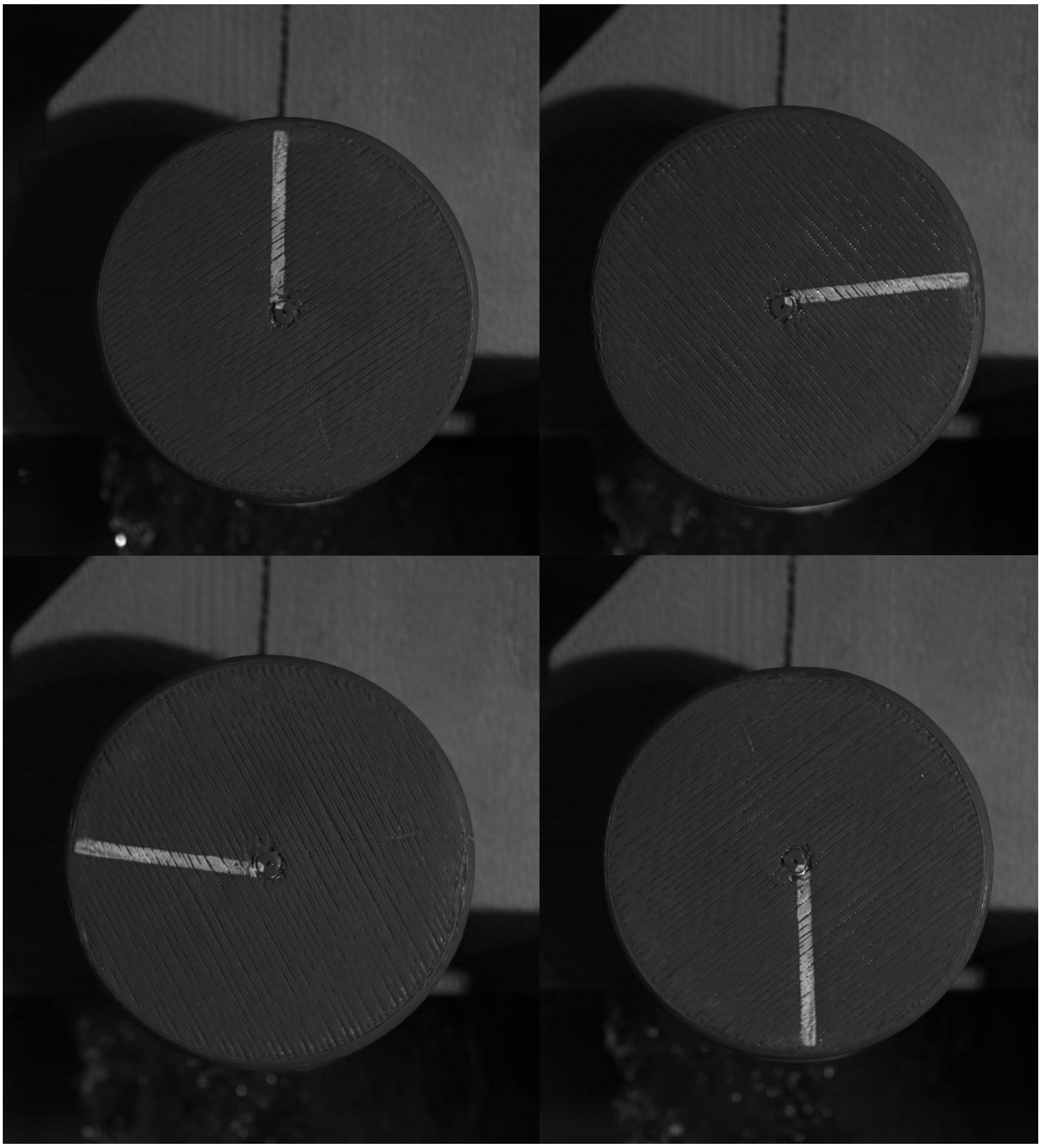

Figure 3-32: one revolution on the high-speed footage in 4 frames. Direction of the rotation can be seen by the white line: 1 upper left; 2 down left; 3 down right; 4 upper right

3.3.3.1 Measuring procedure

The measuring goal was to determine the efficiency of the turbine, which is the parameter of how much water power is being transferred into the rotational power to turn the generator. For the measuring process a discharge was set on the water flow gage. After 10 minutes the water level stabilized and the measuring of other parameters could be done. The other parameters that were measured were the gross head, net head, the rotational speed or RPM and the weight on the scale from the Prony brake was taken.

