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Prospects of Small Hydropower Technology

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Abstract

Small hydropower (SHP) belongs to renewable energy technology group and is a form of attractive power generation environmental perspective because of its potential to be found in small rivers and streams. Many countries use the technology of small hydro as a renewable energy source in order to minimize existing environmental effects in the production of electricity and have the maximum use of water, a renewable resource. This technology has shown prominence on the world stage with seemingly insignificant environmental effects on rivers, water channels, and dams.

Keywords: hydropower, small hydropower, renewable sources

1. Introduction

The renewable energy sources can be auxiliaries in reducing the environmental impacts that energy production using fossil fuels or other nonrenewable resources causes in nature, with its form of clean and sustainable production. Some known forms of alternative generation are hydro, wind, solar, geothermal, and biomass, which are already present in the energy matrix of various countries, and they have highlighted the way governments have proposed to extract energy.

According to the United Nations Industrial Development Organization (UNIDO), the technology applied in small hydropower (SHP) of renewable form allows the development of rural areas and the access to electricity by a portion of the population living in these regions and they contribute to sustainable development and social inclusion. These factors are positive in the evaluation of governments and their public policies [1].

Hydroelectric generation has a high cost of deployment and maintenance, and short-term disadvantage is observed. In the long run, this alternative source becomes attractive for both clean and sustainable generation and advantage of being exploited too close to large consumer centers, reducing costs of distribution for example.

2. Small hydropower

2.1. Definition and classification

There is no an internationally agreed definition for a small hydropower plants, and its classification is based only on a country's level of hydropower development. **Table 1** shows the definition and classification in some countries with prominent in the generation of electricity by small hydropower in the world.

| Country/organization | Micro (kW) | Mini (kW) | Small (kW) |
|----------------------|------------|-----------|-------------|
| Brazil | <100 | 101–1000 | 1001–30,000 |
| China | ≤100 | ≤2000 | ≤50,000 |
| Philippines | - | 51–500 | <15,000 |
| Sweden | - | - | 101–15,000 |
| USA | <500 | 501–2000 | <15,000 |
| India | <100 | <2000 | - |
| Japan | - | - | <10,000 |
| Nigeria | ≤500 | 501–2000 | - |
| France | <500 | 501–2000 | <50,000 |
| New Zealand | - | <10,000 | <50,000 |
| United Kingdom | <1000 | - | - |
| Canada | - | <1000 | 1001–1,500 |
| Russia | - | - | <30,000 |
| Norway | <100 | 101–1000 | 1000–10,000 |
| Germany | <500 | 501–2000 | <12,000 |
| Turkey | <100 | 101–2000 | <10,000 |

Source: Ref. [2].

Table 1. SHP definition and classification in some selected countries.

Hydropower plants are of three types [3]:

- **Impoundment:** this hydropower system is applied to large generation where water is accumulated in its reservoir, using the dam system.

- Diversion: for the generation of electricity with diversion is necessary to build a canal or penstock for a part of the river can go to the generating group. The dam system cannot be required for the diversion system.
- Run-of-river: this system utilizes the natural flow of water in the river and in some situations do not need impoundment.

The choice of small hydropower plant technology is based on the use of the system of run-of-river so that there is little or no dam on the site that owns the hydroelectric project, using the kinetic energy of moving water to move turbines. The system run-of-river decreases the negative effects that the large hydropower plant causes in the plant installation region as the flooding of arable land and disturbances in the temperature and composition of the river [4].

2.2. Characteristic and components

Figure 1 illustrates a typical run-of-river small hydro scheme.

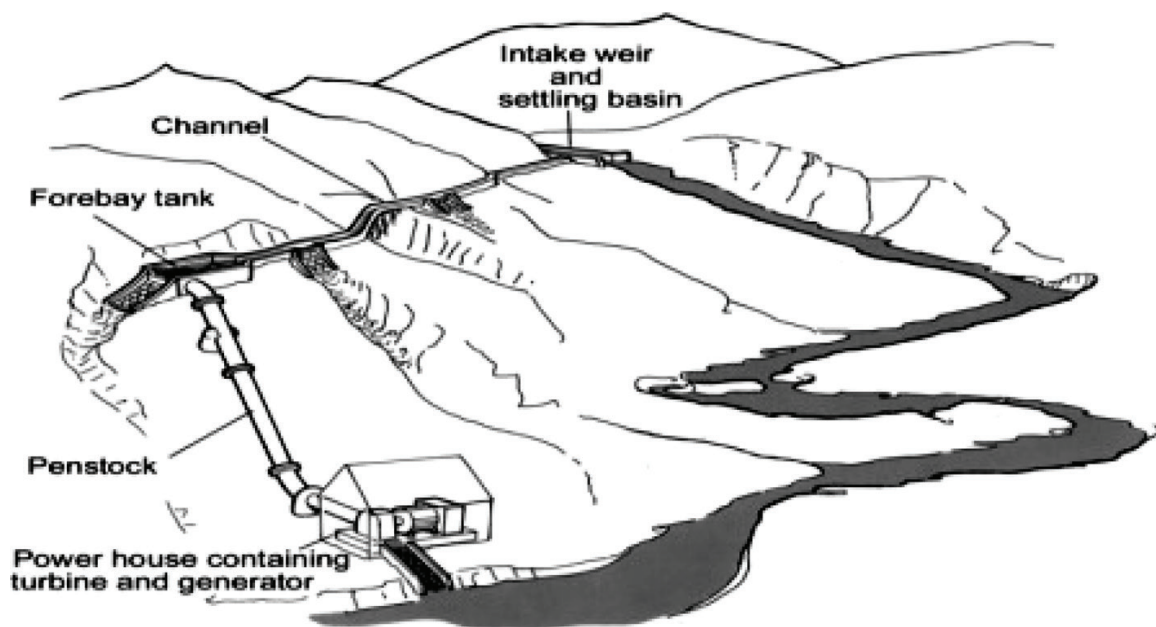


Figure 1. Typical small hydro site layout. Source: Ref. [5].

