Microhydro Equipment & System Design

by Hugh Piggott

A hydro-electric system uses the flow of water down a slope to create electrical energy. The amount of energy depends on how much water is flowing, and on the height difference (head) between intake and turbine. This article covers selecting the necessary equipment, from the intake to power electronics.

Courtesy Tim Redshaw

Courtesy Michael Wallford

1 Intake

An **intake** is required to channel water into the hydro system. A reservoir of water is an ideal microhydro source, but it's not essential and most sites don't have one. Instead, water is diverted from a flowing stream or creek into an intake that must be robust enough to withstand floods. Build a small weir or choose a natural constriction in the stream where you can catch the water.

2 Screen

A **screen** of sufficient area prevents things like vegetation, pebbles, and fish from entering the penstock—the pipe that carries water to the turbine. If placed deep in a very large body of static water, this screen may not need much maintenance. It may just need occasional scrubbing with a long-handled brush. Fast-moving water brings debris that must be cleaned off the screen frequently. The best solution is a sloping screen on top of a box or tank that feeds the penstock. Smooth, perforated stainless steel plate or even mesh is suitable screen material. Aquashear (Coanda-effect) screens are virtually maintenance-free if the approach velocity of the water is correctly engineered.

Divert the flow so it spills over the screen, or embed a collection tank in the bottom of the stream or at the edge of a fall. The mouth of the penstock must be large enough and deep enough in the water that it does not create a vortex and draw air.

Brent Summerville

3 Vent Pipe

A single, vertical **vent** downstream of the screen near the top of the penstock helps bubbles escape, prevents damage to the intake from suction if it gets blocked, and removes any trapped air from the penstock, when it is filling up. A **valve** is essential at the bottom of the penstock to shut off the turbine, but rarely needed at the top. If you fit a valve at the top of the penstock, put it upstream of the vent, so you can drain the penstock if desired. Valves at the turbine end of the penstock should be a type that closes slowly, to avoid pressure surges.

4 Penstock

The **penstock** is the engine that drives the turbine, and is the most important part of the hydro system. This pipe doesn't just deliver water—it also provides pressure (see "Penstock Example" sidebar). The longer the penstock is, the larger its diameter must be, or friction will reduce the pressure, decreasing the energy available. Choice of pipe is a compromise between cost and efficiency—a long pipe often makes the penstock more costly than the turbine.

To make the best of limited water, try to keep penstock pressure losses below 20%. There are many online pipe friction tables and calculators for different pipe materials, but few that will factor in friction increases as pipes get older and dirtier. Oversizing the pipe is a good investment for the future.

5 Manifold

You'll need to figure out how to connect the penstock to the turbine using valves, tees, and elbows to construct a **manifold** (used for multiple nozzles on a turbine). It's important to avoid or limit tight bends with small-diameter pipe or there will be additional friction loss.

6 Pressure Gauge

A **pressure gauge** is key for troubleshooting any hydro system—include one in the manifold. Position it upstream of the nozzle control valves so that the static (gross) head as well as the operating (net) head can be measured. If there is not enough water entering the intake, the pipe will begin to draw in air. Head will drop and demand must be reduced. Don't partially close a valve to restrict flow, because it will reduce the pressure at the nozzle. Close valves fully (but slowly) if you do not want a nozzle in operation.

Ian Woofenden (3)

web extras

"Methods: Hydro Measurements" by Ian Woofenden in *HP170* • **homepower.com/170.14**

"Microhydro Turbine Buyer's Guide" by Hugh Piggott & Ian Woofenden in *HP174* • **homepower.com/174.28**

"Harvesting Surplus Energy, Off-Grid" by Hugh Piggott in *HP179* • **homepower.com/179.46**

"Microhydro Intake Design" by Jerry Ostermeier in *HP124* • **homepower.com/124.68**

Penstock Example

This typical example illustrates how the losses in a penstock are affected by flow rate.