Figure 3-33: Measuring process of the turbine efficiency

For the set discharge of the 2.3 l/s the following data was obtained:

Gross Head

Using the leveling gage the height difference between the turbine and the water surface in the intake pool was measured corresponding to the flow of 2.3 l/s the gross head was **0.51 meters.**

Net Head

The Net head was measured with the measuring tape on the turbine inlet. the measured height was **0.235 meters.**

Rotational speed RPM

Footage from the high-speed camera was rewind and the result for the one revolution was 0.172 seconds. Multiplied to a minute of time gave us the result of **348.8 RPM** or revolutions per minute

Torque

Taken weight on the scale was 30 grams. This weight was multiplied with the gravitational accelerating and the result was 0.2943 Newton of force. This force was taken on the lever distance of 40cm. Multiplying the Newton with the distance gave us the result of **0.1177 Nm** of Torque.

Power of the turbine

Using the formula listed above (36) the power was calculated out of RPM and torque. The resulting power of the turbine was **4.3 Watt.**

Gross and net Waterpower

Later the net and gross head were recalculated in the correspondence to the flow in order to get the amount of waterpower. The result for the gross power (total available power) was **11.51 Watt** and the net power (power available for the turbine) was **6.22 Watt**.

Efficiency

Last the efficiency was calculated by dividing the power of the turbine with the gross and net power separately to get the efficiency of the entire system and the efficiency of the turbine itself. The result was then multiplied with 100 to get percentage values.

Efficiency of the overall system = **37.37%**

Efficiency of the turbine = **69.13 %**

3.3.3.2 Interpretation of results

Following the procedure a variety of measurements were completed. The measurements were divided in two days. To ensure the constancy of data. The measured and calculated data is shown in the tables below:

Table 7: Data measured and calculated on the measurement NR 1

Measurement NR 1

PRM measurement	1	2	3	4	5
Start [s]	0.12	0.16	0.02	0.07	0.30
Finish [s]	0.34	0.34	0.13	0.51	0.68
Rotation [s]	0.21	0.17	0.12	0.44	0.38
RPs	4.67	5.81	8.55	2.25	2.64
RPM	**280.37**	**348.84**	**512.82**	**135.14**	**158.31**

Force measurement	1	2	3	4	5
Weight [kg]	0.027	0.030	0.011	0.068	0.048
Force [N]	0.26	0.29	0.11	0.67	0.47
Length lever [cm]	40.00	40.00	40.00	40.00	40.00
Torque [Nm]	**0.11**	**0.12**	**0.04**	**0.27**	**0.19**

Power Turbine	1	2	3	4	5
Power [W]	**3.11**	**4.30**	**2.32**	**3.78**	**3.12**

Gross water power	1	2	3	4	5
Gross head [m]	0.49	0.51	0.53	0.55	0.44
Discharge [l/s]	2.30	2.30	2.30	2.50	2.30
Gross power [W]	**11.06**	**11.51**	**12.00**	**13.49**	**9.93**

Net water power	1	2	3	4	5
Net head [m]	0.19	0.24	0.18	0.23	0.20
Discharge [m^3/s]	0.0027	0.0027	0.0024	0.0026	0.0025
Net power [W]	**4.52**	**6.22**	**4.17**	**5.83**	**4.88**

Efficiency	1	2	3	4	5
Gross efficiency [%]	**28.14**	**37.37**	**19.31**	**27.99**	**31.45**
Turbine efficiency [%]	**68.79**	**69.13**	**55.59**	**64.79**	**63.93**

On the first measuring day 5 measurement sequences were taken according to the process described in (3.3.3.1) the difference between the measuring sequences was the tightening and relaxing of the Prony brake. The effect of this is seen as the RPM and the torque measurements are different on every sequence. This would simulate de different loads on the generator as the generators resisting force of the magnetic field changes according to the loads that are connected to it. The end result shows that the efficiency of the Turbine stayed between 60 and 70 % through the different sequences of measurement.

Table 8: Measuring the efficiency of the turbine with two different Prony brake settings and different discharges per setting

Measurement NR 2

PRM measurement	1	2	3	4	5
Start [s]	0.080	0.106	0.003	0.056	0.093
Finish [s]	0.330	0.247	0.204	0.218	0.249
Rotation [s]	0.251	0.141	0.201	0.162	0.157
RPs	3.990	7.077	4.967	6.160	6.383
RPM	**239.39**	**424.63**	**298.01**	**369.59**	**382.99**

Force measurement	1	2	3	4	5
Weight [kg]	0.040	0.034	0.050	0.034	0.020
Force [N]	0,.92	0.334	0,.91	0.334	0.196
Length lever [cm]	40	40	40	40	40
Torque [Nm]	**0.157**	**0.133**	**0.196**	**0.133**	**0.078**

Power Turbine	1	2	3	4	5
Power [W]	**3.93**	**5.93**	**6.12**	**5.16**	**3.15**

Gross water power	1	2	3	4	5
Gross head [m]	0.493	0.645	0.65	0.513	0.505
Discharge [l/s]	2.3	2.6	2.6	2.3	2.3
Gross power [W]	**11.12**	**16.45**	**16.58**	**11.57**	**11.39**

Net water power	1	2	3	4	5
Net head [m]	0.22	0.29	0.29	0.22	0.19
Discharge [m³/s]	0.002611	0,002997	0,002997	0.002611	0.002426
Net power [W]	**5.63**	**8.53**	**8.53**	**5.63**	**4.52**

