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Minimizing the Lead-Acid Battery Bank Capacity through a Solar PV - Wind Turbine Hybrid System for a high-altitude village in the Nepal Himalayas

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Abstract

Of the estimated 1.6-2 billion people who lacked access to electricity at the end of the last millennium, millions have gained access to basic indoor lighting through off grid solar PV home systems with lead acid battery storage over the last decade. In Nepal, through government subsidy programs and INGO/NGO projects, around 350,000 solar PV home systems have been installed since 2001, mainly in remote, high altitude Himalayan communities. The author's field experience shows that within 6-24 months, 50-70% of the solar PV home systems are either not properly functioning, or not working at all. This is mainly due to substandard equipment, lack of user awareness, inability to maintain their systems, as well as the nonexistence of after sales services. Thus, an estimated 250,000 "dead", flooded lead-acid batteries are either unsafely disposed of or lying around, posing huge potential hazards for people and the unique yet fragile Himalayan ecosystem. The research conducted demonstrates that by tapping into more than one renewable energy resource, converting the local available solar and wind resources into electricity through a solar PV - wind turbine hybrid RAPS (Remote Area Power Supply) system, the lead-acid battery bank capacity can be minimized by 57%, compared to an equivalent energy generating solar PV RAPS system, without jeopardizing, or reducing the village's load demands. This project shows that wind and solar resources are complimentary to each other over several hours in an average day. Thus, by utilizing both of the local wind and solar resources and converting them into electricity to meet the loads directly or to store into the lead-acid battery bank, it allows an average of 3-4 hours longer electricity generation per day. This enables the design of smaller battery bank capacities for hybrid RAPS systems without limiting the end users' energy services. Hence, long-term health risks to the people, as well as environmental damage to the delicate and exceptional Himalayan flora and fauna through disposed "dead" lead-acid batteries, is reduced.

Keywords: Solar PV; Wind Turbine; Remote Area Power Supply; Rural Electrification; Renewable Energy Resource Assessment;

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1. Introduction

In 2011, the NGO RIDS-Nepal [1] designed and built a small solar PV (160 W_R) - wind turbine (160 W_R) hybrid RAPS system that has been operational since January 2012. The RAPS system's power generation as well as its wind and solar resources have been monitored in order to determine its performance and to understand how complimentary the solar and wind resources are in generating electricity throughout the year. Analyzing hourly data over one year of the solar and wind energy resources revealed that both resources complement each other through the course of an average day. The data indicates, that tapping into both resources extends the average daily electricity generation, meeting the defined load without additional battery discharge, by 3-4 hours compared to solely converting and storing solar energy.

Based on these results, a solar PV – wind turbine hybrid RAPS system, at 4,500 meters altitude for the village of Chala (with 50 homes at 3,800 meters altitude (App. E)) in the north-west district of Humla, Nepal was designed (Fig. 1). Calculating the theoretical RAPS system power/energy generation over the year for the proposed site, considering the village's assumed daily load profile, a battery bank capacity was calculated based on a Matlab generated mathematical algorithm for both, the solar PV – wind turbine hybrid RAPS system and a solar PV RAPS system only. Findings that quantify the extent the lead-acid battery bank can be reduced by tapping into both resources with the village's load consumption pattern are presented and discussed. Further, technical challenges (App. D) for the design of a hybrid RAPS system within such an extreme climate are highlighted.

Fig. 1. Chala Village (3,800 m altitude) with the hybrid RAPS system at 4,500 m altitude and 1,700 m away

2. Methods

The proposed hybrid RAPS system consists of a 6 kW_R solar PV array (24 x 250 W_R solar PV modules) with three, 3.5 kW_R horizontal-axis wind turbines. In order to directly compare the hybrid RAPS system to the solar PV RAPS system, both systems' theoretical annual energy generation were modeled to yield equivalent overall energy output. Thus the reference system, a solar PV-only RAPS system, consists of a 12 kW_R solar PV array. The RAPS system will be connected to the village through a 1,700 m long, underground buried, aluminum transmission cable with 1,000 volts, to minimize current losses. An evenly climbing mountainside, south-west oriented with a 45-degree slope with no vegetation, leads to the mountain top where the RAPS system's wind turbines will be installed (Fig. 1).

