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Pico-Hydro-Plant for Small Scale Power Generation in Remote Villages

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Abstract**:** *The paper presents the potential of pico-hydro plant. The envisaged scheme is well suited in remote rural areas where transmission of power proves uneconomical. Pico-hydro plants can be installed at such places to power one or few homes. The power requirement at such location is minimal during off periods which can be utilized for charging batteries and other electronic gadgets. The pico hydro plants can be installed at much lower financial requirements compared with solar plants and wind mills.*
Keywords: *pico-hydro, micro-hydro, pelton wheel, penstock, hydro-generator.*

I. Introduction

Electricity is the most versatile and widely used form of energy. The global demand for electricity is continuously growing. Availability of useable energy in the form of electricity has gradually assumed an essential component of our daily lives. World trend shows that the demand for electrical energy in developing countries in particular normally grows at a rate faster than the rate at which generation can be augmented. The consequent ever-escalating gap between demand and supply of electricity therefore poses a challenge in technologically developing and advanced countries. As per survey report (January 2014), 7.5 crore Indian households are without access to electricity. The per capita electricity consumption in rural household is found 8 units per month compared to 24 units in urban areas. The reason for such a low level of consumption in rural area is poor access to electricity. The renewable energy act makes the provisions for off-grid small power generations in rural areas. The prospective applications being, solar heating and cooling, renewable energy in transport, promotion of bio-energy and bio-fuels that provides clean energy to all at affordable prices [1,2].

For small, remote communities that require only a small amount of electricity in the range of 1 kW to 5 kW, Pico-Hydro-Plant with smaller turbines of 200 to 300 Watts may power a single home with a head of 1 meter. The setup can be installed at run-of-stream (without dam) and the pipes divert some flow down a gradient through penstock and through the turbine before being exhausted back to the stream [3]. Two examples of pico hydro power can be found in the towns of Kithamba and Thimba in the Central Province of Kenya. These produce 1.1 kW and 2.2 kW, respectively. A five gallon bucket hydroelectric generator was the subject of a work group at 2008 International Development Design Summit (IDDS) at the Massachusetts Institute of Technology. During summer 2013, an energy project in Abra Malaga, Peru was completed using a bucket generator.

II. Development of pico-hydro plant

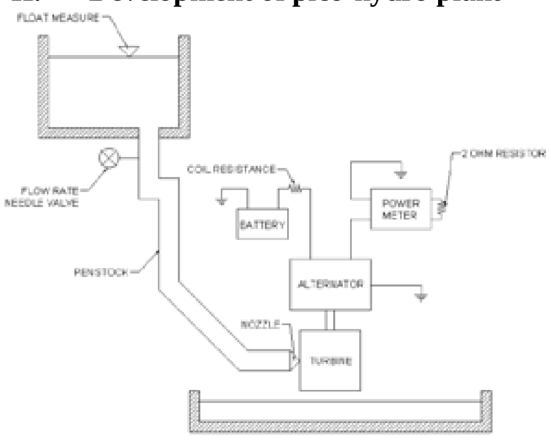

Fig.1 Layout of a Pico-Hydro Plant
(Source: World Renewable Energy Congress, Sweden)

