

Small Pumped Hydro Storage

1. Overview:

Flowing and falling water have potential energy. Hydropower comes from converting energy in flowing water by means of a water wheel or through a turbine into useful mechanical power. This power is converted into electricity using an electric generator or is used directly to run milling machines. Most people in North America understand hydropower as involving big dams and large-scale generating facilities. Small-scale hydropower systems, however, are receiving a great deal of public interest as a promising, renewable source of electrical power for homes, parks and remote communities.

Hydropower systems are classified as large, medium, small, mini and micro according to their installed power generation capacity. Electrical power is measured in watts (W), kilowatts (kW) or megawatts (MW). A micro-hydropower system is generally classified as having a generating capacity of less than 100 kW. Systems that have an installation capacity of between 100 kW and 1000 kW (1.0 MW) are referred to as mini-hydro. Small hydro is defined as having a capacity of more than 1.0 MW and up to 10 MW,

Small and micro-hydro systems have the following components:

- A water turbine that converts the energy of flowing or falling water into mechanical energy that drives a generator, which generates electrical power – this is the heart of a micro-hydropower system
- A control mechanism to provide stable electrical power
- Electrical transmission lines to deliver the power to its destination.

Depending on the site, the following may be needed to develop a micro-hydropower system (see Figure 1):

- An intake or weir to divert stream flow from the water course
- A canal/pipeline to carry the water flow to the forebay from the intake
- A forebay tank and trash rack to filter debris and prevent it from being drawn into the turbine at the penstock pipe intake
- A penstock pipe to convey the water to the powerhouse
- A powerhouse, in which the turbine and generator convert the power of the water into electricity
- A tailrace through which the water is released back to the river or stream

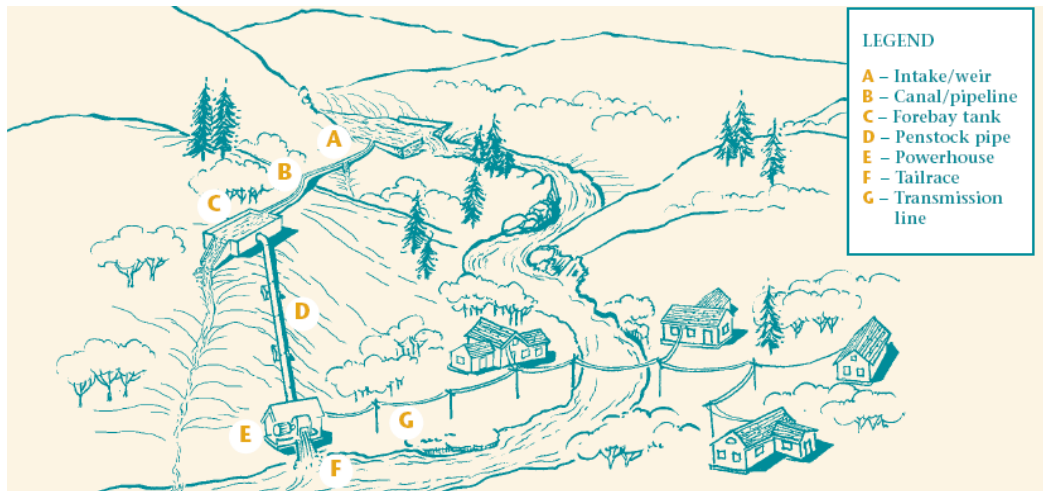


Figure 1: Small/Micro Hydropower System

Many micro-hydropower systems operate “run of river,” which means that neither a large dam or water storage reservoir is built nor is land flooded. Only a fraction of the available stream flow at a given time is used to generate power, and this has little environmental impact. The amount of energy that can be captured depends on the amount of water flowing per second (the flow rate) and the height from which the water falls (the head).