There was no recorded resource data available for the local solar, wind and ambient conditions to calculate the RAPS systems' daily and annual energy generation. Thus, the hourly global solar radiation over the year on the POA (plain of the array), at 35° south inclined, latitude 30.1° North, and longitude 81.6° East, as well as the ambient temperature at 4,500 m altitude, were simulated with Meteonorm 7 [2]. Wind power availability was estimated using the wind speed, the monthly averaged atmospheric pressure (mbar) and relative humidity (%) of the NASA Surface Meteorology and Solar Energy databank [3] at the nearest available elevation of 4,895m. As the NASA databank provided only average monthly wind speeds in 3-hour increments over the day (i.e. a 8 x 12 dataset for the year), the 3-hour values were assumed to be constant and thus used for the hourly wind energy calculation. Further, as the wind speed data was only available for an altitude of 4,895 m, the data was reduced by 5% for an altitude of 4,500 m, to account for a decrease in wind speed due to surface roughness. Fig. 2 presents the wind speed distribution (hours/year) for the RAPS systems' location.

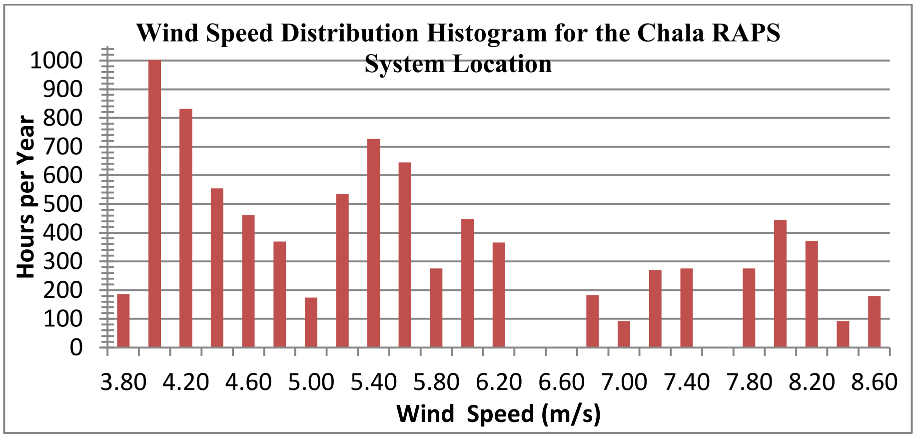

Fig. 2. Annual Wind Speed Distribution Histogram for the Chala RAPS system location at 4,500 m altitude

In order to create an accurate representation of the demand on the battery bank, an estimated daily village load profile based on Chala's daily energy usage, was estimated based on the author's field experience (Fig. 3). Fig. 3 shows Chala's daily priority loads which provide electricity for indoor lighting, torch/mobile battery charging, radio usage, and container heating. A 10 ft. container will house the battery bank, inverter, transformers and energy management system. The container will be installed at the RAPS system location, which will be 800 m above and 1,700 m away from the village (Fig. 1). Due to the harsh climate and the temperature sensitive nature of the equipment, the container will be buried into the ground and air heated, to maintain a temperature above 10°C. The priority load designated towards container heating will guarantee that the container will stay within the ideal temperature range of 15°C-25°C, to provide especially the battery bank ideal temperature conditions. To minimize heat loss within the container, it is insulated with 12.7 mm Styrofoam on all six walls and has an additional 12.7 mm thick wooden floor. Field experience dictated that the priority loads have to be met 100% of the time. In addition to the priority loads, two deferrable loads, a seed oil expeller and an insulated water heating system for increased access to warm/hot water for cooking and improved personal hygiene, are powered when excess energy is produced and the battery bank is already fully charged.

An optimization algorithm was developed using Matlab, in order to determine and compare the theoretical size of the battery bank for both, the hybrid and solar PV only, RAPS systems. The inputs were the modeled power generated for both RAPS systems at the installation site, as well as the load of the village, for every hour over a year. The main objective of the program was to be able to calculate the battery bank size for both the hybrid and solar PV RAPS systems and determined the extent of battery bank capacity reduction for the hybrid versus the solar PV RAPS system. Using the resulting battery bank size simulation, it was able to model the depth of discharge (DoD) for every hour over the year and therefore be able to anticipate the life expectancy of the battery bank for each system.

