ENSY 5100 PROJECT 2: OVERVIEW OF MICRO HYDROPOWER

Submitted by

Shwe Myat Myo Oo

M.S. Energy Systems Candidate

Northeastern University

Contents

1. INTRODUCTION

Small power plants in the range of kilowatts to megawatts have been in use for many years on regulating and re-regulating dams, canals, pipelines and small streams as run-off. The development of such small hydropower potential (including mini, micro, and pico hydropower) became much more attractive during a part of the last decade due to the presence of government incentives for renewable energy generation across the world. Small hydropower is also a way to utilize excess head from existing water infrastructure such as a municipal water system, thereby exploiting an existing niche of untapped energy. Recently, however, investment for small hydro (which has tended to decline after peaking in 2010) has sharply declined due to a significant capacity already having been installed as shown in Figures 1 and 2. Even so, the topic of micro hydropower is worth examining as the full potential of small hydropower in many parts of the world (especially the developing world) has not been exploited and may be an economically viable niche in the future.

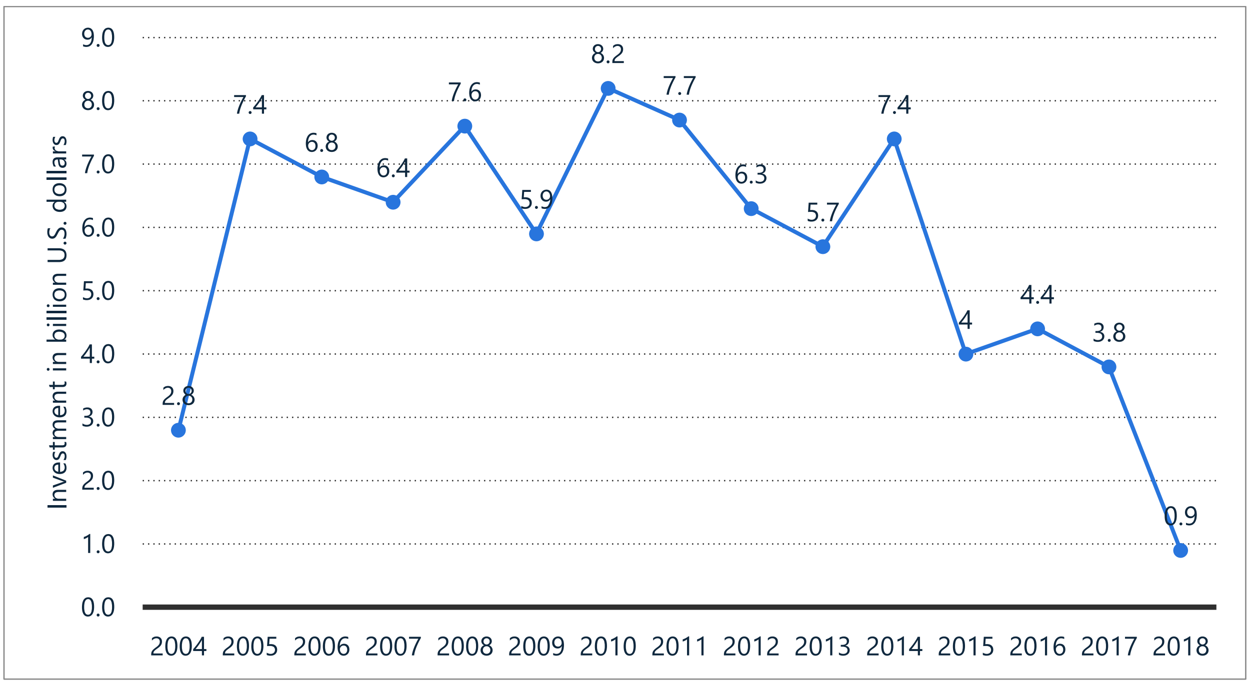

Figure 1: Investment in small hydropower technology worldwide from 2004 to 2018 (in billion U.S. dollars)

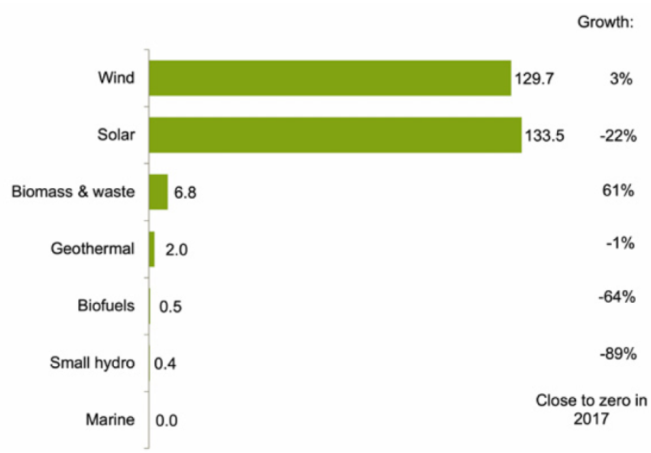

Figure 2: Global investment in renewable energy capacity by sector in 2018 and growth on 2017 (in billion U.S. dollars).