Depending on individual circumstances, many people find that they need to develop their own source of electrical power. Micro-hydropower systems offer a stable, inflation-proof, economical and renewable source of electricity that uses proven and available technologies. These technologies can produce as little as 100 W of electricity at low cost and at very competitive rates, and appropriately designed and implemented systems can provide inexpensive energy for many years. A micro-hydropower system is a non-depleting and non-polluting energy source that has provided reliable power in the past and is one of the most promising renewable energy sources for the future.

Many factors will determine the viability of such a system:

- Local, state, and federal legal restrictions on the development of the hydroelectric site and the use of the water
- The amount of power available from the stream and its ability to meet energy and power requirements
- The availability of turbines and generators of the type or capacity required
- The cost of developing the site and operating the system .

Some of the most important advantages are as follows:

¹ Micro-Hydropower Systems: A Buyers Guide, Natural Resources Canada, 2004, ISBN 0-662-35880-5

- The energy to run hydropower systems is almost free once they are built, even though they usually cost more to build than systems that generate electricity using fossil fuel or natural gas.
- Hydropower systems are inflation-proof because the cost of using the water in the river and stream is not likely to increase, and the cost of fuel for other systems could increase over the years.
- Hydropower systems last 20 to 30 years – longer than most other kinds of generating systems.
- Smaller projects such as micro-hydro systems can be built relatively quickly.
- As a renewable resource, a micro-hydropower system does not depend on oil, coal or other fossil fuel in order to operate.
- It promotes self-sufficiency because its development occurs on a much smaller scale, and most adverse environmental and social effects of large energy development projects are eliminated.
- There is no need for long transmission lines because output is consumed near the source.
- Under favorable circumstances, micro-hydropower is one of the most cost-effective forms of renewable energy.

How to Measure Potential Power and Energy

The first step is to determine the hydro potential of water flowing from the river or stream. You will need to know the **flow rate** of the water and the **head** through which the water can fall, as defined in the following:

- The **flow rate** is the quantity of water flowing past a point at a given time. Typical units used for flow rate are cubic metres per second (m³/s), litres per second (lps), gallons per minute (gpm) and cubic feet per minute (cfm).
- The **head** is the vertical height in metres (m) or feet (ft.) from the level where the water enters the intake pipe (penstock) to the level where the water leaves the turbine housing (see Figure 1).

Power Calculation

The amount of power available from a micro hydropower system is directly related to the flow rate, head and the force of gravity. Once you have determined the usable flow rate (the amount of flow you can divert for power generation) and the available head for your particular site, you can calculate the amount of electrical power you can expect to generate. This is calculated using the following equation:

$$P_{th} = Q \times H \times g$$

P_{th} = Theoretical power output in kW

Q = Usable flow rate in m³/s

H = Gross head in m

g = Gravitational constant (9.8 m/s²)

This is only the theoretical available power, assuming that 100 percent of the power available in the water can be usefully converted. Efficiency of

the system also needs to be taken into account. Energy is always lost when converted from one form to another, and all of the equipment used to convert the power available in the flowing water to electrical power is less than 100 percent efficient. To calculate the most realistic power output from your site, you must take into account the friction losses in the penstock pipes and the efficiency of the turbine and generator.

Small water turbines rarely have efficiencies better than 80 percent. Potential power will also be lost in the penstock pipe that carries the water to the turbine because of frictional losses. Through careful design, however, this loss can be reduced to a small percentage; normally, the losses can be kept to 5 to 10 percent. Typically, overall efficiencies for electrical generation systems can vary from 50 to 70 percent, with higher overall efficiencies occurring in high-head systems. Generally, overall efficiencies are also lower for smaller systems. As a rule, the “**water to wire**” efficiency factor for small systems (for example, up to 10 kW) could be taken as approximately 50 percent; for larger systems (larger than 10 kW) the efficiency factor is generally from 60 to 70 percent. Therefore, to determine a realistic power output, the theoretical power must be multiplied by an efficiency factor of 0.5 to 0.7, depending on the capacity and type of system.