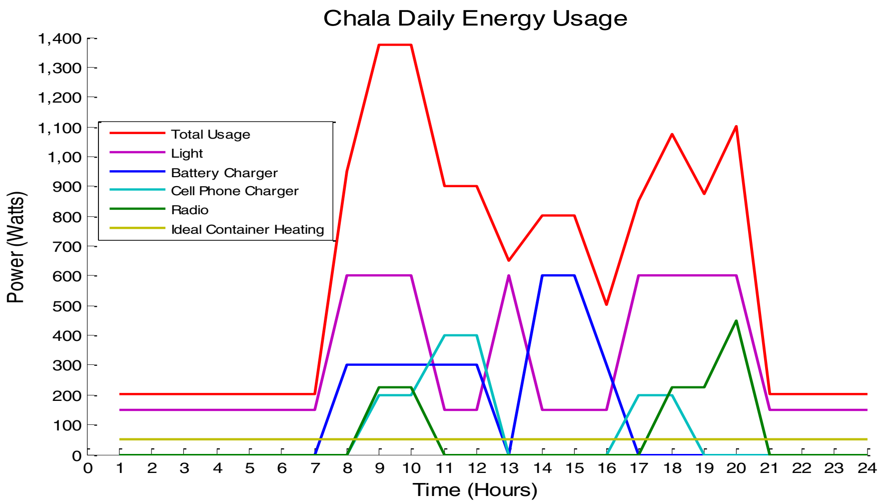

Fig. 3. Average Daily Chala Village Power Profile

In order to simulate the battery bank under as realistic conditions as possible, certain assumptions and constraints were placed on the battery bank, such as the average battery bank energy in/out efficiency was 85%. Further, whenever sufficient power was available to meet the village's load, it was delivered directly from the RAPS systems, without going through the battery bank. In order to assure the longest possible lifetime of the battery bank, it will only be discharged to a maximum DoD of 60% (or SOC (State of Charge) of 40%). The priority loads must be met 100% for every hour of the year, whereas it will be sufficient to meet the deferrable loads for the oil expeller and the water heating system, at least 85% or more of the time over the year. Additionally, in order not to waste energy water will be heated when there is excess power available and when the battery bank is full.

3. Results

The simulation results indicate a clear seasonal dependency on power generation for both, the solar PV array and the wind turbines. The lowest total power output, as expected, was during the monsoon months from July to September, when there are typically minimal wind speeds and solar radiation, due to increased rainfalls and often cloudy skies. The highest individual and total hybrid RAPS system power output was during the colder fall, winter and spring months from October to April, when there are clear skies and large solar radiation, with a high average monthly clear sky index of 0.83 [3]. Low temperatures during those months also maximize solar PV cell power generation as well as wind power generation due to increased air density. The average adjusted NASA databank wind speed for the Chala Hybrid RAPS at 4,500 m was 5.7 m/s, while the average hourly and daily global solar radiation on the 35° south tilted POA (plain of the array), simulated with Meteonorm 7, was 212.4 W/m^2 and 5.098 kWh/m^2 per day respectively. Based on the calculation, the three wind turbines generate an annual average power of 1,124 W and an average winter power of 1,515 W. The 6 kW$_R$ solar PV hybrid array produced an annual average power of 1,242 W and average winter power of 1,609 W (Fig. 4).

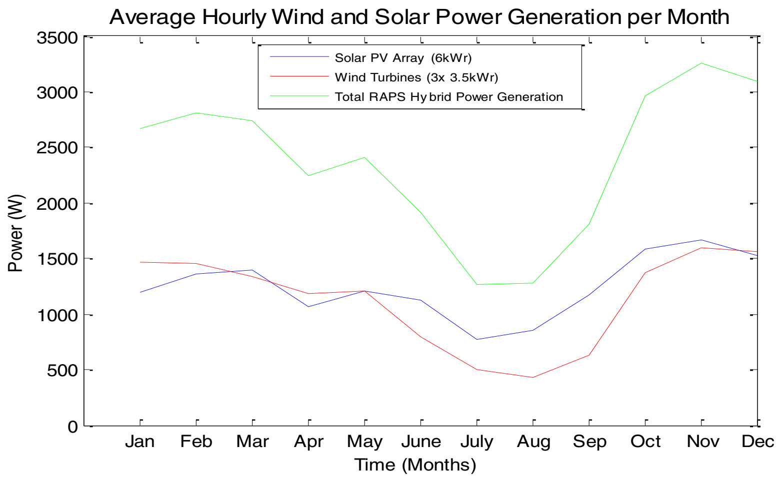

Fig. 4. Average Hourly Wind and Solar Power Generation per Month
for the Chala Village RAPS System Location at 4,500 m altitude

