Potential of Hydroelectric Power Generation using Micro Turbines in Both Developed and Developing Countries

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Abstract

Hydropower is the greatest source of renewable energy; however, the full potential has not been exploited, especially in the area of micro hydro energy generation. The small turbines used can constitute a more cost-effective, environmentally-friendly way to supply communities – both in dense, urban regions in the pipelines of gravity-fed water supply systems and in remote, rural, potentially off-grid ones as run-of-river systems – with electricity.

More and more of these turbines are assembled every year, harnessing the untapped energy potential of moving water to produce clean, cost-efficient electricity and supply small parts of metropolises or sometimes even entire communities in more rural areas with electricity.
In recent years, start-ups have been founded, governments around the world are starting to invest in this relatively new way of implementing the technology. In our hometown Vienna, for instance, several thousand households are already powered by energy generated by turbines in the Viennese mountain spring water supply line.

In spite of all these accomplishments and continuous effort in Western countries, the question remains as to whether the technology has the same potential in developing countries where it could make a huge difference in people's lives, especially those living in rural, remote regions.

The emphasis of our investigation is on research of state-of-the-art technology and whether and how costs can be reduced and efficiency increased to the point where widespread implementation of the technology is possible, in developed (including an analysis of the situation in our home town Vienna) but especially in developing countries (including a model of a micro hydro plant).

Keywords

electrification, micro hydro plants, turbines, MHP model

1. Introduction

1.1. History of small hydroelectric energy generation

The idea of harnessing the potential of the movement of flowing water has been around since the invention of the water wheel 300 BC when mechanical operations such as the milling of grain could be powered by the force of rivers or streams for the first time. They only rose in popularity with the introduction of water turbines in the first half of the 19th century as the efficiency increased significantly due to a complete overhaul of the operating principles and all-new technology. [1, 2]

Benoît Fourneyron is said to be the inventor of the modern water turbine which has replaced most of the traditional water wheels. Due to the heightened demand for energy to power machines which originated from the Industrial Revolution, there was great interest in increasing the efficiency of water wheels. The result was the first 4,5 kW turbine operating at efficiencies of up to 80 percent within the next decade. [2]

Micro hydro plants (MHP) became the world’s most important contributor to the generation of renewable energy. Whereas the trend has shifted towards large size hydro power stations in the second half of the 20th century, there is revived interest in MHP as they are becoming applicable in rural or remote areas, viable with minimal means. [1]

1.2. Definition of MHP

MHP can be classified depending on their output power (most commonly in kilowatts). The classification ‚micro‘ hence describes capacities from 5 kW to 100 kW, as shown in the table below.

Table 1: Definition of Hydro Plant Sizes

Large hydro	More than 100 MW
Medium hydro	15 MW to 100 MW
Small hydro	1 MW to 15 MW
Mini hydro	100 kW to 1 MW
Micro hydro	5 kW to 100 kW

1.3. Principles of hydroelectric power generation

At its most basic level, the energy output of a hydroelectric turbine depends on both the vertical height drop – the so-called water head – and the amount of water impinging on the blades of the turbine, known as the flow. Both of those variables together constitute the basis of power generation:

The pressure of the inflow sets the blades in motion, actuating a shaft connected to the generator.

In order to analyze the benefits and drawbacks of a given system, one has to fully comprehend the meaning of the variables crucial to the calculation.

The water head is a term describing the difference in elevation between the height of the water's origin and the height of the turbine. It is most commonly measured as a vertical distance (f.i. meters) or as pressure (f.i. kilograms per square inch) as this pressure is generated through the downhill movement of the water. When talking about low, medium or high water heads, one refers usually to the classification in the table below.

Table 2: Definiton of Head Sizes

High head	more than 100m elevation difference
Medium head	30m to 100m elevation difference
Low head	2m to 30m elevation difference

The above mentioned water flow expresses the quantity of water hitting the turbine's blades in a given time period. It is therefore measured in volume per time, for instance, cubic meters per second or in the case of micro hydroelectricity, liters per second.