For a project to qualify as a small power plant in the United States, the capacity has to be less than 10 MW to qualify for the small hydro federal incentive program. As of 2015 in the U.S., approximately 4.59% of installed hydropower capacity consists of capacity from small hydropower plants, and only 3% of all dams are utilized for hydropower. Excluding canals and pipelines, the hydroelectric potential of non-powered dams is estimated at 12,000 MW as of 2012. Therefore, sizeable potential still exists for micro and other forms of small hydropower to contribute to energy production in the United States. Similarly, although global funding has declined after a number of small hydro installations, it is possible for private sector energy developers worldwide to continue exploiting smaller water resources for energy production, given the existing potential as shown in Figure 3. Developing nations, in particular, may benefit greatly from exploiting small hydropower for long-term sustainable development in rural areas.

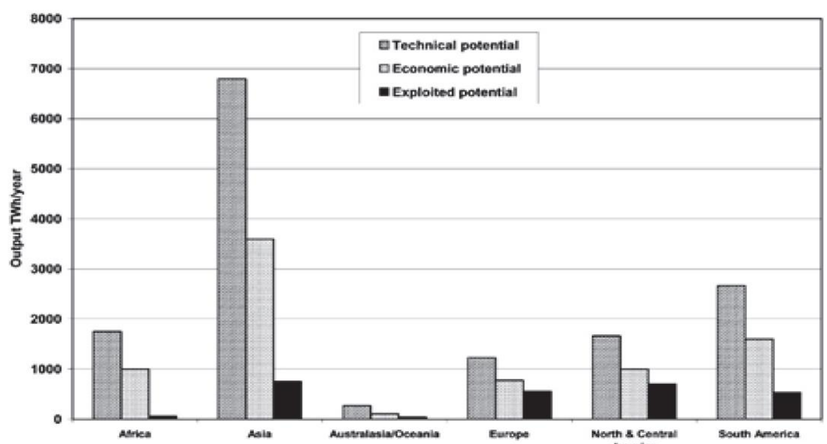

Figure 3: Current scenario of hydropower generation in the world.

2. LITERATURE SURVEY

Micro hydropower is a unique size category of hydropower primarily utilized by private developers as well as small villages and isolated communities in developing nations. Although there is no conclusive consensus on size categories of hydropower plants, it is generally agreed that micro hydropower is on the scale of up to 100 kW. Generally, micro hydropower stations are run-of-river plants where only a small part of river flow is utilized by the turbine, which negates the requirement for a dedicated reservoir and minimizes environmental impact. Micro hydropower may also be integrated as part of a larger infrastructure, such as already existing municipal water systems. The consequent savings in civil work and running costs contribute to making the stations more economically viable. Micro hydropower installations are especially useful in energy recovery within existing infrastructure for multipurpose hydroelectrical schemes, such as a drinking water network or a desalination plant with excess head for a small turbine. Furthermore, hybrid renewable generation schemes (such as PV-hydro plants) on a small scale may utilize micro hydropower to great effect.

The majority of processes and concepts for design and unit selection in micro hydropower (such as hydraulics and stream flow evaluation methods) are essentially the same as for conventional hydropower developments. However, unique problems for micropower exist and the costs of performing feasibility studies and meeting regulatory requirements can make justifying micro hydropower developments difficult on an economic basis. Therefore, it is important to keep simplification and lean design as a consideration throughout the design and implementation process.

The full spectrum of design and implementation for micro hydropower is beyond the scope of this short paper; instead, the focus of discussion will be primarily based on site evaluation, hydraulic structures, required electromechanical equipment (unit selection), and use of power generated in terms of grid integration or isolated use.

3. MICRO HYDROPOWER PROJECT REQUIREMENTS

3.1 Site Evaluation

After determining whether a site has adequate head and flow for micro hydropower generation using hydrology to create evaluation tools such as flow duration curves, the general suitability of a site for hydropower development must be studied. The study for suitability and subsequent implementation of a technical solution is a lengthy, iterative process, where the topography and the environmental issues for a particular site, are paramount. Therefore, thorough knowledge of site evaluation principles and methodologies are needed to avoid dangerous failures in the operation of the plant. For existing infrastructures, an evaluation of operating and remaining potential (such as in Table 1) is the main step in selecting a site and hydropower solution.