Penstock data:
1,000 feet long
2 inches internal diameter
100 feet of vertical fall

We used a pipe friction calculator to determine the net head (shown in green) over the range of possible flows. This line also represents the pipe efficiency (in percent). We then used the rule below to estimate the available power in watts. This is shown in blue.

Power (W) = Net Head (ft.) × Flow (gpm) ÷ 12

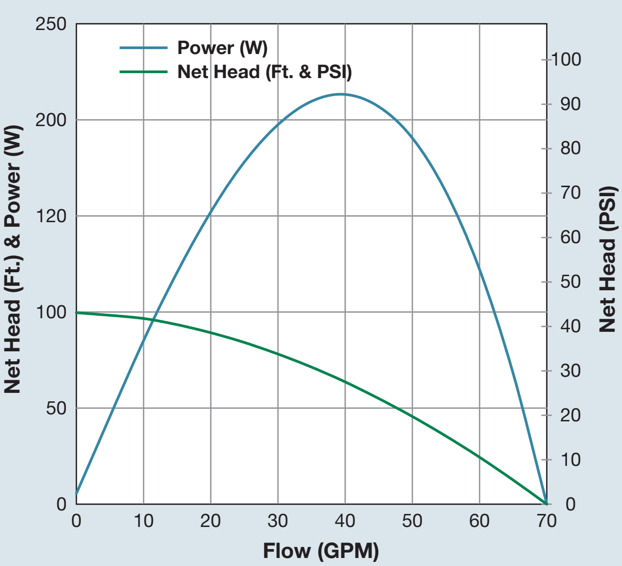
At this site—with 100 feet of head and the valves closed—the pressure gauge should read 43 psi. The flow is controlled by the nozzle sizes fitted in the turbine. If all constrictions are removed so that the pipe runs "full-bore," there will be no pressure on the gauge, and we will see about 70 gpm flow, but no power.

Maximum power for this penstock is achieved by using nozzles that reduce flow to 40 gpm. This coincides with a net head of 66 feet (the gauge will read 28 psi).

However, this 2-inch-diameter pipe may not be the best choice for a 40 gpm flow because the efficiency is only 66%. If 40 gpm is available for enough of the year then it's worth considering the cost of larger pipe; this diameter is a good choice for a site with 20 to 30 gpm flows. Observe how the efficiency is much higher at these slightly lower flow rates.

Your choice of pipe diameter will be governed by the sizes that are available and by how much the pipe costs relative to the pressure loss it incurs. In most cases, a target of 80% to 90% efficiency is cost-effective. But if the pipe is the major cost, or you wish to benefit from short-term high flows, then 66% efficiency could be the right choice.

Maximizing Penstock Efficiency



7 Turbine

The **turbine** must suit the site conditions, matched to the alternator in a package that works for your specific site's head, flow, and operating voltage. A Pelton turbine works well at high heads, or for low flow. For high flow on very low-head sites, a propeller (aka low-head—LH) turbine that sits at the top of a vertical draft tube (see photos on pages 38 and 43). Turgo and crossflow turbines are options for intermediate site conditions. The ranges of all these turbines overlap and are well-documented by manufacturers.

Reliability, efficiency, and cost are important criteria for choosing a turbine. In cases where the rest of the system is very expensive, efficiency is more important than cost. It makes no sense to spend thousands on large pipes and cables, and then sacrifice performance to save a few hundred dollars on the turbine. Look for good technical support, and learn how to do the maintenance.