Fig. 5 demonstrates the hybrid RAPS system's hourly power generation over an average day. As anticipated, the daily solar energy generation was represented by a bell-curved shape, peaking during the midday hours. In comparison, the wind turbines generate more energy during the early morning hours, from 3am-10am, and during the night, from 7pm onwards, when the sun's power was not available or weak, thus complementing the solar resource effectively. The three wind turbines generated an average of up to 2,000 W in the early morning hours from 5am-9am, when the village load is assumed to be the highest (Fig. 3) and before the rising sun is able to generate useful power. On the other hand the solar power array is taking over the bulk of the daily energy generated from the wind turbines from around 10am onwards till 5pm.

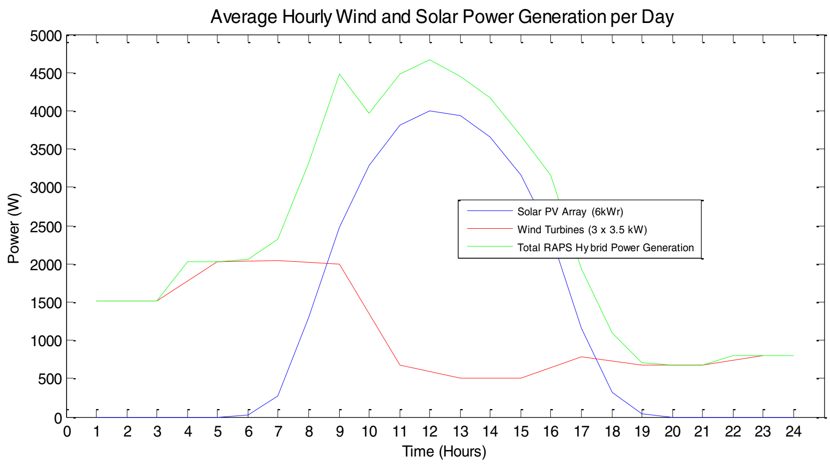

Fig. 5. Average Hourly Wind, Solar, and total Power Generation per Day

Table 1 provides the simulated average power and energy generation for the Solar PV – Wind Turbine hybrid and the Solar PV RAPS systems.

Table 1. Modeled power and energy generation for both RAPS systems: the solar PV – wind turbine hybrid and solar PV-only reference system

	Solar PV Array ($6\ kW_R$)	$3 \times 3.5\ kW_R$ Wind Turbines	Total Solar PV - Wind Hybrid RAPS System	Solar PV Array System ($12\ kW_R$)
Annual energy generation (MWh)	10.880	9.848	20.730	21.760
Daily energy generation (kWh)	29.800	26.980	56.790	59.610
Average power generation (kW)	1.242	1.124	2.366	2.484