The fundamental elements are the weir, the settling tank (the forebay), the penstock, and a small canal or "leat." Water is diverted from the course (main river) through an intake at the weir. The weir is a man-made barrier cross the river, which regulates the water flow through the intake. Before entering the turbine, the particulate matter is removed by passing water through a settling tank. Water is sufficiently slowed down in the settling tank for the particulate matter to settle out. A protective rack of metal bars (trash rack) is typically found near the forebay to protect the turbines from damage by larger materials such as stones, timber, leaves, and man-made litter that may be found in the stream [3].

To understand the factors that affect the benefits of an SHP first is necessary to understand the role that the major components have on a hydroelectric project. Stand out for small hydroelectric power stations the following components [6].

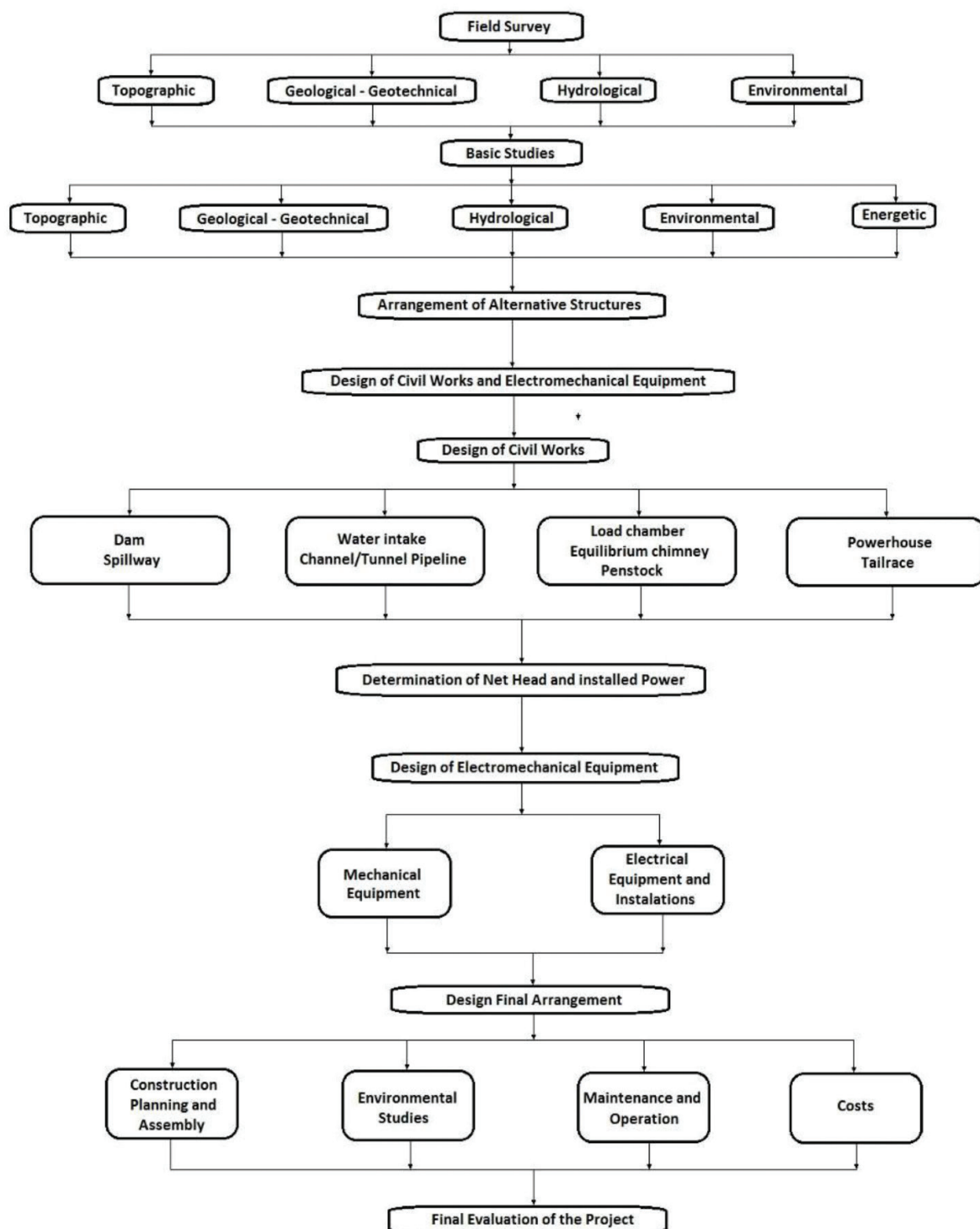
- Dam is the structure of a plant responsible to elevate and keep the level upstream of the engine room, creating artificially a local unevenness.
- Spillway designed in order to drain the greater design flow for the maintenance of the reservoir-required water level, avoiding the risk of the water reaches the dam crest. It is the dam safety structure.
- Generation circuit consists of channels water intakes, pipes or low-pressure adduction tunnels, any surge shafts or load chambers, high-pressure ducts or forced tunnels, external or underground powerhouse, tunnels, and leakage channels. The generation circuit is intended to adduce water for the transformation of mechanical energy into electrical energy.