$$P = Q \times H \times g \times e$$

e = efficiency factor (0.5 to 0.7)

Pelton and Turgo turbines are the most commonly used impulse-type turbines in micro-hydropower systems. These turbines are simple to manufacture, are relatively cheap and have good efficiency and reliability. To adjust for variations in stream flow, water flow to these turbines is easily controlled by changing nozzle sizes or by using adjustable nozzles. Pelton turbines are used for sites that have low flows and high heads. Most small reaction turbines are not easy to adjust to accommodate for variable water flow, and those that are adjustable are expensive because of these units’ variable guide vanes and blades. An advantage of reaction turbines is that they can use a site’s full available head. This is possible because the draft tube used with the turbine recovers some of the pressure head after the water exits the turbine. Some of this type of turbine are now being manufactured that can generate power at head as low as 1 m (3 ft.).

Pump-as-Turbine

For a number of years there has been wide interest in reverse-engineered conventional pumps that can be used as hydraulic turbines. The action of a centrifugal pump operates like a water turbine when it is run in reverse. Because the pumps are mass-produced, they are more readily available and less expensive than turbines. It is estimated that the cost of a pump-as-turbine (PAT) is at least 50 percent less or even lower than that of a comparable turbine. However, for adequate performance, a micro-

hydropower site must have a fairly constant head and flow because PATs have very poor partial-flow efficiency. It is possible to obtain full efficiency from PATs by installing multiple units, where they can be turned on or off depending on the availability of water in the stream. PATs are most efficient in the range of 13 to 75 m (40 to 250 ft.) of gross head. The higher the head, the less expensive the cost per kilowatt; this is generally the case with all turbines.

Table 1: Pump Efficiencies

Prime Mover	Efficiency Range
Impulse turbines:	
Pelton	80–90%
Turgo	80–95%
Cross-flow	65–85%
Reaction turbines:	
Francis	80–90%
Pump-as-turbine	60–90%
Propeller	80–95%
Kaplan	80–90%
Water wheels:	
Undershot	25–45%
Breastshot	35–65%
Overshot	60–75%

Generators

Generators convert the mechanical (rotational) energy produced by the turbine to electrical energy; this is the heart of any hydro-electrical power system. The principle of generator operation is quite simple: when a coil of wire is moved past a magnetic field, a voltage is induced in the wire.

Alternating current (AC) generators are also referred to as alternators. They generate varying voltages, which alternate above and below the zero voltage point. It is this process that produces AC electricity. This same principle is used in all electric generators, from large hydro and nuclear plants to the alternator in your car, although the speed will vary depending on the type of generator used. There are two types of generators: synchronous and asynchronous. Synchronous generators are standard in electrical power generation and are used in most power plants. Asynchronous generators are more commonly known as induction generators. Both of these generators are available in three-phase or single-phase systems. System capacity, type of load and length of the transmission/distribution network dictate whether a single- or three-phase generator should be used.

Induction generators are generally appropriate for smaller systems. They have the advantage of being rugged and cheaper than synchronous

generators. The induction generator is a standard three-phase induction motor, wired to operate as a generator.

Capacitors are used for excitation and are popular for smaller systems that generate less than 10 to 15 kW. All generators must be driven at a constant speed to generate steady power at the frequency of 60 Hz. The number of poles in the generator determines the speed, commonly stated in revolutions per minute (rpm). The more pairs of poles, the slower the speed. The 2-pole generator with a speed of 3600 rpm is too high for practical use with a micro-hydropower system. The 1800-rpm 4-pole generator is the most commonly used. The cost of the generator is more or less inversely proportional to the speed; the lower the speed, the larger the frame size needs to be for equivalent power output. For this reason, generators that operate at less than 1200 rpm become costly and bulky. In order to match the speed of the generator to the low speed of the turbine, a speed increaser such as belt and/or gearbox might be needed.