Efficiency	1	2	3	4	5
Gross efficiency [%]	**35.37**	**36.06**	**36.93**	**44.61**	**27.62**
Turbine efficiency [%]	**69.83**	**69.57**	**71.80**	**91.64**	**69.60**

The second measurement was to prove the consistency of the efficiency as the Prony brake setting is kept the same but the discharge is altered. Two sets of measurements were done. One for each Prony brake setting. The measuring sequence 1 and 2 were with one setting on the brake but the discharge in the sequence 1 was 2.6 l/s and in the sequence two the discharge was 2.6 l/s. The result was that as the flow raised up the head in the intake pool also raised. Due to more flow and head more power was available for production. As the measuring result shows the efficiency of the turbine stayed the same under the both conditions (round 70%). The measurement was then repeated with the second Prony brake setting. The measuring sequences 3 and 5 were pared as the sequence 4 gave a value of 90% efficiency and was discarded from the evaluation (red). The sequences 3 and 5 gave us the much similar result as the 1 and 2, which is an efficiency value of approximately 70 %. In addition the values from the measurement NR 1 and NR 2 gave us a very similar result. The goal of this measuring was to test the conditions when the load on the generator stays the same but the flow conditions in the system change as it is often the case in real hydropoewr systems.

Table 9: Measuring after changing the pipeline connecting the intake and the turbine

Measurement NR 3

PRM measurement	1	2	3	4	5
Start [s]	0.055	0.076	0.001	0.048	0.068
Finish [s]	0.225	0.210	0.145	0.207	0.286
Rotation [s]	0.170	0.135	0.145	0.159	0.218
RPs	5.89	7.43	6.91	6.29	4.58
RPM	**353.65**	**445.57**	**414.75**	**377.36**	**274.85**

Force measurement	1	2	3	4	5
Weight [kg]	0.031	0.033	0.035	0.032	0.03
Force [N]	0.30	0.32	0.34	0.31	0.29
Length lever [cm]	40	40	40	40	40
Torque [Nm]	**0.122**	**0.130**	**0.137**	**0.125**	**0.118**

Power Turbine	1	2	3	4	5
Power [W]	**4.50**	**6.04**	**5.96**	**4.96**	**3.39**

Gross water power	1	2	3	4	5
Gross head [m]	0.533	0.67	0.614	0.553	0.53
Discharge [l/s]	2.6	2.8	2.8	2.6	2.6
Gross power [W]	**13.59**	**18.40**	**16.86**	**14.10**	**13.52**

Net water power	1	2	3	4	5
Net head [m]	0.245	0.29	0.31	0.26	0.2
Discharge [m^3/s]	0.00276	0.00300	0.00310	0.00284	0.00249
Net power [W]	**6.62**	**8.53**	**9.42**	**7.24**	**4.88**

Efficiency	1	2	3	4	5
Gross efficiency [%]	**33.14**	**32.83**	**35.37**	**35.18**	**25.06**
Turbine efficiency [%]	**68.03**	**70.85**	**63.29**	**68.54**	**69.38**

The measurement NR 3 was in order to better the gross efficiency. For this measurement the pipeline was changed from the PVC hose to the PVC piping as found in water supply lines in households. The goal was to reduce the friction in the pipeline due to the smoother inner lining. Although the results showed that it did better the velocity of the water in the pipeline it did not have a major effect on the gross efficiency. As the results show the efficiency of the turbine did not change but the gross efficiency has even dropped a little from the other measurements (NR 1 and NR 2) performed with different piping. The conclusion being that the smoothness of the piping was not the issue rather the diameter was problematic. As the diameter is small, the friction surface is big in correlation to the amount of water flowing through the pipeline. Therefore, it is much wiser to choose a larger pipeline for bringing water from the intake to the turbine.