The amount of energy produced by MHP depends thus on the water head, the water flow and the efficiency of the turbine. As those variables are multiplied in the calculation (cf. 4.), an increase in one of the factors will always result in an increase in energy output. [1]

1.4. Types of turbines

As geographical conditions change from site to site, there are different variations of turbines, based on two fundamental operating principles: reaction turbines and impulse turbines.

Reaction turbines impact the pressure of the water inflow as the water passes through the blades, setting the runner in rotary motion. The speed and the direction of the flow are virtually not affected. The Francis turbine is currently the most common reaction turbine.

By contrast, impulse turbines harness the velocity of the water inflow, slowing it down significantly as it impinges upon the spoon-shaped blades which results in a change of direction. This type of turbine is is therefore applicable in situations with high water heads but low water flow (see Pelton turbine). [4]

1.4.1. Francis Turbine

Contributing to more than 60% of the global hydropower capacities and hence being the most common type of water turbines in use today, Francis turbines are suitable for medium heads and water quantities, usually specifically adapted to fit geographical conditions so as to achieve efficiencies of up to 94%. It is named after the British-American engineer James B. Francis.

Francis turbines consist of five crucial components: The runner, the generator, its distinct spiral casing and two extra sets of adjustable and non-adjustable regulative blades.

The runner is the linchpin of the turbine. As in most turbines, it is the rotary element propelled by the inflow of water impinging radially on curved blades. Via a shaft, the runner is connected to the generator which converts the kinetic energy and pressure into electric energy. The runner is fitted into a spiral casing aimed at regulating the water's velocity. The two extra sets of blades mentioned above, called stay vanes and guide vanes, are placed inside of the casing. The former ones are fixed in order to steer the flow of water in the direction of the runner blades whereas the latter ones are adjustable to control the flow rate. Thus, electricity production can be synchronized with varying demand. The water exits the turbine axially via a so-called draft tube. [5]

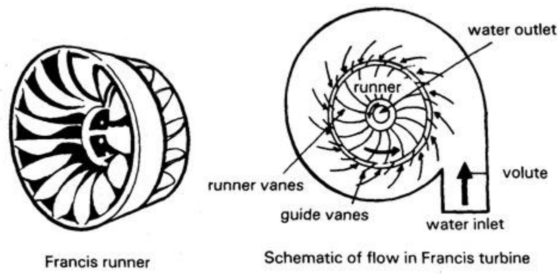

Figure 1: Francis Turbine

produced via the connection to a generator, the water leaves the turbine via a draft tube. [7]

1.4.2. Pelton Turbine

More than one hundred years after its first construction in 1879, the Pelton turbine has become the industry standard for hydroelectric power plants harnessing the water's potential energy when falling high altitudes, in particular with low water volumes. Modern Pelton turbines attain a level of efficiency of up to 90%, rising synchronously with the increase of water heads. They are especially efficient in run-of-river systems (cf. 3.1.3.).

The central part of Pelton turbines are its impulse blades, a set of buckets, each one consisting of two merged spoon-shaped vanes which aim at cutting the flow of water, striking the blades with a comparably high velocity of up to 500 km/h, in half in order to use the kinetic energy of the water effectively. A so-called spear is used the regulate the amount of inflowing water. [6]

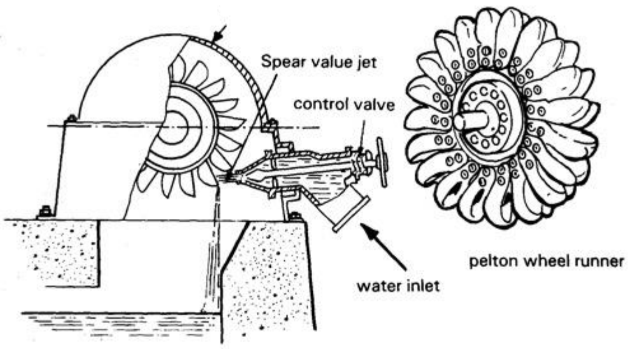

Figure 2: Pelton Turbine

1.4.3. Kaplan Turbine

Contrary to the functional principle of the Pelton turbine, Kaplan turbines make use of high water volumes of up to $800m^3/s$ whereas they do not need high water heads to produce energy. Those conditions usually pertain to water reservoirs and lakes used for hydroelectric power production. Kaplan turbines have an unrivaled efficiency of up to 96%.