For the generation circuit we have:

- Water intake: structure to capture the water to the penstock or channel/adduction tunnel.
- Channel and adduction tunnel: structures responsible for adduct the water to the forced conduct in shunt arrangements.
- Equilibrium chimney: aims to stabilize pressure changes resulting from partial or total change of water discharge in starting conditions, load variations, or load shedding of a generating unit.
- Load chamber: is the structure that makes the transition between the channel and the water intake of the penstock. It is dimensioned in order to meet critical starting conditions and sudden stop of the generating unit.
- Penstock: is the structure that connects the water intake to the powerhouse working under pressure. The penstocks can be external or tunnels.
- Powerhouse: structure that houses the electrical and mechanical equipment. The typical powerhouse arrangement is as in any project of this nature, conditioned by the type of turbine and generator.
- Tunnel or tailrace: located downstream of the suction tube between the powerhouse and the river, is the channel through which the turbinated water is discharged and returned to the river.

2.3. Project steps

The use of a hydroelectric potential is an activity subject to institutional, environmental, and commercial regulations. Throughout the project implementation process, multidisciplinary activities are mixed, constituting the legal framework of the entire project. **Flowchart 1** shows the activities that are typical for the development and study of an SHP, depicting the interdisciplinary of studies.



Flowchart 1. Studies and SHP projects. Source: Ref. [7].

The implementation of a project, which aims to use a hydroelectric project for power generation, has a step cycle including phases that estimate, plan, and execute the project. Based on reference [7], these phases are:

- Estimation of hydropower potential: this step is carried to the preliminary analysis of the characteristics of the river basin, especially with regard to topographic, hydrological,

geological, and environmental aspects, in order to verify their vocation to generate electricity. This analysis exclusively guided in the available data, is done in the office and allows the first assessment of the potential and cost estimate of the utilization of the watershed and the priority setting to the next step.

- **Hydroelectric inventory:** it is characterized by the design and analysis of various falling division alternatives for the river basin, formed by a set of projects, which are compared to each other, in order to select the one that presents the best balance between deployment costs, energy benefits, and environmental impacts. This analysis is done based on secondary data, supplemented with field information, and guided by basic studies cartographic, hydro, energy, geological and geotechnical, environmental, and multiple water uses. This analysis will result in a set of exploitations, its main features are indexes, cost/benefit, and environmental indices. It is part of inventory studies submit alternative utilizations selected a study of integrated environmental assessment in order to support the licensing process. These exploitations then become included in the list of inventoried utilizations of the country, capable of composing the expansion plans described above.
- **Viability:** here the studies are more detailed to the analysis of technical, energy, economic, and environmental viability leading to the definition of the optimum use that will be to power auction. The studies include field investigations on site and include the design of the use of the reservoir and its area of influence and the works of local and regional infrastructure necessary for its implementation. Incorporate analysis of the multiple uses of water and environmental interference. Based on these studies, we are prepared the environmental impact assessment (EIA) and environmental impact report (EIR) of an enterprise specific, with a view to obtaining the preliminary license (PL) with environmental agencies.
- **Basic design:** the design in the feasibility studies is detailed in order to define more precisely the technical characteristics of the project, the technical specifications of civil and electromechanical equipment, as well as social and environmental programs. The basic environmental project should be prepared for detailing the recommendations contained in the EIA in order to obtain the installation license (IL) for the contracting of works.
- **Executive project:** includes the preparation of drawings detailing the civil works and electromechanical equipment necessary for executing the works and installation of equipment. At this stage all appropriate steps are taken for the implementation of the reservoir, including the implementation of environmental programs, to prevent, mitigate, or compensate for environmental damage and should be required to operating license (OL).

2.4. Costs of the project

It is important to analyze the existing conditions at the installation site of a hydroelectric plant in order to minimize the installation costs and maximize power generation. Installation costs vary according to the region of installation, infrastructure, and generation capacity. The equipment is also part of the factors that increase the cost of a plant. The small plants also have high installation costs even with a smaller size [3].

According to Forouzbakhsh et al. [8] and Hosseini et al. [9], during the project study phases of an SHP, it is necessary to divide all the construction costs, operation, and maintenance in two categories: investments and annual costs. Investment costs include the electrical and mechanical equipment, transmission towers, civil structures, and other costs classified as indirect. Already the annual costs are the necessary with maintenance, operation, prevention, and replacement of components and equipment [8, 9].

2.4.1. Investment costs

Direct costs include civil costs, electro-mechanical equipment costs, and power transmission line costs as listed below [8, 9]:

- Civil costs are calculated for the structural aspects of a design and construction of the plant, this includes the dam, forebay, tailrace channel, and penstock, among other aspects that are designed in the feasibility stage of a project.
- Generators, turbines, control systems, substations, protective equipment and actuation, and other electrical equipment belong to the costs of electromechanical equipment during the planning phase of an SHP. The costs associated with electromechanical equipment of an SHP can change according to the potential of the plant.

The cost of electromechanical equipment can also be determined using the power, P and the net head, H of the small hydropower plant from [10]:

$$\text{Cost} = aP^{b-1}H^c(\text{€/kW}) \quad (1)$$

where a , b , and c are coefficients that depend on the geographical, space, or time field where they are being used.

- The transmission line costs include the lines from the generation stage until the arrival of energy in the substation. These costs depend on the location, infrastructure, highways, existing systems, and the generation capacity of SHP. However, the value is high as the size of the transmission line increases.

According to Hosseini et al. [9], the indirect costs include engineering and design (E&D), supervision and administration (S&A), and inflation costs during the construction period [9].

- E&D costs: the parameters such as location and size of the project can change the E&D costs. These costs are analyzed as a percentage of construction costs, along with the equipment and civil works. These factors are different from one region to another. Studies show that the plants with small potential, the cost can range from 5% and it varies in the plant with great potential to 8%.
- S&A costs: the acquisition of land, the cost of management activities, supervision, and inspection belong to S & A costs. This cost is similar to the cost of E & D and is also analyzed as a percentage of construction costs. The values can range from 4 to 7% depending on the installation site.
- The inflation rate during all the project phases must be taken into consideration. Deployment costs must be adjusted to the inflation rate of the period and of the next few years, determined by the average inflation rate of the previous years.