Water network type	Potential type	Number of sites	Output (MW)	Production (GWh/year)	Electricity consumption equivalent households
Drinking water	Operating	90	17.8	80	17780
	Remaining	380	38.9	175	38890
Untreated wastewater	Operating	3	0.4	1,4	310
	Remaining	86	7.1	32	7110
Treated wastewater	Operating	6	0.7	2.9	640
	Remaining	44	4.2	19	4220

Table 1: Hydropower schemes in the water industry in Switzerland: operating and remaining potential (Chenal et al., 1994; SFOE, 1995)

For new sites, surveying technologies are undergoing a revolutionary change, and the use of new and emerging technologies can greatly reduce the overall cost of a project and assist in scheme design. A robust preliminary surveying method is the use of cartography via scaled maps and/or aerial photographs of topography (geomorphologic maps). Modern aerial photography cameras in particular are able to remove distortion from axial tilt and other inaccuracies. With photographs from these cameras, geological imperfections can be easily spotted (photogeology), especially those that affect slope stability that can result in dangerous situations.

After initial surveys, detailed geological surveys of a site on ground should generally be performed. The many possible failure modes for a facility warrant a minimum geomorphologic study of the terrain should be recommended in the first phase of the project. The problem is especially acute in high mountain schemes, where the construction may be in a weathered surface zone, affected by different geomorphologic features such as soil creep, solifluction, rotational and planar soil slides and rock falls. After performing an on-site survey and collecting samples, geomorphologic techniques can then be used to further analyze the site. The most common techniques are lab analysis methods such as soil grading, geophysical studies such as resistivity imaging, structural geological analysis, and borehole drilling for permeability and compressive strength tests (such as in Figure 4). A geophysical refraction seismic essay to define the modulus of dynamic deformation of the rock massif in depth can be recommended in the case of high dams to complement the aforementioned tests.