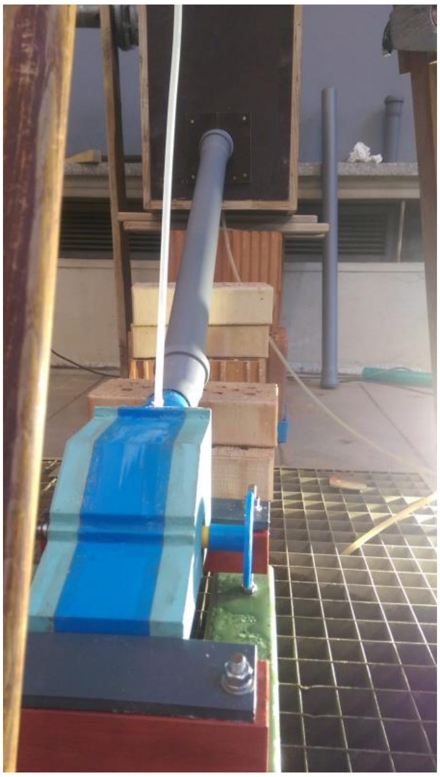

Figure 3-34: The PVC pipeline on the left and the PVC hose pipeline on the right

Conclusion

In conclusion, of testing the 3D turbine prototype is safe to say that it showed promising results as the efficiency of it was around 70% throughout the experiment. The literature suggests that the cross-flow turbines should have an efficiency of 80 %. As this was the one attempt it did prove that with some improvement it could also be 80% efficient. The model build for the testing has a lot of room for improvement. One aspect where it could get better is the waterproofing where this model was lacking in performance. Better waterproofing would stop the water to flow around the sides and more water would hit the runner dues improving the efficiency. The second improvement could be made in the guiding the water to how it hits the blades. This model had a fixed guide vane inclined with 22° of inclination so the water was hitting the blades from the same angle. When the conditions in flow change the moving guide vane could alter the hitting angle of the water and improve the overall efficiency of the turbine. The third aspect for lack in performance are the rotating bearings. They produce friction and as this model was small the friction had a major affect on the efficiency as the total power was only 13 Watts on average. If the turbine is bigger and the total amount of power is bigger the bearings of the runner have less influence on the total efficiency.

All in all the 3D printed turbine has shown a promising result in testing. With a lot of room for improvement it gave satisfying results and proved that the technology of 3D printing could be used in designing and producing of pico hydropower turbines in the future.

4 Water and energy economy overview

The world's energy demand is increasing rapidly year after year. According to the U.S. Energy information administration´s the energy consumption will increase for 48% between 2012 and 2040. See Figure 4-1. This growth is expected to have a very strong support in the fast developing countries situated in Asia including China and India. This increase will also have a dramatic increase on the emission of CO2 gasses, although the one of the fastest growing

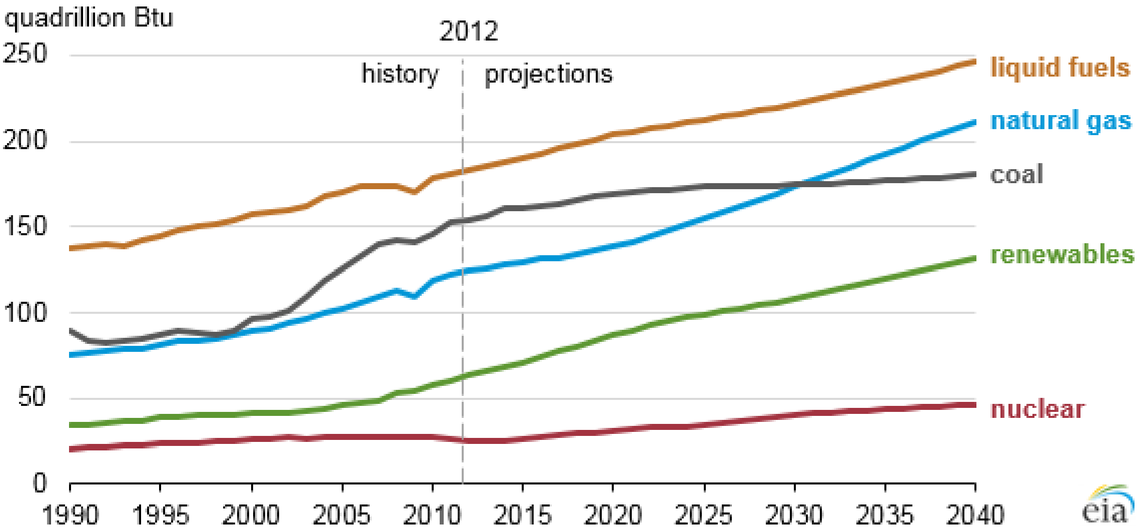

Figure 4-1: Prediction of the energy use and development by sector according to the eia *(Source;* ***Error! Reference source not found.****)*

energy sources according to the projections are the renewable energy source. They are foreseen to have a steady growth of 2.6% per year till 2040. **Error! Reference source not found.**

Also the European Union is well into its energy 2020 strategy project. This project has the goal for the EU participating countries to:

- Reduce CO2 emotions for 20%
- Increase the renewable energy source production to 20% of consumption
- Achieve the 20 % savings in energy
- Achieve a 10% share of the renewable energy in the Transport sector

The EU government is also founding a lot of projects that could help achieve this goals all over the participating countries. [9c]

Water power is one of the cleanest energy sources available. In addition, the efficiency of water power stations is very high compared to other renewable energy sources and is currently in the uprising. As the Hydropower world magazine announced in the article in (2009)

Several new conventional hydroelectric projects enter commercial operation… something not seen in several decades. Examples of new projects include: Sonna in Norway (270 MW), Glendoe in the United Kingdom (100 MW), and Blanca in Slovenia (42.5 MW). For small hydro (less than 10 MW), development opportunities are significant. Provided the mandate by EU member countries is implemented on a timely basis, the European Small Hydropower Association (ESHA) estimates that installed small hydro capacity could reach 16,000 MW by 2020 – a more than 4,000-MW increase over current levels. [10c]