To demonstrate the feasibility of pico-hydro plant, the water reservoir having sufficient capacity may be kept few meters above the ground [4]. The water flows downhill through the penstock. More the height of reservoir, more is the water acceleration for prime moving system which strikes the turbine blade and makes the hydro-generator to rotate. Such a small scale generation may improve the quality of life where transmission of power proves uneconomical in remote villages. In residential applications, depending on the water source and site characteristics, these turbines promise to generate from 4 to 15 KW (or more) continuously. The output of this range of turbines may be from 100 to 1,500 W (and up) depending on the hydro resource. Low-power turbines are available in an array of output voltages, 12 to 120 volt DC, and 120 to 480 volt AC. It is important to note that the output of low-power turbines at higher voltages (120 to 480 VDC) is almost three-phase and the frequency will vary with the rotational speed of the turbine. The first step in designing a pico-hydro system is to evaluate the water resource by measuring the head (vertical drop) and flow of the stream. These two measurements are necessary to calculate the energy potential. The next step is to design a system that effectively harnesses this potential. Hydro sites and end users' needs vary, and a wide range of equipment and system configurations are available to properly match the conditions. Intakes can be as simple as a screened box submerged in the watercourse, or they may involve a complete damming of the stream. The goal is to divert debris- and air-free water into a pipeline. Effectively getting the water into the system's pipeline is a critical issue that often does not get enough attention. Poorly designed intakes often become the focus of maintenance and repair efforts for hydro-electric systems. A large pool of water at the intake does not increase the output of the turbine, nor does it likely provide useful storage, but it allows water to calm so debris can sink or float. An intake that is above the bottom of the pool, but below the surface, avoids the grit on the stream bottom and most of the floating debris on top. Another way to remove debris is to direct the water over a sloped screen. The turbine's water falls through, and debris passes with the overflow water. The potential for energy production in a hydropower plant is determined amount of water available, water loss due to flood spill, bypass requirements or leakage, difference in head between upstream intake and downstream outlet, hydraulic losses in water transport due to friction and velocity change and the efficiency in energy conversion of electromechanical equipment. The total amount of water available at the intake is usually not be possible to utilize in the turbines because some of the water will be lost or will not be withdrawn. This loss occurs because of water spill during high flows when inflow exceeds the turbine capacity, because of bypass releases for environmental flows, and because of leakage. The inefficiency is due to hydraulic loss in the water circuit (intake, turbine and tailrace), mechanical loss in the turbo-generator group and electrical loss in the generator.

Cross sectional area of natural water course [14]:

$$A_r = \frac{(a+b)}{2} * \frac{h_1 + h_2 + h_3 \ldots . + h_k}{k} \quad m^2$$

a width of top river in meter
b width of bottom river in meter
h height in meter

The surface speed:

$$V_{rs} = \frac{L}{t} \quad m/s$$

L length of traverse in meter
t time elapsed to traverse L meter

The average flow speed:

$$V_r = 0.75 * V_{rs} \quad m/s$$

The flow rate:

$$Q \; = A_r * V_r \quad m^3/s$$

Minimum value of submersion:

$$h_s \geq D_h * \left[1 + 2.3 \frac{V_{em}}{\sqrt{g * D_h}}\right] \quad m$$

D_h hydraulic diameter of down-stream conduit (m).
V_{en} entrance velocity (m/s).
g gravitational constant (m^2/sec)

Internal Penstock Diameter:

$$D_p = 2.69 * \left(n_p^2 * Q^2 * \frac{L_p}{H_g}\right)^{0.1875} \quad m$$

n_p manning coefficient
L_p penstock length in meter
H_g gross head in meter

Recommended minimum wall thickness of penstock

$$t_p = \frac{D_p + 508}{400} + 1.2 \quad \text{mm}$$

Saddles are designed to support weight of penstock full of water. The vertical component of weight to be supported in KN

$$F = \left(W_p + W_w\right) * L_{ms} * \cos\theta$$

W_p weight of penstock per meter in KN/m
W_W weight of water per meter in KN/m
L_{ms} length of penstock between mid points of each span(m)
θ Angle of pipe with horizontal

Maximum length between support:

$$L_{mms} = 182.61 \frac{\sqrt[3]{\left(D_p + 0.0147\right)^4 - D_p^4}}{P_w}$$

P_w unit weight of penstock full of water (kg/m)
Power generated in turbine:

$$P_t = \rho g h_n Q \eta_t$$

ρ Water density (1000 kg/m^3)
H_n net head (meter)
η_t turbine efficiency (usually 80 to 90%)
The equation of rotating system:

$$\frac{d\omega}{dt} = \frac{1}{j\omega}\left(P_t - P_l - B * \omega^2\right)$$

ω Turbine speed in radian per sec
P_t turbine power (watts)
P_l load power (watts)
B turbine and generator friction torque coefficient in newton meter/ rad per sec.
J moment of inertia of whole rotating system in kg/m^2.

$$\omega = \sqrt{\frac{(P_t - P_l)}{B}\left(1 - e^{\frac{-2B}{J}t}\right) + \omega_o^2 * e^{\frac{-2B}{J}t}}$$

Turbine speed in RPM

$$N = \frac{60\,\omega}{2\,\pi} \quad \text{rpm}$$

Specific speed

$$N_s = \frac{N * \sqrt{P_t}}{H_n^{5/4}} \quad \text{rpm}$$

A. Penstock

Fig. 2 Generator and Penstock at La Florida
(Source: Five Gallon Bucket Pico-Hydro Electric Generator)