Kaplan turbines resemble Francis turbines in their appearance, both using a spiral casing, guide vanes and a runner. The water inflow enters axially into the runner, moving the curved blades due to an effect called the airfoil effect (due to the blade's curvature, a difference in pressure and velocity between the two sides is achieved). Energy is

2. Potential in Developed Countries

2.1. Situation in Vienna

The viennese water supply system is divided into two separately functioning unities, the first and the second water pipe.

2.1.1. The First Water Pipe

The first water pipe is an 112 kilometer long water pipe system, that transports mountain spring water from the Rax- and Schneeberg-area to the southern border of Vienna from where it gets distributed to the viennese households through an approximately 248 kilometers long pipe system.

The pipe is capable of supplying Vienna with a daily maximum of 220.000 m^3 of water, resulting in 80.300.000 m^3 annually, equalling 80.300.000.000 liters per year.

Four major hydroelectric power stations including high performance turbines are located along the first water pipe. Altogether, these four power stations generate a total of 6.6 million kWh annually and can provide 1.500 households with eco-friendly electricity.

The hydroelectric power station of Hinternasswald is the biggest of the above mentioned four power stations located along the first water pipe and does not only generate electricity for Vienna, but also for Hinternasswald itself, a small village located in a mountain valley of the rural Rax area which is, due to its location, foreclosed from general infrastructure. There is no connection to the general electricity supply system, but through the hydroelectric power station Hinternasswald is able to generate its own electricity and supply the 35 households of Hinternasswald with eco-friendly electricity. The additional, non required electricity, is fed into the Viennese energy supply system and used by approximately 23.000 Viennese.

2.1.2. The Second Water Pipe

The first water pipe, the second water pipe collects water in the Hochschwab area and transports it to Vienna through a 183 kilometers long pipe.

Similar to the first water pipe, the second water pipe is capable of supplying vienna with a daily maximum of 217 000 cubic meters of water, resulting in 79.205.000 m^3 annually, equalling 79.205.000.000 liters.

In terms of hydroelectric power generation the second water pipe might be considered the more interesting one as eleven hydroelectric power stations are located along the water supply line. In total, these eleven hydroelectric power stations generate a yearly average of 64.455.000 kWh. This amount of electricity covers the yearly consumption of around 15.500 Viennese households, equalling the electricity consumption of 31.000 individuals at an average household size of two people.

The biggest and most efficient hydroelectric power stations in terms of energy generation are Gaming 1 and 2. They are linked to each other.

At first the water passes through Gaming 1's 588 meter long pressure pipeline with an incline of 31% that allows the water to develop even more pace and therethrough more pressure. At the end of the pressure pipeline the water crosses two Francis Turbines, generating an annual average of 42.000.000 kWh of electric power. After crossing the Francis Turbines of Gaming 1 the water might either be fed again to the second water pipe and brought directly to Vienna, or fed to Gaming 2, which works similarly. The water passes another 2250 meter long pressure pipeline with a medium head of 28,7 meters before it runs through another Francis Turbine, generating an average of 6.000.000 kWh per year.

2.2. Vienna as a Role Model for other Metropolises

With its unique and outstanding resource handling the Viennese water supply system can certainly serve, with special focus on the electricity generation process, as a role model for other metropolises.

The Viennese water supply system supplies 1.8 million inhabitants with fresh mountain spring water, this equals the need of water of many other metropolises, such as Milan, Barcelona, Munich or Budapest.

All of the above mentioned metropolises and many others have similar natural conditions as Vienna in terms of their topographical characteristics – located nearby mountains or upheavals.
These upheavals can be a great benefit to metropolises as they are the most important factors and requirements for gravity-fed water supply lines and therefore francis turbine-systems.

