Modular Pico-Hydro Power System for Remote Himalayan Villages

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Abstract

This paper describes the key learnings made during the final design and construction of a pilot modular pico-hydroelectric project described earlier in Zahnd, A., et al, 2017, pursued due to its ability to grow dynamically with the user demand and ability to pay as they learn to use and value electricity. The paper discusses practical experience from the operation of the system since it was commissioned in November 2018, data collected from the integrated monitoring system, and feedback from local users and the local system operators. Recommendations for future systems based on this modular approach are also discussed.

Keywords: RAPS, Rural, Electrification, Pico-hydropower, Hybrid Power System, Utilization Factor, Community Development, Prepay Electric Meter, PAYG, STS, Renewable Energy, Technology, off-grid, power generation

1. Introduction

Pico-hydro and micro-hydro power (MHP) systems in remote regions of Nepal have had limited long term success due to seven reasons outlined in Sturdivant, R., et al., 2017. A whole new modular approach was envisioned and outlined in Zahnd, A., et al., 2017 to address all seven reasons, and a pilot system using this approach was completed in the Fall of 2018 in the village of Mohari in the Jumla District of Nepal. RIDS-Nepal's new approach addressed the seven reasons of system failure or under-performance outlined in Tab. 1.

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Tab.1: Seven Reasons for Failure of Past MHP and Pico-Hydro Power Systems

Feature or Equipment	Traditional Approach	RIDS-Nepal Approach
Water Canal	Exposed Canal: Susceptible to destruction from small surface landslides common in the region	Buried Pipe/Penstock: Delivery of the water to the turbines with protection from the elements and surface landslides. Increases reliability. Farmable land can remain in service.
Modularity	Single Turbine: Offers no system redundancy and it's difficult to add additional turbines due to phasing issues.	Modular turbines, battery storage, and inverters: Allows redundancy to increase reliability and sustainability, lower replacement cost if one fails, system continues to provide power, and the ability to expand capacity as the village's electrical demands and economic vitality increase.
Generator Drive	Belt Drive: Belts usually break within 0.5 to 3 years and are expensive to replace. Without an economic system, a belt failure can doom the entire system.	Direct-Drive: Each turbine is directly connected to its own generator. Eliminates risk of belt failure, increasing system reliability. Use of permanent magnets increases overall efficiency.
Transmission Lines	Overhead Transmission Lines: Uses very soft wood from local dead trees which rot since they are not treated to resist moisture. Alternatively, metal posts are used which often cannot support high wind and snow loads, or heavy wet clothing draped on transmission lines to dry. Support failure results in line fault.	Buried Armored Transmission Lines: Removes the risk of rot and failure of above-ground supports. Transmission lines are protected from mischief and the elements, and energy theft is much more difficult. Reduces deforestation and all negative impacts which come along with it (increased landslides, soil loss, increased time and risk for women to collect firewood etc.).
Surge Capability	No Surge Capability: Peak demand over generator capacity results in brown/black out, or requires load shedding.	Battery Surge Capability: A small bank of batteries allows the system to deliver peak power in excess of generator capacity, important for starting motors needed to drive economic development.
Economic System	No Financial Plan: No economic plan to support maintenance and operations. No plan for collection of fees.	Use Prepay (Pay-As-You-Go) Meters: The system will only deliver power if you have pre-paid into a maintenance and operations fund.
Excess Energy	Dumped To Exit Water: Excess power is dumped into the exit water stream as heat. Utilization rates of only 10% or lower are achieved.	Excess Energy Utilized In The Village: Excess energy can be dissipated in ubiquitous water heater elements to heat shower water for improved hygiene and biogas slurry for improved production. It can also be dissipated in air heater elements to heat buildings such as a community center.

A video of the project can be found at RIDS-Nepal, 2019b.

This paper describes the key learnings made during the final design and construction of this pilot project, practical experience from the operation of the system since it was commissioned in November 2018, data collected from the integrated monitoring system and feedback from local users and the local system operators.

It should be stressed that this is a research project to investigate the modular concept, especially its ability to grow dynamically or alongside the village's increasing power demand over time. This includes reducing the number of operating turbines to better understand the energy needs of villages with first-time access to electricity; or operating all turbines in parallel to verify the system can run smoothly when summing power from all turbines, and to understand the maximum power capability of the system.