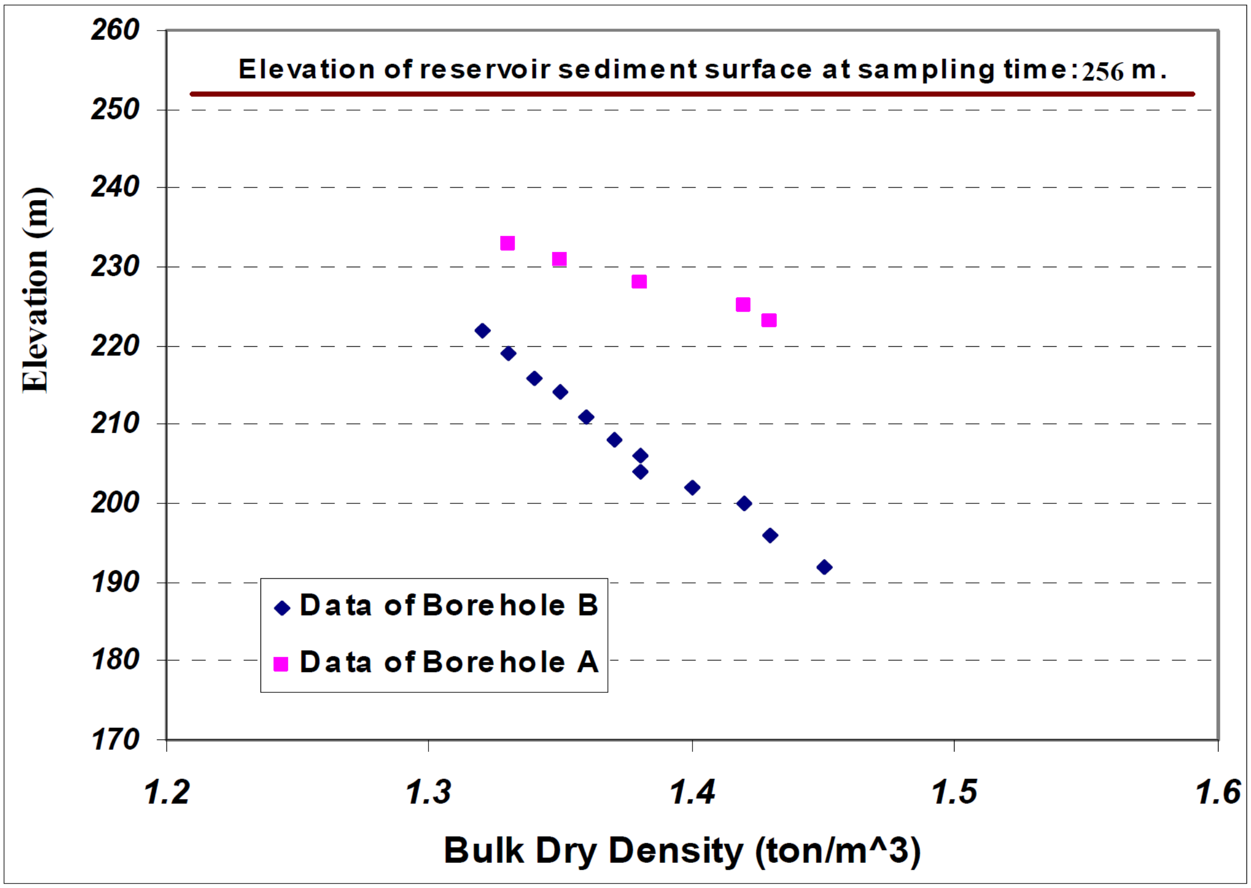

Figure 4: Measured bulk dry density versus Elevation of sampling for obtained samples from two boreholes during the Dez hydropower project in southwest Iran.

To illustrate the importance of site evaluation techniques, it is useful to examine a case study of failure where terrain materials were not fully considered—the Ruahihi canal failure in New Zealand. As shown in Figure 5, the scheme had a 2000m canal laid along a side slope, leading to 750 m of concrete and steel penstocks. The canal was excavated in soft ignimbrite (debris from a volcanic explosion) and lined with a type of volcanic clay.

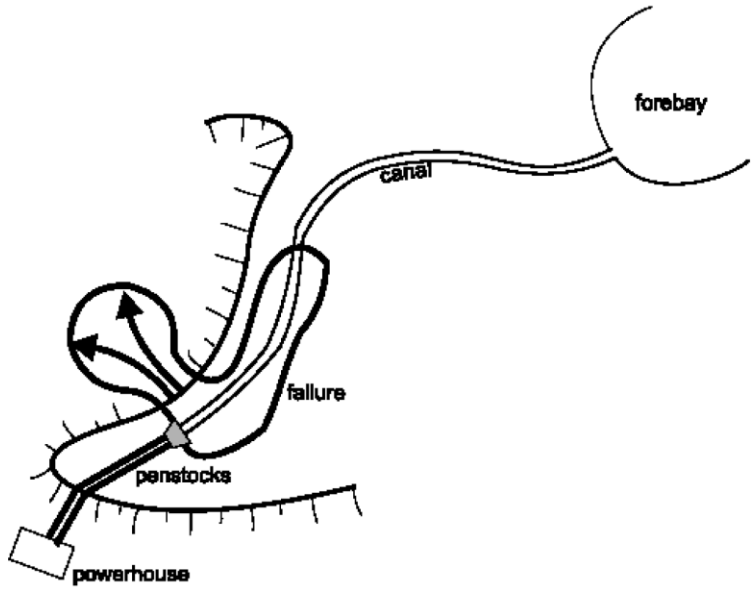

Figure 5: Schematic of the Ruahihi canal.

The brown ash dried and cracked during construction but due to its unusual characteristics, the cracks did not seal when the canal was filled, resulting in water leaking into the ignimbrite below. When the leak was discovered, perforated pipes were driven in to drain the bottom of the slope. However, this hid the problem and exacerbated the situation since the leaking water caused caverns to form in the fill. When the Ruahihi project officially opened, a large section of the canal suddenly collapsed a day later as shown in Figure 6.

Figure 6: A photograph showing the effects of the Ruahihi canal failure.

3.2 Hydraulic structures

Micro hydropower generally has a significantly smaller investment in the construction of hydraulic structures compared to larger size categories. Although the small scale of micro hydropower is a major factor, another consideration is that many projects are run-of-river plants or integrated into existing water use infrastructure. The most common structures in a hydropower scheme are diversion structures such as dams, spillways, and fish passes, and water conveyance systems such as intakes, canals, and penstocks.