Most hydro turbines require at least a short run of pipe to bring the water to the machine, and some turbines require piping to move water away from it. The length varies depending on the distance between the source and the turbine. The pipeline's diameter may range from 1 inch to 1 foot or more, and must be large enough to handle the design flow. Losses due to friction need to be minimized to maximize the energy available for conversion into electricity. Plastic in the form of polyethylene or PVC is the usual choice for home-scale systems. Burying the pipeline is desirable to prevent freezing in extremely cold climates, to keep the pipe from shifting, and to protect it from damage (cows, bears, etc.) and ultraviolet (UV) light degradation.

Table I: Head Loss In Pvc Pipe

Pipe Size	Head Loss (cubic feet per second)						
	0.05	0.1	0.2	0.33	0.45	0.66	0.89
2 inch	0.128	0.465	1.680	3.570	6.060	9.920	-
3 inch	0.018	0.065	0.233	0.493	0.836	1.790	3.060
4 inch	0.004	0.016	0.057	0.123	0.202	0.437	0.752
6 inch	-	0.002	0.008	0.017	0.029	0.062	0.103
8 inch	-	-	-	0.004	0.007	0.015	0.025

One advantage of using HDPE material instead of PVC is that it does not require protection from sunlight, therefore making it easier to install and maintain. The pipe joints can be heated, welded to create vertical and horizontal bends. Along the penstock, it may be necessary to include additional outlets to allow debris to be flushed out or to release the trapped air. For a typical 2 kW generator requires 0.6 cubic feet per second with a 100 feet head. Three hundred feet of 3 inch PVC pipe carrying 0.6 cubic feet per second from an upstream diversion has a head loss of 3 x 10.2 = 30.6 ft. Thus the diversion must be 100 + 30.6 = 130.6 feet above the generator to compensate for the friction or head loss in the pipe.

B. Turbine

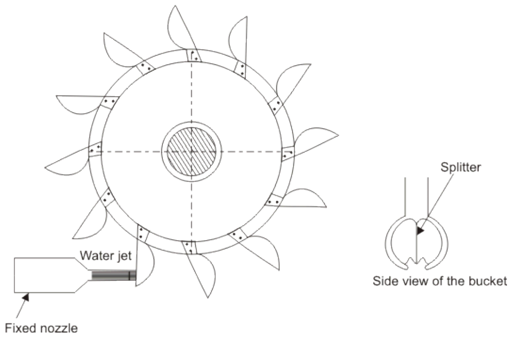

Fig. 3 Pelton Wheel (Water wheel)

The turbine or waterwheel acts as prime mover for hydro-generator. The choice of turbine depending upon site, head and flow is very important. In impulse turbine, the water is routed through nozzles that direct the water at some type of runner or wheel (Pelton and Turgo are two common types). Reaction turbines are propeller machines and centrifugal pumps used as turbines, where the runner is submerged within a closed housing. With either turbine type, the energy of the falling water is converted into rotary motion in the runner's shaft. This shaft is coupled directly or belted to either a permanent magnet alternator, or a "synchronous" or induction AC generator. Most of the turbines have efficiency range between 60 to 70%.

Table II: Groups Of Impulse And Reaction Turbine

Turbine Runner	**Head Pressure**		
	High	**Medium**	**Low**
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	Crossflow
Reaction		Francis Pump as turbine	Propeller kaplan