2. Design and Construction

This section describes the design and construction of the system, including key learnings observed during the construction phase of the project.

2.1 Intake

The water intake was constructed in the Spring of 2018. To reduce the wear and tear on the turbines, two levels of sedimentation were used as shown in Fig. 1. First, gabion walls were used to divert most of the river flow to a pre-existing channel which is especially important during the monsoon season, forming a settling pond behind the gabion walls. Additional gabion walls formed the overflow for this pond. The flow of water through this first settling pond is not adjustable. A second settling pond constructed with cement and a locally manufactured sluice gate provides additional settling. The sluice gate is used to adjust the water flow into the second, three-dimensionally shaped pond as shown in Fig. 2 to achieve an even slower flow rate for improved sedimentation, but sufficient to provide all the water needed by the turbines.

Fig 1: Two Levels of Sedimentation Tanks

Remote areas such as the Himalayas are already being impacted by global warming, resulting in higher than usual river flows. Gabion walls have been constructed to withstand more than the normal flood levels.

Fig. 2: Three Dimensionally Shaped Settling Pond

2.2 Penstock

The penstock, 490m long, was constructed with 5 m sections of HDPE pipe manufactured in Nepal. 180mm diameter PN2.5 pipe was used closer to the intake where pressure is low, then 200mm diameter PN4, then 200mm diameter PN6 closer to the turbines where the pressure reaches its peak at $5 * 10^5$Pa (5 bar). The 5 m sections of pipe were thermally welded using a jig and a plate heated by electricity from an 1800W generator as shown in Fig. 3. Even though the plate worked well, properly aligning adjacent pipes proved to be a challenge, especially the PN2.5 sections which were not entirely round, and had thin walls that required more precise alignment. In spite of the difficulties of 98 thermal welds, the penstock was created without leaks.

Fig. 3: Thermally Welding the Penstock

We had planned to bury the entire length of the penstock, but this turned out to be impossible because too many large boulders blocked the path of the relatively inflexible large diameter HDPE pipes needed to supply water to all 6 turbines. Furthermore, the inflexibility of the penstock made it difficult to follow the contours, so sections of the penstock are buried, while others are elevated on stone walls as shown in Fig. 4. Still, the whole penstock was either buried or covered with mud and stones to protect it from the elements and to continue to use the fields for agriculture. In the future smaller diameter HDPE pipes delivered on rolls pose a realistic alternative. These pipes are much more flexible, allowing them to better follow trenches that have been dug to avoid the boulders. Fewer turbines will be fed by one pipe to reduce the losses due to the smaller diameter, so multiple smaller pipes will have to be laid instead of one large diameter pipe.

Fig. 4: Elevated Section of Penstock

2.3 Turbines

Fig 5: Six Turbines, Saddles, and CPVC Supply Lines

Fig 6: PowerSpout PLT-HP Turbine

The penstock is connected to a 200mm gate valve in the 'turbine house' where six turbines are mounted on a concrete exit channel as shown in Fig. 5. Six HDPE saddles were placed on a 5m section of 200mm HDPE pipe downstream of the gate valve. The two nozzles of each turbine were connected to this pipe via 50mm CPVC pipes and a CPVC Tee.

PowerSpout Pelton PLT-HP turbines from Ecoinnovation were used (Powerspout 2019), shown operating in Fig. 6. These turbines appear to be nearly optimal for remote systems because they are light enough (~20 kgs) to be carried on a single person's shoulder, removing the need for helicopter transport; they can be repaired by local personnel in the village using very economical parts; and they are much more efficient than the crossflow turbines commonly used. Our performance monitoring showed an overall efficiency of 72% from water flow to electricity available in the power room, which is quite high compared to the 45% provided by the typical crossflow turbine in a pico or micro-hydro power plant.

The pilot system can generate 6.6kW at 47m net head, with approximately 20 Liter s^{-1} flow, when all 6 turbines are running. Power output can be reduced to just 1.1 kW with only one turbine running to serve the initial power needs of a small village just being introduced to electricity. For example, the village of Mohari, with approximately 40 households consuming power almost exclusively for LED lighting, can easily be served by just 1 turbine.

