Technical Analysis of the Performance of a Small-Scale, Centralised Village Photovoltaic System in Tulin, Humla Nepal

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I declare that, except where indicated the work in this dissertation is my own work and has not been previously submitted for a course at another institution

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Abstract

A Photovoltaic system in the remote village of Tulin, a Himalayan village in Nepal, has been extensively monitored for the past 12 months. This monitored data was analysed to determine whether the design expectations have been met in the context of a remote rural community.

Battery voltage, solar radiation, PV output, temperatures, load profile and performance ratio were analysed to determine how the system components were performing.

It was found that the system components operated remarkably well, with the load always being met. BB voltage stayed fairly constant with a low battery voltage observed only after a system fault. Performance ratio was well within the expected range and the solar radiation values measured were as expected. The various prototype charge controllers sometimes did not operate as designed and high BB voltages were observed as a result. The load profiles were slightly different to what was expected but still within the average daily loads range.

Photovoltaic electrification for small villages in remote and rural locations is a successful method of alleviating the impoverished villages' energy needs of lighting within the home. The successful implementation of the PV system in Tulin could be a show case for other community development projects, since the extensive monitoring over the past year has provided insight to understand and mitigate weaknesses. Tulin is one of the first of many proposed PV electrification

systems and so the lessons learnt of whether it meets its design goals and its performance outcomes provides valuable information for future installations.

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List of Acronyms

AH	Air Heater
Amp	Ampere
AUD	Australian Dollar in 2007
BB	Battery bank
CC	Charge controller
CD	Compact Disc
DC	Direct current
DT80	Datataker 80
IEA-PVPS	International Energy Agency Photovoltaic Power System Program
IEC	International Electrotechnical Commission
MB	Mega Bytes
PC	Personal Computer
POA	Plane of Array
PR	Performance Ratio
PV	Photovoltaic
PVSyst 4.1	Photovoltaic Systems software version 4.1
RIDS-Nepal	Rural Integrated Development Services- Nepal
Rs	Nepali Rupees in 2007
SHS	Solar Home System
USB	Universal Serial Bus
V	Voltage
Wh	Watt hour
WLED	White Light Emitting Diode

Wr	Rated Watt Power

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Thank you also to my family, for your love, ongoing support and understanding, especially to my mother, Anne Donohue, whose strength has been an inspiration.

1 Introduction

1.1 Background

Photovoltaic (PV) electrification in rural regions of developing countries has the potential to alleviate problems associated with poor health, decreased life expectancy, low literacy levels and environmental degradation.

In the small mountain village of Tulin in northwestern district of Humla, Nepal, people were using smoky, tree resin wood splinters called “jharro” for night lighting. The use of traditional biomass meant forests were being depleted, and there was a high risk of respiratory health problems and premature deaths occurring due to indoor pollution. Also without suitable light it is hard for children to read and learn at night. (Zahnd, Alex. 2006) Tulin lies within the solar belt of 30° N and thus enjoys a good solar resource. As part of a long-term holistic community development (HCD) project this small village has been provided with a solar PV electrification system for lighting in one of the Rural Integrated Development Services (RIDS) –Nepal program.

(RIDS-Nepal) is a non-profit Social Non Governmental Organisation (NGO) and works in partnership with the ISIS Foundation, which is their main donor organisation (RIDS, 2007). As part of the project the installed PV system in Tulin has an extensive monitoring program allowing the operation of the system to be carefully analysed. The program focuses on providing the “Family of 4” for each family in the whole village; a term that refers to a provision of a smokeless cook stove, pit latrine, clean drinking water and light from PV electrification, enabling synergetic long-term benefits from each project. This study focuses on the PV electrification element only.

Part of the problem with PV electrification in rural areas is there is no foolproof recipe for designing a successful PV dissemination project. (Stern, Richard.1995) The aim of this study is to use the monitored data for Tulin to identify how the PV electrification system is performing and what lessons can be learned for future such installations.

1.2 Objectives

The objectives of this study are to determine if the installed PV system in the Tulin village of Humla, Nepal is performing as expected. This objective is achieved by analysing the monitored data from Tulin to determine if the design approach for an isolated Nepalese village has been successful. The analysed data is used to assess whether the system performance is matched to the system's expected performance. To do this a number of questions need to be asked. Is the solar resource as expected? What are the load profiles? How are the batteries performing? What is the output power of the array? Through analysis of individual components' performances, the question may be asked; how well is the system performing overall? What is the PV system's performance ratio? Can the PV system provide the energy services as designed? What are the limitations of the system? By addressing these questions the overall objective will be addressed and a final question asked; what lessons can be learned for the future design of village PV systems?

2. System Description

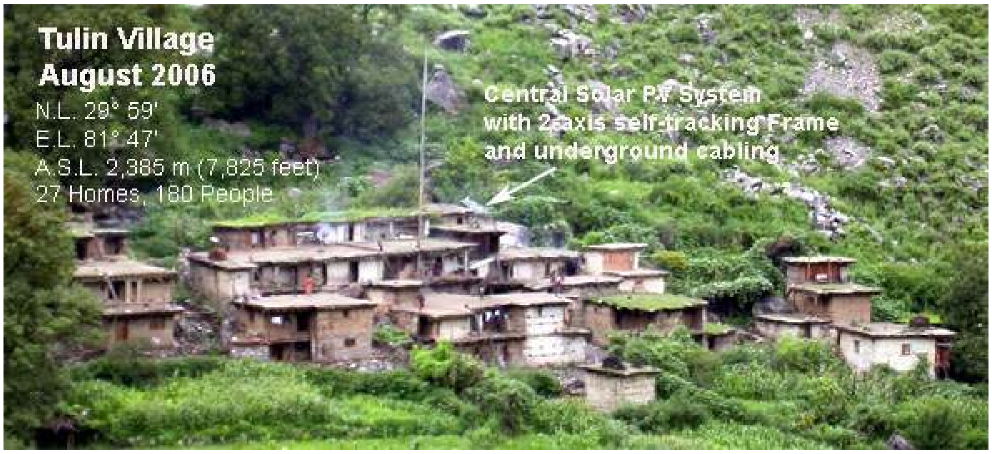

Fig: 1. Tulin PV centralized electrification village. (Photo courtesy of Alex Zahnd.)

Figure 1 shows the Tulin village with its central solar PV system and the surrounding houses that are powered by this array. The system was designed for 27 homes but an extra home has been added between the time of installation and the onset of monitoring the system. The dc reticulated power has underground cabling to each of the 28 homes. To aid the research aspect of the Tulin project an air heater was installed in September 2007, to act as a dump load when the BB was full. For the duration of this project the air heater never really worked as it was designed to. This issue is explored further in Section 4.2.

Figure 2 gives a schematic of the centralised PV system.

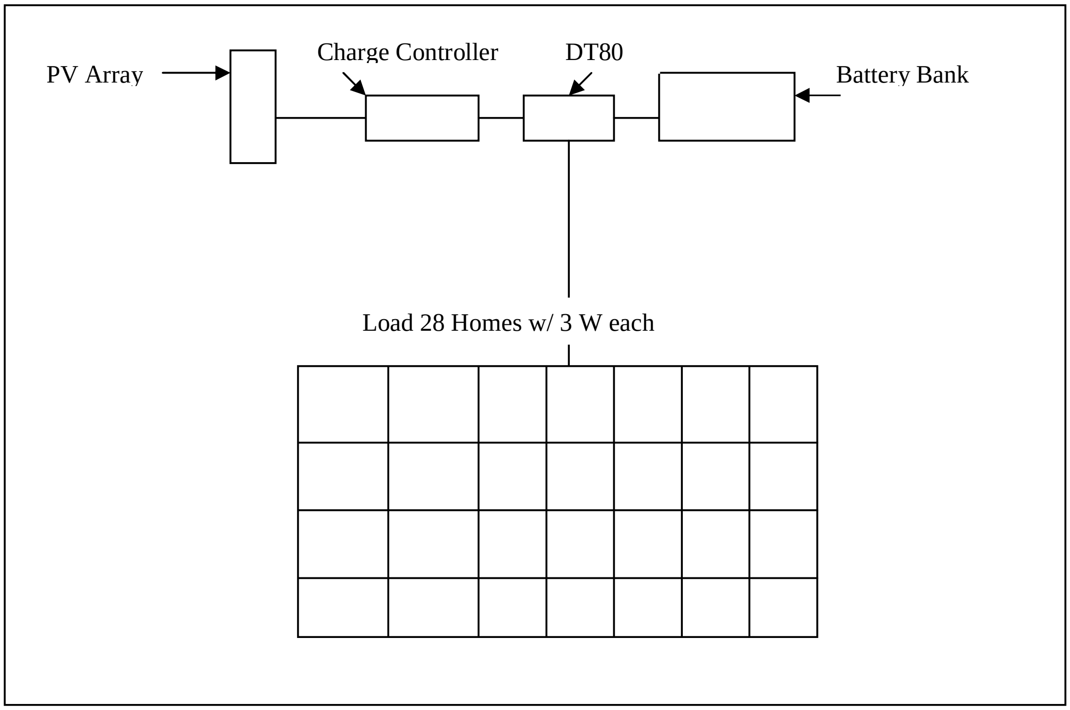

Fig. 2: Schematic of PV Centralised System

2.1 Load estimation

The load estimation was calculated by combining the number of homes requiring light, the number of lights per home and the expected length of time the users would require the light.

There were 27 homes in Tulin village in the installation year 2005. Each home received three WLED (White Light Emitting Diode) lamps each consuming 1W with a total of 81W. The lights are expected to be used for 5-7 hours a day, and so if the upper limit is used this would give a total 81W * 7h = 567Wh per day. If a conservative 20% additional power consumption is assumed for the losses over the whole system the average daily energy required is 567*1.2 = 680Wh rounded up to 700Wh. The losses are transmission losses, with some distance to the homes as far as 100m from the centralized PV system. Other contributing factors are increased loads when RIDS-Nepal staff are collecting data via laptops, and a 5-10% safety margin due to the remoteness of the village. (Zahnd, Alex. 2008)

The expected population growth is approximately 2-2.5% per year. With a population of 200 people this becomes a population growth of 4 – 5 people per year.

The required lighting needs were given as 5-15 lux for common indoor tasks (cooking, cleaning, sitting, and socializing) and ≥ 25 lux for reading tasks and home work and reading/studying for the children who attend school. (Zahnd, Alex. 2007) Although these lighting levels are very low compared to Australian standards, they provide better lighting than was previously available through traditional biomass methods.