7


Pelton

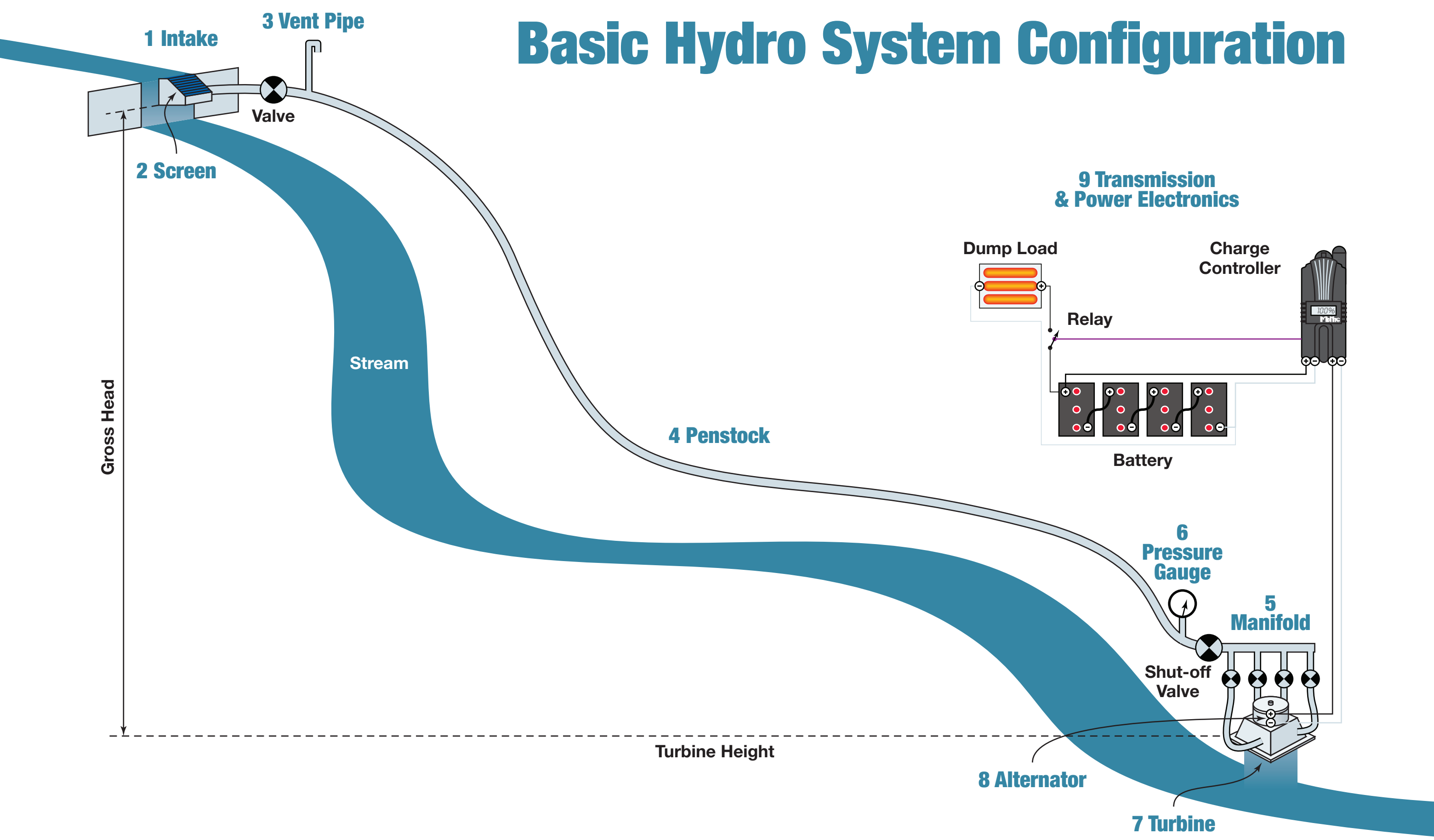

Turgo

Courtesy PowerSpout (2)


Hugh Piggott

Propeller

Basic Hydro System Configuration



8 Alternator

Almost all domestic-scale microhydro turbines are supplied with **permanent-magnet alternators (PMAs)**. The turbine's output is converted to DC and fed to battery/inverter systems or to grid-tied inverters. Some manufacturers custom-build their alternators, but others find mass-produced brushless PM motors a cost-effective solution because they are low-cost, efficient, and reliable.

On larger systems, induction motors are sometimes used instead of PMAs for the same reasons. Induction motors can produce off-grid AC. Larger turbines that produce AC for direct use are more often supplied with brushless alternators with wound-field coils and automatic voltage regulators.