By generating energy and furthermore saving electricity through a gravitational water supply system, Vienna is able to reduce CO_2 emissions and electricity consumption. In addition, the 71.055.000 kWh of electrical energy generated by turbines and hydroelectric power stations cover the annual electricity consumption of about 17.000 Viennese households, equalling the consumption of about 34.000 individuals – approximately 21% of the Viennese population.

If other cities used this technology CO_2 emission could be inhibited and electricity produced eco-friendly and simply as byproduct of water supply.

3. Potential of MHP in Developing Countries

3.1. Advantages of MHP

3.1.1. Efficiency and Independence

An amount of flow as little as 8 liters a minute and a drop as low as one meter can be sufficient to generate electricity with MHP. Micro "hydro plants are well adapted to decentralized energy production in remote areas and easily adjustable to local energy demand", therefore fostering independence and flexibility making them ideal for remote off-grid communities. Furthermore, "developing countries can manufacture, implement" and run MHP themselves as a result of the "low-cost versatility, longevity" as well as limited maintenance and running costs of MHP. Moreover, transmission losses are minimal due to the close vicinity of the MHP to the consumers. [1, 8]

3.1.2. Reliability and Predictability

MHP provide communities with a steady and continuous supply of electrical energy, especially when compared to other small-scale sources of renewable energy, enabling accurate forecasting and therefore long-term planning and assurance of energy supply. Its reliability and predicability are one of MHPs' greatest strengths as "often these systems are more dependable than the local power main". [1]

3.1.3. Ecological Impact

MHP are designed to “function as a ‘run-of-river’ system“ powered by water which is neither consumed nor polluted during the process and later “directed back into the stream with […] minimal or no impact on the surrounding ecology“; even more so if the site is designed carefully. MHP can avoid, for instance, constituting an obstacle to the fish migration if precautions like fish ladders or environmentally friendly runner blades are installed. Innovations like these and improvements to the “methods of operating MHP and above all the willingness of all actors to integrate environmental concerns are steadily reducing these local environmental impacts“. [1]

3.1.4. Cost Effectiveness

Energy generated by MHP is „one of the cheapest renewable sources of energy“, due to low maintenance costs and its longevity („the life of systems can be as long as 50 years or more without major new investments (the average life span considered for investment purposes however is about 30 years)“ (cf. 4.1.)). Still, MHP “can be cost-intensive to build“ depending heavily on “site characteristics, power plant size and location“. Further reduction of costs is one of the most salient goals in MHP development and research (cf. 3.2) [1, 8]

3.2. Cost Reduction

Searching for ways to further reduce costs of MHP is of utmost priority to exploit the full potential of MHP in developing countries.

3.2.1. Hydropower as marginal equipment

MHP can be constructed as a marginal equipment for dams, “dinking water supply or other industrial equipment“[2], for instance as a replacement of pressure control valves in the pipelines of water supply networks. This helps to minimize costs of civil engineering, leaving above all “hydromechanical and electromechanical elements“[2].

3.2.2. Standardization

Standard designs play a huge role in the process of reducing costs of MHP. The problem lies in the “total operation range of small hydro“ [2] as pointed out by G. Mc Hamissh while speaking at the First Conference on Small Hydro in 1982:

”To cover the market you are talking about 100, 200 standard designs and, with the market as it is at the moment one manufacturer can receive in one year an order for maybe 10 to 20 designs.”

This statement was as true back then as it is now. Adapting the equipment to the hydrological, geological and topographic circumstances at each individual site is very important; as a matter of fact, it is one of the biggest strengths of MHP. However, there must be some sort of standardized production of individual elements of MHP to lower costs. The solution might lie in a combination of standardized processes and components, but some “elements related to power production (turbine runner, high pressure part,...) should be individually calculated and manufactured to optimize the available potential“. Additionally, hydrological data banks should be created to learn from corresponding data of MHP sites around the world as one should avoid bad choices of equipment and therefore suboptimal efficiency. [8]

4. Model of a Possible Implementation Process of a Water Supply System Including MHP in a rural area

We identified MHP in water supply systems as an easy and relatively inexpensive way to reach development goals. On the one hand, this is of course providing tap water to people but the intention of this model was also to explain how MHP could be integrated to generate energy at the same time that can be used to power light bulbs and heat water.

