The Importance of Monitoring and Performance Analysis of a Rural Solar PV Electrification Project

Malla Avishek[1], Zahnd Alex[2], Dr. Haddix McKay Kimber[3], Ellul Alicia[4]

[1]Rural Intregrated Development Service (RIDS) -Nepal
[2] Kathmandu University & RIDS-Nepal
[3] University of Montana & The ISIS Foundation
[4] Planet Contracting Services
[1]avishek.malla@gmail.com , [2]azahnd@wlink.com.np

ABSTRACT

Over the last decade there has been a significant increase in the number of projects implementing solar Photovoltaic (PV) systems for rural electrification. Unfortunately many of these systems are not able to provide the energy services expected by end-users, nor attain their projected life expectancy. Thus, many projects fall short of their intended aim. Long- term monitoring of solar PV systems in their installed context, to analyse their detailed performance over time and local seasonal shifts is almost unheard of, especially in developing countries. The vital information gained through monitoring is essential to understand a system's actual field performance. This leads to more appropriate system design, considering the local context in regard to the prevailing meteorological conditions and energy service demands.

Since November 2006, RIDS-Nepal, with the support of the ISIS Foundation, has been monitoring and recording twenty-one parameters for a 2-axis, central-tracking solar PV village system, installed in Tulin village, in the remote high altitude north-west district of Humla, Nepal. The system provides continuous electricity for 3 WLED (white light emitting diode) lamps for each of the twenty-eight households in the village. This paper presents a detailed description of the solar PV data monitoring system as well as graphical presentations and descriptions of the monitored parameters. The analysis focuses on daily solar PV power output, battery bank's performance, load usage and load patterns as well as the system's performance ratio.

INTRODUCTION

Tulin village is located at latitude 29°59'23.48" North, longitude 81°46'57.05" East and lies at 2'377 meters above sea level. It is a three hour walk along the trekking route to Mansharowar in Tibet from Simikot[1].Twenty eight households of the village are electrified with a $300W_R$, 2-axis, self tracking, solar PV system powering a 300Ah, 24V deep cycle battery bank with an autonomy period[2] of 3 days. Each house is connected through underground cabling to the battery bank and has 3 WLED lamps installed, consuming 1 watt each.

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[1] Headquarter of Humla District
[2] Days without sunshine

Fig.1: Tulin village with 28 households and with the 2-axis tracking central PV system

METHODOLOGY

Eleven fundamental parameters are monitored and ten additional parameters are consequently calculated to determine the status and the performance of the solar PV village system and its equipment. They are measured and the data recorded using a DT80 dataLogger[3] (see Fig. 2). The measured parameters are identified in the following table:

Tab. 1: Fundamental parameters measured and equipment / type of sensors used

S.N	Parameters	Sensor Type	Units
1.	Ambient Temperature	T-type thermocouple	ºC
2.	Battery Bank Temperature	T-type thermocouple	ºC
3.	PV Cell Temperature	T-type thermocouple	ºC
4.	Horizontal Solar Radiation	80SPC, SolData Pyranometer[4]	W/m^2
5.	Solar Radiation on the Plane of Array (POA)	80SPC, SolData Pyranometer	W/m^2
6.	Solar PV Array Current	HXS 20-NP[5] Current Transducers	Amperes
7.	Solar PV Array Voltage	Direct to dataLogger DT80 connected	DC Volts
8.	Battery Bank Voltage	Direct to dataLogger	DC Volts

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[3] DT80 from dataTaker: http://www.datataker.com/products/dt80.html

[4] http://www.soldata.dk/ and http://www.soldata.dk/PDF/pyrano%2080spc%20A4%20-%20UK.pdf

[5] http://www.lem.com/hq/en/content/view/148/126/

		DT80 connected	
9.	Battery Bank Current In / Out	HXS 20-NP Current Transducers	Amperes
10.	WLED Load Voltage	Direct to dataLogger DT80 connected	DC Volts
11.	WLED Load Current	HXS 20-NP Current Transducers	Amperes

The DT80 data logger system is installed in the power house, along with the battery bank and the main analog volt and ampere indicators (see in Fig. 3 top left corner). Figures 2 and 3 show some of the details.
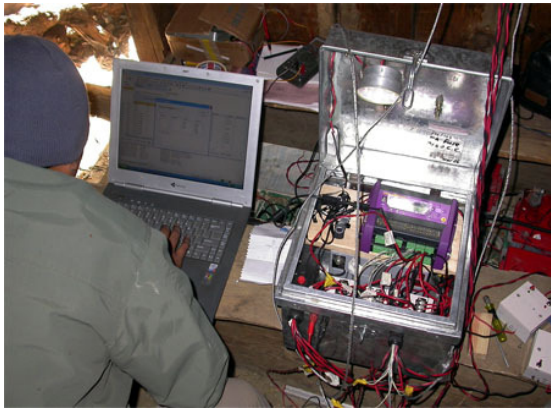

Fig. 2: Sensors connected to the DT80 data logger. A special protective casing was fabricated for the monitoring equipment. The DT80 is separately powered with two $20W_R$ Solar PV modules and a 30Ah sealed deep cycle battery. Care needs to be taken that the mice can't easily get access to the wires.

Fig. 3: Installation of the data logging system in Tulin village. The program, specifically written for the data logger DT80, is loaded and tested. The sensors' cabling is carefully connected to the data logger.

The dataTaker[6] DT80 samples each of the parameters every 10 seconds and averages it over one minute. The averaged values are recorded in the DT80's internal memory under three different time schedules:

- five minutes (averaged)
- one hour (averaged)
- one day (24-hours averaged)

The data is downloaded monthly to a USB stick directly from the dataTaker DT80.