2.2 Resource estimation

Tulin has the following geographical data: Latitude of 29°59'23.48" North, longitude of 81°46'57.05" East and an altitude of 2377 meters above sea level. (Zahnd, Alex. 2007)

As no local recorded solar irradiation data was available at the time of the design of the Tulin village solar PV system, yearly monitored data from the nearby RIDS-Nepal High Altitude Research Station (HARS) in Simikot was used to approximate an average monthly solar radiation for Tulin. HARS has three pyranometers (horizontal, 30º South inclined and on a tracking frame) and data logging equipment to measure and record solar radiation. (Zahnd, Alex. 2004) Simikot is approximately 3900m in air distance from Tulin, or 4 hours walk. A monthly solar radiation profile for Tulin was estimated by reducing the HARS average monthly solar radiation values by 20%, given that the Tulin lies deeper in the valley and it has a higher horizon (by 15 to 20 degrees) than Simikot. (Zahnd, Alex. 2007) Simikot global solar radiation values from one year of data are presented in Table 1 below, along with the estimated horizontal global solar radiation values for Tulin, (calculated by decreasing Simikot values by 20% for each month.)

Table 1: Global Solar Radiation Data for Simikot and Tulin.

Month	**Simikot Solar Radiation**	**Estimated Tulin (20% less)**
Jan.	3.396 kWh/m^2/day	2.177 kWh/m^2/day
Feb.	4.133 kWh/m^2/day	3.306 kWh/m^2/day
Mar.	4.953 kWh/m^2/day	3.962 kWh/m^2/day
Apr.	5.650 kWh/m^2/day	4.520 kWh/m^2/day
May	5.082 kWh/m^2/day	4.066 kWh/m^2/day
Jun.	4.454 kWh/m^2/day	3.563 kWh/m^2/day
Jul.	4.331 kWh/m^2/day	3.465 kWh/m^2/day
Aug.	3.996 kWh/m^2/day	3.197 kWh/m^2/day
Sep.	5.025 kWh/m^2/day	4.020 kWh/m^2/day
Oct.	4.673 kWh/m^2/day	3.738 kWh/m^2/day
Nov.	4.386 kWh/m^2/day	3.509 kWh/m^2/day
Dec.	3.475 kWh/m^2/day	2.780 kWh/m^2/day
Yearly Ave.	4.463 kWh/m^2/day	3.570 kWh/m^2/day

Tulin’s global solar radiation on the Plane of Array (POA) is estimated to be 5.3kWh/m^2/day. This estimation was calculated by using the measured radiation values for the POA global solar radiation on the tracking PV frame system at HARS in Simikot and applying the 20% reduction because of Tulin’s high horizon due to the high mountain range 360º around. (Zahnd, Alex. 2007) This measured data from Simikot are for the time period of one year at the time of design of the Tulin system. Since the design, three years of solar radiation data for Simikot have been collected and the average values have not changed much. (Zahnd, Alex. 2007)

2.3 System Design

Back of the Envelope (BOE) calculations give an estimate for the size of the PV array and BB required to meet the desired load.

$$\text{Array size} = \text{Load}/\ (\text{PSH}*\text{temp derating factor}*\eta_{batt,}) \qquad \text{(Equation 1)}$$

$$= 700Wh\ /\ (5.3*(75-75*(0.44\ \%\ *\Delta T)\ *\ 0.75)$$

Assumptions:

- $\eta_{batt,}$= battery efficiency, charging discharging of 75%,
- temp derating factor = 0.44 % / ºC
- PSH = solar radiation of 5.3 PSH.
- Modules = 75W
- ΔT = 60° C which is very high and was chosen to have some safeguard, usually the PV modules are around 25-40º C above ambient.

Thus the PV array size is calculated:

= 700Wh / (5 .3* (75-(75*(0.44*ΔT/100)))* 0.75)) = 3.19 PV modules @75W_p output under assumed meteorological conditions.

Therefore 3.19 x 75W_p PV modules to be installed, but since the system is a 24V system it was rounded up to 4 x 75 W_p PV modules.

$$\text{Required Battery Bank Capacity} = (\eta*\text{daily load})/\text{DoD} \qquad \text{(Equation 2)}$$

Where η = number of days of autonomy, which is 3 days.

And DoD = maximum allowed depth of discharge, which is 30%, then

Required BB capacity = 700Wh*3/0.30 =7000Wh, The system voltage is 24V, therefore the BB capacity = 7000/24 =292 Ah.

A BB of 6, 12V batteries of 100Ah capacity each was installed as a 24V system. That means 3 parallel strings of 2 batteries each to give a total installed capacity of 300Ah, @ 24V. Thus the total BB's energy storage capacity is 24V* 300Ah = 7 200Wh.

The system was designed on the conservative side to allow for growth in the load over the next 4-5 years and extreme meteorological and climatic circumstances.

PVSyst4.1 design software was also used to calculate the appropriate PV system size required for the village. (PVSyst4.1, 2007)

The following entries were made to PVSyst4.1:

- Geographical inputs including Latitude, longitude, altitude, global solar radiation given in 2.2;
- Time zone for Nepal, given as time zone 6, which equates to legal time – solar time = 0h 33m;
- Albedo values for Nepal, given as (Nov– Mar) 0.25, (April – Oct) 0.20; the albedo increases in the winter months because of a higher reflection due to the snow covered ground.
- User needs of 700Wh/day;
- Global solar radiation values on a horizontal surface given for Tulin, as given in Table 1 above.
- System components (batteries, PV modules, regulator) as given in 2.4;
- Loss of load given as 5%;
- Manually adjusted monthly tilt angle of array between 5° and 60°;
- Daily East West rotation angle between -20° and 20°

- Azimuth 20°W of S;
- Horizon heights given as -180°=35, -38°=13, 38°= 17, 179° = 35.

The results of the PVSyst4.1 analysis are presented in 2.7, Expected Performance.

Figure 3 shows a schematic diagram of the small scale PV village in Tulin. Note that the load has increased from 81W to 84W, between the time of installation and monitoring the system. This was due to the building of a new house Tulin and given lights, which increased the number of houses to 28 and increased the load to 84W.

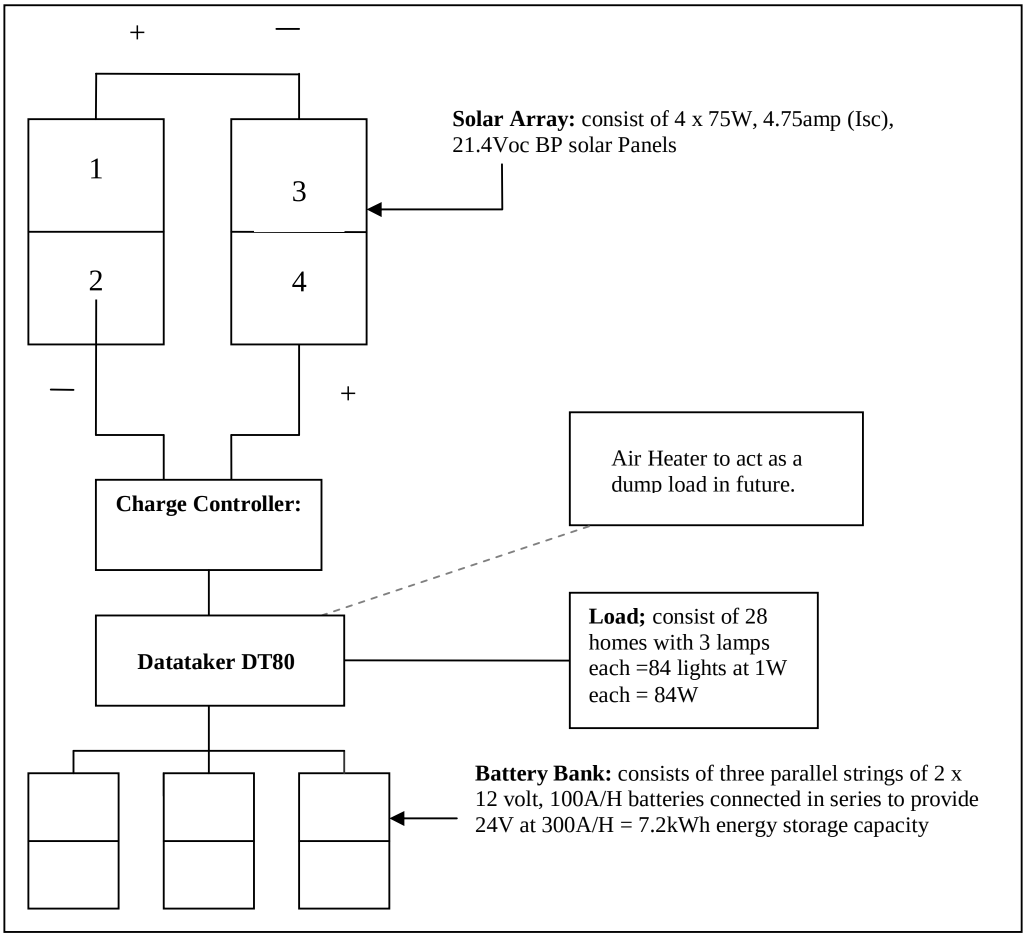

Fig. 3: Tulin PV System Schematic Diagram

Figure 3 shows the schematic diagram for the PV system in Tulin, designed by Alex Zahnd and installed in April 2005.

The small scale PV electrification system was installed in the Tulin village of Nepal in 2005. The system was installed as part of a long-term holistic community development project, instigated and carried out by RIDS Nepal and the Tulin village community. (RIDS, 2007)

2.4 System Components

The system components are chosen for their reliability with an emphasis on sustainable spare parts, maintenance and local manufacturing, due to the remote nature of the Nepalese village, Tulin and the development of the local economy.

PV array

The PV array consists of four $75W_{p,}$ BP275F solar PV mono-crystalline modules to give a total installed rated capacity of 300 $W_{p.}$ Table 2 gives the specification for the BP275F modules

Table 2: PV Module Specifications: (from Specification Sheet given in Appendix 1.)

Panel Specification

Manufacturer	BP Solar
Product Spec.	BP275F
Nomial Peak Power	75 Watt
Short Circuit Current (Isc)	4.75 Amp
Open Circuit Voltage (Voc)	21.4 Volts
Peak Current	4.45 Amp
Peak Voltage	17 Volts
Min. Power	70 Watt
Temp Coefficient	0.44%

The PV module has a 25 year life expectancy. The PV irradiation diagram is given in Appendix 2.