Permanent-magnet alternator (PMA)

Ian Woofenden

Induction motor as alternator

Courtesy Hi Power Hydro

9 Transmission & Power Electronics

The farther the turbine is from where the electricity is used, the more expensive it may be to run **wire**. As with the penstock, you must weigh cost versus the energy loss. Wire used at common battery voltage is heavy and expensive—not because it is DC**,** but because low voltage has greater wire loss. For example, you'll need 16 times more copper in a cable for a 12-volt microhydro turbine than you would for a 48-volt turbine of the same power. It is common to use even higher DC voltages—like 200 VDC—feeding a maximum power point tracking (MPPT) charge controller or a grid-tied inverter. (High voltages can be lethal. Stop the turbine and isolate the wiring before working on connections.) The only advantage of AC for power transmission is that you can use transformers to easily step the voltage up at the turbine and back down at balance-of-system electronics. MPPT devices (controllers and inverters) now make this unnecessary.

Most small off-grid hydro systems are **battery-based**, so the accumulated energy can be stored and used when needed. The battery will not cycle as much of the energy as it would in a PV system, but it still needs to be suitably chosen to maximize its service life. You will need to program the charge controller with the correct voltage settings for your chosen battery type. Larger hydro systems may be able to be used off-grid without batteries, but there will need to be a lot of surplus water power available.

Power electronics—**charge controllers and inverters**—for microhydro systems have evolved rapidly in recent years, becoming more sophisticated and useful, and less expensive. They can:

- Convert power. A high DC voltage in the transmission wire is stepped down to battery voltage or converted to grid AC.
- Maximize power output with MPPT by adjusting operating voltage. Solar controllers and grid-tied inverters can often work as well for microhydro turbines as they do for PV modules. MPPT software finds the best operating speed for the flow conditions. Make sure the equipment is compatible with your turbine and warranted for microhydro use.
- Charge controllers limit the charging current during most of the battery's recharging cycle, based on voltage settings for your battery type.
- Energy diversion serves two functions. First, it protects against turbine overspeed, which can produce noise, wear, and possible damage. Turbines become unloaded when charge controllers limit the flow of energy from the turbine to the battery. Similarly, grid-tied inverters delay connecting the turbine during startup, resulting in overspeed. Diversion of energy to a heating load avoids these issues by keeping the turbine under load.

The second reason for diversion is to maximize your turbine's value by using all of the available energy. A well-designed battery system has regular energy surpluses. Rather than using a "dump load," it's better to take the opportunity to heat water or even your home.

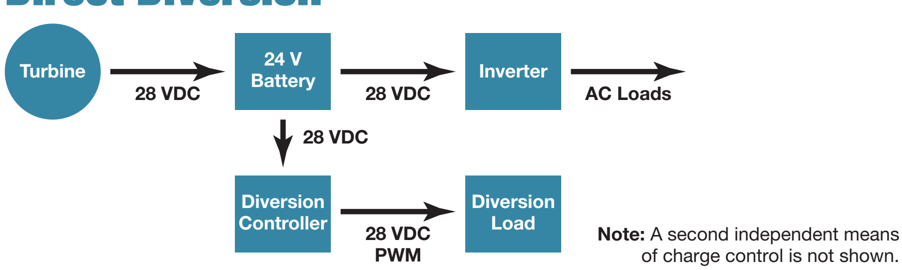
Courtesy MidNite Solar

Direct or MPPT?

It is possible to connect a turbine's PMA directly to batteries via a simple rectifier, but you will need a pulse-width-modulated (PWM) diversion controller, such as Morningstar's TriStar, to control your battery charge rate. Be aware that this is not a fail-safe method. If it cuts out on overload, the battery can be overcharged, which can cause expensive damage and even explosions. To protect against dangerous overcharging, the *National Electrical Code (NEC)* requires the diversion load to be oversized in relation to all of the charging sources. For safety, the *NEC* also requires a second independent means of charge control.