ANALYSIS

Local available Solar Energy Resource

An important parameter for the design of a solar PV system is the peak sunshine hours per day over the course of each month of the year. The global solar radiation in Tulin is measured on two surfaces, the plane of the array (POA), representing the received

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[6] Logging instrument (www.dataker.com.au)

global solar radiation on the solar PV modules in the array, and the horizontal global solar radiation, which is the international standard, allowing a comparison with other international data. These two parameters are measured with a pyranometer, a calibrated silicon solar cell, SolData 80SPC, with an accuracy of +/- 3% against a thermopile Kipp & Zonen CM 21 pyranometer[7].
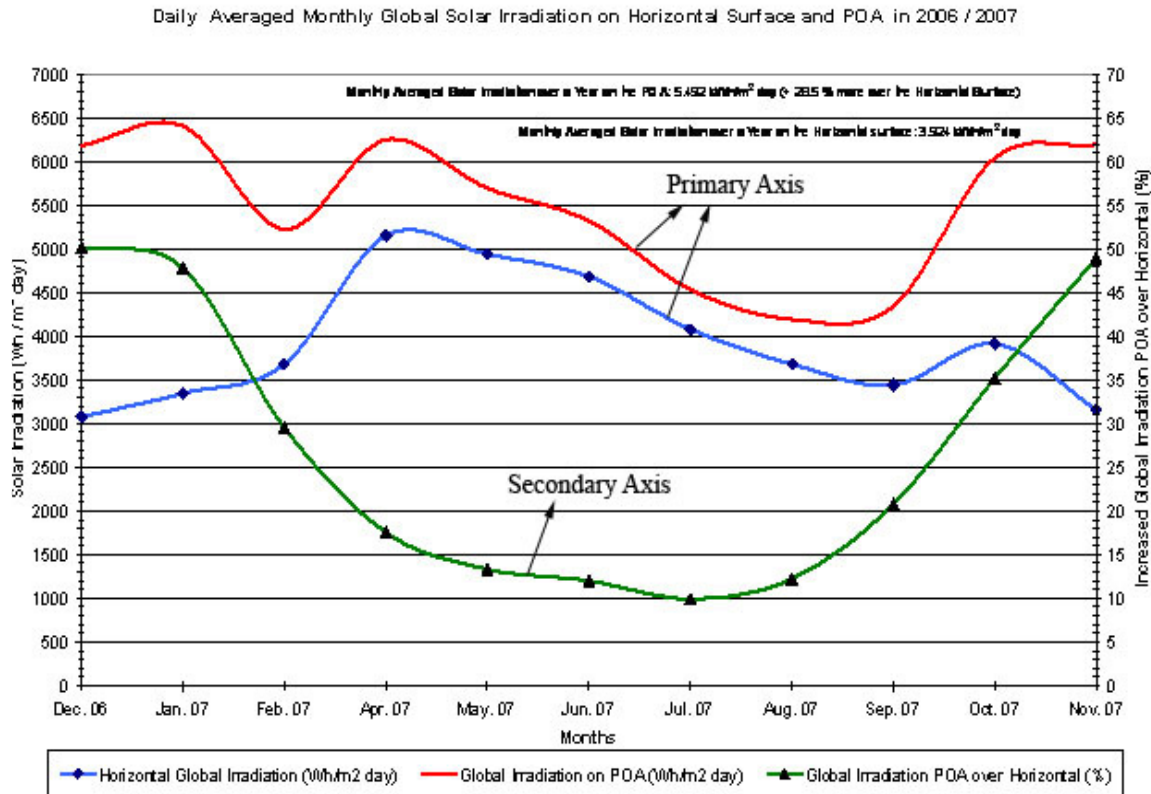

Fig.4: Daily average horizontal and POA global solar irradiation per month for the year 2006/2007

Figure 4 shows the averaged daily global solar irradiation (Wh/m^2 per day) received in Tulin village over the period of a year, from December 2006 to November 2007.

The important features of the locally available solar resource identified from the data analysis are as following:

1. The average solar irradiation on the 2-axis tracked surface over the year was 5.492kWh/m^2 per day.

2. Annual solar irradiation received on the tracked surface was 28.5% more than on the horizontal surface.

3. The maximum solar irradiation on the 2-axis tracked surface over the year was 6.412kWh/m^2 per day, while the minimum was 4.194kWh/m^2 per day.

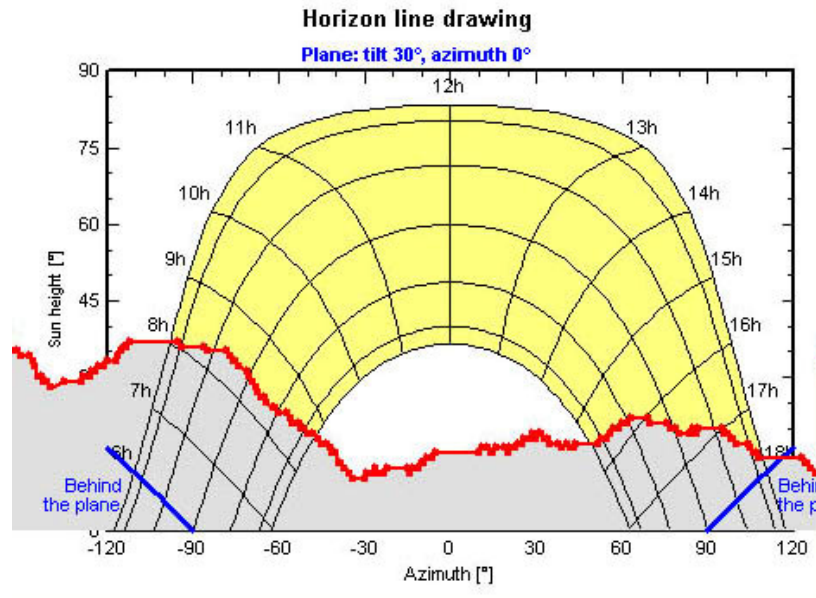[7] http://www.kippzonen.com/?product/1491/CMP+21.aspx