A single axis tracking with manually adjusted tilt frame mounts the 4x $75W_p$ PV modules panels to maximise their exposure to direct solar throughout the day's solar global radiation. It rotates east to west automatically and back to east in the morning and the tilt of the array is manually adjusted by the local O&M trainee bi -weekly or monthly according to the month of the year, adjustable from 5° south (July) - 60° south (December).

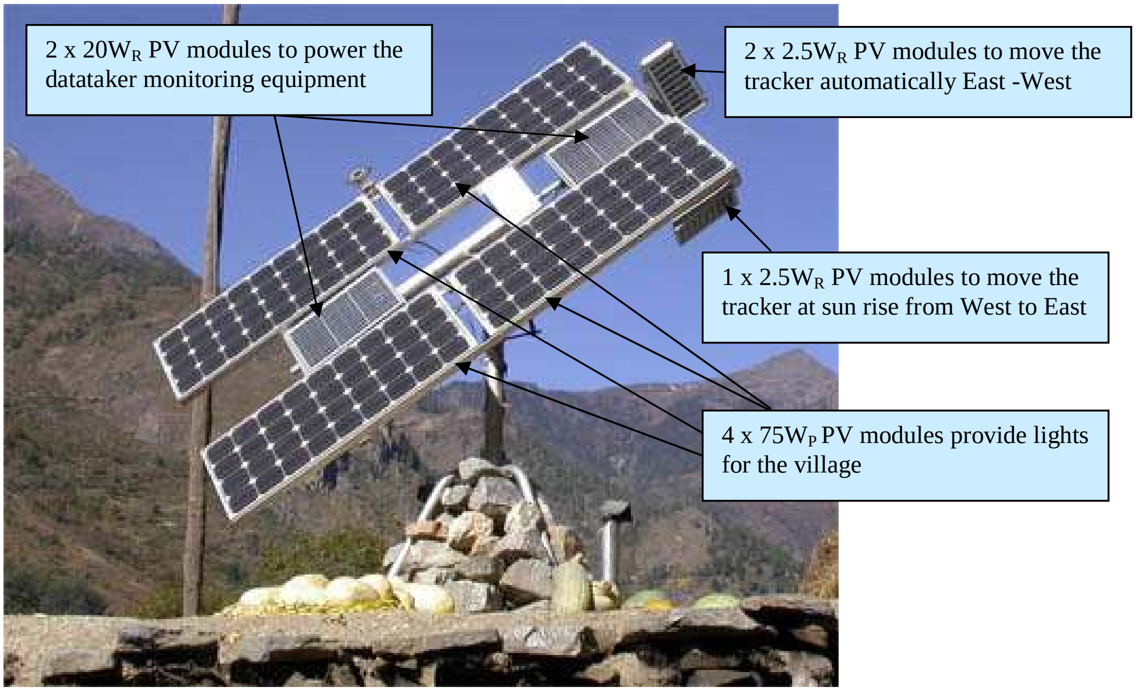

Fig. 4: Tulin's PV array on tracking frame. (Photo courtesy of Alex Zahnd.)

Battery bank

The system has an installed battery capacity of 24V x 300Ah. The system is a 24V DC system, therefore the battery bank (BB) consists of 6 x 12V Volta, flooded lead-acid, deep cycle batteries, each with 100 Ah capacity. There are 3 parallel strings each of 2 batteries, giving a total BB capacity of 7.2 kWh.

The battery specifications are given in Table 3 below:

Table 3: Battery Bank Specifications (PVSyst4.1 file)

Battery Specification	
Manufacturer	Volta
Model	90SB
Capacity@ C20 rate and 20ºC	100 Ah
Specific Gravity	1250 gram/liter
Battery cell Voltage minimal	1.75-1.85 V
Battery cell Voltage maximum	2.25V - 2.35 V
Installed Capacity of BB	300 Ah
Installed Voltage	24Volts
Number of Batteries	6

The estimated number of days of autonomy for the design is 3 days.

BB's life expectancy is 5-8 years if used as defined. The instructions for use are as follows: a minimum BB voltage of 23.8 V, a maximum BB voltage of 28.8 V and a max DoD of 30% after 3 days of no sunshine. An average maximum DoD of 10% per day, as given in the battery specifications (Zahnd, Alex. 2007) for 3 days gives a 30% DoD of the BB after 3 days with no sun.

BB enclosure is a wood box sealed with local dung and insulated with local available pine tree needles. The wooden box was locally manufactured. The size of the box is approximately 1.8.m long and 80 cm wide so that a distilled (rain water) water plastic drum fits in the box. The box is covered with a wooden lid and has ventilation holes at the top and bottom to allow any hydrogen generated during charging to escape, and to keep the temperature at an ideal temperature of between 15 and 25 ºC

Charge Controller

A charge controller was installed between the PV array and the batteries to regulate the supply from the power source and to protect the batteries from too low discharge. The charge controller specifications are given in Table 4 below.

Table 4: Charge Controller Specifications (Zahnd, Alex. 2007**)**

Charge Controller Specification
24 Volts
15 Amps in from PV array and 5Amps to the load
High Cut Voltage and start of trickle charging at 28.8 VDC
Low Cut Voltage at 23.8VDC to protect the BB

These charge controllers are designed and manufactured in Nepal by PPN (Pico Power Nepal.) By design it cuts off the PV array when the battery is fully charged and disconnects the load when the battery reaches its low voltage cut out of 23.8 VDC. The charge controller has outlets for solar, battery, load and air heater. Due to the nature of the research project, during the course of the monitoring period three different charge controllers were used. The first two were pulse width modulators (PWM) and the third was a simple serial CC, opening the PV array line to BB.

The various prototype CCs were tried and tested as part of the Tulin research project. This was the cause some data loss and BB voltage highs identified at different times (this is further explored in Section 4.2.5). A photo of the CC is included at Appendix 3.

WLED:

WLED lights are also designed and manufactured in Nepal by PPN.

They have a life expectancy of >50'000 hours which is approximately 20-25 years with 7 hours use a day. The WLED lights specifications are given in Table 5 below.

Table 5: WLED Specifications (specification sheets are available at the websites given as links in the table below.)

White Light Emitting Diode (WLED)				
Manufacturer	Model	Lumens/W	Max. Current	Voltage DC
Nichia	NSPW510BS[1]	24	20mA	3.6
Luxeon	Luxeon Star[2]	30	350mA	3.6
Installed WLED				
Type	No. of Diodes	Wattage		
Nichia NSPW510BS	9	0.85		
Luxeon Star I	1	1.3		

Each home has two Nichia NPSW510 BS (9 diodes) and one Luxeon (1 diode) WLED lamp installed. The Nichia NSPW510BS used have 28lm/W and work from 10VDC up to 30 VDC. Thus one WLED lamp with 9 (NSPW510BS) diodes, driven at 3.6 V 20mA has about 24 lumens (consuming 0.85W) at an angle of ~50 degrees. Each house has two NSPW510BS lamps and one Luxeon Star with about 30lm/W. Thus driven at 3.6V and 350mA it has about 38 lumens

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[1] http://www.nichia.co.jp/specification/led_lamp/NSPW510BS-E.pdf

[2] http://www.lumileds.com/products/line.cfm?lineId=1

(consuming 1.25W) at an angle of ~110 degrees. (Zahnd, Alex. 2007) A photo of the lamps is included at Appendix 4.

Air Heater

The air heater is 24V and can take current up to 15 amperes. The air heater was installed in the system in March 2007 as part of another research project but was not connected. In September 2007 the air heater was connected. Although the air heater voltage and air heater current were monitored from the time of connection there has yet to be any documented data to show that the air heater has been successful in dumping excess power. The potential for the air heater to prevent the BB from overcharging and enabling improved accuracy of monitored data such as PV efficiency exists and would improve the PV module efficiency. A photo of the AH is included at Appendix 5.

Cables, wiring and switches

The copper cable between the PV array and charge controller (CC) to BB is 8 mm in diameter. The length of the cable from the PV array to CC is 10 meters, and from CC to BB is 2 meters with a life expectancy of 25 years. The size of the copper cable from the BB to the various houses varies according to the distance, in order to minimise the voltage drop. The WLED lamps are designed to run between 10V - 30 V DC so it is a matter of cost efficiency to have a certain voltage drop, as thicker cables (and thus with less voltage drop) is expensive.

2.5 Monitoring System

The system is monitored using a DT80 data logger that measures 22 parameters. The datataker has its own energy supply from 2 * 20W PV modules. The parameters monitored are outlined in Section 3.1. The DT80 has an internal memory of 64 Mb storage capacity; and the monitored data is stored here until the data from the DT80 is downloaded in Tulin using a USB memory stick by one of two trained RIDS-Nepal staff members, Sher Bahadur and Avishek Malla. This USB memory stick is carried by hiking to Simikot, and then downloaded onto the PC. The information is written on a CD and sent to RIDS-Nepal in Katmandu. Where further data checking and graphical presentation is undertaken, at this stage the data were sent via email to the author in Australia. The power to the battery, load and air heater are regulated by the charge controller. They go through their respective current transducers plugged in to the DT80.The specifications for the datataker are found on the website: http://www.datataker.com/Library/Product_Data_Sheets_TS/DT80_TS0059C6.pdf

2.6 Maintenance

Ongoing maintenance occurs at least bi-weekly (and generally more often). At these times, trained RIDS-Nepal staff visit Tulin and together with the local trained O&M trainee, check the BB distilled water, temp, and Voltage, clean the PV module and adjust the tracker.

2.7 Expected Performance

The expected performance was estimated using results from PVSyst.

The relevant output obtained from PVSyst is presented in Figures 5 to 9, which allows an estimation of the expected performance of the PV system in Tulin.

Global Solar Radiation

Figure 5 shows the expected global solar radiation on a horizontal surface.