Good quality grease must be used with any turbine's bearings. The first batch of grease we used was counterfeit. One container actually had a chili in it! Grease should be ordered only from an SKF agent.

Fig 7: Unwinding Armored Transmission Cable from the Spool

The PowerSpout turbines come with an integrated 3-phase bridge rectifier to produce DC, allowing multiple turbines to be wired in parallel to feed each charge controller in the village.

2.4 Transmission Lines

Buried armored transmission lines, 300m long, were used to send the DC power to the power room in the village. Generators operate at 300VDC, allowing the use of smaller diameter transmission lines. This was chosen partly for cost savings, but mostly to simplify transport and construction. The cables came on large rolls as shown in Fig. 7, and even these reduced diameter cables were extremely difficult to manage by a large number of local people since there are no forklifts or trucks available in the village.

2.5 Power Electronics

The power electronics including the charge controllers, battery bank, and inverters are housed in the power room in the village shown in Fig. 8.

Fig. 8: Power Room

Studer Innotec provided three VS-70 charge controllers (Studer Innotec, 2019b), three Xtender XTM-4000 4000W inverters (Studer Innotec, 2019a), and various accessories for the project. The system was very easy to set up to generate 3-phase power to the village. The MPPT algorithm in the VS-70 charge controllers is designed for solar applications, and is unstable with hydro turbines. However, the VS-70 supports a fixed-voltage “Upv-fixed” MPP mode which maintains the input at a specified voltage. This works very nicely with hydro because the operating conditions are quite constant. A manual search of the MPP is sufficient when the project is commissioned. The Upv-fixed MPP algorithm proved to be extremely stable.

Four ubiquitous N-200 truck batteries were used in the system. The truck batteries are recommended over deep cycle batteries because they stay charged due to the continuous power generation, and they have a much higher maximum charge current rating than deep cycle batteries, allowing them to accept all available power from the turbines.

The system is set up so the VS-70s always accept all available power from the turbines to keep them from spinning too fast and creating voltages that could damage the system. A battery-side diversion load controller keeps the battery from being overcharged as described in Section 2.8.

One subtle configuration setting is needed to ensure every VS-70 in the system accepts all power available to it. Each VS70 will determine its own charge state independently if its setting 14036 is set to ‘No’. Although this sounds innocuous, in some cases this causes a single VS-70 to accept less than the full power available to it, even though its battery charge voltage setting is much higher than the current battery voltage. This causes the turbines to spin faster, creating potentially damaging voltages. VS-70 setting 14036 must be set to ‘Yes’ so every VS70s will synchronize its charge state to the state determined by the overall Xtender system.

Other types of renewable energy sources, e.g. wind and solar, can have their own VS70 charge controller to supply power to the batteries without affecting the operation of the turbines.

2.6 Distribution System

Two three-phase spines are routed through the village, one to the East of the power room in the center of the village, and one to the West. Single phase lines are connected to the three-phase buss bars at 12 locked junction boxes distributed through the village to minimize the length of these single-phase lines. The boxes, shown in Fig. 9, were designed by RIDS-Nepal and manufactured in Kathmandu.

Buried armored cables are used for the three-phase spines through the village, and the single phase lines to each customer. This helps prevent energy theft, mischief, and environmental damage.

Fig 9: Junction Box with 3-Phase Buss Bar and Prepayment Meters

2.7 Prepay Electric Meters

Itron donated ACE9000 SSP DIN-R electric meters and Customer Interface Units for the project (Itron 2019). These meters are stored in the junction boxes to help prevent energy theft, and the customers enter 20-digit Security Token Service (STS) tokens into the Customer Interface Unit (CIU) in their homes. The STS Association (STS Association, 2019) owns the STS technology which is the dominant technology used in electric prepayment meters.

Although STS prepay electric meters are inexpensive and ubiquitous, software systems needed to vend tokens to village-level ‘utilities’ are not. A number of prepaid electricity vending solution providers exist for large utilities, but none have been identified that are designed for village-scale ‘utilities’. The cost of support, crafted for large-scale utilities, far exceeds any amount of revenue the providers can get from these small developing villages.