Dams and weirs are primarily intended to divert the river flow into the water conveyance system leading to the powerhouse. Dams also produce additional head and provide storage capacity. The choice of dam type depends largely on local topographical and geotechnical conditions. For instance, if sound rock is not available within reasonable excavation depth, rigid structures such as concrete dams are difficult. Conversely, for narrow valleys, it can be difficult to find space for separate spillways, and concrete dams can be the natural choice with their inherent possibilities to integrate spillways and other features in the dam body. According to the ICOLD (International Committee of Large Dams), a dam is considered "small" when its height, measured from its foundation level to the crest, does not exceed 15 m, the crest length is less than 500 m and the stored water is less than 1 million cubic meters. These parameters can be important because of the complicated administrative procedures often associated with the construction of large dams. In terms of dam type, embankment dams (such as the one shown in Figure 7) are common globally mainly due to the following characteristics:

- They can be adapted to a wide range of foundation conditions.
- Construction uses natural materials, which can often be found locally, limiting needs for long transportation.
- The construction process can be continuous and highly mechanized.
- The design is extremely flexible in accommodating different fill materials.

However, newer dams (especially large dams) tend to be Concrete Faced Rockfill Dams (CFRD) or Roller Compacted Concrete (RCC) designs.

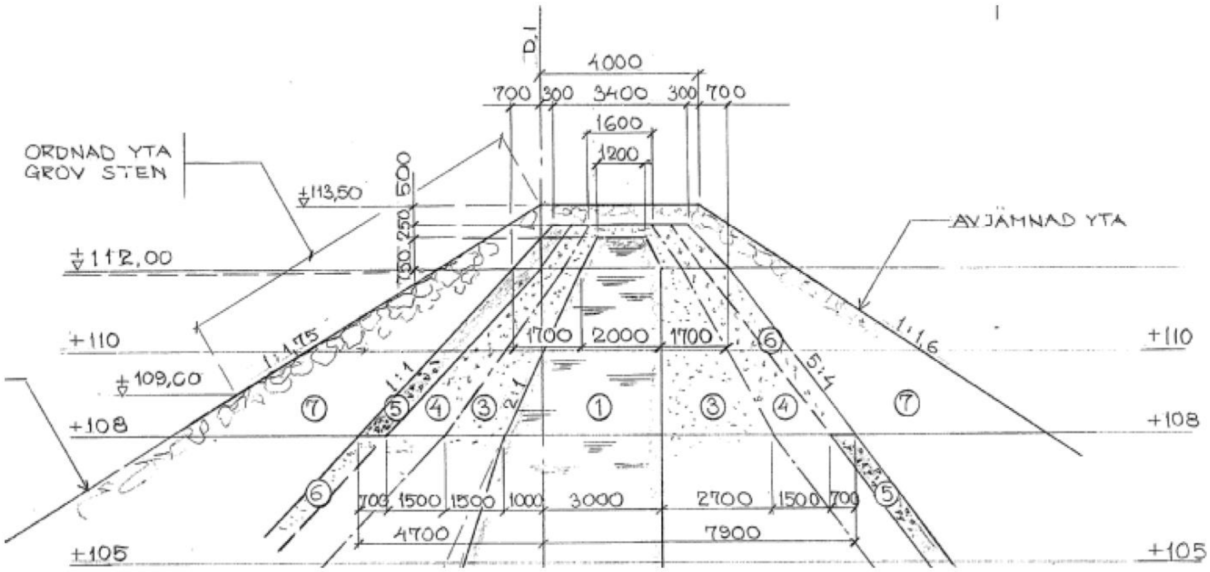

Figure 7: A zoned embankment dam with moraine core.

The large majority of small hydro schemes are of the run-of-river type, where electricity is generated from discharges larger than the minimum required to operate the turbine. In these schemes a low diversion structure is built on the streambed to divert the required flow whilst the rest of the water continues to flow over it. Such a structure is commonly known as a weir, whose role is not to store the water but to increase the level of the water surface so the flow can enter into the intake.

Weirs and spillways (overflow passages) can be subdivided into fixed and mobile structures (such as in Figure 8). Smaller fixed structures are generally referred to as weirs, whereas larger structures are often referred to as spillways. Spillways are often divided into ungated and gated spillways, corresponding to fixed and mobile structures, the ungated spillway in fact being a large-scale weir.

Fixed storage structures, such as weirs and ungated spillways have the advantage of security, simplicity, easy maintenance, and are cost effective. However, they cannot regulate the water level and thus both the water level and energy production fluctuate as a function of discharge. Mobile storage structures such as gated spillways can regulate the water level such that it stays more or less constant for most incoming flow conditions. Depending on gate configuration and discharge capacity they may also be able to flush accumulated sediment downstream. These structures are generally more expensive than fixed structures, for both construction and maintenance, and their functioning is more complicated.