Fig. 5: The yearly sun path diagram for Tulin village and its 360° horizon, indicating all the mountain peaks (red line) surrounding the village, thus limiting the interception of the daily solar radiation according to the different seasons.

As shown in Fig. 5, Tulin receives fewer hours of sunlight due to the high surrounding mountains. Sunlight is especially limited during the 4 winter months from November to February. Due to the clustered arrangement of the houses and limited peak sun hours, a 2-axis central tracking PV system was chosen by RIDS-Nepal. Tracking from East-West is achieved with a bi-directional 1.5VDC motor, powered by the relative voltage difference between two $2.5W_R$ solar modules positioned at 30° to each other. Back tracking to East in the morning is done by a $2.5W_R$ module positioned at the East side of the PV array frame (see Fig. 6). The second axis, the North-South axis, is manually adjusted from 5°-60°, depending on the seasonal variation of the sun path angle (see Fig. 7). The increase in solar radiation in the POA shows the benefit of our locally developed and manufactured 2-axis tracking system (as seen Fig. 1, 6, 7). During the period under study, the monthly adjustment of the North-South tracker was not routinely carried out by the locally trained users residing in the village. Data recorded over the same time period with the same tracking system in our Simikot office, 6km aerial distance south of Tulin, shows, that if the North-South adjustment is carried out periodically, the system's annual solar reception can increase by an additional 8%-12%. This demonstrates the necessity for routine staff training as well as support to the end-users in the villages.

In Fig. 6 the various components of the Tulin 300 W_R 2-axis Solar PV Tracking System are indicated. Also important to notice is that the central tracking system is installed without any cement due to the prohibitive transport cost (12-fold price compared to the purchase price) and thus the inability of the local people to maintain it if in the future additional cement is needed. Instead the frame is developed in such a way that it can be filled with stones, which are widely and easily available in the village. Further, the PV system does not take any space away from the already utilised and limited roof tops. Thus the tracker system integrates seamlessly with the daily tasks such as drying grass, vegetables and fruits as well as the children's games. This is part of the development of contextualised technologies.
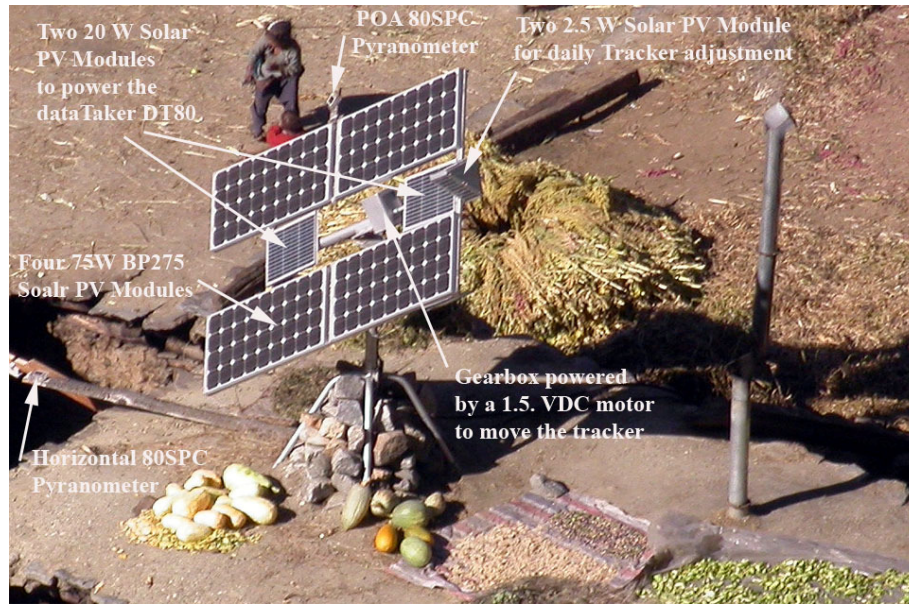
Fig. 6: Tulin 300 W_R central PV System. Two 2.5W_R solar modules positioned at 30° to each other power the 1.5 VDC motor which turns the tracker daily from East – West according to the sun's daily path.

Fig. 7: While the sun's daily East-West path is automatically tracked, the sun's seasonal elevation is bi-weekly manually adjusted. This allows a much simpler technology to be applied for the remote place, increasing the sustainability while minimising the maintenance requirements.