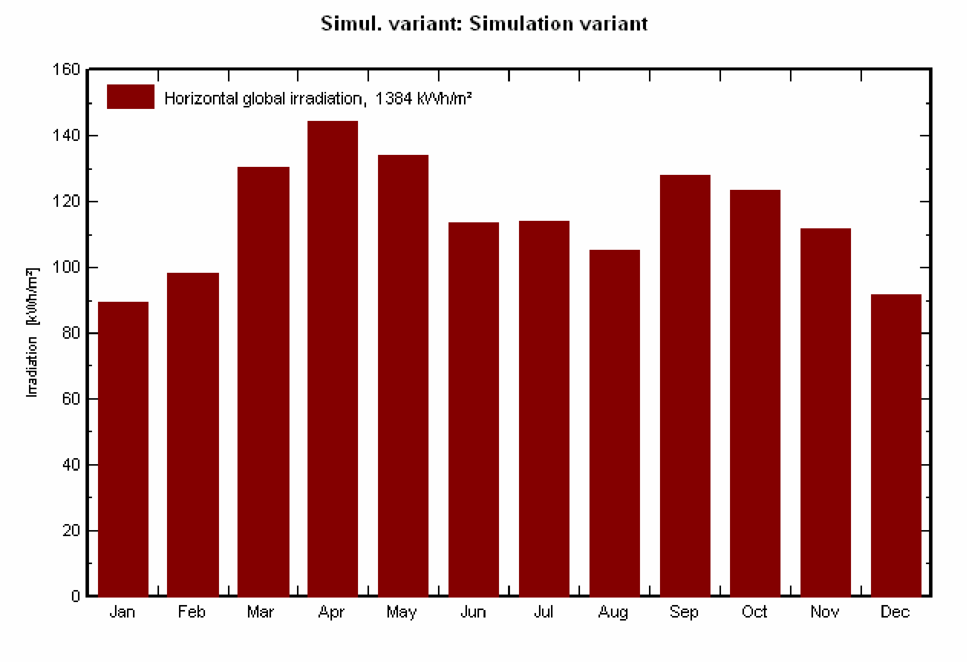

Fig. 5: Expected Global Solar Radiation on a horizontal surface

As can be seen from Fig. 5:

- The annual average horizontal solar radiation can be expected to be 1384kWh/m^2.
- This equates to 1384/365 days = 3.79 kWh/m^2/day.

- A seasonal variation in solar radiation is expected: mid-season months are expected to have the highest levels of solar radiation, while summer months have lower levels as a result of the monsoon.

Figure 6 shows the expected global solar radiation on the plane of array (POA) on the 2-axis tracker. The operation of the tracker is explained in the PVSYst4.1 inputs in Section 2.3 System Design.

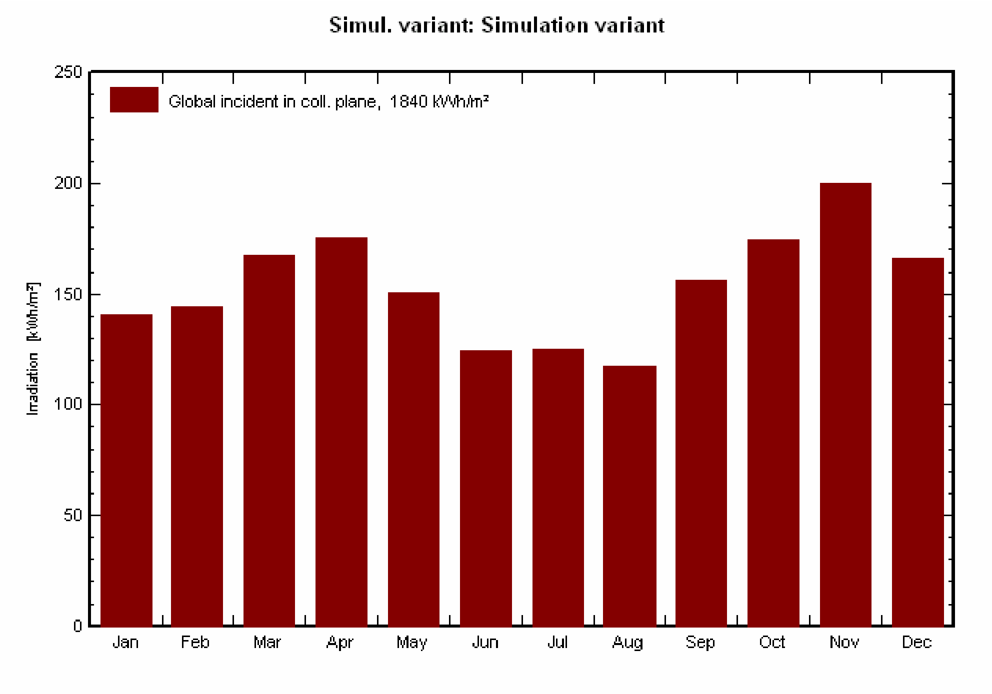

Fig. 6: Expected Global Solar radiation on the POA

As can be seen from Fig. 6:

- The solar radiation is expected to increase as a result of the array on a 2-axis tracking system.

- The yearly solar radiation on the POA is expected to be 1840kWh/m^2/day. This equates to an average of 1840 / 365 days = 5.04kWh/m^2/day, or an increase of 33.5%.

Battery Bank Voltage

Figure 7 shows the expected BB voltage over a year

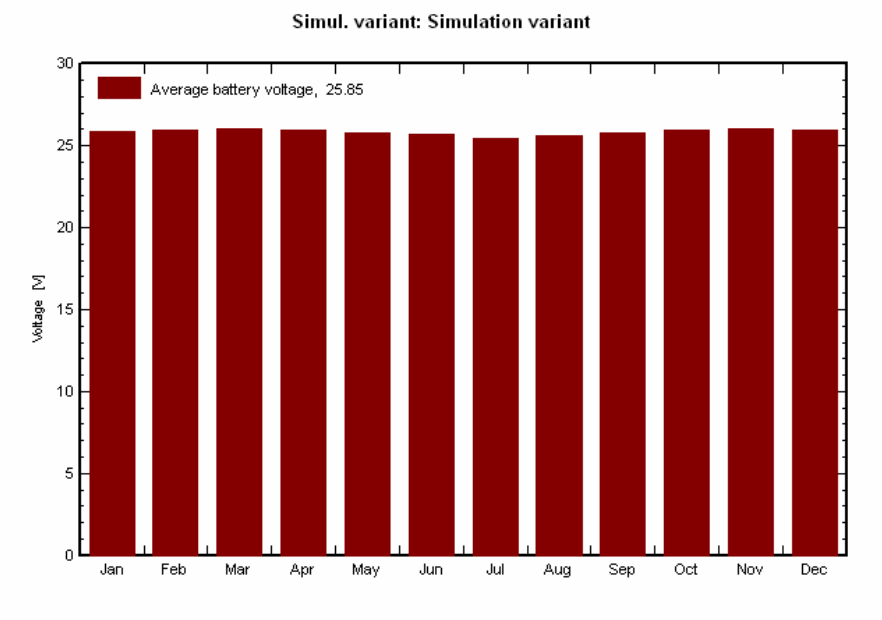

Fig. 7: Expected Monthly Averages for the Battery Bank Voltage.

As can be seen from Fig. 7:

- The BB voltage is expected to remain fairly constant throughout the year.
- The BB voltage annual average is expected to be 25.85V.

PV output

The output for the PV array as forecasted by PVSyst4.1 is given as monthly averages in Figure 8 as the array virtual energy at MPP.

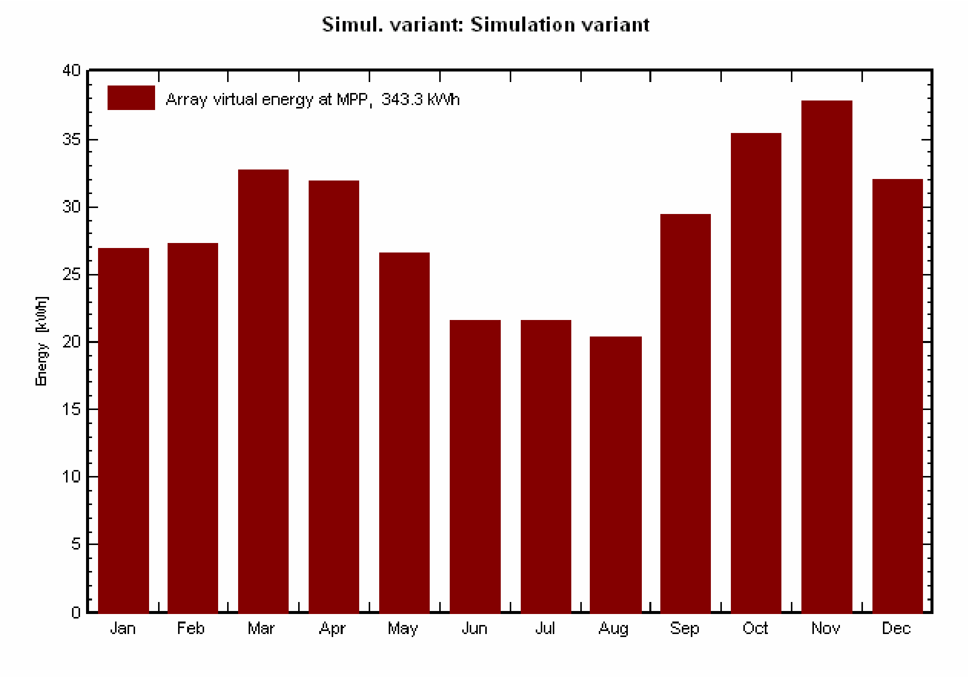

Fig. 8: Expected PV Output

As can be seen from Fig. 8:

- The yearly average for the 300W$_p$ PV array output is expected to be 343.3kWh.

  This equates to 343.3/ 365 days = 940.5Wh/day.

- There is no MPP in the Tulin system but this is a very similar measurement to the PV array output power measured by the DT80 for Tulin.
- The PV output is not coinciding with the global solar radiation on the tracking axis, as it should. This could indicate that the batteries are often full and so the PV is reduced.

Performance Ratio

Figure 9 shows the expected performance ratio and the solar fraction of the PV system. Performance ratio is defined in Section 3.2.