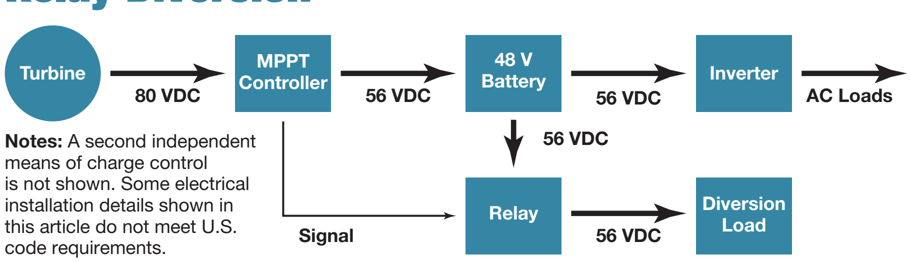
Sometimes, MPPT charge controllers have auxiliary ports that make diversion easy, to prevent turbine overspeed or to harvest surplus energy. Or you may use a diversion controller alongside your MPPT. Set the MPPT controller's battery voltage setpoints slightly higher than the diversion controller, and it will serve as a safety net in case the diversion control fails. In the "Direct Diversion" illustration below, the diversion controller plays a critical role for safety, so redundant capacity is recommended. In the case of MPPT, there is no danger of overcharge.

Direct Diversion



Note: A second independent means of charge control is not shown.

Relay Diversion



Notes: A second independent means of charge control is not shown. Some electrical installation details shown in this article do not meet U.S. code requirements.

Case Studies

Low-Power Turbine with Hot Water Diversion

Andrew has a vacation house on an island that he visits when he has time. He had been using an old diesel generator with batteries and an inverter for lighting and small appliances. Then he decided to tap the nearby stream that runs past the house. The stream has a fall of 80 feet; its flow varies depending on rainfall.

Andrew put in a Harris turbine that has four nozzles of various sizes, each controlled by a valve on a manifold. During the rainy season, the turbine can generate 300 W (7.2 kWh of energy per day). When the house is unoccupied, he adjusts nozzle choice to leave the turbine running at 80 W (nearly 2 kWh per day) to keep the 400 Ah battery charged. A TriStar controller diverts surplus energy to heat the top of a 30-gallon tank-style water heater. Even 80 W of heat can produce 10 gallons of hot water over a 12-hour period. When the water in the tank reaches 120°F, a relay switches the diversion to an air-cooled dump resistor in the battery shed.

Andrew runs the diesel generator to power his washing machine and for battery charging. During this time, the inverter/charger raises the battery voltage, which triggers the water heater—even though the inverter can control its own charging cycle. But the heater is only a small load for the generator, and hot water is useful for clothes washing.