The authors also believe that a nation-level business, operated by a Nepali company, could aggregate many village-scale ‘utilities’ and provide the vending solution and local support to them. The prepaid electricity vending solution providers could support just a few local people, educated with the necessary skills, who would then provide local-language support at a much lower labor cost to the local village-level ‘utilities’. This business could serve existing pico, micro, and mini grids, so the number of meters served by the district-level business could rapidly grow to a level that would warrant interest by large-scale prepaid electricity vending solution providers. This prepay aggregation service, by itself, would probably not economically justify the creation of such a business. But this same business would likely be economically viable if it also provided design, installation, and maintenance services for a large number of village-level electricity systems. The prepay aggregation would just be the way they would guarantee a revenue stream needed to support their operation. The company iPay (iPay, 2019) was a partner on this project, providing the prepaid electricity vending solution and support.

2.8 Useful Dump Loads

Pico and micro hydroelectric systems typically use diversion load controllers to balance the consumption and generation of the system, using either PWM or phase modulation to divert excess power to the water heater resistors in the water returned to the river. This is a total waste of a valuable resource with no added valuable energy service to the consumers.

The Studer Innotec VS-70 charge controllers used in this project are configured to consume all available power from the turbines by setting its float voltage well above 54.4V. A commercial Morningstar TS-60 diversion load controller (Morningstar 2019) monitors the battery voltage to keep it at 54.4 V. If the voltage rises slightly the TS-60 will increase the duty cycle of its PWM output which drives air heater resistors in the community center. Loads in excess of the TS-60’s 60A rating are driven by MOSFET based SSRs mounted to aluminum sheets for heat sinks. They are triggered simply by monitoring the PWM output waveform from the TS-60 diversion load controller, scaled down to acceptable voltages using a resistor divider.

A means to improve the utilization factor of renewable energy systems by dumping excess power to a set of prioritized loads was described in Stambaugh, M., et al, 2017. It proposed that a PWM diversion control signal could be routed to one of a set of dump loads based on priority. The highest priority load that needed additional power based on its temperature took all the excess power. Battery-side diversion was used instead of AC-side diversion because this modular pilot system can continue to operate even if the inverter driving an AC dump load is off-line for maintenance or failure. Two issues were discovered during the final design stage that led to a different solution. Both of these issues resulted from the need to use battery-side diversion operating at 54.4 VDC.

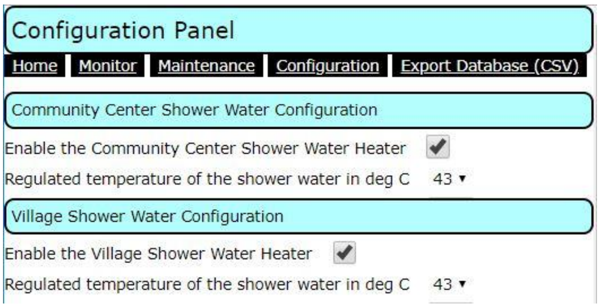
- High power resistive loads operating at 54.4VDC are expensive and far from ubiquitous.
- High currents required to dissipate all excess power at 54.4VDC cannot economically be run to remote locations in the village for convenient use.

Fig 10: Installation of AC Relay Board and Hot Water Tank for Showers

A Linux-based 3360 control computer provided by Schweitzer Engineering Labs (Schweitzer Engineering Labs, 2019) ran the code used to improve utilization, monitor the system, and provide the prepay electricity vending terminal. This ultra-high reliability computer was chosen because only a single Linux computer was used in the system, and its remote location makes replacement very difficult.

The utilization improvement code monitored battery voltage, production, and consumption to determine if there was sufficient power available to turn on useful loads such as shower water heater elements. Hysteresis was used to ensure the loads were not turned on and off rapidly. A small 'AC Relay' board was mounted next to each useful load as shown in Fig. 10 to monitor its temperature. It also included two 10A relays which are used under computer control to turn on or off power to the water heater resistors. 500W and 1000W resistors were used to provide 0, 500, 1000, or 1500W to the useful load depending on the availability of power. The AC Relay board incorporated an Arduino which communicated with the control PC via buried RS-485. RF communication was not used due to licensing issues in Nepal. The AC Relay board is described more fully in Yeh, J., et al, 2019a.