Electrical power can be generated in either AC or direct current (DC). AC has the advantage of allowing the use of common household appliances and tools and is much more economical for transmitting power to homes. DC current can be used in two ways – either directly as DC or converted to AC through the use of an inverter. The main advantage of DC is ease of battery storage.

Generator Efficiency

Full-load efficiencies of synchronous generators vary from 75 to 90 percent, depending on the size of the generator. Larger generators are more efficient, and three-phase generators are generally more efficient than single-phase ones. The efficiency will be reduced by a few percentage points when being used at part load (e.g., at 50 percent of the load). Efficiency of induction generators is approximately 75 percent at full load and decreases to as low as 65 percent at part load. Permanent magnet DC generators have efficiencies of more than 80 percent at full load. It is crucial to take these figures into account when selecting a generator because the overall efficiency of the system will be affected.

Pumped Storage Hydro

Pumped storage hydroelectricity produces electricity to supply high peak demands by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine. Pumped storage schemes currently provide the only commercially important means of large-scale grid energy storage and improve the daily load factor of the generation system. Hydroelectric plants with no reservoir capacity are called run-of-the-river plants, since it is not then possible to store water.

Less common types of hydro schemes use water's kinetic energy or undammed sources such as undershot waterwheels. Small hydro units in the range 1 MW to about 30 MW are often available from multiple manufacturers using standardized "water to wire" packages; a single contractor can provide all the major mechanical and electrical equipment (turbine, generator, controls, switchgear), selecting from several standard designs to fit the site conditions. Micro hydro projects use a diverse range of equipment; in the smaller sizes industrial centrifugal pumps can be used as turbines, with comparatively low purchase cost compared to purpose-built turbines.