Another area of significant growth for the hydropower sector in Europe, especially in the central region of the continent, is in pumped storage. In addition to supplying additional electricity during times when demand for power is highest, pumped storage’s ability to balance power production and regulate the transmission network, in light of increased use of intermittent renewables, particularly wind, is attractive. As many as ten pumped-storage facilities are under construction, including 178-MW Avce in Slovenia, 540-MW Kopswerk 2 in Austria, 480-MW Limberg 2 in Austria, and 141-MW Nestil in Switzerland. Several more potential projects are being investigated. Installed hydropower in Europe totals approximately 179,000 MW. European countries with the largest amounts of hydro include France, Italy, Norway, and Spain. Maintaining and, in many cases, upgrading, this existing infrastructure continues to be an important focus throughout Europe. [10c]

4.1 Energy economy of Pico Hydro systems

The main target of Pico hydropower is to provide electric power in remote or rural locations (Figure 4-2). There are 1 billion people that are living in rural locations and do not have access to electricity according to the International Energy Agency. These households are dispersed across the landscape or find themselves in rough, inhospitable and mountain terrain. Pico hydro power is a good solution for such sites as it can provide a steady, clean and efficient elec-

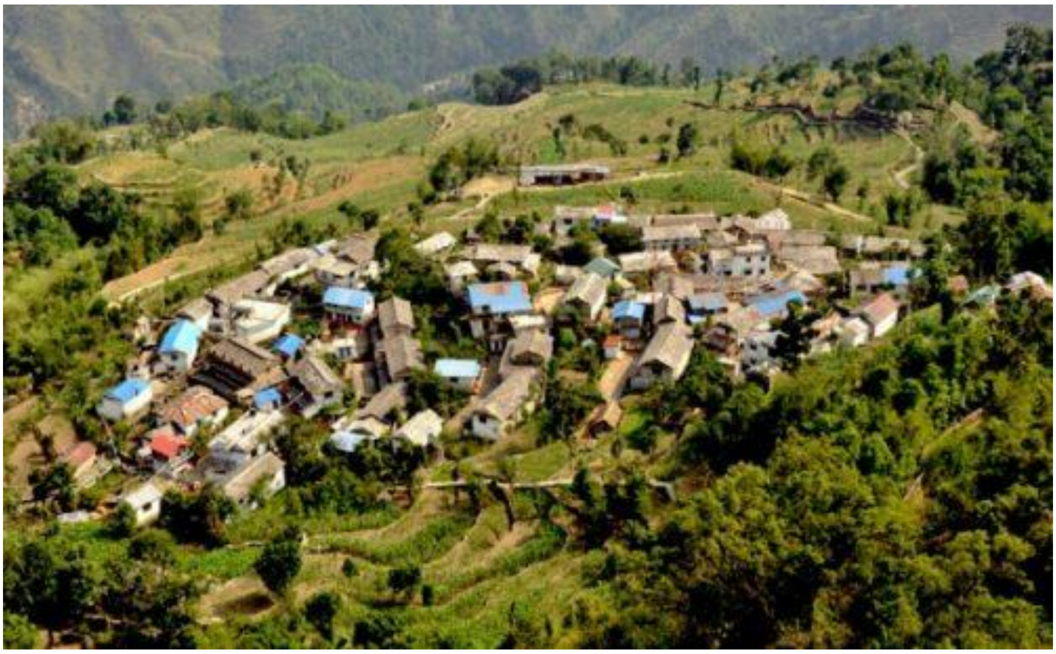

Figure 4-2: Example of a rural settlement in mountainous terrain of Nepal
(Source: https://www.nepalmountaintrekkers.com/sirubari-village-tour/, 2017)

tricity production at low cost, where the connection to the main utility grid would be very expensive, provided that a water stream is running nearby. The peak electrical Power output of 5 kW from a Pico hydro system can provide electricity for a single Household or a small community. It can satisfy the basic needs to power, Light bulbs, televisions, refrigerators, telecommunications etc. In addition also the remote medical facilities, base camps, telecommunication stations, and many other consumers are the potential users of the Pico hydro power. [11c]

One of the benefits of Pico hydro turbines is that they do not require a big amount of civil work to be done, as on the other hand with small hydro turbines the investment costs are much higher. In addition there can be more than one turbine units powering the remote community. With the ability to provide one village with several Pico turbines as compared to one small turbine unit is beneficial as we can ensure that the households still have sufficient power supply in case, if one Turbine brakes down. Also the grid costs are smaller when it does not have to have the capacity to drive large loads. [11c]