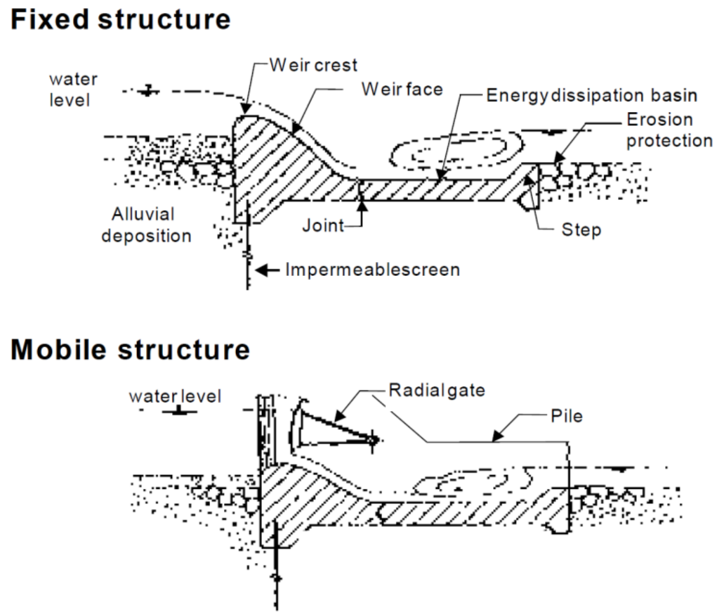

Figure 8: Fixed and mobile spillway structures.

Water conveyance systems for hydropower include structures such as penstocks, whose general design principles remain unchanged for any size category. The main design challenges for penstocks are to minimize friction losses while providing the cheapest viable solution.

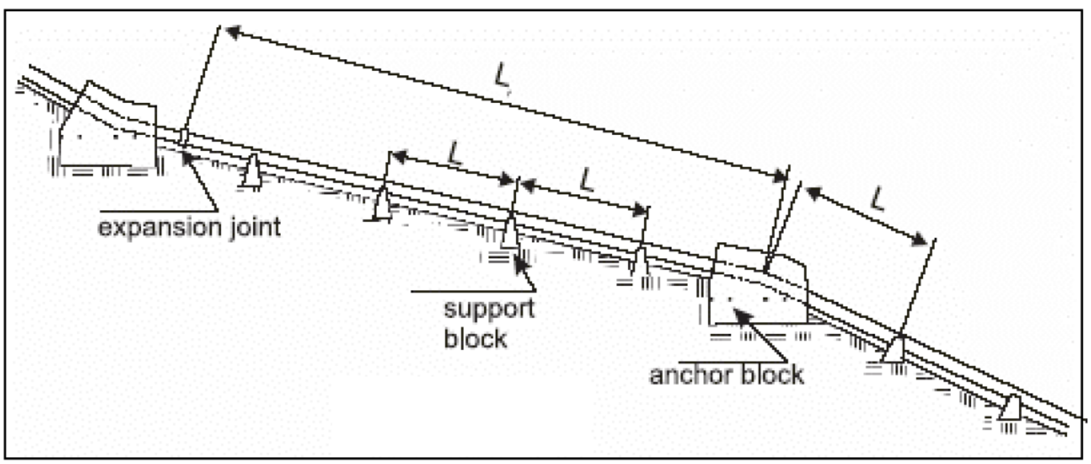

Figure 9: A sample penstock.

3.3 Electromechanical Equipment

The primary subjects of interest in terms of electromechanical equipment for hydropower are turbines, generators, pumps, and motors. Although a four-machine arrangement is possible where each piece of equipment is separate, many modern plants (especially micro hydropower plants) tend to prefer integrated systems with a pump-turbine and integrated motor/generator. The general theory, concepts and design principles for unit selection based on design head, design flow, and unit efficiency under different conditions remain the same for micro hydropower as for every other size category. For 'off-the-shelf' small hydro units, standard pumps used in reverse as turbines, and pump-turbine manufacturer guidance for design via detailed nomographs of turbine parameters such as performance, dimensions, and efficiency curves are generally available. However, new technologies for turbines are making micro hydropower more viable and a continually evolving field. Furthermore, modern analysis techniques such as CFD (computational fluid dynamics) are ensuring improved design iterations, lower prototyping costs, and better accuracy in new designs.