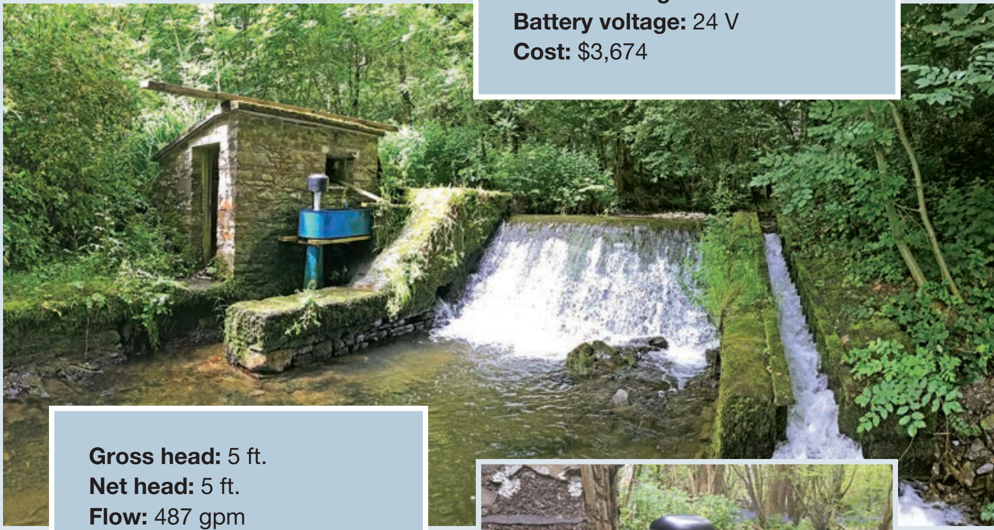
Hugh Piggott

Gross head: 80 ft.
Net head: 66 ft.
Flow: 42 gpm
Penstock length: 400 ft.
Penstock diameter: 2.0 in.
Turbine power: 0.30 kW
Turbine type: Pelton
Turbine make: LoPower Harris
Generator: PMA
Turbine voltage: 24 VDC
Battery voltage: 24 V
Cost: $3,674

Low-Head Grid-Tied Upgrade

Tim has an old mill site with a 5-foot head. He can't increase the head easily because of the need to maintain fish passage, which also diverts some of the flow from the turbine. He installed a PowerPal LH turbine with a Mastervolt grid-tied inverter, but recently upgraded to a PowerSpout LH with Ginlong Solis Mini inverter. The PowerSpout unit fit the existing spiral flume, but its output could be improved by a straighter flume, which could also include more turbines for use in wet weather.

The inverter communicates with Tim's router by WiFi and a "powerline" ethernet adapter, enabling him to view his system's energy production online. The turbine produces a steady 300 W most of the time, adding up to more than 2,000 kWh each year. Tim has a feed-in tariff contract whereby this energy is metered and he is paid 10 cents per kWh in addition to offsetting his utility bill.



Gross head: 5 ft.
Net head: 5 ft.
Flow: 487 gpm
Penstock length: 5 ft.
Penstock diameter: 8.0 in.
Turbine power: 0.30 kW
Turbine type: Low-head
Turbine make: PowerSpout
Generator: PMA
Turbine voltage: 200 VDC
Battery voltage: None
Cost: $2,003

Courtesy Tim Redshaw (3)

Hybrid System with Direct 24 V Battery Charging

When Nigel bought a large off-grid house on the Scottish west coast, he installed a 16 kW diesel generator; six OutBack VFX3024 inverters; and a 3,000 Ah, 24 V battery. Nigel's 500 feet of 5-inch pipe gives up to 323 gpm at 100 feet of head from the stream (with 10% loss). Three ES&D Stream Engine turbines charge the battery, and ES&D helped him configure the turbines for the site. The turbines were connected to the battery with wiring suitable for the 100 A combined output current, and two TriStar PWM controllers in diversion mode regulate the charging voltage. Metering in the house enables Nigel to monitor power and energy from the systems, along with battery voltage and water pressure.