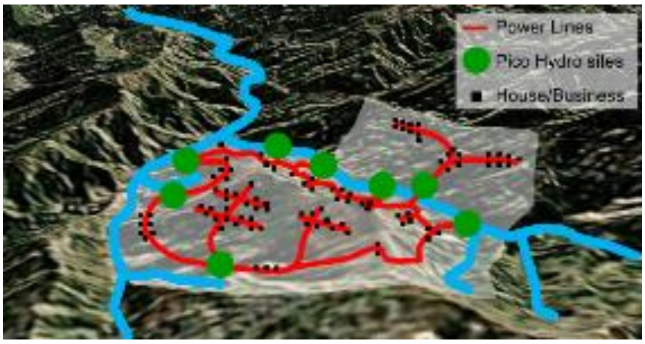

Figure 4-3: Pico-hydropower off-grid network concept, where each unit is exactly the same and the network expands as more units are purchased. *(Source;[11c])*

Other aspect of the Pico turbines benefits are the environmental issues. While constructing small Hydro power plants it has to be ensured that the needed head is provided for the high Power production. This demand requires a construction of a dam which disrupts the ecosystem and additional costs have to be taken into count to compensate for this. In the case of Pico systems, the constructed dams can be kept small so that the fish living in the stream are still able to wonder up and down the stream. This is an important fact because the wondering of the fish is crucial for their breeding and survival. In the case of rurally located communities the survival of the wild life in the water stream is of most importance as they are also depended on them as food source.[11c]

Figure 4-4: Barroco stream in Portugal (Source; *http://www.permaculturinginportugal.net/blog/tag/pico-hydro/, 2017)*

There is a number of studies done for implementing the Pico hydropower in rural environments from which you can find some listed in the literature [1d],[2b].

The other opportunities for of grid clean electricity production in remote areas are wind turbines and solar photovoltaics. The table 10 provides brief comparison of the three systems:

Table 10: categorization of renewable sources by source
(--bad; - unsatisfying; + satisfying; ++ good)

Power source	Efficiency	Operating cost	Investment cost	Daily production	Life span
Wind turbine	+	++	++	+	++
Solar PV	-	++	--	-	+
Hydro turbine	++	++	+	++	++

To conduct the exact cost comparison is almost impossible as they vary from the conditions on the site where they are installed. All of these systems are designed to fit the site where they will be operating to get the most of the surrounding conditions. Note that these systems are not in competition rather they should be used together to provide clean end environmental friendly electric power for remote areas.

Figure 4-5: Renewable energy sources from left to right (wind, water, solar)
(Source; http://enformable.com/2016/09/renewable-energy-viable-option-for-future-energy-needs/, 2016)

4.1.1 Advantages of Pico hydropower

- Low investment costs and simple design
- Long life span (over 25 years)
- Low operating costs
- Renewable energy source

4.1.2 Disadvantages of Pico hydropower

- Site must be provided with a water stream
- Water stream has to provide enough Flow
- Some additional construction must be built to provide the turbine with enough Head if not provided naturally
- Individual designed to site conditions (cannot be standardized)

Referring to the 3D printed Pico turbines a great benefit lies in the mobility of the production. As mentioned the Pico hydro turbines cannot be standardized. A design for a 3D turbine can be done on a portable computer and immediately printed out by a portable 3D printer. This makes the production of the turbines and other power station components possible anywhere in the world. Such mobility of production gives the 3D printed Pico systems a huge benefit over conventional fabrication methods, as they can provide good, fast and efficient solutions directly on site.

4.2 Application possibilities of 3D printed Pico Turbines

As discussed in previous subchapter the main application of the Pico hydro-power is to supply the electric power to remote locations where the utility grid is not connected. The primary targets for that are locations in the third world and undeveloped countries. On the other hand Pico 3D printed Pico turbines can also find their place in the modern world as in small and large communities. For example, there are according to some sources 33.000 weirs alone in Austria already constructed. Their use is primarily for flow regulations and flood control. With small modifications, such weirs could be fitted with Pico Turbines and produce electric power for the community Figure 4-6.

Figure 4-6: River bank reconstruction and weirs built for flood control in St. Getraud (Austria)

Another way to implement the Pico turbines is to power remote measuring equipment where solar or wind power cannot be used. For example the streams are fitted with measuring equipment to collect data of the changing water levels. This data is important for the flood control as it is used to approximate the flood wave conditions of a specific stream.

Figure 4-7: water level measuring station
(Source; http://www.quantum-hydrometrie.de/q_log_cam.htm, 2016)

Also the application of the Pico turbines in water supply lines could be beneficial. As the conditions in the water supply lines are known and steady the modules could be constructed so they would fit the dimensions and the conditions of the water lines. Power produced could be used to power the pumps that run the Water supply systems in the villages and cities. Such pipeline modules could also be used in other pipelines such as irrigation systems on the farmlands and snow blowers on the ski slopes.