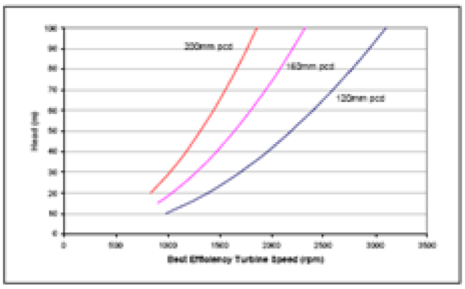

Fig. 4 Graph Showing Operating Range of Three Pelton Runner Diameters

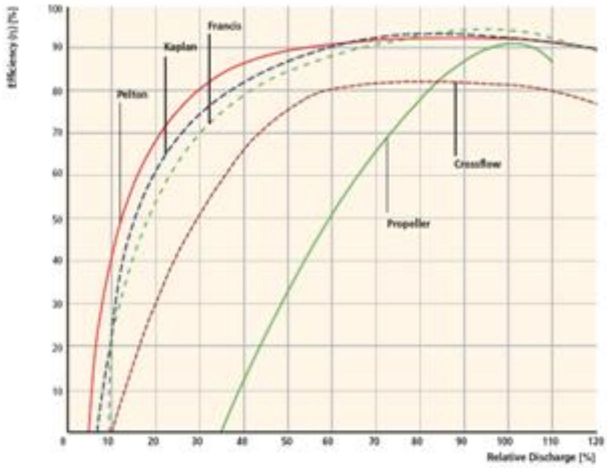

Fig. 5 Typical Efficiency Curves for Different types of Hydro Power Turbine [13]

Flow rate (Q) = $0.83\left(\frac{bd}{144}\right)\left(\frac{100}{t}\right)$

Q Flow rate in cubic feet per sec
b stream width in inches
d average stream depth in inches
t time for float to drift 100 ft in seconds

Power output in kW = 0.0846 x ExQxH

H head in feet
E percentage of hydro electric plant

C. Generator

Induction generators and synchronous generators produce AC power. Induction generators are preferred in remote areas because they are robust and very reliable. An electronic controller connected to out of generator matches power produced to the loads in order to prevent the voltage going up and down.

Installed Capacity of Hydro Power (P) = $\gamma Q H_n \eta$

γ specific weight of water
Q water discharge in m^3/Sec
H_n Net head in meters
η Sum of turbine and generator efficiency

Hydrualic power = Head in meters x flow in litres per sec x 9.81
Mechanical power = net hydraulic power x turbine efficiency.
Electrical Power = Mechanical Power x Generator Efficiency.
Annual Hydro Energy Generation = E x t (kWh/anum)

Fig. 6 Pico Hydro Generators

Table III: Generator Output For Different Heights And Flow For A 300 W Pico Hydro Generator

Height (m)	Height (ft)	Flow Rate (m^3/sec)	Flow Rate (GPM)	Output (watts)
4	13	0.0025	39	40
7	23	0.0046	73	130
10	33	0.0055	87	200
14	46	0.0054	87	300

Table IV: Required Water Flow And Head For Pico Hydro Plants

Generator Output in kW	Head, (feet)				
	10	20	50	100	200
	water flow cubic feet per second				
0.5	1.2	0.6	0.24	0.12	0.06
1	2.4	1.2	0.5	0.24	0.12
2	4.7	2.4	0.9	0.5	0.24
5	11.8	5.9	2.4	1.2	0.6
10	23.6	11.8	4.7	2.4	1.2

Sometimes, a synchronous generator is deliberately chosen as it yields greater efficiencies than asynchronous (induction generators). The introduction of battery storage to stabilize the output and dry season shortages presented an opportunity to make this a more integral part of the design by utilizing the associated benefits.

Table V: Comparison Of Generators Suitable For Pico-Hydro Turbines

Type	Source	Speed
Induction	Standard industrial motor used as generator	1000, 1500, 3000
Synchronous Brushed	Commonly used with petrol and diesel engines	1500, 3000
Synchronous Brushless	Occasionally with diesel engines	1500, 3000
DC	Car or truck alternator	1200 or 2000

D. Powerhouse

The planned dimension of powerhouse is sufficient for safe operation and maintenance of all equipment included within it. A shallow foundation is required on an adequate bearing soil stratum, with a concrete slab cast to provide a rigid base for the turbine and generator. A channel at the base slab is needed for outflow of water from the system. The powerhouse should be secured to prevent unauthorized access.