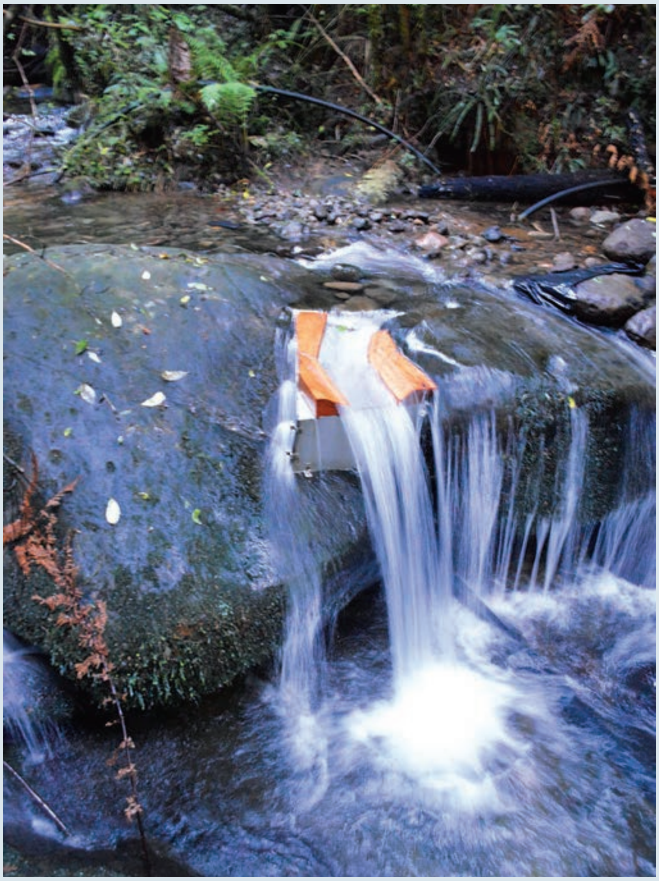
When there is enough water, the system produces 2.5 kW, and there is no need for the diesel generator. To protect the battery from overcharging, surplus energy is diverted to an air-heating diversion load. A relay in one of the OutBack inverters also sends surplus energy to a 40-gallon water heater and acts as an "independent means" to control voltage.

The stream's flow rate is volatile. When the rain stops, Nigel has to close valves at the manifold, which reduces the flow and avoids drawing air into the penstock. At times, there is not enough flow to generate any power, so Nigel added a 5 kW PV array to the system for the drier periods, which are often sunny. The array is more than 100 feet from the battery, so he wired the modules at 90 V through TriStar MPPT controllers to reduce the required wire diameter for a long wire run.

Hugh Piggott (3)

Gross head: 100 ft.
Net head: 80 ft.
Flow: 323 gpm
Penstock length: 500 ft.
Penstock diameter: 5.0 in.
Turbine power: 2.70 kW
Turbine type: 3 Turgos
Turbine make: ES&D
Generator: PMA
Turbine voltage: 24 VDC
Battery voltage: 24 VDC
Cost: $64,500

Off-Grid Home with MPPT-Controlled Hydro



Courtesy Kane (3)

Kane built his house at the edge of the New Zealand bush, far from the grid. A stream flows through his property, and an early priority was to install a microhydro system to provide electricity for running the builders' power tools.

Permitting requirements were extensive and expensive. Stipulations included ensuring a minimum flow in the stream, which he accomplished by deliberately diverting some water. In the summer, when the stream's flow drops, he may need a small PV system.

Kane fitted a custom tank onto the sloping faces of two boulders at the top of a low waterfall, cutting the rock faces to accept the edges of the stainless-steel tank, secured by a dozen rock-bolts. A fine screen on top filters debris from reaching two PowerSpout Pelton turbines. A MidNite Classic MPPT controller connects them to a 48 V battery and a pair of OutBack VFX inverters. The microhydro system was designed using the manufacturer's online calculation tool, but produces 15% more than the estimated 2,050 W output. The MPPT controller optimizes the turbine speed, by tracking to the best voltage, to obtain maximum power. This is the default configuration for PowerSpout off-grid systems.

When the batteries initially reached full charge, the Classic started to taper down the current to prevent battery voltage exceeding the absorption-charge setpoint, and the unloaded turbines started overspeeding. Turbine voltage rose dramatically, but this had been foreseen and remained within the 250 V controller's wide operating window. But it was noisy and put excessive load on the turbines' bearings.

Kane consulted with PowerSpout, who advised him to divert current from the battery side of the controller. One of the Classic auxiliary ports has a "waste-not" mode that can drive solid-state relays (SSRs) in PWM to regulate battery voltage (similar to a TriStar). Kane connected two solid-state relays (SSRs) to the inverter's DC buses and the problem was solved. The SSRs divert up to 60 A into resistor dump loads (located outside the shed) to prevent overspeed. Later, Kane will use the other auxiliary output in the Classic to drive a water heater relay so he can use the surplus enerMgy. Living off-grid has not forced him to do without the normal appliances of a modern New Zealand home, and the system generates enough surplus to charge an electric car.