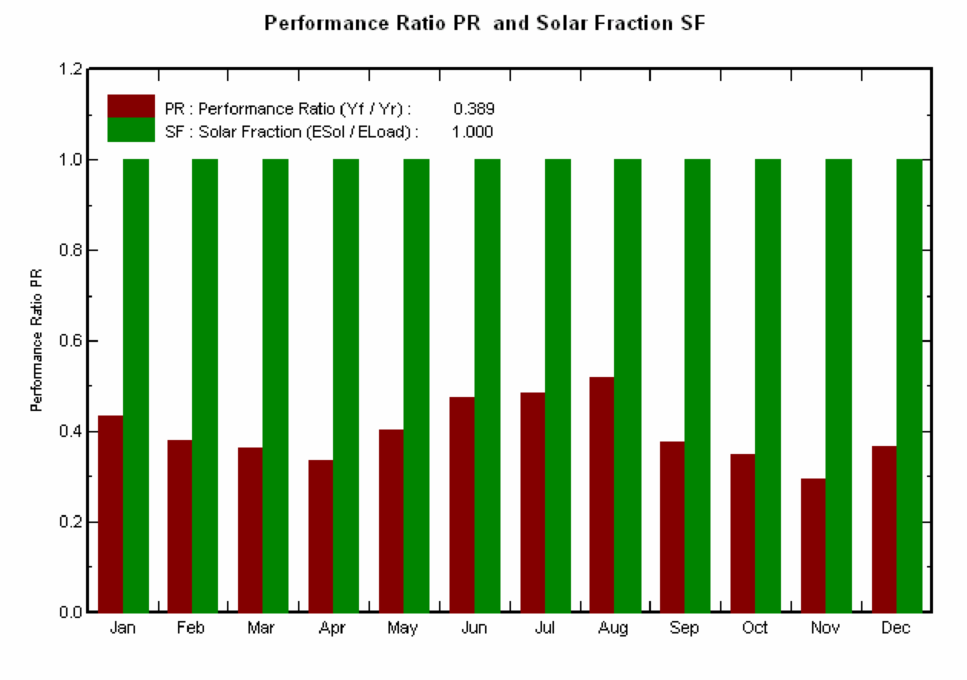

Fig. 9: Expected Performance Ratio

As can be seen from Fig. 9:

- The yearly average performance ratio is expected to be 0.389, which is very low.
- There is an expected seasonal variation in PR with the best PR seen in the summer months of July and August.
- The energy service (all WLED lamps) can be provided throughout the year as the solar fraction is 1. This parameter is not explored in the Tulin monitored data.
- A low PR was taken into consideration in the Tulin system as it is a prototype and research system with data monitoring.

The conclusions from the PVSyst4.1 results indicate that the solar resource is consistently good and the expected BB voltage will be constantly at a high state of charge.

The PV output and performance ratio are expected to be on the lower side and this may be a result of the PV array being oversized for research purposes and to prepare for load growth over the next 5 years.

3. The Monitoring Program

3.1 Measured Parameters

The main parameters that were measured by the monitoring system in Tulin and used in this study are outlined in Table 6 below.

Table 6: Measured Parameters

Parameter	**Symbol**	**Unit**	**Device**
Horizontal Global Solar radiation	GH	W/m2	Pyranometer SPC80
Plane of Array Global Solar Radiation	GI	W/m2	Pyranometer SPC80
Generated Solar PV Module Voltage	Pv(v)	Volts	DT 80
Generated Solar PV Module Current	Pv(I)	Amps	Calibrated Current Transducer
Battery Charging Voltage	B(V)	Volts	DT 80
Current Flowing From Charge Controller Into the Load	L(I)	Amps	Calibrated Current Transducer
Voltage Measured Btwn Charge Controller and Load	L(V)	Volts	DT 80
Solar PV Module Temperature	T(PV)	deg Cels	DT 80 w/T-Type Thermocouple
Ambient Air Temperature	T(A)	deg Cels	DT 80 w/ T-Type Thermocouple
Battery Bank Temperature	T(BB)	deg Cels	DT 80 w/ T-Type Thermocouple

Ambient Temperature; T_a,(ºC) The maximum expected ambient temperature range for a Nepalese village in the Humla region is between –20ºC and 40ºC.

PV Temperature; T_{mod} (ºC) The expected temperature range of the PV panels under full sunshine reaches approximately 15°C to 25ºC above ambient temperature, i.e. -5ºC- 65ºC.

Battery Bank Temperature; T_{BB} (ºC)

Two T-type thermocouple are glued on the side (so that the thermocouple touches the battery well and is covered from the ambient temperature by a piece of wood). The thermocouples are half the battery height and are positioned in the middle of each a battery. The average value is measured and logged.

The expected temperature range of the BB is 10ºC to 25ºC. As is the case with all the temperature values, the T-type thermocouple temperature sensors have a measuring range of -40 °C to + 150°C, which covers the expected temperature ranges discussed above.

Horizontal Solar Radiation; G_H (W/m^2) The expected range is 0 to $1500W/m^2$ measured with an 80SPC SolData pyranometer (Soldata, 2007) on a horizontal plane, at the horizontal house roof height where the PV array is located, or 2378 metres above sea level.

Plane of Array Solar Radiation; G_I (W/m^2)

The expected range is 0 – $1500W/m^2$. The pyranometer is located on the PV tracking array, at about 1.5m above the house roof, or 2380 metres above sea level.

PV Voltage; V_{mod} (V) The expected voltage range of the PV modules is 0 – 42.8V, i.e. the open circuit voltage of the array since the V_{oc} of each panel is given by the specifications as 21.4V. This parameter is measured by the DT80, which has two ranges for volts 0-2.5 and 0-30V.

This parameter is not examined in isolation but is necessary for the PV power analysis. See Equation 3 below.

PV Current; I_{mod}(Amp) The expected ampere range of the PV modules is 0 –12 Amps @1150W/m$^{2.}$ This parameter is not examined isolated but is necessary for the PV power analysis. See Equation 3 below.

Battery Voltage; V_{BB}(V) The expected voltage range of the BB is 23.8-28.8V

Load Current, I_L (Amp) The expected ampere range of the load is 0 –5Amps. This parameter is not examined in isolation but is necessary for the load analysis. See Equation 4 below.

Load Voltage, V_L (V) The expected voltage range of the load is 24 – 28V. This parameter is not examined isolated but is necessary for the load analysis. See Equation 4 below.

3.2 Derived Parameters-

The derived parameters, i.e. those calculated from the measured parameters in Section 3.2 are outlined in Table 7 below.

Table 7: Derived Parameters

Parameter	Symbol	Unit	Calculation
Power Generated By the PV Array	P_{mod}(W)	Watts	$V_{mod} * I_{mod}$
Power Demanded By the Load	L(W)	Watts	$V_L * I_L$
Performance Ratio	PR	dimensionless	Y_f / Y_r

PV Array Power, P_{PV} (W) This is derived by the following calculation:

$$P_{PV} = V_{mod} * I_{mod} \qquad \text{(Equation 3)}$$

The expected wattage range for the PV array power is 0 –340W.

Load Power, P_L (W) This is derived by the following calculation:

$$P_L = V_L * I_L \qquad \text{(Equation 4)}$$

The new design load is 84W. This is expected to be the maximum load value since there are no power outlets and only 84W (28 homes * 3Wlamps) worth of lighting. However the system is capable of producing $I_{L\,(}$max) * $V_{L\,(}$max) = 5A*28V= 140W. The air heater was not taken into consideration here as during the study period the air heater did not operate as it should have.

Performance Ratio

(PR) is defined as the ratio of the final yield to the reference yield, given by a dimensionless number. (IEA-PVPS Task 2, 2000).

$$PR = Y_f / Y_r \qquad \text{(Equation 5)}$$

Where

$Y_{r:}$ *Reference yield (kWh/kW$_p$)*

$Y_{f:}$ *Final PV system yield (kWh/kW$_p$)*

The performance ratio is calculated daily and then averaged over the month for only the days of full data.

Final PV system yield is the daily (monthly or annual) plant useful energy output E_{use} per kWp of installed PV array power. (IEC 6174, 2004).

$$Y_f = E_{use} / P_o \qquad \text{(Equation 6)}$$

Where

E_{use} = *Net useful energy delivered to the load (kWh)*

P_o = *Rated power output of the system (kWp)*

For the PV system in Tulin E_{use} is chosen as the load, i.e. P_L.

Reference yield is the daily (monthly or annual) in-plane irradiation GI divided by the STC reference in-plane irradiance (IEC 6174).

$$Y_r = G_I / G_{STC} \qquad \text{(Equation 7)}$$

Where

G_I = *In-plane Irradiation (kWh)*

$P_o = G_{STC}(= 1kW/m2)(kWp)$

Representative days were chosen to analyse the components interaction in the operation of the system. First the month of January was selected for winter and June for summer as these were the months closest to the winter and summer solstices that had the most complete data set. May was selected for the representative mid-season month.

The representative days was chosen by finding a day where the averages for daily load, daily solar radiation, PV power and BB voltage are within the month's averages by 10% for each parameter. The monthly averages for these parameters are located at Appendix 6

3.3 Data Validation

RIDS-Nepal staff, responsible for the research projects, checks each data set. Each parameter measured and recorded is checked according to a defined data range. Data out of that range are discarded and substituted with the average of the previous and following data. The number of 10-minute data entries that required substitution was not available to the author at the time of writing. The ranges for each parameter are defined in Sections 3.1 and 3.2. Days of incomplete data were discarded when monthly averages were calculated; the discarded days are presented in Table 8 below.

4. Results

The monitoring period was almost 12 months from the middle of November 2006 until the end of October 2007. A brief explanation of the incomplete data is given in Table 8.

Table 8: Incomplete or Missing Data

Dates of Data Missing	**Reason for Lost Data**
16th Dec. -5th Jan. (21 days)	Wires burnt in powerhouse
7th Feb. – 8th Feb. (2 days)	Power failure
10th Feb. – 23rd Feb. (14 days)	Wires burnt in powerhouse
March (31 days)	Data Missing
27th Sep.-4th Oct. (8 days)	Air Heater burnt down and damaged CT's in DT80
25th Oct (1 day)	10 hours missing as DT80 was updated

77 days of data were not present in the approximately 12 month monitoring period. The total number of days available in the monitoring period were 365 –15 = 350, (15 being the first 15 days of November 2006.) The percentage of data

that was available for analysis was (350 – 77)/ 365 = 75% of the days. This is a fairly complete dataset.

4.1 Measured and Derived Parameters

4.1.1 Global Solar Radiation on a Horizontal Surface

Figure 10 shows the average daily horizontal global solar radiation values for each, along with the yearly average. It also shows the estimated Tulin solar data extrapolated from the Simikot measured data.