Power Generation

Tulin's solar PV village system has 4 x 75W_R BP275F mono-crystalline solar PV modules installed. The system's voltage is 24VDC, with a peak power output of 300W_R.
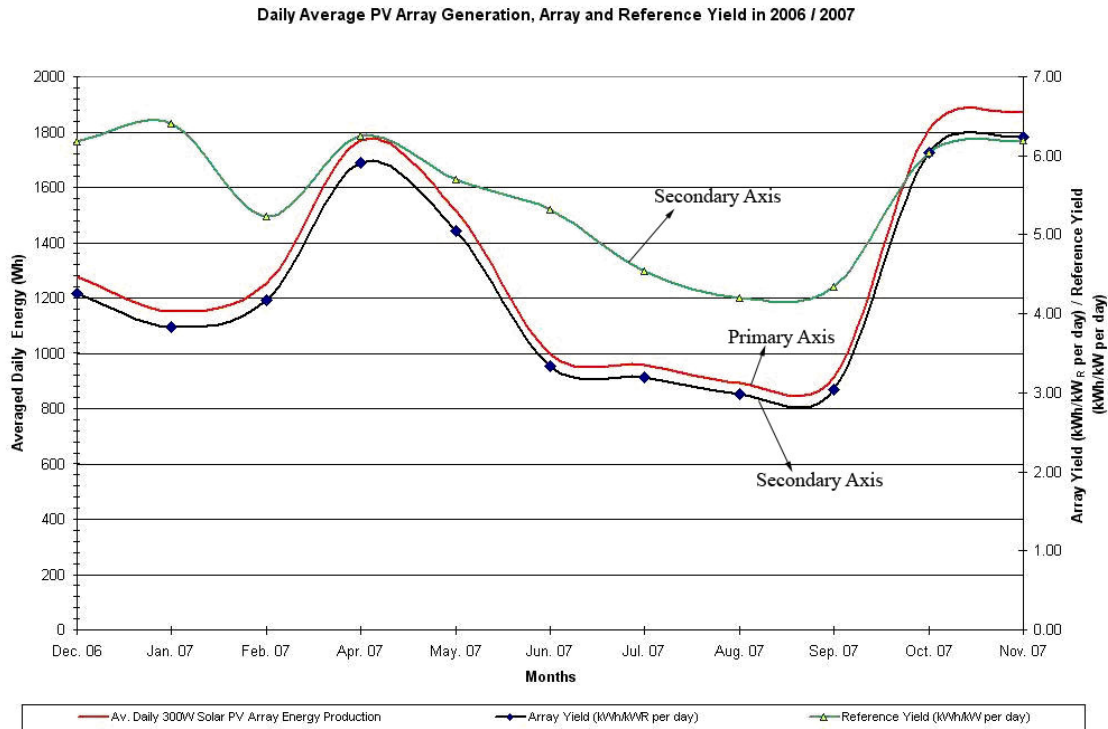
Fig. 8: Daily average 300 W_R Solar PV Array Energy Generation, Array and Reference Yield for each month from December 2006 – November 2007

Figure 8 shows the daily average energy generation, Array[8] and Reference Yield[9] over the year.

The important features of the Solar PV array performance identified from the data analysis are as following:

1. On an average 1.310kWh energy per day was generated over the course of a year. During this period the PV system achieved an overall average efficiency[10] of 9.47%.

2. From figure 8 it can be seen that a minimum of 0.894kWh energy per day was generated during August which is the worst month due to the monsoon climate, during which it can rain, for days at a time. The average minimum generation is well over the maximum average load described in one of the following sections.

3. Figure 8 shows that a maximum of 1.871kWh energy per day was generated during one of the clear, sunny days in November.

4. A clear seasonal energy generation pattern can be seen due to the pertaining seasonal, climatic and meteorological pattern. This is particularly evident when the lower energy generation is observed during the monsoon season and snowfall, from end of May to September and December to January respectively. Spring (mid-February to May) and early winter (October to November) seasons

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[8] It is defined as the ratio of the daily array energy generation to the peak installed capacity of the system
[9] It is the number of peak sun hours (PSH, defined as number of hours per day with 1000 W/m^2 global solar radiation received in a day)
[10] Solar PV Array Efficiency = Power Generated by PV Array /(Solar Irradiation x Total Area of the Array)

are sunny with clear skies, consequently generating more energy per day.

Energy Storage

A well designed battery bank energy storage unit is essential in a RAPS (Remote Area Power Supply) PV system which is not connected to the grid, as the power generation is inherently intermittent. Tulin village has a battery bank with a capacity of 300Ah @ 24 VDC (six 12VDC, 100Ah deep cycle batteries). The battery bank is designed for 3 days of autonomy, which means that the system can meet the average total village load demand without sunshine for up to three consecutive days with a maximum Depth of Discharge (DoD) of 30%.

The battery bank in Tulin remains on a constant high state of charge (SOC) each day, as the average daily DoD measured is low, between 3.29%-8.85%. The charge controller switches to trickle charge by open circuiting the PV array, as the battery bank reaches above 90%-95%. This keeps the battery bank protected from being overcharged. Thus the PV array power output is not fully utilised in relationship to what it could produce under the prevailing meteorological conditions.