Any number of distributed useful loads can be placed throughout the village. The control PC provides a GUI shown in Fig. 11 that lets the operator specify the relative priority of each load, and the target operating temperature. The highest priority load gets available power if it needs it, up to 1500W. If there is any power left over the next highest priority load gets it if needed, etc. The air heater resistors in the community center, one of which is shown in Fig. 12, are the lowest priority loads, and are able to accept all generated power, e.g. if nothing else needs any.


Configuration Panel

Community Center Shower Water Configuration

Enable the Community Center Shower Water Heater ☑

Regulated temperature of the shower water in deg C 43 ▾

Village Shower Water Configuration

Enable the Village Shower Water Heater ☑

Regulated temperature of the shower water in deg C 43 ▾

Fig. 11: GUI to Set Relative Priority and Temperature of the Hot Shower Useful Loads. The GUI for Other Useful Loads is Similar

Because ubiquitous 230VAC water heater resistors are used in the distributed loads, and power is supplied through the existing village distribution system, these loads are quite economical.

The RS-485 communication cables are buried in the same trench as the armored 230VAC distribution cables. They are run in 15mm HDPE pipe to provide protection from animals.

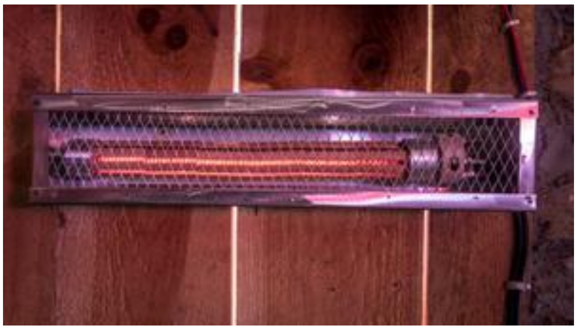


Fig. 12: Air Heater Resistor in the Community Center

2.9 Failsafe

Because we are running the turbines at 300VDC under MPP load, their output can reach about 900V if the Studer VS-70 charge controllers stop consuming all available power. Although this should never happen, Murphy's Law says it will, so two levels of failsafe are employed in the turbine house to limit the voltage. Custom solutions were used due to the high cost of multiple (three) 600V diversion controllers capable of handling the required current.

The first is a custom PCB described in Yeh, J., 2019b, that will dump power via discrete IGBTs using PWM to a bank of water heater resistors in the output stream from the turbines. It contains an Arduino that regulates the turbine output to around 400 VDC, much lower than the 600VDC rating of the VS-70 charge controller, but much higher than the normal 300VDC operating voltage of the system. Two 230VAC water heater resistors are wired in series to withstand the higher DC voltages. The Arduino is also used in the monitoring system described in section 2.10.

The second is another custom circuit board that triggers a discrete SCR when the turbine output voltage rises to around 460VDC. It is a very simple circuit using a precision opamp comparator to quickly trigger the SCR. Once triggered, the turbine output is dumped to the same bank of water heater elements. The turbines must be turned off to reset the SCR.

300VDC was chosen as the operating voltage for the turbines to reduce the cost and weight of transmission cables while providing low losses. However, this increased the potential no-load voltage to over 600VDC, the rating of the VS-70 charge controllers. Preventing this over-voltage significantly complicated the design and cost of the system. Although cost-effective custom solutions were created for the pilot system, this presents yet another challenge to system replication.

200VDC would be a better choice because the no-load voltage would remain below 600VDC, allowing the elimination of the custom over-voltage regulation circuitry and the dump load resistors in the turbine house. Dropping the operating voltage to 200V would increase the transmission current by 1.5x, which would increase the transmission losses by 2.25x. Either fatter conductors could be used in the transmission cable, or the extra losses could be tolerated. The 300m transmission lines each conducted as much as 6.6A at 300VDC to the power house. 4mm2 copper was used for conductors, with losses of around 5.4%. By dropping to 200VDC operation the losses would have increased to about 12.2%, which is probably a good tradeoff to eliminate the complexity and custom over-voltage protection circuitry. Alternatively, fatter conductors would be needed.