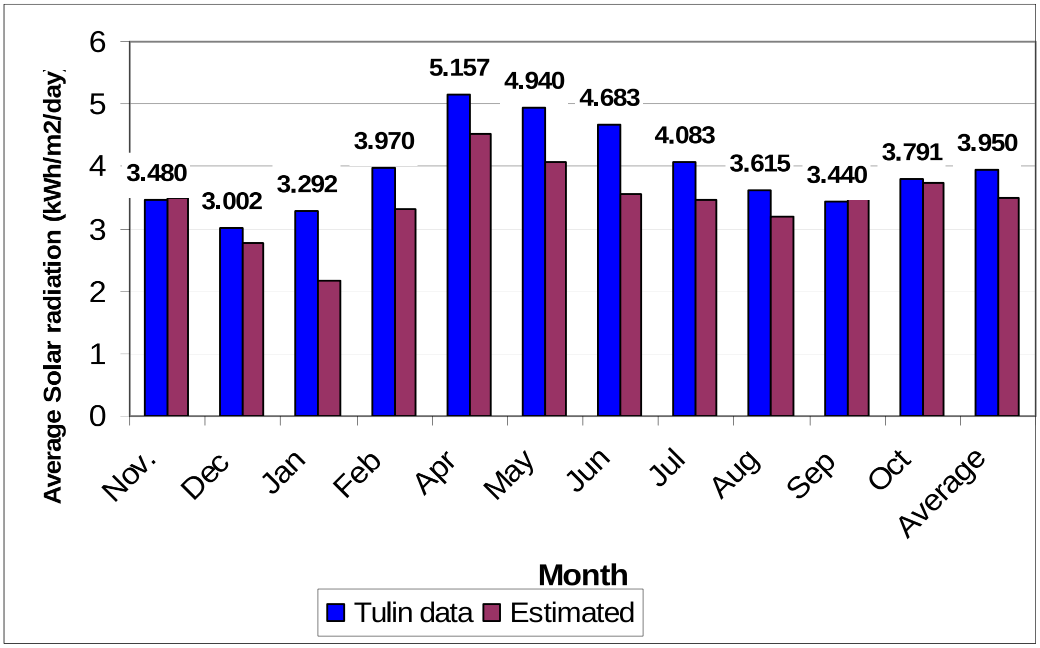

Fig. 10: Average Daily Solar radiation on a Horizontal surface for each month.

As can be seen from Fig. 10:

- The yearly average is 3.950kWh/m^2/day.
- There is notable seasonal variation in the global solar radiation on a horizontal surface, which varies which various between 3.00kWh/m^2/day

for December and 5.16kWh/m^2/day in April which is a variation of 72% over the year, or -24.1% to + 30.6% deviation from the yearly average.

- Solar radiation during the winter months (Dec–Feb) is between 3.002kWh/m^2/day and 3.971kWh/m^2/day, which is considered an average solar resource.
- In all months except November the real measured global horizontal solar radiation is higher than the extrapolated data from the nearby high altitude research station (HARS) in Simikot.
- The highest solar radiation is in the mid-season months of April to June (spring), rather than the summer months, as might be expected, based on potential clear sky solar radiation values.

Possible reasons for this include:

- There are a higher number of unclear days in the summer months because of the monsoon season, where there are heavy clouds. In the monitored year the monsoon period was reported to have been "mid-June until the first week of October." (Malla, Avishek, 2007)
- Lower global solar radiation in summer may also be a result of more diffuse radiation in the summer months.

4.1.2 Global Solar Radiation on the Plane of Array (POA)

Figure 11 shows the average monthly global solar radiation values along with the yearly average.

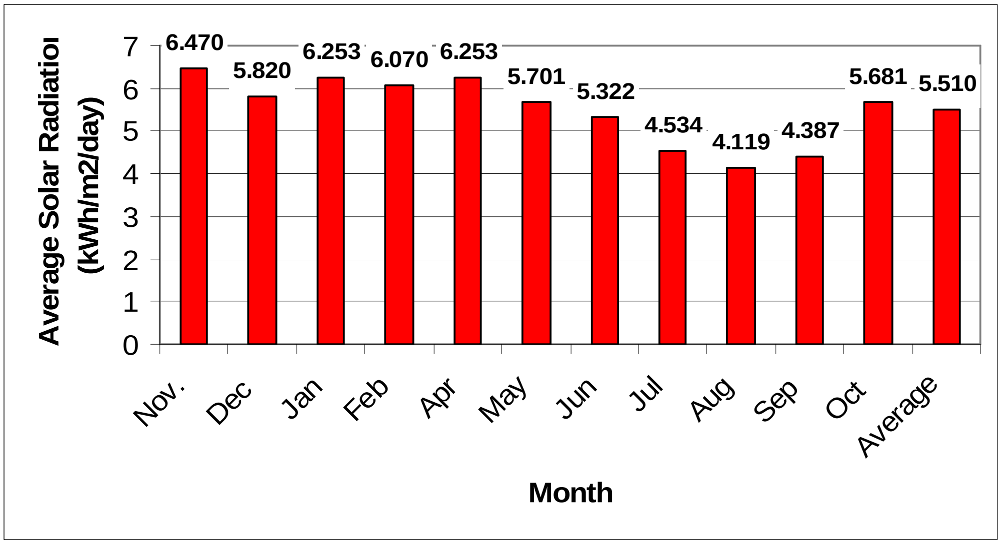

Fig. 11: Average Daily Global Solar Radiation on the Plane of Array (POA) for each month.

As can be seen from Fig 11:

- A yearly average solar radiation value on the plane of array (POA) is 5.51kWh/m^2/day, or 39.5% higher than the horizontal global solar radiation value. This is a higher increase than forecasted by PVSyst, which expected an increase of 33% (See Fig.6 in Section 2.7).
- Due to the PV tracking frame, solar radiation values are not as seasonally varied when measured on the POA. The variations are between 4.12kWh/m^2/day for August and 6.47kWh/m^2/day in November, which is a variation 57% over the year, or -25.2% to + 17.4% deviation form the yearly average.

4.1.3 Solar Radiation Comparison

Figure 12 shows the average monthly global solar radiation values on a horizontal surface and on the POA respectively along with the yearly averages.

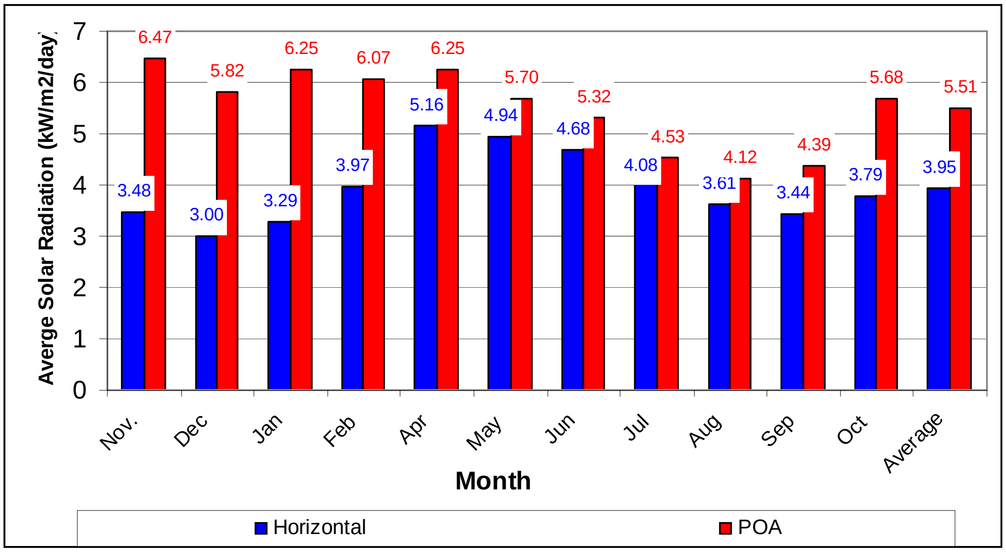

Fig. 12: Comparison of the Global Solar Radiation on a Horizontal surface and on the POA.

As can be seen from Fig. 12:

- The received global solar radiation on the POA, due to the PV tracking system increases significantly compared to the horizontal global solar radiation, with a yearly average increase of 39.5% as seen in Table 9 below.
- At times the increase in POA solar radiation is not as significant as others. The numeric differences vary between 0.45kWh/m^2/day for July and 2.99kWh/m^2/day in November.
- The difference in received global solar radiation between POA and horizontal is greater in the winter months (+ 93.9% in Dec) than the summer months (+11.1% in July.) This is as expected since the pyranometer measuring horizontal radiation is closer to perpendicular to the sun in the summer months.

- The value of tracking the sun can be seen in Table 9, which shows significant differences in horizontal solar radiation compared to POA solar according to each month.

Table 9: Percentage increase from Horizontal to POA Solar Radiation

Month	Solar Rad (H)	Solar Rad (POA)	% More Rad on POA
Nov, 06	3.48	6.47	85.9%
Dec, 06	3.00	5.82	93.9%
Jan, 07	3.29	6.25	90.0%
Feb,07	3.97	6.07	52.9%
Apr,07	5.16	6.25	21.3%
May,07	4.94	5.70	15.4%
Jun,07	4.68	5.32	13.6%
Jul,07	4.08	4.53	11.1%
Aug,07	3.61	4.12	14.0%
Sep,07	3.44	4.39	27.5%
Oct,07	3.79	5.68	49.9%
Yearly Ave	3.95	5.51	39.5%

Table 9 shows:

- The percentage increase for each month in global solar radiation on the Plane of Array (POA) compared to horizontal (H) using horizontal as the basis, the percentage increase equals (POA-H)/H
- There is a yearly percentage increase of 39.5%, therefore on average over the year the PV array is receiving almost 40% more solar radiation because of the tracking system.
- The expected increase in solar radiation was 35% to 40 %(Zahnd, Alex, 2007) so the measured value of 39.5% is well within the range and 19.7% higher than PVSyst4.1 estimated at 33%.
- April to August has the smallest percentage increase over the year. This may be due to the fact that at times "Humla staff forgot to decrease the

angle of the tracker, April to August." (Malla, Avishek. 2007) The north-south manual adjustment between 5° and 60° has to be carried out every two weeks or at least once a month for best results.

- The percentage increase in solar radiation on the POA is greater in the winter months than in the summer months, as in order to have the PV array perpendicular during the winter months; it has to be under a south-north axis angle of 50°- 60°.

4.1.4 Load Profile

Figure 13 shows the average monthly load values including the maximum and minimum loads for each month.