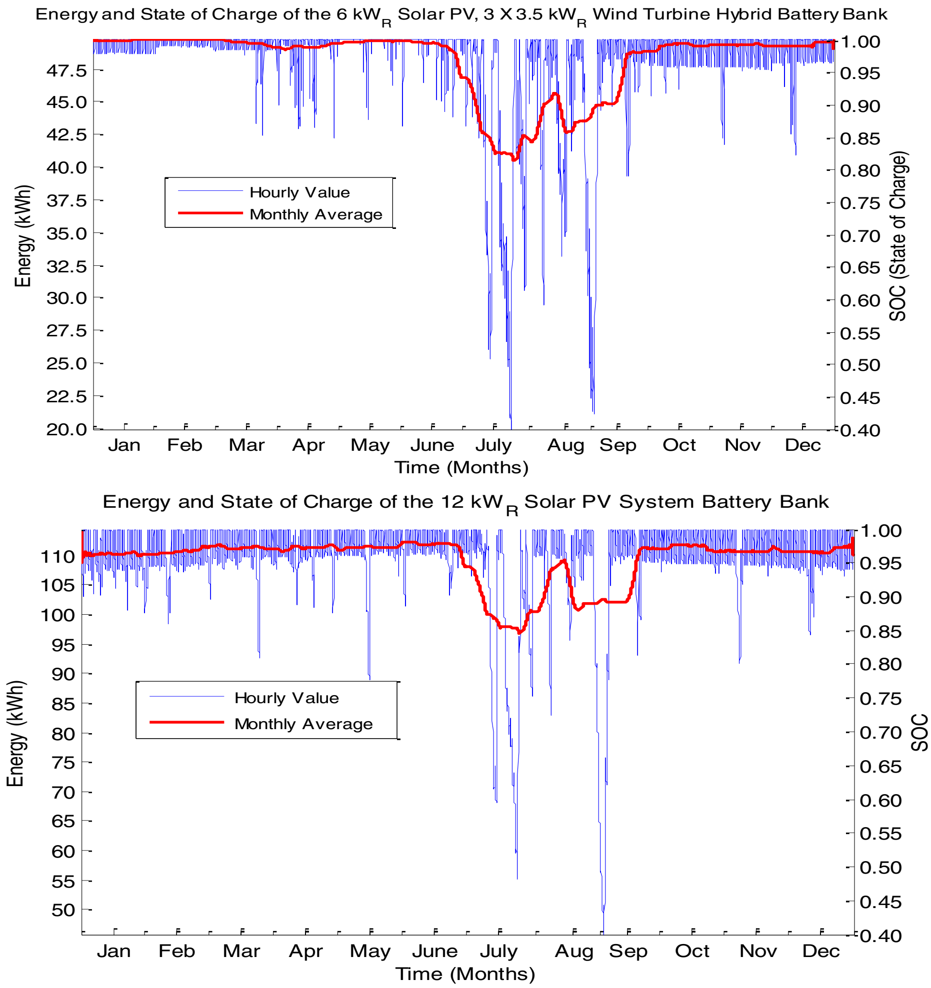

Fig. 6: Energy Capacity Profile and SOC (State of Charge) of the battery banks for the (a) Solar PV – Wind Turbine Hybrid RAPS System (b) Solar PV-only RAPS System Battery Bank over the Year. Monthly moving average is also shown.

Matlab simulation results for the RAPS systems' power generations, considering the defined battery bank constraints and the village's daily load profile for the year, show that the battery bank capacity for the hybrid system was required to be 49.8 kWh while that for the solar PV system was 114.5 kWh. Therefore the solar PV – wind turbine RAPS system's battery bank capacity was reduced by 64.7 kWh, a reduction of 56.5%. Fig. 6(a)/(b) show the energy stored in the hybrid and solar PV RAPS system battery banks respectively for every hour over the year, as well as the monthly average energy contained in the battery bank.