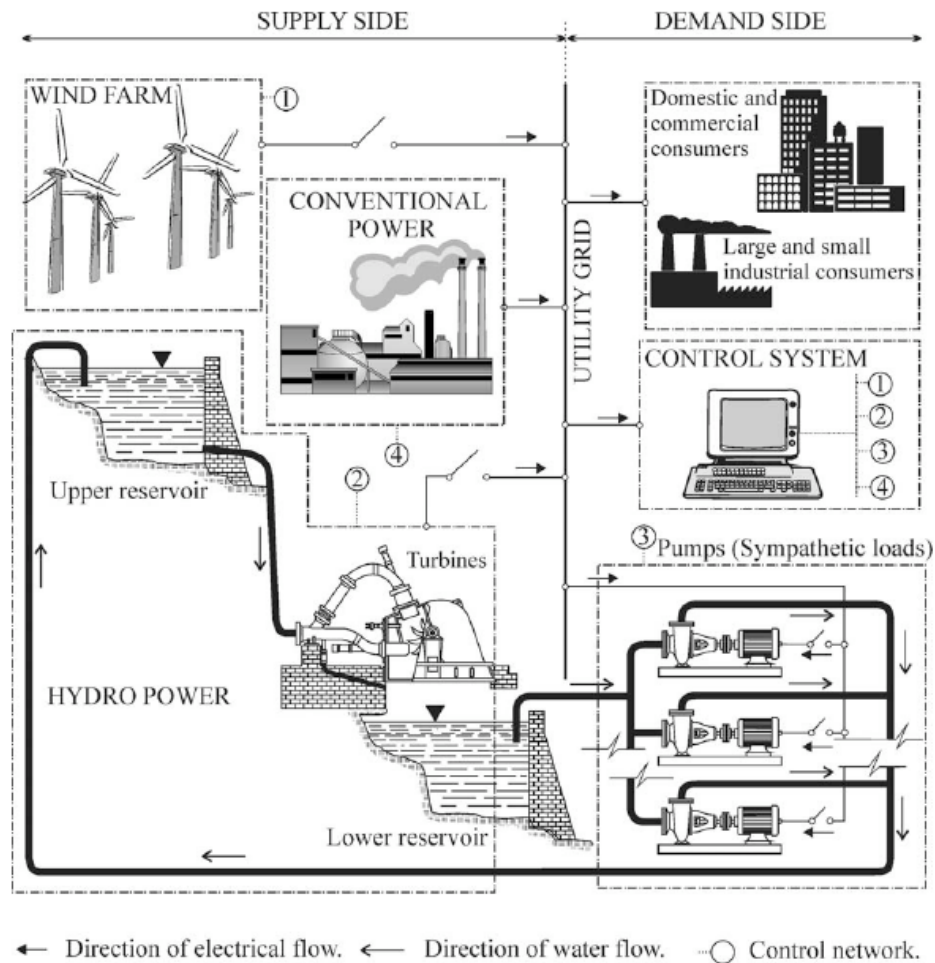


Figure 2: Pumped Storage Hydro System

Cost of pumped hydro storage

A pumped storage station costs in excess of US\$2500/kW and the overall losses are about 25%. Most pumped storage stations store sufficient water for 6-10 hours of operation.²

Hydro and Pumped Storage General Benefits

General Benefits

- Avoids curtailment of firm and intermittent renewable energy sources such as geothermal, solar and wind.
- Creates firm dispatchable generation during high load demand (on-peak) periods (i.e., firms up intermittent renewable generation);

Dynamic Benefits

- Synchronous (spinning) reserve;
- Frequency regulation;
- Load regulation;
- Increased system reliability;
- Coverage of steep load gradients

Hydro and Pumped Storage Hydro Challenges

- Permits
- Environmental impacts;
- Safety;
- Community opposition.
 - 6 MW hydro on Kauai;
 - 2-4 MW hydro on Maui
 - 14 MW of Hawaii;
 - Hydro-electric on Molokai.

2. Status of Commercial Readiness

Hydro-electric systems are commercial. Small hydro units in the range 1 MW to about 30 MW are often available from multiple manufacturers using standardized "water to wire" packages; a single contractor can provide all the major mechanical and electrical equipment (turbine, generator, controls, switchgear), selecting from several standard designs to fit the site conditions. Micro hydro projects use a diverse range of equipment; in the smaller sizes industrial centrifugal pumps can be used as turbines, with comparatively low purchase cost compared to purpose-built turbines.

3. Appropriateness to Hawaii

There are very limited hydro resources in Hawaii and these have been exploited. Hawaii has approximately 27 MW of hydro-electricity generation as follows:

- HELCO purchases as available from Wailuku River Hydro – 11 MW;

² Pumped storage hydro estimates: Big Island \$2,400 - \$2,800 per kW, Maui \$3,400 per kW, Art Seki, MECO IRP – 3 Advisory Group Meeting 1 Nov 2005

- HELCO generates as available from 1 MW Waiiau plant and 2.4 MW Puueo plant;
- MECO purchases as available from HC&S – 6 MW;
- MECO signed a Power Purchase Agreement with Makila Hydro at Pioneer Mill site – 500 kW
- Kauai – 8 MW

Pumped Hydro Storage

There is currently a limited installed base of pumped hydro storage in Hawaii but this is an area with the greatest potential for this form of energy storage. The major barriers include permitting, environmental impact studies, safety, and community opposition.

Past Pumped Storage Hydro Studies

- Oahu
 - 160 MW – 8 hours of storage at Koko crater and Keau crater
- Big Island
 - 30 MW – 6 hours of storage
 - Puu Waa Waa (North Kona)
 - Puu Anahulu (North Kona)
 - Puu Enuhe (Kau)
- Maui
 - 30 MW – 6 hours of storage
 - Maalaea (Kaanapali)
 - Kohama (Lahaina)