Fig. 7 Power House

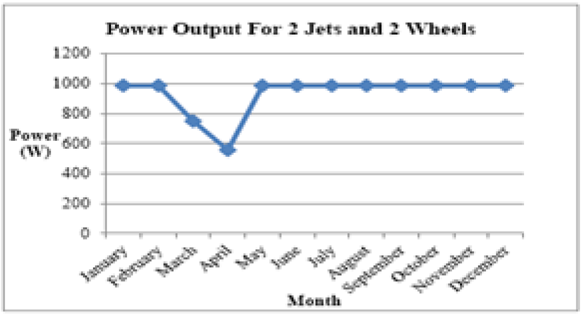

Fig. 8 Monthly Power Output of a Typical Pico-Hydro Plant

E. Dump Load

A dump load is an electrical resistance heater that must be sized to handle the full generating capacity of the pico-hydro turbine. Dump loads can be air or water heaters, and are activated by the charge controller whenever the batteries or the grid cannot accept the energy being produced, to prevent damage to the system. Excess energy is "shunted" to the dump load when necessary. The envisaged scheme offers the potential of excess power at all times. Additionally, the turbine shaft could be connected to a mechanical load such as a flour mill or any non critical load. A discussion with the village is required to identify the most suitable option.

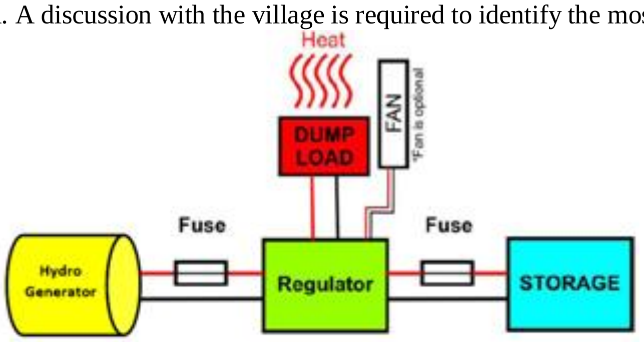

Fig. 9 Dump Load

F. Battery Bank

By using reversible chemical reactions, a battery bank provides a way to store surplus energy when more is being produced than consumed. When demand increases beyond what is generated, the batteries can be called on to release energy to keep your household loads operating. Sometimes

when battery gets fully charged, it is advisable to turn off the generation to reduce the operation time and extend the component lifetime. The prime advantage of using a battery bank with inverter is that is eliminates the need for controls to regulate the speed or load of the generator and saves a significant capital cost.

G. Metering

System meters measure and display several different aspects of pico-hydro-electric system's performance and status—tracking how full the battery bank is, how much electricity the turbine is producing or has produced, and how much electricity is being used. Operating the system without metering is like running a car without any gauges—although possible to do, it's always better to know how well the car is operating and how much fuel is in the tank.

H. Main DC Disconnect

In battery-based systems, a disconnection between the batteries and inverter is required. This disconnect is typically a large, DC-rated breaker mounted in a sheet metal enclosure. It allows the inverter to be disconnected from the batteries for service, and protects the inverter-to-battery wiring against electrical faults.

I. Inverter

Inverters transform the DC electricity stored in battery bank into AC electricity for powering household appliances. Grid-tied inverters synchronize the system's output with the utility's AC electricity, allowing the system to feed hydro-electricity to the utility grid. Battery-based inverters for off-grid or grid-tied systems often include a battery charger, which is capable of charging a battery bank from either the grid or a backup generator if the creek isn't flowing or if the system is down for maintenance. In rare cases, inverter and battery banks are used with larger, off-grid AC-direct systems to increase power availability. The inverter uses AC to charge the batteries, and synchronizes with the hydro-electric AC supply to supplement it when demand is greater than the output of the hydro generator.

J. Breaker Panel

The AC breaker panel, or mains panel, is the point at which all of a home's electrical wiring meets with the provider of the electricity, whether that's the grid or a microhydro-electric system. This wall-mounted panel or box is usually installed in a utility room, basement, garage, or on the exterior of a building. It contains a number of labeled circuit breakers that route electricity to the various rooms throughout a house. These breakers allow electricity to be disconnected for servicing, and also protect the building's wiring against electrical fires. Just like the electrical circuits in your home or office, a grid-tied inverter's electrical output needs to be routed through an AC circuit breaker. This breaker is usually mounted inside the building's mains panel. It enables the inverter to be disconnected from either the grid or from electrical loads if servicing is necessary. The breaker also safeguards the circuit's electrical wiring.

K. Kilowatt-Hour-Meter

Most homes with grid-tied microhydro-electric systems have AC electricity both coming from and going to the utility grid. A multichannel KWH meter keeps track of how much grid electricity you're using and how much your RE system is producing. The utility company often provides intertie-capable meters at no cost.