In terms of turbines, many designs for micro-hydro systems have been researched, and different turbines operate in different head and flow conditions as shown in Figure 10. Aside from

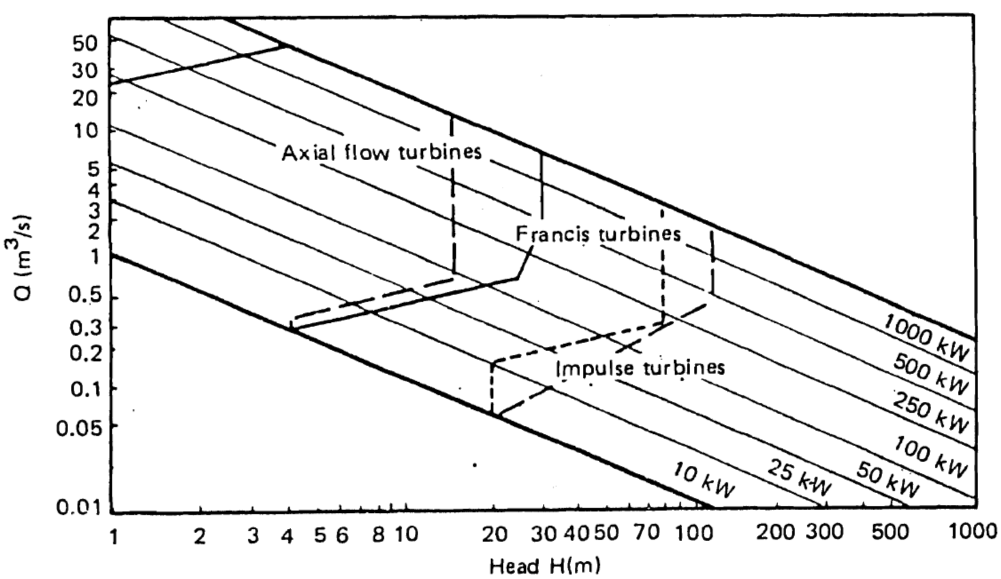

Figure 10: Application range of different types of turbines for micro hydro and mini hydro installations.

conventional designs such as the Pelton turbines shown in Figures 11 and 12, Alexander et al. have studied flat blade propeller and radial and mixed-flow turbines that can be manufactured in developing nations, while Fuller and Alexander have also designed single-tangential-inlet volutes for those turbines to match the incoming flow angles with rotor blade angles without guide vanes. Singh and Nestmann have experimented with axial-flow propeller turbines focusing on ease of manufacture, by characterizing changes in geometry and how they affect performance characteristics. Lee et al. have studied a counter-rotating micro-hydro turbine to replace pressure reducing values in city pipelines. Sutikno and Adam have designed a micro-hydro turbine that operates with a head of less than 1.2 m. Simao and Ramos have studied many different hydraulic machines for low power generation and compared performances between machines. Many recent designs are based on virtual prototyping methods using CFD software and are focused on utilizing water resources previously considered unviable, as shown in Figure 13.

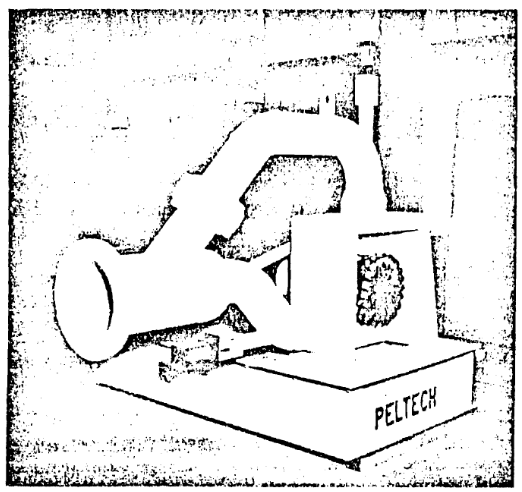

Figure 11: Pelton-type turbine equipment for microhydro installations.

Figure 12: Mülhau: Drinking water turbine (2-nozzle Pelton turbine), from a micro hydropower installation that is part of a drinking water network.

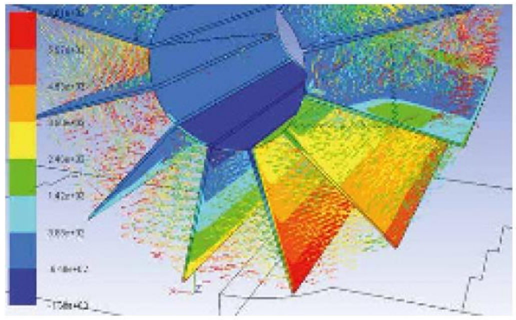

Figure 13: Pressure contours and velocity vectors for a CFD simulation of a hydrostatic pressure machine as part of the EU HYLOW (hydropower converters for very low head differences) project.