2.4.2. Annual costs

To obtain the net benefit of a project, annual costs, in addition to investment costs should be calculated. Annual costs include depreciation of equipment, operating and maintenance (O&M), and replacement and renovation costs [9].

- Depreciation of equipment: the service life, wear, and factors that may change the operation of the equipment need to be analyzed during the economic planning of the project.
- O&M costs: the amounts spent on professionals in an SHP project, such as salary, insurance, taxes, and consumables, are attached to the annual costs. These expenses are corrected with the annual inflation local. It is used on a 5% inflation rate for the correction of the costs of the professionals. These costs represent 2% of total annual investment costs.
- Replacement and renovation costs: some items of the main electromechanical components and of great importance as generator windings and turbine runners will need to be replaced or exchanged sometimes. It is believed that the costs required for maintenance and repairs of equipment will have the same value as the total elapsed equipment after 25 years. Therefore, equipment wear costs should be determined for each component or equipment needed in the power generation process in an SHP.

2.5. Principles

The basic hydropower principle is based on the conversion of a large part of the gross head, $H(m)$ into mechanical and electrical energy. Hydraulic turbines harness the water pressure to convert potential energy into mechanical power, which drives an electric generator and other machines. The energy that has water is directly proportional to the pressure and flow. **Figure 2** shows several components of an SHP.

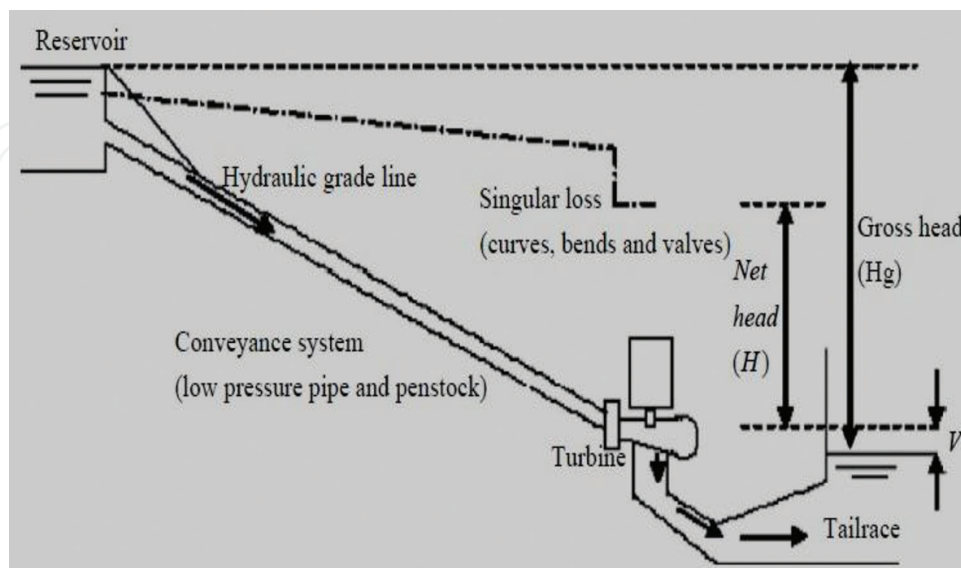


Figure 2. Components of a small hydropower. Source: Ref. [11].

Generally, the hydraulic power P_0 (kW) and the corresponding energy E_0 (kWh) over an interval of time Δt (h) are

$$P_0 = \rho g Q H \quad (2)$$

$$E_0 = \rho g Q H \Delta t \quad (3)$$

where ρ and g are the density of water (kg m^{-3}) and Q acceleration due to gravity (ms^{-2}), respectively. The final power, P delivered to the network is smaller than P_0 . The power output of any hydropower plants is given by

$$P = \eta P_0 \quad (4)$$

where η is the hydraulic efficiency of the turbo-generator.

First, to set the type of hydraulic turbine of a project, it is observed the head and the volume of water in the river or the local plant installation. However, for a complete and objective analysis for choosing the turbine must consider the efficiency and cost of each existing type of turbine. There are two types of the turbines for the SHP [6]:

- Impulse turbine—pelton, cross flow, and turgo.
- Reaction turbine—propeller, Francis, and Kaplan.

3. Turbine selection

Hydro turbines can be categorized into two groups: impulse turbines and reaction turbines. The difference relates to the way that energy is produced from the inflows [3].

3.1. Impulse turbine

Impulse turbine uses the kinetic energy of water to drive the runner and discharges to atmospheric pressure. The runner of impulse turbines operates in air and is moved by jets of water. According Okot [3], “the water that falls into the tail water after striking the buckets has little energy remaining, thus the turbine has light casing that serves the purpose of preventing the surroundings against water splashing.” This type of turbine has great applicability in systems with a large falling water and low flow. Three types of impulse turbines are common in power plants: the pelton, the cross flow, and turgo [3].

3.1.1. Pelton

The pelton turbine (**Figure 3a**) has a high operating head. Because the operating head is so high, the flow rate tends to be low, amounting to as little as 0.2 cfs. The turbine requires the flow through the inlet to be highly pressurized, making the proper penstock design crucial. The pelton utilizes a nozzle located in the spear jet, which is used to focus the flow into the buckets on the runner. The spear jet and buckets are designed to create minimal loss; this leads to a potential efficiency of 90%, even in small hydro applications. A pelton turbine can have up to six spear jets (shown in **Figure 3b**), which effectively increase the flow rate to the turbine resulting in a greater power production and efficiency [12].