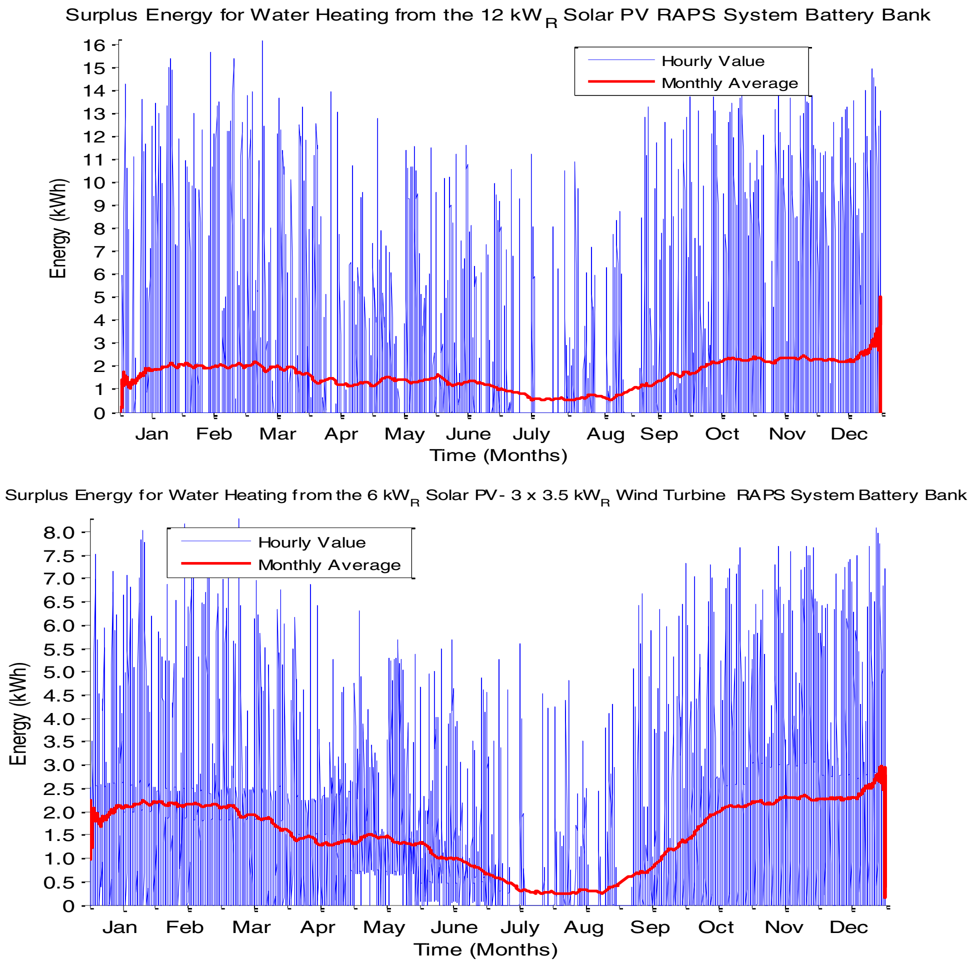

Fig. 7: Surplus Energy from the (a) Solar PV RAPS System and (b) Solar PV - Wind Turbine Hybrid RAPS System for Water Heating over the Year

For both the 115 kWh solar PV system and the 50 kWh hybrid system battery bank, the priority loads were met every hour, while the total loads were met 99.99% throughout the year. Over the year, the solar PV and hybrid system failed to meet the 2 kW oil expeller loads each only during one hour, falling short of 21 Wh early in September, and 472 Wh during late July (Fig. 6), for the solar PV and hybrid system respectively. However, traditionally, the oil expeller is used only after the harvest season from late October to end of winter. Over the year, the solar PV system will provide 13,939 kWh excess energy for heating water while the hybrid system will provide 13,117 kWh. The hourly excess energy to heat water is presented in Fig. 7 for the solar PV and hybrid systems respectively. The hourly average energy provided for water heating is 1.50 kWh for the hybrid system and 1.59 kWh for the solar PV system.

Both systems' batteries only discharged to the maximum DoD of 60% once during the entire year. The hybrid and solar PV RAPS system battery banks discharged below 50% of its respected capacity nearly an equivalent number of hours over the year, 55 and 56 times for the hybrid and the solar PV battery bank respectively. The hybrid system battery bank discharged past its 40%, 30%, 20% and 10% DoD capacity a bit more frequently than the solar PV system battery bank. In total, the solar PV system battery bank discharges 1,906 times a year to a DoD between 5% and 60%, while the hybrid system battery bank only 1,224 times. This is reflected in the average hourly battery banks' SOC values, 97% for the hybrid system and 95% for the solar system.

4. Discussion

Although the hybrid and solar PV systems produce a comparable amount of energy over the year, the 50 kWh battery bank capacity of the hybrid system was 56.5% smaller than the 115 kWh solar PV system battery bank. Despite the reduced battery bank energy storage capacity, both systems were able to meet the defined priority loads at any time throughout the year, as well as the total annual village load of 7,461 kWh, 99.99% of the year. The battery bank reduction was due to the complimentary nature between the wind and solar resources, by tapping into both resources rather than utilizing the solar energy only. Results indicate that wind power was able to produce energy when solar energy was unavailable or weak during the night, early mornings and evenings. Even during the 3 month monsoon season, from July to September, with increased diffuse solar radiation because of the stratus clouds overcasting the sky for long time periods combined with low wind speeds due to minimal atmospheric pressure differences, the wind turbines support the minimal power output of the solar PV array (Fig. 4).