3. Operation

This section describes key learnings observed during the operation of the system since November 30, 2018.

3.1 Charge Controllers and Inverters

Studer Innotec supplied their Xtender system including three VS-70 charge controllers and three XTM-4000 inverters, as well as other accessories. The authors are very satisfied with the performance of the properly configured Studer Extender system in this modular pico-hydro-electricity application.

3.2 Air Heater Resistors

Commercial 230VAC air heater resistors were purchased in Kathmandu. They were constructed with eight sections of Nichrome wire, connected in series, on a ceramic core. The resistors as configured would consume very little power at 54.4 VDC, so they were modified so only two sections are wired in series instead of eight. As a result, the Nichrome wire dissipated the same power per section at 54.4 VDC as the original resistor did at 230 VDC.

3.3 Pressure Regulation

At one point the gate valve was partially closed to reduce pressure, or the net head, at the turbines. This was done to explore the operation of the system when power generation is close to the demand of the village. This worked fine, but the position of the gate valve moved slowly due to vibration and other factors, resulting in a gradual reduction of the pressure and generated power. This particular gate valve is not a good pressure regulating device, and we suspect other gate valves available in Nepal have similar properties. Given the modularity of the system, turning off turbines is probably a better approach to controlling the generated power.

3.4 Failsafe

Testing revealed that the PWM control of the Arduino-based custom circuit board described in section 2.9 is too slow to react before the opamp-based crowbar circuit triggers. Fortunately the VS-70 charge controllers are extremely reliable at consuming all available power from the turbines, so nuisance tripping of the opamp-based crowbar has never occurred once the VS-70's were configured correctly. Both the Arduino-based and the opamp-based custom boards are still used to provide redundant protection in case a VS-70 charge controller stops consuming power for any reason. Neither of these custom circuit boards is needed if the turbines are configured at the PowerSpout factory to be operated at 200VDC.

3.5 Prepayment System

The prepayment system was very popular with local government officials. They readily saw how important it was to the long-term success of any system. Although they were familiar with prepayment for cell phones, they had never seen prepayment meters used in an electricity system.

Several issues were observed with the prepaid electricity vending solution from iPay, but they should be attributed to operator error. This should be expected because the training model of utility-scale solutions is optimized for large utilities, not village-scale utilities whose personnel are not literate in English. Although good documentation was provided, on-site training classes are not economically viable for village-scale utilities.

The solution vended 20-digit tokens as specified by the STS standard. These were printed as roman numerals instead of Nepali numerals, but at least they were consistent with the numerals printed on the Customer Interface Unit (CIU) keys. Errors did occur when entering the 20-digit tokens into the CIUs, but the CIU reported that the token failed, and the entry was retried. In a few cases failed tokens were reported by the user after several entry attempts. In reality, they were entered incorrectly multiple times.

3.6 Prioritized Dump Loads

The availability of hot showers as shown in Fig. 13 has been extremely popular, not just to the villagers, but also to the government officials who visited the site during its inaugural celebration in May 2019. People were dancing in the showers. Although we currently do not have Pay-As-You-Showers, the goodwill this service creates significantly improves the users' willingness to pay for the operation and maintenance of the system.

The heated community center rooms are also appreciated by the village. Elder women are given seats next to the heaters, and seem to enjoy this honor immensely. Although the community center isn't heated to Western standards, it improves comfort significant enough to attract tourists and researchers in the future.

The local operator had no trouble understanding the GUI used to set priorities and the target temperature of each useful load.

Fig. 13: Hot Showers!

By heating the shower water, biogas digester, the community center, and other services that are useful to the village, 100% of the available energy can be utilized for useful loads, much better than the typical small system in Nepal. Tab. 2 compares the utilization of the pilot project in Mohari to the system serving the nearby village of Chaura using the traditional MHP approach.