L. Electronic Load Governor

The function of electronic governor is to maintain the correct speed (rpm). It monitors the output voltage and frequency adding or subtracting electrical load to compensate for human effort. For a 5 kW pico hydro generator, the load at any instant must be 5 kW. If a person switches off a load of 1500 watts, the governor senses the rising frequency and compensate by switching on a different 1500 watts dump load. An electronic load governors are highly effective for small hydro power plant upto 12 kW.

M. Realize the Potential

Hydro-electric systems have great potential, but several things can make using this technology difficult. Diverting the water in a stream or creek is likely subject to regulation by local authorities and may require seeking approval. You also may need to contend with droughts or floods. All hydro turbines have moving parts that require maintenance and periodic replacement. The most common maintenance chore is keeping debris out of the intake [5-8]. Despite the various challenges, most of the problems can be easily overcome. If installed correctly and properly maintained, a pico or micro-hydro system can provide many years of service. The predictable and often ample output is the envy of those restricted to using only wind or solar electricity [9]. At night, when the usage of electricity is minimal, the system charges battery bank and thus becomes ready for another day of energy use when demand peaks up.

N. Types of Electrical Loads

Electrical loads that are normally connected to a pico-hydro system at rural area are lighting, battery chargers, radios, televisions, ventilation fans and refrigerators [10]. For the proposed pico-hydro system, however, the generating capacity is much lower compared to the existing pico-hydro system at rural area. Thus, the main function of the proposed system is for battery charging. A battery allows the future use of small electrical loads and can be recharged when required. Examples of future use of small loads particularly during electricity blackouts are LED lighting, mobile phone battery charging and toys battery charging.

O. Stand Alone System

The energy produced by the generator is directly fed to the load with little controllers. It is ensured that the generator gives an output of 230 volts, 50 Hz. A variation of ±5% percent is allowed because all the electrical appliances have little tolerance limits. The pressure of water jet out of the penstock is maintained so that the generator rotates at its rated speed. A speed measuring mechanism may provide a feedback to the flow control to maintain at its rated value.

P. Grid Connected System

The generator output is fed to charge the battery bank. The inverter with 48 pulse number is enough to feed to the grid. Dealing with harmonics and power factor correction becomes crucial.

III. Pico Hydro Potential In India

Union ministry of new and renewable energy (MNRE) has announced a financial assistance to the tune of Rs 110,000 for setting up 'Pico hydroelectric power projects' in the state of Kerala. The Energy Management

Centre, Kerala, is the nodal agency for identifying potential investors for setting up the pico hydroelectric projects in the state. According to centre director Dharesan Unnithan, Idukki and Wayanad districts have been identified as highly potential areas for setting up the projects.

IV. Discussion

The prominent impacts include changes in flow regimes and water quality, barriers to fish migration, loss of biological diversity and population displacement but can also provide multiple benefits beyond energy supply. Technological innovation and material research can further improve environmental performance and reduce operational cost. With a changing climate, the resource potential could change due to changes in river flow particularly in precipitation and temperature in catchment area. This may lead to changes in runoff volume, variability of flow and seasonality of the flow (e.g., by changing from spring/summer high flow to more winter flow), directly affecting the resource potential for pico- hydropower generation. Changes in extreme events (floods and droughts) may increase the cost and risk for the such hydropower projects. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation and decreasing storage services.

V. Future Work

The electrical output of a Pico-hydro generator keeps on fluctuating and hence a controller is required to keep the voltage within its permissible limits. An off-grid pico-hydro with a simple voltage controller is sufficient to fulfill the load requirement as it is isolated. But when it is grid connected, it has to be routed through battery bank. This opens up new research areas in the field of voltage and frequency controller, grid code compliance, reactive power control, power factor correction, automatic reduction of active power generation according to active power droop characteristic in over frequency [11-12].

VI. Conclusion

In relation to rural development the simplicity and low relative cost of micro hydro systems open up new opportunities for some isolated communities in need of electricity. With only a small stream needed, remote areas can access lighting and communications for homes, medical clinics, schools, and other facilities. Micro-hydro can even run a certain level of machinery supporting small businesses. One seemingly unexpected use of such systems in some areas is to keep young community members from moving into more urban regions in order to spur economic growth. Also, as the possibility of financial incentives for less carbon intensive processes grows, the future of micro-hydro and pico-hydro systems may become more appealing.

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