By diverting excess energy to heat water when the battery bank is full, both RAPS systems are able to utilize energy that otherwise would be wasted. Fig. 7 represents the hourly, as well as the average monthly excess energy delivered by the solar PV (a) and hybrid RAPS (b) systems. The graphs demonstrate that both systems' battery banks can deliver an average of ~2 kW during the colder months from October through to April for water heating[1], which can be used to cook rice faster, boil water for tea and to have access to warm/hot water for improved personal hygiene, all energy services which would need to be provided otherwise with additional firewood consumption. A comparison of the hourly excess energy provided to heat water (Fig. 7(a) with 7(b)) shows that the 12 kW_R solar PV-only system contributed up to 16 kWh energy per hour for water heating, compared to 8 kWh energy per hour for the hybrid system. These high solar PV power output values for water heating are due to the very cold and high midday solar radiation conditions during the colder seasons, maximizing the solar PV power generation, while the local demand is low near midday (Fig. 3). However, the monthly average excess energies delivered by both RAPS systems show that they provided nearly equivalent amounts of excess energy for water heating. This is also supported by the yearly total energy generated from the solar PV system with 21,760 kWh, and 20,730 kWh for the hybrid system (Table 1), at an hourly average power of 2.366 kW for the hybrid, and 2.484 kW for the solar-only system. Solar energy, being a highly fluctuating resource, was able to provide peak excess energy for water heating during the middle of the day but not during the morning or night time. In contrast, the solar PV – wind turbine hybrid RAPS system was able to provide a more consistent, less fluctuating amount of hourly energy for the village's loads and water heating. Due to the smaller capacity of the hybrid RAPS system's battery bank one would assume that the demand on the battery bank from the load would require it to more frequently be discharged to greater

[1] Considering a 2,000 liter insulated water tank with an overall efficiency of 60%, a cold water inlet temperature of 10°C, a cp value for water of 4.2 kJ/°C kg, the 2,000 liter water can be heated up over a 24-hours period to around 40°C, helping minimize the firewood consumption for cooking the daily rice, or start to boil a kettle of tea, or for a hot shower, thus improving the personal hygiene of the local people and helping to minimizing the already the extension deforestation.

depths and thus it would be full less frequently. However, this is not the case despite the smaller capacity it was still able to provide comparable quantities of excess energy for heating water for the village.

Furthermore, even though, the battery bank of the hybrid RAPS system had a 65 kWh smaller capacity, it overall experienced a slightly higher average SOC of 97%, compared to the solar PV battery bank with 95%. The lower average SOC of the solar PV system battery bank was chiefly because solar power is generated only during the day and fluctuates both, seasonally and daily. Therefore the battery bank needs to be drawn upon more frequently. However, the hybrid system's battery bank has to discharge past 10%, 20%, 30% and 40% of its capacity more frequently than the solar PV system's battery bank does. Fig. 6 shows that both systems' battery banks' are discharged to their greatest depths between the middle of July and early September, which is the monsoon season.

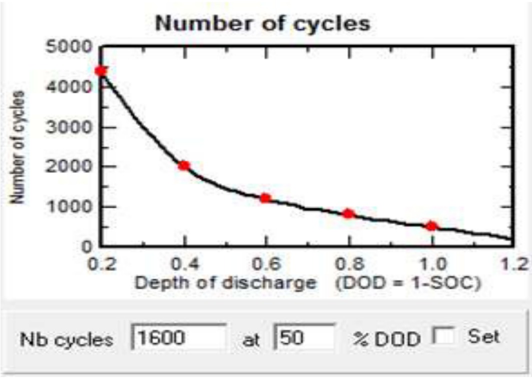

Fig. 8. Number of cycles versus the DoD for the Sonnenschein, A600, 10 OPzV 1200 GEL-VRLA, deep-cycle, tubular battery

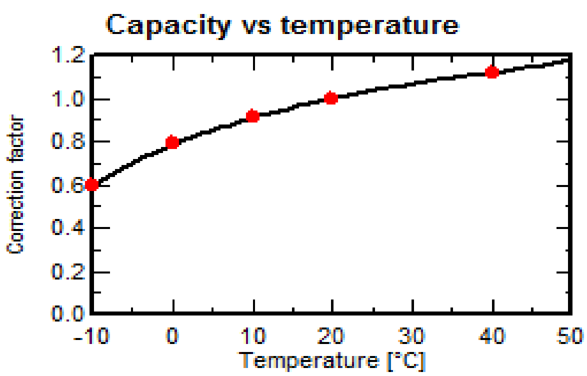

Fig. 9. Sonnenschein, A600, 1200Ah capacity at C_{10} solar battery Ah capacity correction factor versus the discharge temperature in °C.