Over the year the array efficiency was recorded to be 9.47% with a maximum of 11.89% in October. A lot of energy is being lost due to the high capacity status of the battery bank. This is expected for the first few years of the Tulin PV system as the system was designed for a 10 years maximum battery bank life expectancy and thus the system and battery bank is designed to provide the full energy demand by the local community after 5-6 years of population growth and increase in energy requirement.
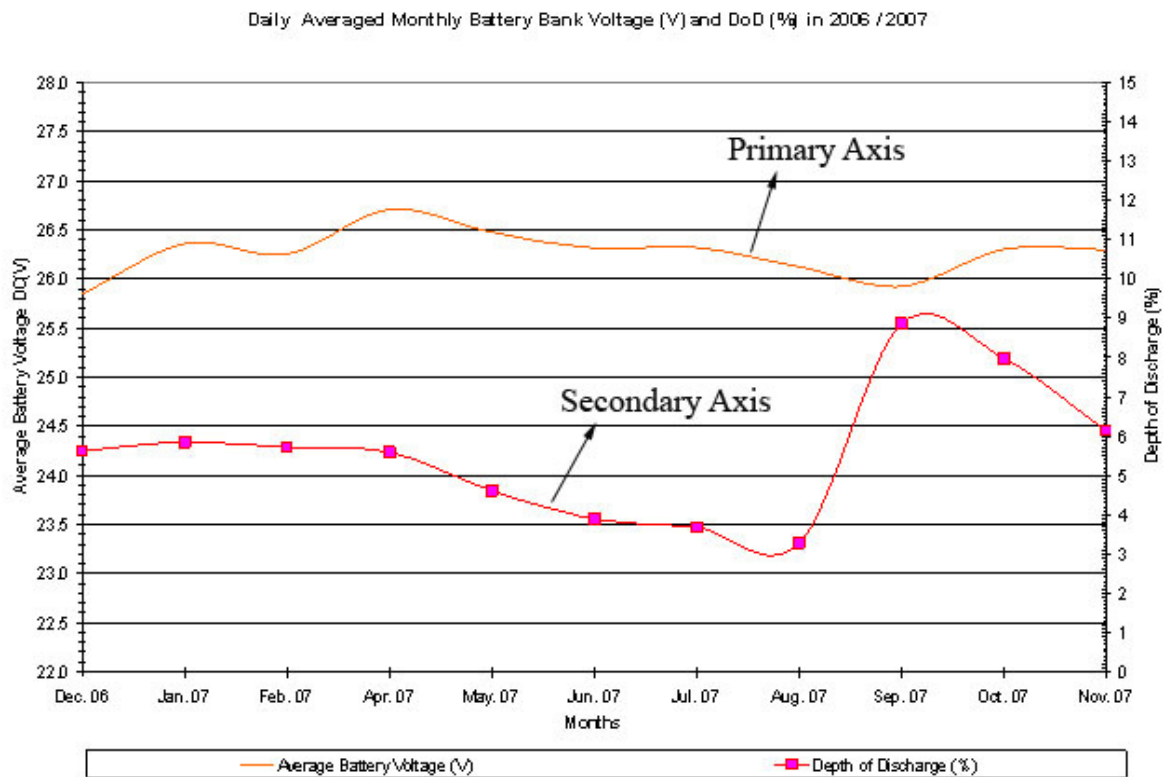

Fig. 9: Daily average battery bank voltage and depth of discharge per month for 2006/2007

The above graph shows the average battery bank voltage and the battery bank's average daily depth of discharge (DoD) per month over the year.

The important features of the battery performance identified from the data analysis are as following:

1. The battery bank's voltage never dropped below 25.84 VDC, with a yearly average of 26.27 VDC.

2. Over the course of the year on average 0.939kWh energy per day, generated by the PV array is fed into the battery bank.

3. The maximum energy input into the battery bank recorded was 1.510kWh/day in November, where as the minimum was 0.613kWh/day during the monsoon month in August (see Figure 7).

4. The daily DoD on an average was 5.57% over the year. The maximum daily DoD was 8.85% in September, whereas a minimum of 3.29% in August.

5. The DoD trend reflects the living pattern of the villagers. Beside the shorter nights, during the summer months (June to August) some of the villagers move to the higher altitude (3000-4500 m.a.s.l[11]) meadows with their animals. This reduces the village population and hence results in lower daily DoD during this period. Once they returned with their livestock in early September, more people were in the village, and the longer winter nights slowly set in. Both of these factors increase the demand for the lights, resulting in higher daily DoD of the battery bank.

The constant high battery bank voltage level indicates a good, high SOC of the battery bank throughout the year. Thus, over the year all the load demands for the designed indoor lighting could be provided without interruption. That means there was 0% loss of load (LoL) due to insufficient power generation by the solar PV system or insufficient energy storage capacity of the battery bank. The initially designed low DoD value has certainly added to the overall system cost, but factors such as expected population growth, days of autonomy period, potential of unauthorised connection of a high load demand (or misuse of the PV system) and extended battery bank life expectancy were accounted for in the design.

Load Demand

Each of the 28 houses is connected through armoured underground cabling to the battery bank and has three WLED lamps, each consuming 1 watt (see Fig 12, 13). Thus a total theoretical maximum load of ~ 100 W (28 households x 3 watt plus max. 20% system losses) at any given time is expected.