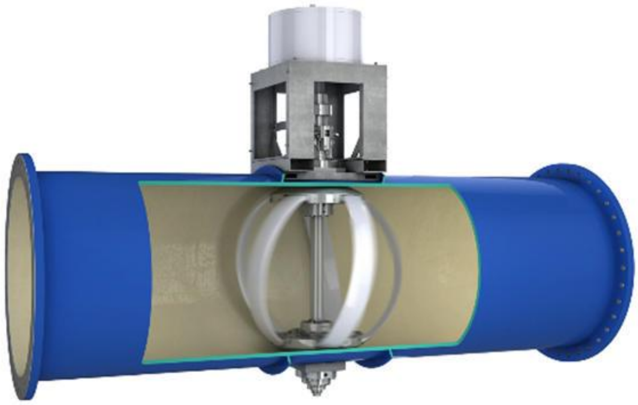

Figure 4-8: Concept for a turbine implemented in the water line piping
(Source; https://wearechange.org/portlands-new-pipes-harvest-power-drinking-water/, 2017)

The more commercial use of the Pico power plants would be in privet households or remote holiday villas. As mentioned in the theoretical overview (chapter 1) we could install a Pico hydropower system at our home to save on the electric costs. As this system would not be enough to power a complete modern household, it could be beneficial to ensure us a great amount on savings and make our household friendlier to the environment.

5 Summary

This master´s thesis is proposes the question if the 3D printing technology is viable to produce components for use in pico hydropower systems. The aim of the thesis is to test the capabilities of a real 3D printed prototype and compare it to till products that are currently being produced.

The first chapter (1) is designed to provide the basic information on the hydropower systems. It starts wit the explanation on how to use hydropower for electric power production. In the subchapter (1.2) the basic components are explained as to which role do they play in the overall design and what affect do they have on the efficiency of the hydropower system.

The second chapter (2) provides information on how to plan a hydropower system. It gives an idea of how to engage a planning process and prepare the information needed for later design. For a proper design of a hydropower system, two parameters are needed (head and flow) and the subchapters (2.1.1 and 2.1.2) provide methods on how to measure this parameters in a stream of flowing water.

The third chapter (3) provides an example on how to proceed from the concept to the finished product. First it explains the basics of hydrodynamics in the pipeline and later in the turbine itself (only for Michell-Banki turbines). Graz University of Technology is explained in detail and the results of the tests are provided and commented on in order to explain the purpose of testing. The tests show that a 3D printed turbine was able to produce 6 Watt of rotational power with an efficiency rate of 70%.

The last chapter (4) provides the economical point of view on the 3D printed pico hydropower plants. This chapter starts with the world and EU overview on the topic of water and renewable energy economy and later provides information on the existing developments of pico hydro as the application possibilities for the 3D printed pico hydropower plants.

6 Synthesis

The goal of this master´s thesis is to answer the question, if the 3d printing technology can be used for production of components that a pico hydropower system consists of.

The answer to this question is presented in the chapter (3) of the master´s thesis where the prototyping experiment is concluded. As it is written in the interpretation of results (subchapter 3.3.3), the 3D printed turbines can provide a fast cheap and efficient solutions when it comes to constructing turbine components. The test results showed that the prototype was able to produce rotational power at a 70% efficiency rate. In comparison with currently professional developed cross-flow turbines, an efficiency rate of 80% was achieved. The conclusion of mentioned subchapter also provides points where improvements of the prototype can be made in order to boost efficiency.

Also a study of possible applications for 3D printed hydropower plants was concluded. It showed that such hydropower plants have a variety of possible applications. They can help people living in rural environments to produce their own electric power. Also they could be used in city water supply lines to provide it with extra electrical power at the peak of consumption. In addition, they could be used to make a modern household more energy efficient and friendlier to the environment, by providing it with renewable source of energy (chapter 4).

7 List of literature

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[2d] SCHNEIDER J.; HARB G.; KNOBLAUCH H., „Fluss- und Sedimenthydraulik VU – Übungsteil“, Version 20130620, Graz University of Technology, Graz 2013

8 List of figures

9 List of tables

Appendix

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Preparation date: 09-06-2016 Version No.: 2.0

Technical Data Sheet

ABS by Innofil3D BV

Filament suitable for all commercially available leading brands 3D FDM/FFF printers

IDENTIFICATION OF THE MATERIAL	
Trade name	Innofil3D ABS
Chemical name	Acrylonitrile Butadiene Styrene
Chemical family	Thermoplastic Copolymers
Use	3D-Printing
Origin	Innofil3D BV

GUIDELINE FOR PRINT SETTINGS	
Nozzle temperature	240 ± 10 °C
Bed temperature	80 – 100 °C
Bed modification	Tape
Active cooling fan	No/Yes (up to 25%)
Layer height	0.08 – 0.2 mm
Shell thickness	0.4 - 0.8 mm
Print speed	40 – 80 mm/s

Settings are based on a 0.4 mm nozzle

MATERIAL PROPERTIES		Test Method
Melt temperature	Not applicable	ASTM D3418
Glass transition temperature	~ 105 °C	ASTM D3418
Melt Flow Rate[1]	43.1 g/10min	ISO 1133
Melt Volume Rate[1]	45.9 cm3/10min	ISO 1133
Density	1.04 g/cm3	ASTM D1505
Odor	Little odor	/
Solubility	Insoluble in water	/