The objective for determining the number of discharge cycles for each battery bank was to be able to estimate its theoretical lifetime expectancy under the prevailing power generation pattern, the village load profile and the environmental conditions. The life time of a remote and hard to access RAPS system is commonly designed for 20-25 years. Thus, with the Chala RAPS system being so isolated, with high air and porter transportation and installation costs, the battery bank has to last for the entire RAPS system's life, or ≥20 years. The battery technology, enabling such long life expectancies, if properly installed and used within the correct specified parameters, is the 2 Volt, deep-cycle, tubular, gel, VRLA battery. For the present research conducted the Sonnenschein A600 10OPzV 1,200 GEL-VRLA battery was chosen, as, according to the manufacturer, it can undergo 1,200 discharge cycles to 60% DoD, assuming the battery is maintained at a constant temperature of 20°C. According to Fig. 8, from the PVSyst5.62 [4] equipment library, the A600 battery can undergo about 1,600 discharge cycles to 50% DoD. Considering that the hybrid and solar PV battery banks were discharged to 50% 55 and 56 times per year, the theoretical lifetime expectancy for the battery banks were 29 years for the hybrid and 28.7 years for the solar battery bank respectively. Fig. 9 shows that the battery bank's capacity is directly dependent on the temperature and thus how important it is to keep the battery bank within a defined temperature range, ideally between 15°C - 25°C. This is one of the many technical challenges in such a remote and harsh environment and thus the container, where the battery bank, inverter and energy management systems will be installed, needs to be heated.

Further, the Sonnenschein A600 solar battery discharge time dependent on the discharge current (village load) at a room container temperature of 15°C have been simulated. Starting with an initial full battery bank, with no additional energy being feed into it from the RAPS system, the maximum annual village load of 3.84 kW, drawing 80 A out of the 48 VDC battery bank, the average load throughout the year of 864 W, drawing 18 A, and the minimum load (480 W) with 10 A discharged can be provided for 14.2 hours, the average load for 63 hours and the minimum load for 113.5 hours respectively. That means that the designed battery bank can provide the average village load, without being charged due to “unfortunate/bad” weather conditions (no sun shine and no wind), for 2.5 – 3 days independently.

5. Conclusion

The potential health hazards to people and the fragile Himalayan ecology due to the estimated 250,000 unsafe disposed flooded lead-acid batteries from premature and poorly designed solar PV systems for basic improved electricity access, is an important environmental and health issue to be addressed.

RIDS-Nepal has designed, installed, ran and monitored a small solar PV – wind turbine RAPS system since January 2012 [5]. Data demonstrates that the wind and solar resources complement each other, resulting in daily 3-4 more hours longer electricity generation. Hence, due to the increase in hours that electricity is generated, primarily at night, the lead-acid battery bank can be minimized without increasing the risk for loss of load for the users.

These results formed the basis for the design of a very remote, high-altitude hybrid RAPS system for Chala village’s 50 families. The RAPS system will be at 4,500 m altitude, and similarly the local wind and solar [6] resources will be tapped into in order to minimize the battery bank capacity without compromising the village’s daily load profile. A Matlab simulation program was developed to simulate two different RAPS systems, one utilizing the wind and solar resources and one using only the solar resource. With the same resource data, simulations revealed that the hybrid RAPS system’s battery bank can be reduced by 56.5% compared to the solar PV RAPS, without any loss of load or minimized energy services or quality to the local end user community. That means that by tapping into more than one local available renewable energy resource and converting it through renewable energy technologies such as a solar PV – wind turbine hybrid RAPS system, the energy storage capacity can be significantly limited, without jeopardizing the users expectations of the RAPS system’s energy services. The simulations ensured that the battery banks would be able to provide the load profile assumed throughout the RAPS system’s life expectancy, which is between 20-25 years. Further, instead of flooded lead-acid batteries, sealed, deep-cycle, valve regulated lead-acid (VLRA) gel batteries have been chosen, as they are maintenance free and, if properly designed and run under the correct conditions, have a far longer life expectancy with significant lower threats and hazards to people and the environment.

Thus, tapping into more than one renewable energy resource provides a practical solution against the present enormous potential hazards for the fragile high-altitude Himalayan environment and the people, in particular for small children and pregnant women, from unsafe disposed “dead” flooded lead-acid batteries from failed solar PV systems.

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