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[11] Meters Above Sea Level

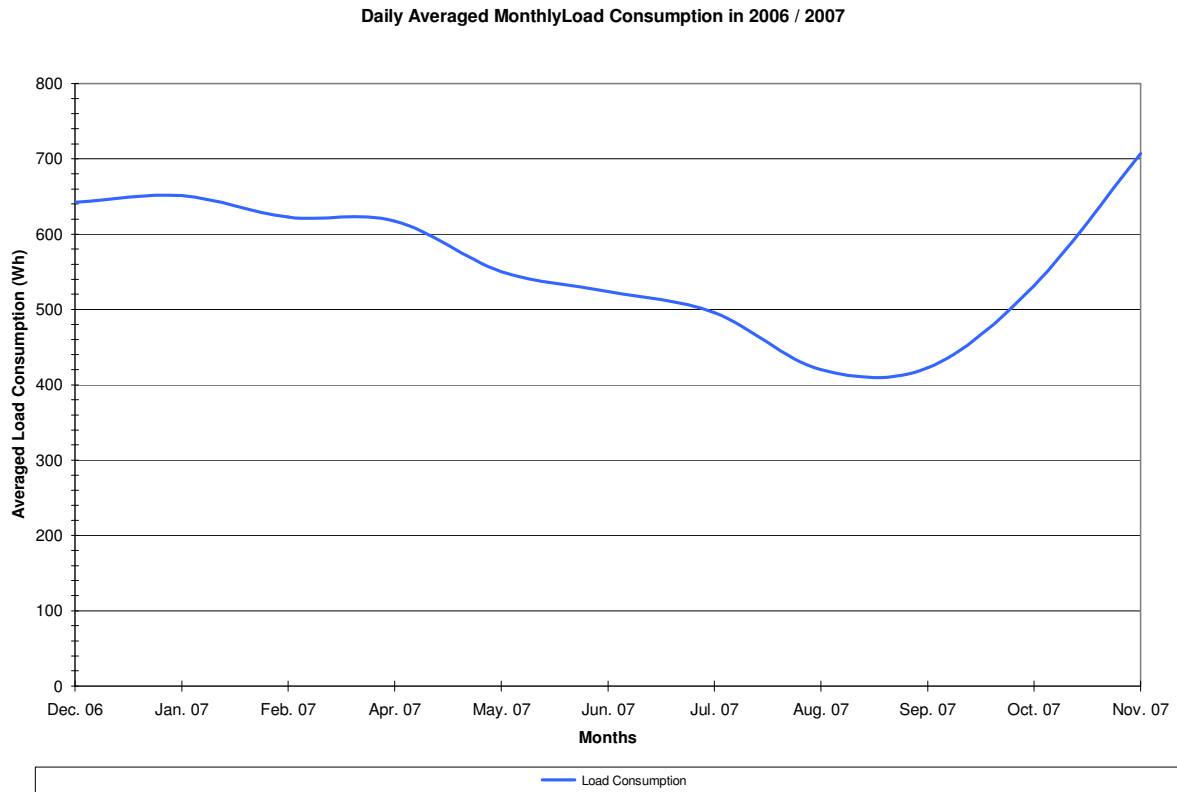**Daily Averaged MonthlyLoad Consumption in 2006 / 2007**

Fig. 10: Daily average village load (Wh) consumption per month for the year 2006/2007

The above graph shows the average daily load consumption per month over the year.

The important features of the end users usage pattern identified from the data analysis are as following:

1. 0.562kWh was calculated as the average daily consumption for indoor lighting over the period of a year.

2. Maximum energy demand of 0.707kWh/day was recorded in November (during the longer winter months when the lights are on for longer time periods) and minimum of 0.419kWh/day in August (during the shorter summer months).

3. While a maximum load demand of 101W was recorded in August, an even higher load of 225.5W was once recorded in September This suggests that an additional, unauthorised (or misuse of the PV system) external load/appliance was connected to the system. An average base load of ~20W was recorded all over the year, suggesting that even during the day people are using some lights. Though daytime usage was not initially anticipated during the system design phase of the project, it is perfectly understandable, since local homes are built with only very small windows with no glass to keep out the cold and wind. Thus people learned quickly the benefits WLED lamps provide during the day time as well as at night. In addition to the darkness of the home interiors increasing usage during the day, the recorded data leads us to believe that some people may leave the lights on all night long to drive away evil sprits.

4. The graph in Figure 10 reflects a clear pattern of the seasonal load demand as

previously discussed in point 5 under energy storage.

5. The data shows that the average daily load profile differs from what was expected. Initially, the solar PV system's load profile was defined to be ~8 hours a day, with two peak energy demands, one in the morning hours and one in the evening hours. However, our data suggest that for a few short time periods, additional loads were connected to the system. This could have been for charging additional external batteries for flashlights or for other equipment such as radios. These additional, unauthorised loads can lead to faster discharging of the battery bank and lower average battery bank voltage, and thus faster aging of the battery bank. Also the PV system is exposed to a higher risk of short circuits or the destruction of system parts. This information was shared with the villagers, and they agreed to look out for any misuse and to put an end to such activities. For future system designers this experience serves as an indication of the necessity to include unforeseen loads in the system design and to include necessary precautions to protect the system from unanticipated high loads. This could be achieved by including electronic power limiting circuit breakers or relevant low voltage recognition equipment which, once a set threshold is reached, cut the village power supply.

System Performance Ratio

The Performance Ratio (PR) is used to indicate the overall effect of losses on the solar PV array's rated output under defined meteorological conditions due to the solar PV modules' temperature incurred losses, only partial utilisation of the available solar irradiation (due to a full battery bank, inaccurate PV module angle or shading etc.), and system component inefficiencies, cable losses or system equipment failures (IEA PVPS Task 2, 2000).