[1]Test conditions: T = 210 °C; m = 2.16 kg

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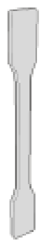
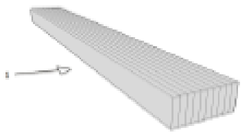
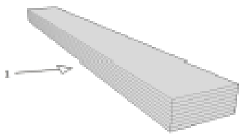
MECHANICAL PROPERTIES | TENSILE TEST		Test Method	ISO 527	
All test specimens were printed using an Ultimaker 2+ under the following conditions: Printing temperature: 210 °C Heated bed temperature: 60 °C Print speed: 40 mm/s Number of shells: 2 Infill under 45°	 Printed vertical (Z-axis)		 Printed horizontal (X,Y-axis)	
Infill	50%	100%	50%	100%
Tensile strength (MPa)	4.4 ± 0.6	6.5 ± 1.8	17.0 ± 0.8	29.3 ± 0.8
Force at break (MPa)	2.7 ± 1.8	7.8 ± 1.3	13.6 ± 0.8	26.4 ± 1.8
Elongation at max force (%)	0.5 ± 0.1	0.7 ± 0.1	2.3 ± 0.1	2.4 ± 0.1
Elongation at break (%)	0.5 ± 0.2	0.7 ± 0.1	4.8 ± 0.9	3.7 ± 0.9
Relative tensile strength (MPa/g)	0.7 ± 0.1	0.8 ± 0.2	2.5 ± 0.1	3.0 ± 0.1
Emodulus (MPa)	1031 ± 53	1358 ± 139	1072 ± 38	2030 ± 45

MECHANICAL PROPERTIES | IMPACT TEST	Test Method	ISO 179
All test specimens were printed using an Ultimaker 2+ under the following conditions: Printing temperature: 210 °C Heated bed temperature: 60 °C Print speed: 40 mm/s Number of shells: 2 Infill under 45° 1→: impact direction	 Charpy (en)	 Charpy (ep)
Infill	100%	100%
Impact strength (kJ/m^2)	39.3 ± 3.3	35.4 ± 3.4
Impact energy (mJ)	1500.0 ± 134.4	1371.6 ± 125.9

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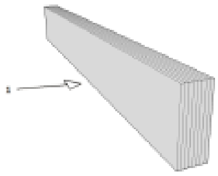
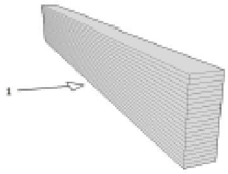
MECHANICAL PROPERTIES | FLEXURAL TEST		Test Method ISO 178
All test specimens were printed using an Ultimaker 2+ under the following conditions: printing temperature: 210 °C heated bed temperature: 60 °C print speed: 40 mm/s number of shells: 2 Infill under 45° 1→: bending direction	 Normal	 Parallel
Infill	100%	100%
Flexural modulus (MPa)	1965.3 ± 115.5	1680.8 ± 127.9
Maximum force (MPa)	67.3 ± 2.3	72.6 ± 1.0
Deformation (%)	4.3 ± 0.1	4.4 ± 0.1

FILAMENT SPECIFICATIONS		Test Method
Diameter 1.75	1.75 ± 0.05 mm	Innofil3D
Diameter 2.85	2.85 ± 0.10 mm	Innofil3D
Max. roundness deviation 1.75	0.05 mm	Innofil3D
Max. roundness deviation 2.85	0.10 mm	Innofil3D
Net weight on reel	750 g ± 2%	Innofil3D

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LIST OF COLORS AND CERTIFICATIONS*						
			Certifications/approvals			
Colour	Code	RAL nr.	10/2011[1]	FDA[2]	2011/65[3]	EN 71-3[4]
Naturel	0001	N/A	Yes	Yes	Yes	Yes
Black	0002	9005	Yes	Yes	Yes	Yes
Red	0004	3020	Yes	No	Yes	Yes
Blue	0005	5002	Yes	Yes	Yes	Yes
Yellow	0006	1003	Yes	Yes	Yes	Yes
Green	0007	6018	Yes	Yes	Yes	Yes
Orange	0009	2008	Yes	No	Yes	Yes
Pink	0020	N/A	Yes	No	Yes	Yes
Silver	0021	9006	Yes	Yes	Yes	Yes

* This overview is generated using information obtained from the raw material suppliers.

Certifications/approvals	Description
[1] Regulation EU No 10/2011:	Union Guidelines on Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food (Europe)
[2] FDA:	Food and Drug administration approval (U.S.A.)
[3] Directive 2011/65/EU:	The restriction of the use of certain hazardous substances in electrical and electronic equipment (Europe)
[4] Directive 2009/48/EC; EN 71-3:	Safety of toys - Part 3: Migration of certain elements (Europe)

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