To prove the feasibility of the technology and ways of implementation we decided to develop cost functions and efficiency calculations and model them onto a rural area of a maximum of 5.000 people. The system consists of two main parts. First is the water supply system itself and then there are the MHP. In many cases where micro turbines would be feasible there might already be some sort of water supply system, but there are many examples of rural areas where this is not the case. Therefore, we calculated the cost of the two systems independently.

4.1. Cost Estimations for a Piped System with Surface Water and Gravity-Fed Supply

4.1.1. Introduction

Using surface water from a river, for instance, bears great chances for the generation of renewable energy. A piped water system can be installed in rural areas. These systems must only meet certain criteria that concern many remote villages without water and/or energy supply: a nearby water source with a head of about 20–100 meters.
With the installment of a water pipe system, it is not only possible to provide communities with tap water, but also – with a small modifications and reasonable costs – a supply of energy. This can be achieved through micro turbines placed within the pipes or implemented as a run-by-river system.

The supply is cost-efficient as the system is intended to be gravity-fed. Installment costs for micro turbines are reasonable, although – in the context of Less Economically Developed Countries (LEDC) – still quite expensive; nonetheless, they amortize within the duration of only a few years due to savings in energy costs. Additionally, they provide a huge benefit: supplying people with electricity in their homes.

One of the potential problems can be the quality of the raw water. Key to tackling this issue is to abstract surface water with good quality. Although treatment might not be needed in many cases, this model proposes the installment of a slow sand filter. Often slow sand filter (SSF) are used in rural areas as surface treatment (pre-treatment, coagulation/flocculation, sedimentation, filtration and disinfection), because conventional treatment could by no means be sustainable. [10]

Slow sand filters operate with a continuous flow with the velocity in the range of 0,1 to 0,3 m/hour. They are recognized by the World Health Organization as a superior technology for the treatment of surface water sources and "under suitable circumstances, slow sand filtration may be not only the cheapest and simplest but also the most efficient method of water treatment.“ [9, 10]

4.1.2. Calculation of Piped System

The proposed water supply system would use surface water or a natural spring and would have to be gravity-fed to both keep costs low and useable for energy generation. For a larger rural village of 5.000 people, this system would include 1000m of transmission pipes, 20km of distribution network, more than 50% of household connections and even treatment using the efficient and reliable technology of SSFs. Moreover, there would be a dedicated reservoir to cope with high demand during morning and evening time. This helps reducing costs and makes the technology also available to areas with low water flow rates. Our estimations for water consumption are very conservative with only 108 liters per capita per day (lcd). This is not an advantage, but actually a disadvantage for our calculations because it reduces the overall power output of the system. The consumption of water per person could be higher without necessarily adapting the system.

Table 3: Estimated Capital and Recurrent Cost of the Piped System [10]

Cost Components	Capital Cost in EUR	Annual O&M Cost in EUR/year
Total Cost	€1.469.551,00	€42,42
Cost per Capita	€293,91	€8,00

The total cost might seem expensive at first, but when taking into consideration the costs per capita it appears far less expensive. Moreover, these costs might have to be covered be the inhabitants: In some cases there might already be some sort of a water supply system or substitutes by the regional government, state or in the form of humanitarian aid.

Operation and maintenance (O&M) are relatively low if only SSFs are used as can be seen in table 3. Other works on pipes and renovation, for instance, recur less frequently. The expected lifetime of the entire system components are 30–50 years, although it can vary with regard to the main components. Intake, pipe network and distribution pipes are estimated to have a lifespan of about 50 years, the reservoir between 30–50 years – depending the characteristics and quality of the water – and the treatment plant about 35–40 years. Although, as explained above, the O&M costs are mostly expended on the SSF. The only infrastructure with little durability are the household connections with a lifespan of about 25 years.