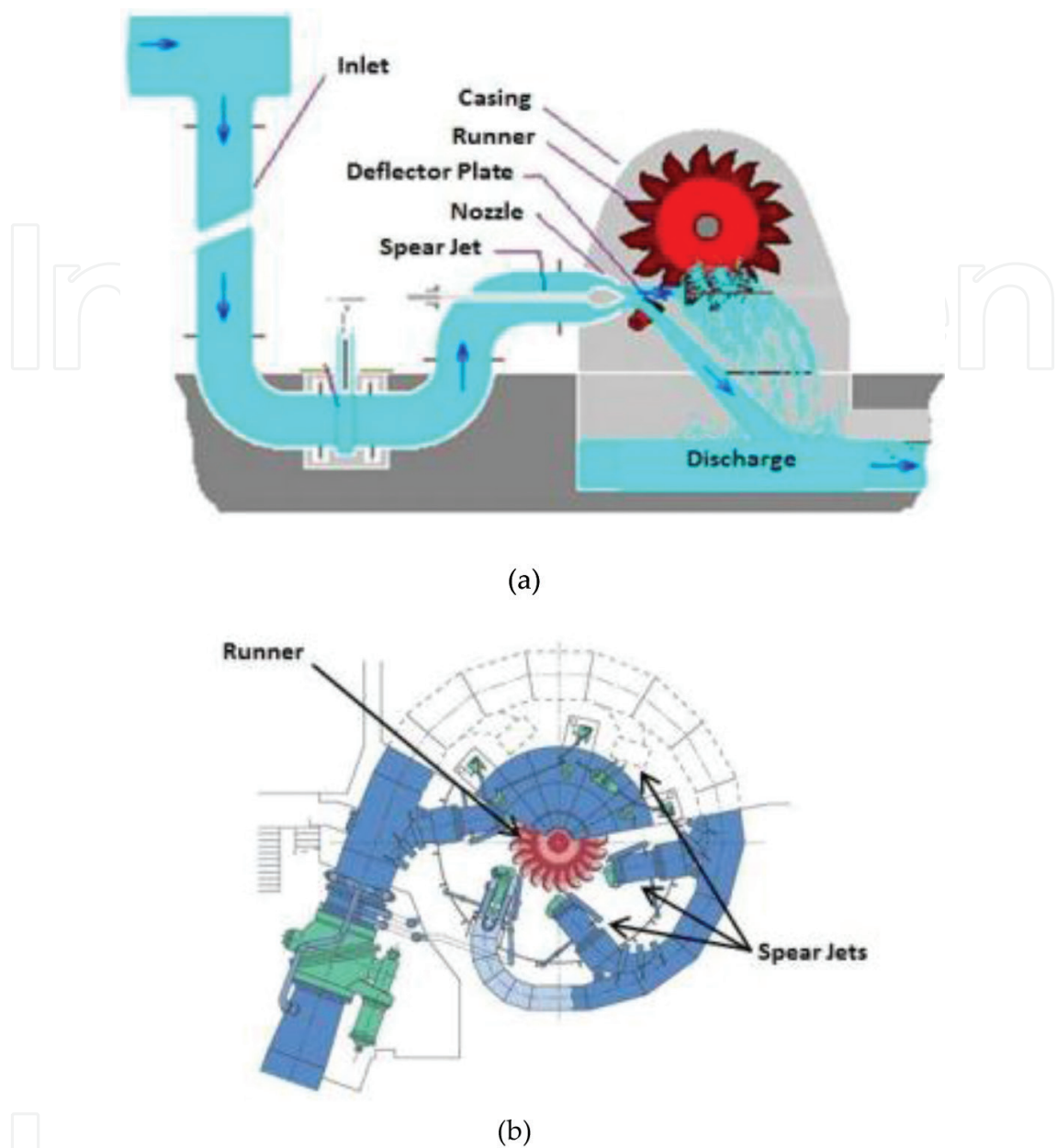


Figure 3. (a) Pelton turbine schematic. (b) Cross section of pelton turbine. Source: Ref. [12].

3.1.2. Cross flow

The cross-flow turbine (**Figure 4**) is named for the way the water flows across the runner. This is because several cross flow in its construction have at its entrance two or more inlet guide vanes. This impulse turbine class displays for a variety of flow rates at high efficiency. By altering the operation of the inlet guide vanes to better suit flow conditions, flow can be directed at just a portion of the runner during low inflow, or the entire runner when higher flows dictate. As evident from the efficiency curve, the cross flow is able to maintain a consistent efficiency [12].

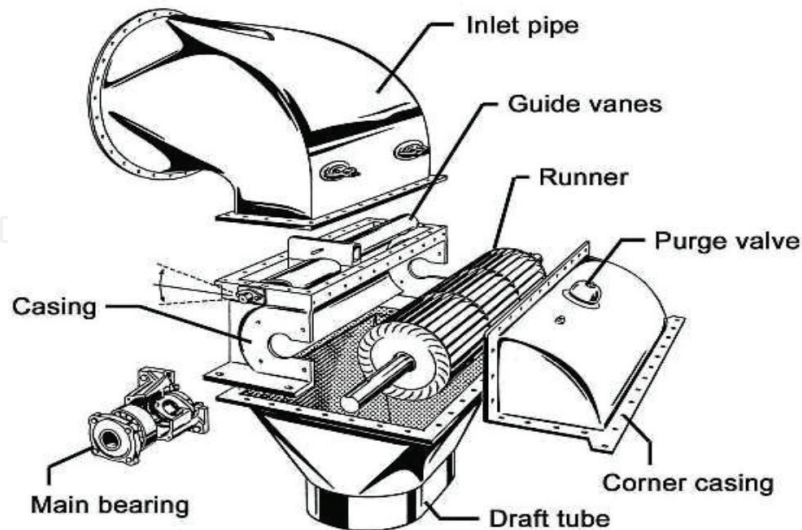


Figure 4. Cross flow schematic. Source: Ref. [12].