Tab 2. Utilization Comparison

Daily Energy	Chaura's Hydroelectric Approach Serving 200 Households (HH)	RIDS-Nepal's Hydroelectric System Serving 40 Households (HH)
Potential Generation	20 kW * 24hrs = 480 kWh	6 kw * 24hrs = 144 kWh
Power room equipment (considered overhead, not a 'useful load')	NA	80W * 24hrs = 2 kWh
Consumption for lights	200 HH * 2 * 5W * 10hrs = 20 kWh	40 * 3 lights * 3 W * 12hrs = 4.3 kWh
Consumption for cell phone charging	100 HH * 5W * 2hrs = 1 kWh	30 HH * 5W * 2hrs = 0.3 kWh
Consumption for TV	NA	2 HH * 60W * 4hrs = 0.5 kWh
Village Shower Center	NA	1.5kW * 4hrs = 6 kWh
Community Center Showers	NA	1.5kW * 4hrs = 6 kWh
Community Center Lights	NA	20 * 7W * 15hrs = 2kWh
PCs, Laptops	NA	5 * 100W * 10hrs = 5 kWh
Community House TV for education	NA	100W * 5 hrs = 5 kWh
Heating Community Center	NA	112.9 kWh
Total utilized for useful loads	21 kWh (4.3%)	144 kWh (100%)

4. Participation

Fig. 14: Building Elevated Penstock

4.1 Planning

The local community and government officials participated throughout the planning phase of the pilot project through periodic information and discussion meetings to define the location and scope of the power plant.

4.1 Construction

The village committee decided that each household in the village had to donate 100 days of work toward the construction of the modular pico-hydroelectric project and the community center in order to connect to the electricity system. For each day not worked the household had to pay 500 Nepali Rupees (approximately 4 € or 4.5 USD in July 2019). Only two households, about 5%, did not connect because they were absent from the village for the duration of the project. Otherwise almost everybody participated, examples of which are in Fig. 14-16.

Fig. 15: Laying Penstock in Steep Section

Fig. 16: Just About Everyone Participated!

The village community also gathered and processed local building materials such as wood, stone for walls, and sand for concrete.

4.3 Financing Operations and Maintenance

Each household pays 150 NRP (approximately 1.2 € or 1.36 USD in July 2019) per month to connect to the electricity system, and this includes 3 kWh per month. Because high efficiency LED lighting was installed throughout the village, 3 kWh is usually sufficient for basic lighting and cell phone charging, but not enough for a TV. Additional energy costs 50 NRP (approximately 0.4 € or 0.45 USD) per kWh. Although any off-grid system will cost more than a grid-tied service, the rate paid in Mohari is not that much higher than the average residential rate for grid-tied energy in Hawaii (0.33 USD per kWh). Half this revenue pays a salary for the operator, a resident of the village. The other half goes into a maintenance fund to pay for any needed repairs or maintenance.

This financial commitment seems small by western standards, but is significant for subsistence farmers. Some of the villagers wanted the connection fee to be reduced to 50 NRP/month. Their request is understandable since there is no monthly fee for most other systems in the area. Considerable time was spent educating the villagers that the lack of a monthly fee is one of the reasons these neighboring systems often fail early in their lifecycle. Additional time was spent educating them on the value of electricity for education and economic development to give their children opportunities in this ever-changing world. The final solution was that 150 NRP/month connection fee would be collected for each household, which includes 3 kWh per month, but the more affluent residents would help pay the connection fee for the poorest ones.

5. Data Collected

5.1 Monitoring System

A wide range of operational parameters of the system are captured every 15 minutes and exported daily to the RIDS-USA.org website. They can be viewed via the web at http://mohari.rids-usa.org/monitor.php (RIDS-Nepal, 2019a). An improved presentation which will be accessed using the same URL is under development as of July 2019.

The monitoring system stores data from several sources. The power electronics from Studer Innotec provides many parameters dealing with energy production and consumption, as well as battery status. Examples include battery voltage, temperature, and state of charge; output kVA and kW from each inverter; and input voltage and power to each charge controller. Various water and air temperatures in the system, including the temperature of the shower water, are sampled by the custom PCBs mentioned earlier in this article. The monitoring system also captures how much power is being delivered to heat the water for the two showers.

5.2 User Feedback

The village users and the local and regional political leaders are all very happy with the system. Thanks partially to its modular nature, it has been running non-stop since it was commissioned in Nov 2018, aside from very brief interruptions for normal maintenance and enhancements, as compared to traditional systems in the area that are turned off for long periods of time each day and often live a very short life. The additional loads in the village also help everyone realize the power of electricity, even before the village economy grows by utilizing it.