The performance Ratio is the ratio of Final yield[12] to the Reference yield i.e.

$$PR = \frac{Final\,Yield\left(kWhPerDay\Big/kW_R\right)}{Reference\,Yield\left(kWhPerDay\Big/kW\right)}$$

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[12] Final Yield is defined as the ratio of the daily load consumption to the peak installed capacity of the system

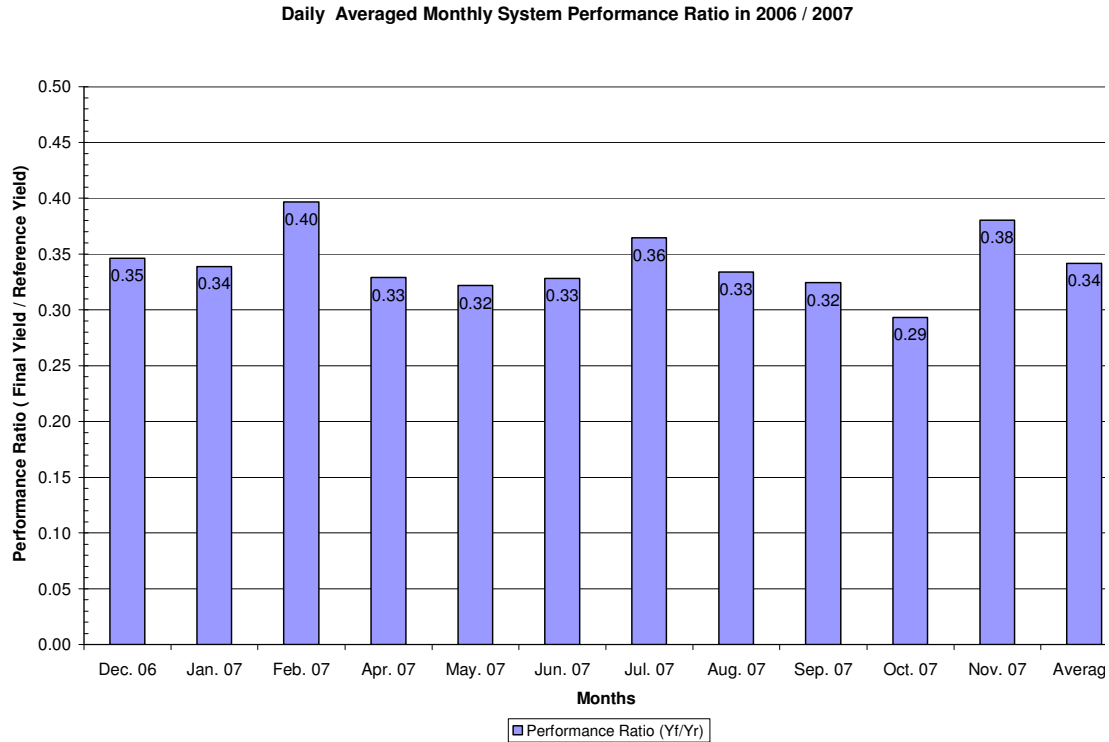**Daily Averaged Monthly System Performance Ratio in 2006 / 2007**

Fig. 11: Daily average Performance Ratio per month for 2006/2007

The figure above shows the daily average system Performance Ratio PR per month from December 2006 to November 2007.

Figure 11 demonstrates some key performance features of the system:

1. A maximum PR value of 0.40 was recorded for the month of February. This value shows lower capture losses[13] compared to other months, as the sun is not yet as strong and the sun hours not as long as during the later spring months. Further, the February winter month nights are still long, corresponding with higher load consumption.

2. A minimum PR value of 0.29 was recorded on October. This is a result of higher capture losses as higher PSH values are recorded in October per day, resulting in surplus energy generation with the battery bank being often greater than 90% full. The DoD graph in Figure 9 is not directly indicative of this finding, since we suspect that in the month of September extra loads were plugged into the system, discharging the battery bank more than otherwise would have been the case. As the graph presents the monthly average values, the October monthly average is not directly indicative of the lowest PR value over the year.

3. On a yearly average the PR is 0.34. From an analysis of 260 systems, the IEA-PVPS Task 2 report mentions that the annual PR of stand-alone (no backup)

[13] Array capture losses incur mainly when the battery bank is nearly full (90%-95% SOC) or full, as then the charge controller open circuits the PV array power flow to the battery bank. Thus the available excess power can not be utilized and thus is considered a loss. Other capture losses include PV module temperature incurred losses, wind and shading losses.

solar PV systems ranges from 0.1 to 0.6. The Tulin village solar PV system is a prototype system and was designed for minimum LoL in order to have continuous performance data and an uninterrupted practical experience for the local users. Due to these demands set for the system at the design stage, we expected a slightly decreased average PR value and an increased total system cost.

The PR value is dependent on the load usage. An oversized RAPS Solar PV Systems as in this case has higher system losses which results from a more frequent disconnection of the PV array from the fully charged battery bank. Correspondingly, it is not entirely correct to say that a system with a higher PR value indicates a more economical system. The Tulin village solar PV system was intentionally oversized to allow higher reliability, lower LoL, and a population and load demand growth over the course of its first 5-6 years of operation. Further, it is a first-time experience for this community to have basic electric indoor lighting. With these parameters under consideration, it is expected that the performance ratio of the Tulin solar PV system will improve over time.

System efficiency

As previously mentioned, the PR value in itself is not sufficient to give the overall picture of the system's operation. Hence additional parameters have to be monitored to completely understand the system. One such additional parameter is the system efficiency, which can be calculated by specifying the ratio of solar PV array power generation and load consumption at standard test conditions (STC).

$$\text{System Efficiency} = \text{Final Yield} / \text{Array Yield}$$

Accordingly the average system efficiency of the Tulin solar PV system over the year was 78.8%. On an analysis based on more than 30 stand-alone systems installed worldwide, with peak power varying from 450Wp to 5000Wp, Mayer and Heidenreich conclude that "good" systems are those with efficiencies ranging from 75%-95% and with a PR greater than 0.3. A high efficiency value indicates few or no technical problems in a system (Mayer and Heidenreich, 2003). Measuring the system efficiency factor along with the PR value gives a clearer idea of the system's operation.