Gross head: 215 ft.
Net head: 195 ft.
Flow: 104 gpm
Penstock length: 2,180 ft.
Penstock diameter: 3.8 in.
Turbine power: 2.35 kW
Turbine type: 2 Peltons
Turbine make: PowerSpout
Generator: PMA
Turbine voltage: 80 VDC
Battery voltage: 48 VDC
Cost: $40,511

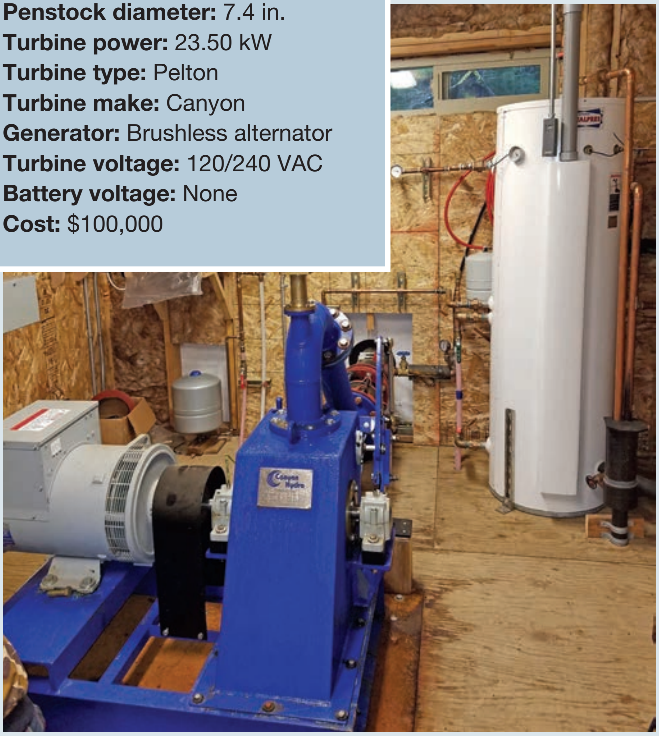
Direct AC Turbine on a Remote Island

Aurora Power & Design had already installed a successful 5.5 kW battery-based triple Turgo microhydro system at a fishing lodge, saving the owners hundreds of thousands of dollars in generator operating costs. When the time came to add a 25 kW turbine at a nearby site, they chose a stand-alone "islanded" direct AC Pelton turbine from Canyon Industries. With so much power, there was no need for batteries. The turbine can meet peak loads easily. Much of the surplus is stored in hot water.

The power quality is excellent, as the turbine speed and frequency are controlled by a Thomson and Howe load-control governor. A custom water tank was built with 1,500 W and 2,500 W elements that are turned on in succession as needed, to maintain constant turbine speed despite the changing demands of the fishing lodge's electrical loads. The controller makes fine adjustments by PWM switching one heater. A second (optional) controller is given priority over this basic one. It harvests excess energy for heating water in the lodge when needed, intervening before the heat is dumped to the large tank. Heat stored in the large tank next to the microhydro turbine is also pumped to a radiant heating system in the lodge to reduce heating costs and use all of the energy produced.

Courtesy Aurora Power & Design (3)

Gross head: 275 ft.
Net head: 261 ft.
Flow: 601 gpm
Penstock length: 1,500 ft.
Penstock diameter: 7.4 in.
Turbine power: 23.50 kW
Turbine type: Pelton
Turbine make: Canyon
Generator: Brushless alternator
Turbine voltage: 120/240 VAC
Battery voltage: None
Cost: $100,000



Go Ahead & Do It!

These are just some examples of successful microhydro systems. There are hundreds more possible features and permutations, including automatic flow control, AC coupling, crossflow turbines, and reservoir intakes.

Because every site is different, some problem solving is inherent in designing a custom system. But with a good basic design and responsive technical support, the system can be easily tuned. If you have a suitable site, a microhydro system is very worthwhile, providing consistent clean energy.