6. Summary

Based on the operation of this pilot system for one year, RIDS-Nepal’s modular approach to pico and micro-hydroelectric systems appears to have solved many of the problems seen with the traditional approach used in remote regions of Nepal. The use of buried penstock, transmission, and distribution lines reduces maintenance and deforestation, preserves farmland, and helps prevent energy theft. The modular use of smaller more contextualized Powerspout direct-drive turbines result in high system reliability through redundancy. Repairs are more economical to small remote systems incorporating prepayment meters to ensure a modest revenue stream. Its surge capability will be useful in starting motors needed for economic expansion. And finally, the full use of the produced power has increased the value of the system, making the end users more willing to pay into the economic system enforced by the prepay meters.

This pilot project was created to explore and verify the operation of the system with different configurations simply by turning the modular components on or off, for example to operate a single turbine, or all six. It was scaled to run as many as 6 turbines, supplying over 6 kW, which is much larger than that needed by a small village being introduced to electricity. Most early adopters of electricity will need only one or two turbines, and won’t need 3-phase transmission at first. Replicated systems also won’t need quite as extensive monitoring, but will need enough to enable remote support by more educated personnel. Another project is planned to explore the costs of a minimum system needed to support a reasonable sized village just being introduced to electricity.

The end goal of this project is the broad replication of this approach which will require design and installation guides, finding ways to manufacture some of the components in Nepal, creation of an ecosystem needed to support the projects, and working with the Nepali government’s AEPC (Alternative Energy Promotion Center) by recommending policies needed for broad replication. Some of these tasks are currently being pursued.

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8. References

iPay, 2019, http://ipay.co.za/ (accessed 25 July 2019)

Itron, 2019, https://www.itron.com/-/media/feature/products/documents/brochure/ace9000-ssp-dinr.pdf (accessed 28th July 2019)

Morningstar, 2019, https://www.morningstarcorp.com/products/tristar/ (accessed 28th July 2019)

PowerSpout, 2019, https://www.powerspout.com/collections/pelton-plt (accessed 28th July 2019)

RIDS-Nepal, 2019a, http://mohari.rids-usa.org/monitor.php (accessed July 28, 2019)

RIDS-Nepal, 2019b, “Modular Pico-Hydro Power Plant Prototype Project in Mohari Village, Jumla, Nepal”, RIDS-Nepal youtube channel with videos for illiterate people and education, https://www.youtube.com/playlist?list=PLM5tNUriiE49lBkt4TVQScwvnfKpSCBUs (accessed 26th July 2019)

Schweitzer Engineering Labs, 2017, https://selinc.com/products/3360/ (accessed 25 July, 2019)

Stambaugh, M., et al, 2017, “Improving the Utilization Factor of Islanded Renewable Energy Systems”, Proceedings of the ISES Solar World Congress 2017, DOI: 10.18086/swc.2017.16.04

STS Association, 2019, http://www.sts.org.za (accessed 25 July 2019)

Studer Innotec, 2019a, https://www.studer-innotec.com/en/products/xtender-series/ (accessed 28ty July 2019)

Studer Innotec, 2019b, https://www.studer-innotec.com/en/products/variostring-series/ (accessed 28th July 2019)

Sturdivant, R., et al, 2017, “Pico-Hydro Electric Power in the Nepal Himalayas”, IEEE Green Technologies Conference (GreenTech), 2017, DOI 10.1109/GreenTech.2017.40.

Yeh, J., et al, 2019a, “Prioritized Load Control System for Pico-Hydroelectric Power in the Nepal Himalayas,” submitted to IEEE Green Technologies Conference (GreenTech), 2020.

Yeh, J., et al, 2019b, “Programmable Turbine Failsafe System for Pico-Hydroelectric Power in the Nepal Himalayas,” submitted to IEEE Green Energy and Smart Systems Conference, 2019

Zahnd, A., et al, 2017, “Modular Pico-Hydro Power System for Remote Himalayan Villages”, World Renewable Energy Congress XXVI. DOI 10.1007/978-3-319-69844-1_45