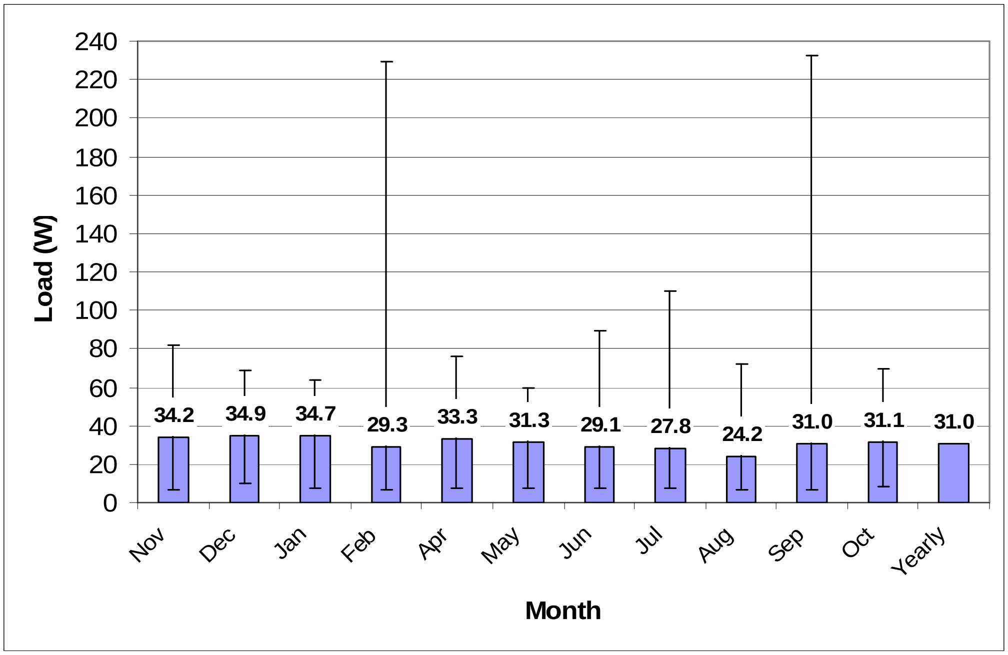

Fig. 13: Average hourly load values for each month in the analysis period.

As can be seen from Fig 13:

- The average hourly load is between 24.2W and 34.9W and the average for the year is 31.0W. The average daily loads are presented in Figure 14 below.
- The minimum load is never zero. Since the tracker and datataker are powered by their own PV modules this base minimum load is a result of lights being on.
- The load has a possible maximum of approximately 90W. There were 28 values that exceeded 90W that needs to be further investigated.
- The month's load maxima that will be examined are February and September in Section 4.2.

Figure 14 shows a representative diurnal load profile for summer, winter and midseason represented by respectively June, January and May; this allows hourly maximum and minimum values to be noted.

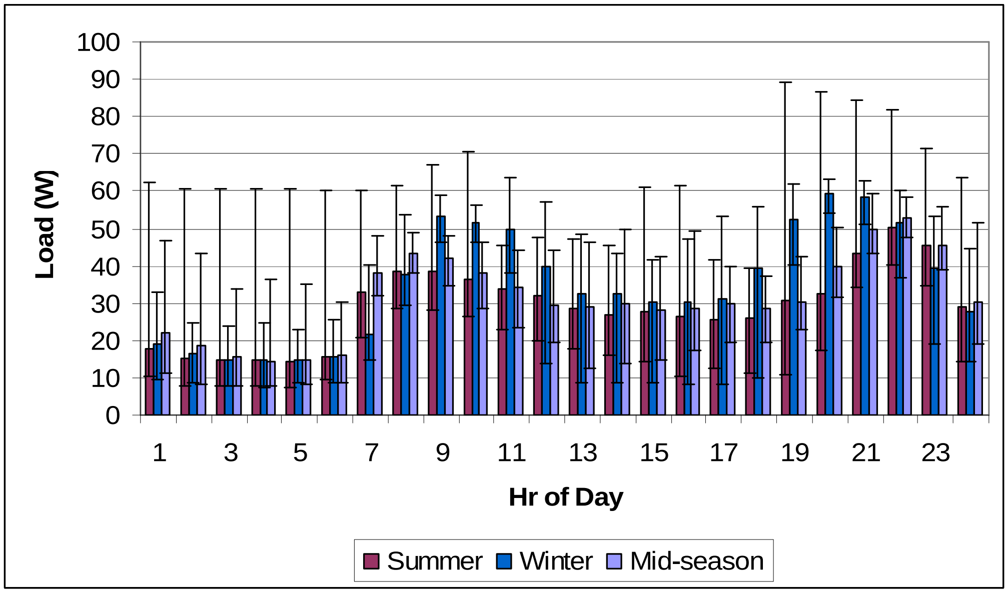

Fig. 14: Average Diurnal WLED light Load Profile

As can be seen from Fig. 14:

- There is never a zero load, indicating that some lights are left on throughout the day and night.
- There is a different load profile to the design load of 7 hours use per day. Since the beginning of the monitoring period, the villagers requested the ability to switch the lights on and off according to their needs, as their mud and stone house are very dark inside even during the day.
- The maximum and minimum values given by the error bars show that the load profile remains relatively the same over time, with increases in the morning and the evening and a dip during the middle of the day and at night.
- Differences according to season are notable, with a clear pattern of increased load as the seasons change from summer to mid-season to winter. As the hours of daylight decrease and people spend more time indoors and use their lights more.
- Between 10 and 15 lights, were left on all night. This could partly be due to the cultural belief that lights protect the villagers from evil sprits. The load profile strongly suggests that this might be happening, with about half of the homes of the villages having each one WLED on all night. Not all the households are strong Hindu believers and thus have not such great fear of evil spirits. (Zahnd, Alex. 2007). This could explain why only approximately half the households have the lights on all night.

Figure 15 shows the average daily load fro each month.

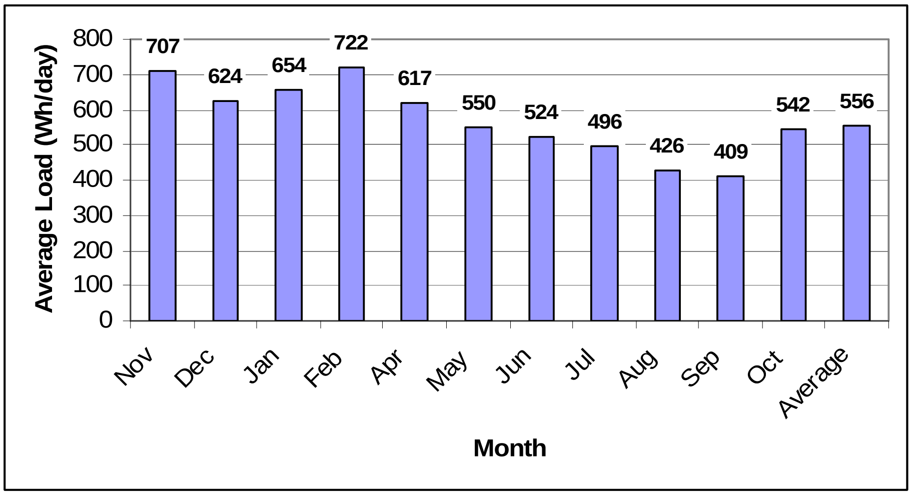

Fig. 15: Averaged Daily Load for each month.

As can be seen from Fig. 15:

- The average load has a correlation with seasons, with a clear increase in the average daily load over the winter months (Nov-Apr, likely due to the shorter daylight hours as discussed above).
- While the actual light use pattern over the day changed, not all lights were on at the same time. Therefore the average daily load has not really increase and has stayed between 409Wh and 722Wh, dependent on the month, with an average of 556Wh.
- The average daily load for the year is 556Wh, which is below the initial design load of 700Wh but very close to the expected load profile of 3lamps * 28 homes * 7 hours = 588Wh.

4.1.5 Battery Voltage

Figure 16 shows the average BB voltage for each month including the maximum and minimum and average voltage values, together with the average battery temperature.

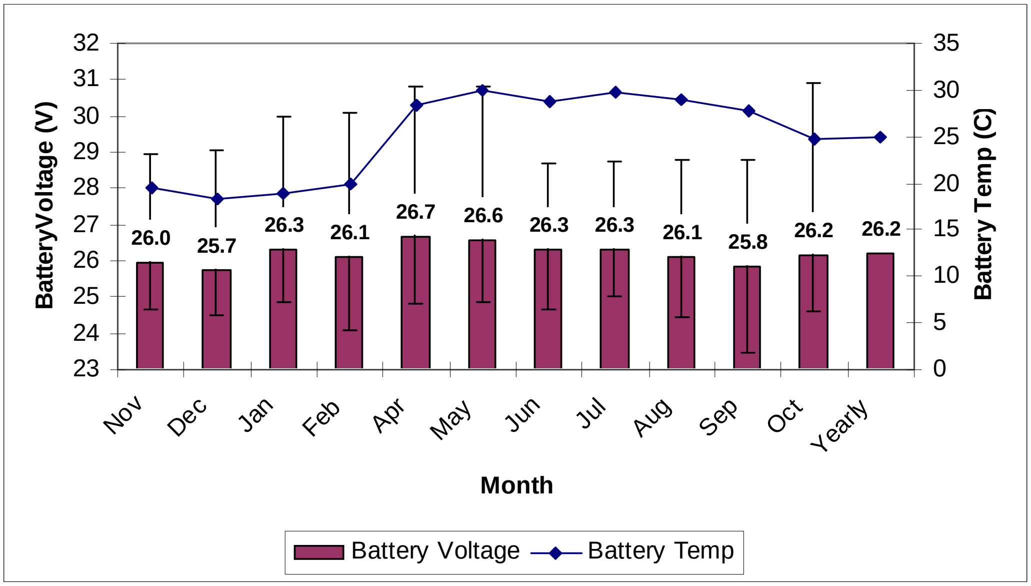

Fig.16: Variation of Battery Bank Voltage and Battery Temperature over the Year

As can be seen from Fig 16:

- The average battery voltage over the year stays relatively constant, with a yearly average of 26.2V; the monthly average range is from 25.8V to 26.7V.
- The y-error bars show the battery voltage range for each month indicating that although there are some months where particularly high battery voltages occur, the battery voltage never gets below 23.4V and only in one month does it get below 24V.