CONCLUSION

Comprehensive monitoring is essential in order to know a system's performance under real field conditions. For instance the solar PV array under study in this project was found to be operating at an overall efficiency (generated electrical power by the solar PV array surface per m^2 divided by the received global solar radiation per m^2) of 9.47% over the year, though slightly higher future efficiency values are expected with the increase of the village load demand compared to the current average load. The local geographical and meteorological conditions justify the use of a solar PV array tracking system with the POA results showing that 28.5% more energy is captured with the POA than the horizontal array. Furthermore, the monitoring system provides a detailed understanding of the varying village load patterns over the course of each day, month and each season of the year. From these findings, important lessons can be learnt.

The monitoring system's data also show that the village solar PV system may occasionally have been misused, which otherwise would have not been possible to know. One of the lessons learned is of the importance of incorporating a load disconnection unit to protect the system from higher than designed currents being drawn. Additionally, the data revealed the fact that alongside the energy storage system,

the battery bank needs to be calculated and designed with appropriate energy storage capacity, in order to provide the villagers with the energy they need during the predicted number of days without sunshine.

Overall, the data collected by our monitoring system show that the Tulin solar PV system is performing well in general, as designed and as expected. Crucial parameters such as the locally available solar resource, the solar PV array's power generation, the battery bank's daily voltage, SOC and energy storage levels, as well as the village load consumption, were monitored and recorded. These data give an excellent overall understanding of the system's performance, providing a detailed record of each individual parameter and the operation of the system overall. This would not be possible without a data logging system, which is lacking in most solar PV systems installed in similar contexts throughout the region. Monitoring of a solar PV system under various meteorological conditions over the course of several years allows for the improvement and optimisation of the solar PV system through adjustments made on the initial design calculations. These adjustments then help to avoid unnecessary system failures, and improve economic efficiency of new PV systems based on real field experience. Careful monitoring and system adjustment in this fashion helps to improve the delivery of quality energy service to the consumers by minimising any system downtime. Further, the data and knowledge gained from these experiences, appropriately contextualised, can provide the development community with important tools to improve the design of solar PV systems for particular contexts. This is beneficial for end-users, for equipment manufacturers, and for researchers interested in RAPS systems implemented through solar PV technology.

A professional and contextualised solar PV system design for a defined local context and application is essential for long-term reliability and sustainability. This information can only be acquired through detailed and long-term data collection and analysis for whole solar PV systems in the installed context. The data gained through monitoring can improve the design of solar PV systems and their long-term sustainability. To date, the long-term performance of the small scale solar PV systems installed elsewhere in Nepal has been inconsistent. The approach described above offers a solution to this situation. We suggest that eventually the painstakingly data-rich, carefully monitored and optimised project approach described herein for Tulin may be able to transform the performance and sustainability of other systems in regions throughout Nepal.

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APPENDICES

Fig. 12: 1 watt WLED (White Light Emitting Diode) lamp, manufacturing in Nepal with original Nichia NSPW 510BS diodes from Japan.

Fig. 13: WLED Lights have replaced "Jarro" (resin soaked wood burned for lighting), providing a cleaner and brighter indoor environment.

BRIEF BIOGRAPHY OF PRESENETERS

MALLA, Avishek is a mechanical engineer and is currently working on his Masters in Renewable Energy at Murdoch University, Australia. He was awarded the gold medal from former King Gyanendra Bir Bikram Shah Dev for graduating with the highest grade in 2005. From 2005-2007 he was involved in academic teaching and research in renewable energy focusing on solar photovoltaic and solar water heater technologies at Kathmandu University. From 2007 -2008, he worked with the non-profit NGO RIDS-Nepal on long term holistic community development projects implemented in Humla, one of the poorest and remotest regions of Nepal.

ZAHND, Alex has a mechanical engineering degree from Switzerland, and a Masters in Renewable Energy from Murdoch Australia. He has been in Nepal since 1983 and works in holistic community development projects since 1996 in the remotest and poorest mountain communities in the Himalayas. Since 2001 he has also been a member

of expatriate staff of Kathmandu University, involved in teaching Renewable Energy courses as well as in applied research of renewable energy technologies. Since 2002 he combined his extensive field experience and applied academic research projects by developing and leading a long-term HCD project and a High Altitude Research Station, in the very remote and impoverished north western district of Humla, through the established non-profit NGO RIDS-Nepal (www.rids-nepal.org). He is also working on his PhD on the role of renewable energy technology in holistic community development, with practical applications in Himalayan villages in Nepal.

HADDIX MCKAY, Kimber is a cultural anthropologist who specializes in demography, health and human behavioral ecology. Dr. McKay has worked both full time and as a consulting anthropologist designing studies of health and treatment of illness in remote areas of Nepal and Uganda. She has lived and worked in Nepal frequently from 1994 to the present, and assisted in the design of locally appropriate development schemes aimed at improving health conditions, particularly in the use of sustainable energy technologies and in public health-related interventions such as latrine design, improved/smokeless cook stoves, lighting schemes, community based health training, and drama programs with specific health-related messages. She works with The ISIS Foundation as Manager, Humla and Research, and is an associate professor of Anthropology at the University of Montana, Missoula, MT, USA.

ELLUL, Alicia has a degree in Science from the University of Sydney, with a mathematic major and a Masters in Renewable Energy from Murdoch University. Alicia is currently a sustainability consultant for Planet Contracting Services, an electrical and renewable energy company working in the Sydney region. This company aims to reach developing countries and help achieve PV systems to small villages such as Tulin, in Humla Nepal, in the future.