4.2. Cost and Performance Estimations for the Implementation of MHP

This is the heart of the model. Since there always is a water flow, energy is always produced when active. Within our calculations we used two scenarios: francis turbines that are active during a period of 18 and 22 hours per day. We used these figures instead of the theoretical value (24 hours) because they more resemble the average values we observed with our best-practice examples in metropolises like Vienna (6.800 hours per year).

For the calculation of the water flow that is required in the formula for the power, it is necessary to estimate the water flow of our pipe system. In general, it is recommended that the projected water use per day can be supplied during a 2-hour peak demand period. [11]

With 5.000 inhabitants (calculating with 25% more for later population growth) and a lcd of 108 l/s the daily required water would be 6.750 m^3. Hence, our water flow amounts to 94 l/s.

Table 4: Water Flow Calculation

Daily Usage	People (+25%)	Daily required water	in 2 hours
108 liters	5000	675.000	7.200 s
		Water Flow (q)	94 l/s

For the efficiency of the turbines we estimate the rate of 90% which lies well within the bandwidth of 75-95% because modern turbines tend to be more efficient. [cf. 1.4]

The last parameter missing is the falling hight (h) which we estimate at 40m, but can be of course higher and with that produce even more energy. The reason why we estimate it at 40m is because we want it to be feasible and realistic under conditions that are prevalent in most LEDC.

$$P = \mu * \rho * q * g * h$$

Figure 4: Power Output Calculation for Micro Turbines

Table 5: Calculation of Power Output for Model MHP

water density (ρ)	water flow (q)	head (h)	Efficiency (μ)	Power available
1.000 liters	94 l/s	40	90%	33,11 kW

	Scenario 1		Scenario 2	
Hours per day	18	596 kWh	22	728 kWh
Hours per year	6570	217.524 kWh/a	8030	265.863 kWh/a
Model Household	200 kWh	1.088 households	200 kWh	1.329 households
Medium	400 kWh	544 households	400 kWh	665 households
Higher	1.200 kWh	181 households	1.300 kWh	205 households

As can be seen in the calculations above with a water flow of 94 l/s, a head of 40m and a efficiency of 90% the power available from the turbine would be 33 kW. Expressed in terms of kWh per year for the two scenarios would be 217–265 kWh respectively. In addition, we added several scenarios for power consumption using various figures from outer countries: standard, economical, medium and high. With regard to households this would translate to a maximum of 1.329 households in our model and only 205 households with a higher standard. These figures might now appear low but it is important to take into consideration that the higher standard is seldomly found in LEDC and the amount of individuals provided with green electricity is significantly higher (average of 4–5 people per household). That shows us that between 25–100 percent of all households in our model can be powered by the turbine's energy depending on the level of consumption; or even more if the head or the flow is increased.

When taking a look at the costs, this is where the effectiveness of the turbines becomes obvious. 250.000 kWh per year can be produced by the power of a single turbine costing only €45 per capita for the model village with O&M per capita of less than a euro. Furthermore, it can clearly be observed that the turbine is less expensive than the water supply system which serves as a great benefit to villages already having such a system implemented.

Table 6: Estimated capital and recurrent cost of the MHP

Cost Components Turbine	Information	Capital Cost in EUR	Annual O&M Cost in EUR/year
Total Cost	-	€225.139,50	€1489,89
Cost per kW	33,11 kW	€6800,00	€45,00
Cost per Capita	5000	€45,03	0,3€

4.3. Model Conclusion

Installing such turbines should not be a question of feasibility or costs. There can be no doubt about the advantages of these turbines and the value added for the inhabitants. Water supply and electrification combined can be achieved with cost-effective method for un der €330 per capita and yearly O&M costs of under €10.

5. Conclusion

MHP are a environmentally-friendly and cost-effective source of renewable energy. They help to foster independence in remote off-grid areas. Standardization and innovations could reduce costs tremendously making MHP even more competitive in comparison with other energy sources. As explained in our calculation model, they are in fact a feasible option for a renewable energy source in remote areas of developing countries.

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