Although generators may be fabricated independently and attached to turbines for micro hydropower, many systems on this scale are modular systems, which combine a turbine, generator, and load controller into a single unit. They are broadly categorized into LV (low-voltage) and HV (high-voltage) generators. LV units are composed of a low-voltage brushless permanent magnet generator mounted on a Harris housing with a turbine. HV units are preferred where water is far from power needs (up to 3 kilometers) or where greater power is required. These units use brushless alternators for reliability and versatility and produce 110, 220 or 240 V unregulated AC which can be stepped down with a transformer and rectifier.

Pump-as-turbine units (PATs) are becoming an attractive option for micro hydro power generation in many rural mountainous areas due to design simplicity and the wide availability of off-the-shelf pumps in many countries (which reduces capital costs and enables easy maintenance and operation). Furthermore, such integrated units negate the need for a separate motor purchase and the hassle of assembling components that may be incompatible with one another.

Other important electromechanical components of hydropower systems are synchronous converters such as a doubly fed induction generator (DFIG) as a permanent magnet synchronous machine (PMSM), interfacing systems for hybrid power generation such as PV hydro hybrid generation, and PID controllers for various aspects of hydropower system control. Although the installation of such systems are much more complicated in large hydropower projects compared to micro hydropower, the presence of simple controls in a micro hydropower installation are highly beneficial to its autonomous operation and has the potential to significantly augment maintenance diagnoses.

3.4 Use of Generated Power

Power generated at a power plant can be used at the location of the plant itself, or can be fed into a power grid which distributes the electricity over a larger area. In the case of micro hydropower, there are two main options for power usage. Generation units below 5 kW are better suited for local consumption, the recipients often being communities or small groups of communities. For this type of isolated off-grid system, the power generated can be used for the local power requirements of a community such as powering mills and auto-hammers for blacksmithing (revenue-generating activities) as well as basic requirements such as lighting and cooking. Off grid technology is a quite recent option, however, and is still being developed. High performance electronics has made rapid progress in the inverter sector, enabling the conversion of electricity form to suit that of the grid. In general, hydropower generation capacities of 5 kW and above are fed into a grid, meaning that micro hydropower systems can also generate enough electricity to be connected to the grid for selling excess electricity. Conversely, during off-peak hours, electricity may be purchased cheaply from the grid to use a micro hydropower pump-and-turbine system in reverse for pumped storage. Therefore, although grid integration complicates the required infrastructure in a micro hydropower system, the increased versatility and viability of the systems can outweigh the additional costs and complications.

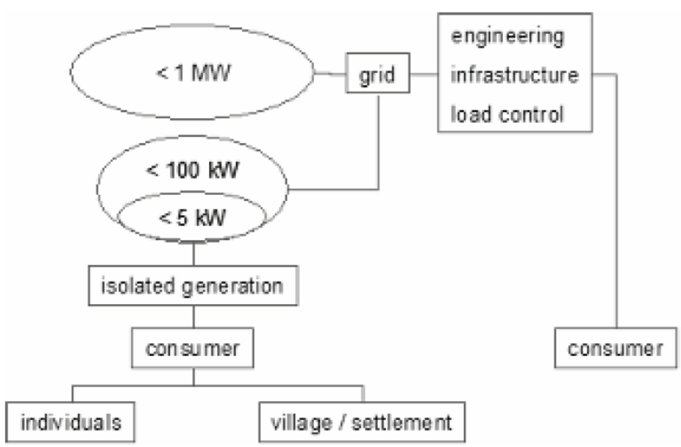

Figure 14: A decision flowchart for generated power usage based on amount of power generated.

4. CONCLUSIONS

Despite recent declines in investment, micro hydropower is an avenue for development with a high potential in many countries. In many cases, small hydropower developments can be achieved with minimal impact, supporting local economic and environmental goals without requiring additional diversions from existing natural water ways. With the aid of superior new analytical tools and significant improvements to manufactured equipment, micro hydropower has the potential to become a viable contender for small-scale energy generation on par with or superior to other renewable energy generation methods such as solar or wind.

In light of such potential for micro hydropower, this paper has attempted to provide a high-level short overview of micro hydropower generation. In doing so, the primary focus has been on site evaluation, the necessary hydraulic structures, electromechanical equipment, and grid integration. As micro hydropower is an extremely broad topic with many more avenues for discussion, further content such as environmental impact and economic viability analysis have not been covered in light of scope constraints. A detailed presentation of quantitative calculation methods for flow data evaluation, design of hydraulic structures, pumps and turbines, and other aspects of project evaluation have similarly been omitted. Exploration of these topics are highly recommended for any deep dive into the literature of micro hydropower.

Further literature recommendations include a survey of the relevant mathematical methods, such as time-domain modeling and stability analysis, used to model micro hydropower systems, as well as the software used to model plant operations such as Simulink.

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