3.1.3. *Turgo*

This turbine is similar to the pelton, but with different shape of the buckets and the jet strikes the plane of the runner at an angle. The turgo turbine has some differences compared to the pelton turbine that in some projects your application can be favorable. This turbine has a high overall efficiency and low maintenance due to its running speed being higher, allowing a direct coupling most likely between the turbine and generator. The turgo turbine can have a smaller diameter compared with the pelton because the flow rate passing through it is not limited as input discharged jet, increasing energy production [3].

3.2. Reaction turbine

The turbines of reaction generate energy by mutual activity of pressure and flow of water. They operate when the rotor is involved in a casing pressure and is completely under water. According to Okot [3], “the runner blades are profiled so that pressure differences across them impose lift forces, akin to those on aircraft wings, which cause the runner to rotate.” Unlike impulse turbines, reaction turbines are applicable in places with low height drop and higher flow of water. Examples are the turbines: propeller, Francis, and Kinetic [3].

3.2.1. *Propeller*

Okot [3] claims that a propeller turbine has a generally axial flow passageway of three to six blades, depending on the designed water head. For efficiency, the water needs to be given a swirl before entering the turbine hall. Sites with low flow of water are suitable for propeller turbines. Bulb, Kaplan, and Straflo are examples of propeller turbines.

Also according to Okot [3], “for adding inlet swirl include fixed guide vanes mounted upstream of the runner and a snail shell housing for the runner, in which the water enters tangentially and is forced to spiral in to the runner.. In the case of Kaplan turbine runner blades are set.” Adjusting the turbine blades and guide vanes can significantly improve efficiency in a wide range of flows; however, it is expensive and so can only be economical in larger systems. Where there is potential for small plants and flow and waterfall are somewhat constant, propeller turbines unregulated are commonly used. **Figure 5** shows a typical propeller turbine.

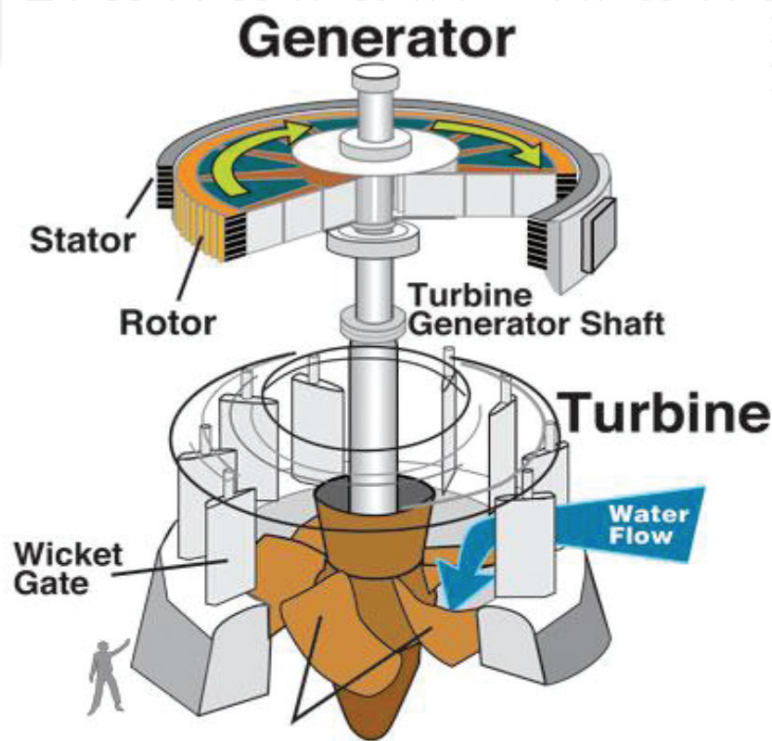


Figure 5. Propeller schematic. Source: Ref. [3].

3.2.2. Francis turbine

One of the more classical designs of hydraulic turbines, the Francis turbine has an efficiency curve, which can function in different situations of height and flow, and its constructive aspects have adjustable guide vanes and fixed runner blades [12].

For this turbine (**Figure 6**), Okot [3] claims that the turbine “generally has radial or mixed radial/axial flow runner which is most commonly mounted in a spiral casing with internal adjustable guide vanes. Water flows radially inward into the runner and emerges axially, causing it to spin. In addition to the runner, the other major components include the wicket gates and draft tube.”

Francis turbines can have an efficiency of 90% when the project height is average but can be inefficient when the flow measured at the site is very different from the design flow. This turbine can be set to an open trough or be attached to a penstock [3].

3.2.3. Kinetic

Kinetic turbines harness the kinetic energy of water to produce energy, i.e., it takes advantage of the natural flow of water. Thus, the kinetic systems do not use deviations or artificial

channels; they use the natural course of the river. However, they can be applied in such conduits [3]. **Figure 7** shows a type of kinetic turbine.

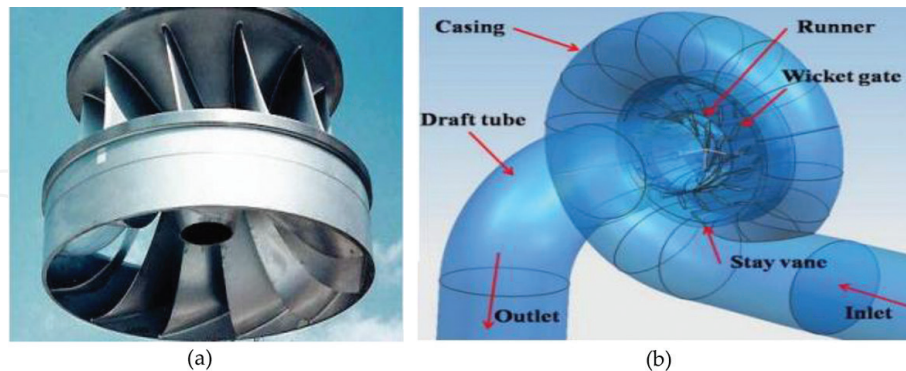


Figure 6. (a) Francis runner. (b) Francis schematic. Source: Ref. [12].