Cost Estimate

- Big Island - \$2,400 to \$2,800 per kW
- Maui - \$3,400 per kW

Electricity from Water Treatment

Water pumping for domestic water supplies represents a major electrical power expense. Given the barriers to PHS in Hawaii, it is also the nearest – term hydro opportunity. For example, on the Big Island, the Department of Water Supply (DWS) is HELCO’s largest customer with an annual energy bill over \$9 million in 2004. Energy consumption is expected to increase by 10% per year on a Business-as-Usual case. As a result, the DWS and other island water utilities are exploring the use of hydro generator systems to generate electricity as water is distributed from high elevations to lower elevations. The DWS installed 2 systems in 2004. The design is illustrated in Figure 3 and has the following design feature:

- Hydro turbines are mounted on the tank covers;
- Piping bottlenecks that reduce head to hydro units are eliminated;
- There are no Pressure Reducing Valves (PRV) on transmission pipes. PRVs only on distribution lines
- If applicable, booster pumps are installed for reverse flow operation when required during drought, and for greater system flexibility

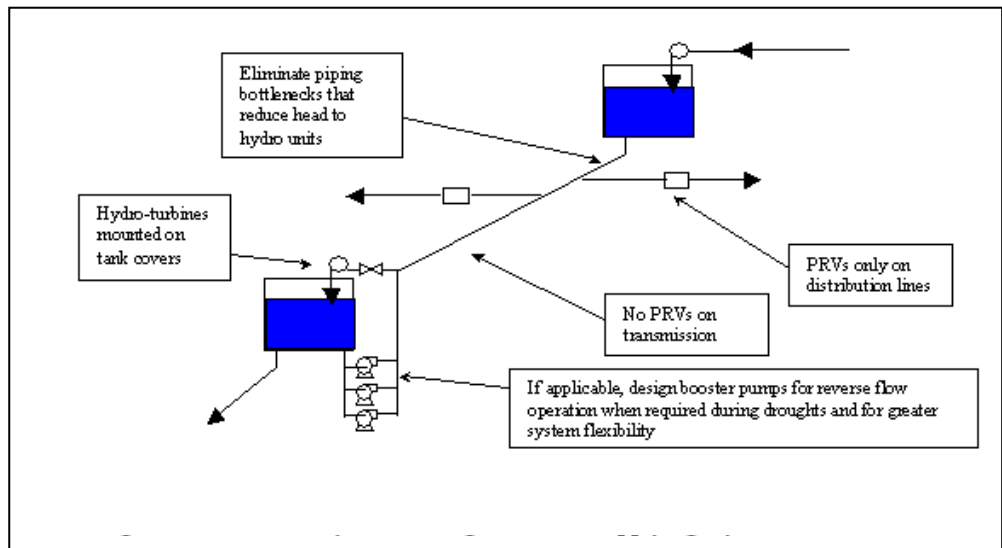


Figure 3: DWS Micro-Hydro Design

This project involves the installation of a 40 KW hydroelectric generation unit at the Kahaluu Shaft Tank location in North Kona District. The project consisted of installing a new equipment pad, a new pressure reducing valve (PRV) and a 40kW hydroelectric generation unit. The new hydroelectric system parallels the PRV and allows operation of the system as it was prior to installing the unit. The hydro-unit is electrically inter-tied to HELCO’s service connection located on the control building. The electricity produced by the hydro-unit will be used on-site. Any excess power generated will be accounted for by HELCO and credited to DWS for future power usage at the site based on HELCO’s Net Metering contract.



³ Clyde Young, Hawaii County Department of Water Supply

Figure 4: This 45-kilowatt turbine, installed in a water treatment plant in Hawaii, pulls double duty: It generates electricity while also reducing water pressure in pipes leading from higher elevations to a storage tank.

4. Considerations

There are no obvious near-term opportunities for large pumped hydro storage systems in Hawaii. There are however some opportunities for small pumped hydro storage. The most obvious opportunity is to utilize the existing water utility systems that already have the basic permits in place, are unlikely to generate community oppositions, and have the quickest installation times. The electricity generated can be used to offset the huge electricity expense currently being experienced.