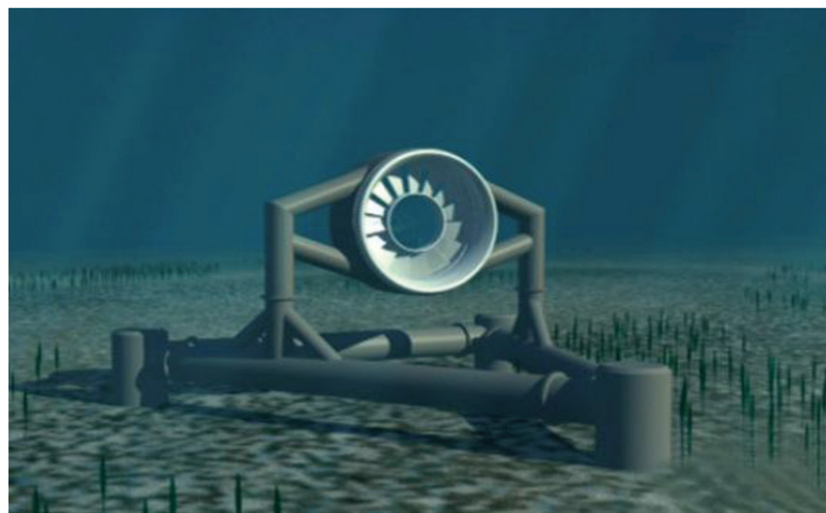


Figure 7. Hydrokinetic model. Source: Ref. [13].

3.3. Selection

In small hydroelectric plants, determining the type of turbine that will be able to operate, as the design data, it can be made in standard sizes turbine, although there is a difference in terms of efficiency. The chart (**Figure 8**) below shows seven major types of turbines and their recommended range of head and flow [12].

The graph of **Figure 8** can be used in the stage of preliminary studies to choose which type of turbine according with the project height and the water flow in the plant installation site and analyze their hydroelectric potential. According to the chart, if the local is identified at a height of 100 feet and a flow of 100 cfs, the turbines of Kaplan, Francis, and cross flow are presented as options, each with its advantages and disadvantages.

The hydraulic turbine manufacturers offer an efficiency curve. This curve shows the relationship between flow and fall of water and how efficiently they are analyzed according to the results of these two variables. It is possible to analyze each type of turbine and its comportment in the several situations of the project. Generally, a flatter efficiency curve represents a

turbine that can operate under broad ranges of head and flow. Curves that are steeper and narrower are indicative of a turbine designed for more focused ranges of operation. **Figure 9** shows the turbine efficiency chart.

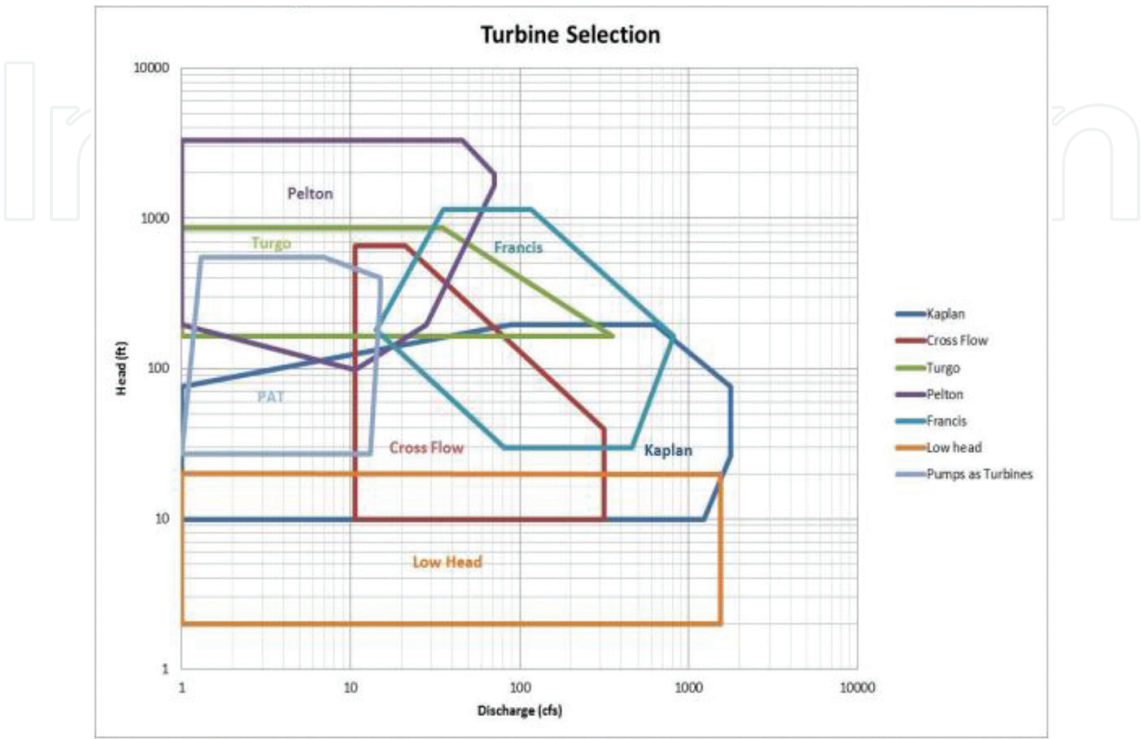


Figure 8. Turbine selection chart. Source: Ref. [12].

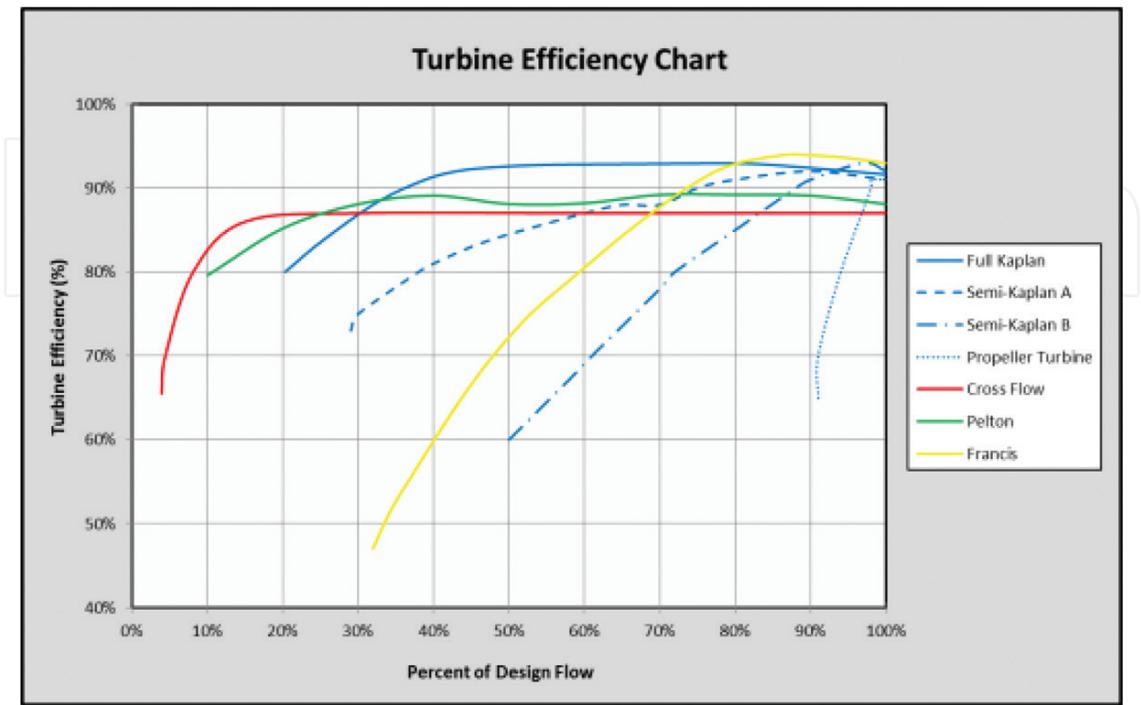


Figure 9. Turbine efficiency chart. Source: Ref. [12].

4. Socioeconomic and environmental aspects

Small hydropower is a key element for sustainable development due to the following reasons [1]:

- Proper utilization of water resources: in small hydro, small creeks, and streams are able to provide and generate energy. You can enjoy local without large storage of water, reducing the social and environmental impacts for the local population.
- Small hydropower is a renewable source of energy: the resource used by SHP, the water, to generate energy is a renewable resource. Therefore, this project is classified as a renewable energy to enjoy the water and generate electricity.
- Small hydro is a cost effective and sustainable source of energy: the SHPs have a simple construction, smaller, and its operating equipment to generate power is low cost compared to large plants. The cost of electricity generation is the free inflation. The period includes the construction and operation is short and the financial return happens quickly.
- Small hydro aids in conserving scarce fossils fuels: the use of water to generate electricity by power plants replaces fossil fuels and petroleum products. If there is the possibility of replacing nonrenewable resources, the SHP is a good choice.
- Low polluting: one of the great contemporary concerns is the relationship of power generation with the environment and reducing the negative impacts. Renewable energy sources reduce GHG emissions and contribute to sustainability. There is a research that puts the SHP as a renewable energy source that reduces GHG emissions and assist in the sustainable development of rural regions. As the SHP does not have large reservoirs and the adaptation of the local population with the project does not suffer many impacts, it is a good choice for electrical projects. The technology of SHP should be harnessed with a form of mitigation of greenhouse gases, along with other renewable forms of generating electricity [1].
- Development of rural and remote areas: there is a deployment potential in remote and mountainous areas for the installation of small power plants. The use of this renewable source of energy in these regions allows the economic and social development.
- Other uses: other benefits are found in regions where small plants are installed, such as irrigation, water supply, tourism, fisheries, and flood prevention.
- The SHP technology is solid and its power house can be built in a few years and has a great life cycle. The civil engineering works, as the dam, can operate for more than a century and require little maintenance. In other mechanical equipment such as turbine, there is the development of research to increase their energy efficiency and reach levels of up to 90% utilization [14].

5. Conclusion

Small hydropower technology is one of the most common technologies used for electricity generation for rural population in both developed and developing countries. Inclusion of the remains of this resource in the energy mixes could lead to sustainable development. Small hydroelectric power plants contribute to meeting the needs of regions where there is no a

major technological development and they are able to improve the population's quality of life with the creation of jobs, increase the local economy, and enhancement of the region.

The benefits of the SHP projects fit into the ease of smaller investments and faster build-operate periods. The areas for power generation are smaller, enjoy raw materials, and local labor and the cost of generation compared to other energy projects are also lower. However, the social, political, economic, historical, regulatory, and environmental issues may limit further development of this technology.

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