- Battery temperature, which varies from 18°C to 30°C, is also shown as it can affect battery voltage.
- Battery temperature follows a seasonal pattern as would be expected, with the highest temperatures over the summer months.
- Of particular interest are the months when the battery voltage is the lowest, seen in Figure 16 as December, February and September. These months are investigated in Section 4.2.
- The months where high battery voltage (over 30V) are observed, namely February, May and October are investigated by analysing the actions of the charge controller (CC) in Section 4.2.5.
- Referring back to the global solar radiation values for the year the low December battery voltage observed can be explained by the low solar radiation for this month. The low battery voltage levels for February and September are more likely to be due to the high, unauthorised loads as seen in Figure 13.

4.1.6 PV Array Power Generation

Figure 17 shows the average daily output $300W_p$ PV array (Wh) for each month, along with the global solar radiation values on the POA for each month.

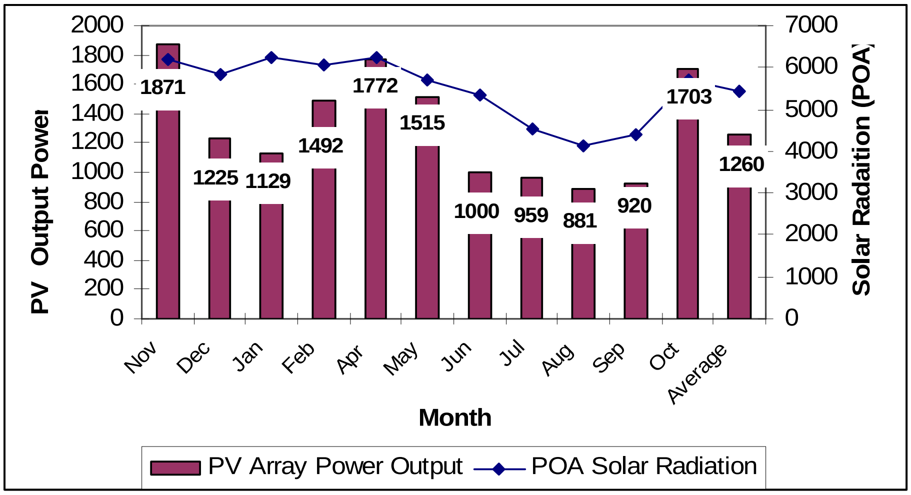

Fig. 17 Average daily PV array energy output values for each month.

As can be seen from Fig. 17

- The average yearly 300W$_p$ PV array power output is 1260Wh/day.
- The PV array power follows a seasonal trend similar to that of POA global solar radiation, with mid-season months, April, May, October and November having the highest levels of PV array power output.

4.1.7 PV Performance Ratio (PR)

Figure 18 shows the performance ratio for each month in the analysis period.

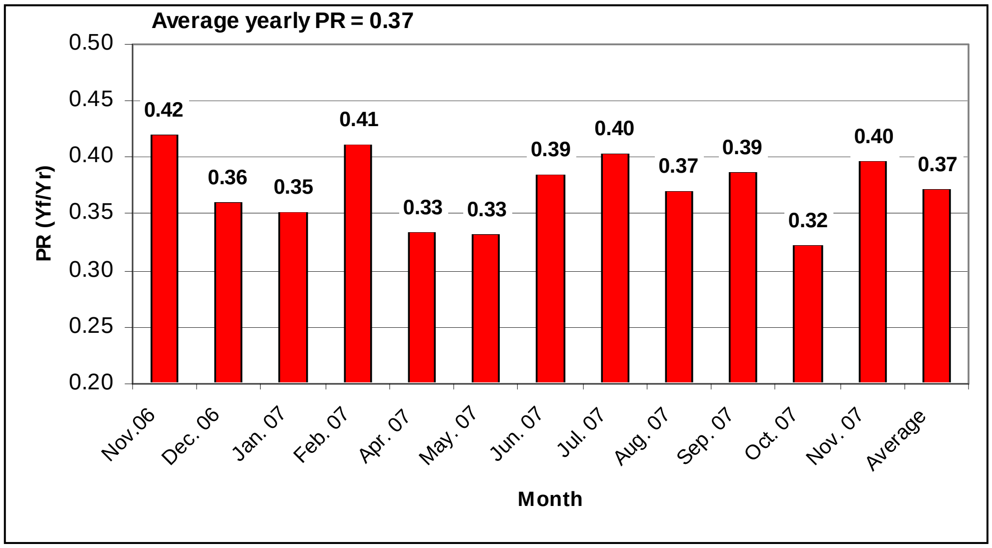

Fig. 18: Average Performance Ratio for each month.

As can be seen from Fig. 18:

- The performance ratio ranges from 0.32 to 0.42, which is considered to be on the low side (Poissant, 2008). A lower PR was expected, as the Tulin PV system was intentionally oversized.
- The performance ratios for the stand-alone system in Tulin are well within the ranges given by the IEA-PVPS Task 2 shown in Section 5.6.
- The yearly average PR for Tulin is 0.37, which is very low. This is also explored further in Section 5.6.

4.2 Results of Interest

This section explores the interaction of the components operating as a system and any unusual data that were observed.

In particular the high loads in February are explored, as are the high loads in September and consequently the low battery voltage in this month. The operation of the charge controller is explored and seasonal variations briefly discussed.

4.2.1 Operation of System

This section examines the way in which the components operate within the system to and comments on the seasonal variations between summer and winter using a representative day graph. Figure 19 shows the system components performance on a representative summer day (June 21).

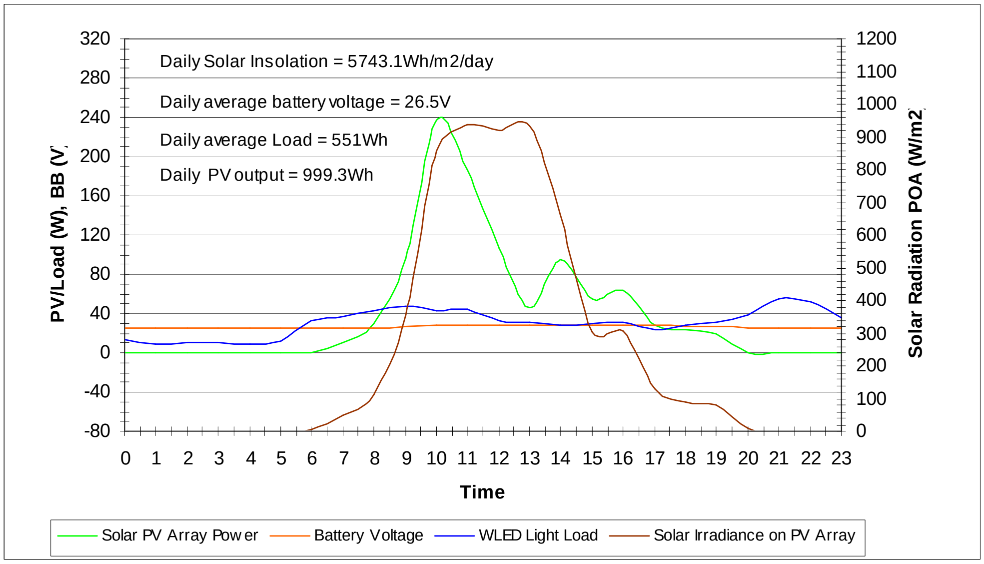

Fig. 19: System performance for the 21st June (a representative day in summer).

As can be seen from Fig. 19:

- The PV array power output increased steadily with the solar radiation in the morning
- At 10 am battery voltage reached a maximum of 28V and the CC reduced PV array voltage and hence PV array power output fell.
- PV output array power increased later in the day, after 1pm as BB voltage dropped and the CC thus connected again. Finally PV array power output decreased again as BB voltage dropped with decreasing global solar radiation towards the evening, after 4pm.
- The load profile is typical with loads increasing in morning and evening.
- The loads were never at a zero level.
- Battery voltage did not vary greatly during the day but increased with increased PV array power output in the morning and decreased with increased load in the evening.

Figure 20 shows the system components' performance on a representative winter day (January 6).

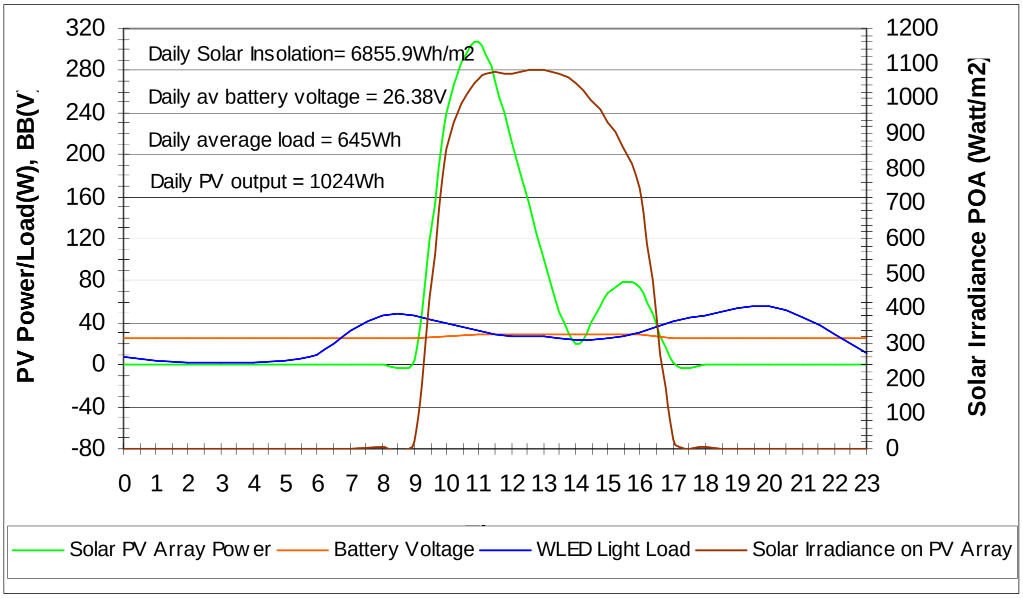

Fig. 20: System performance for the January 6 (a representative day in winter.)

As can be seen from Fig. 20:

- The PV array power output increased steadily with the global solar radiation in the morning.
- Between 10a.m (BB = 26.9V) and 11a.m (BB =29.6V), the CC reduced PV array voltage and the BB was trickle charged, causing PV power output to fall.
- PV array power output increased again after 2pm (BB =29.6V) and then decreased again after 4pm as the global solar radiation and BB voltage decreased towards the evening.
- The load profile is typical with loads increased in morning and evening.
- The loads got very low (2W) although never fell to zero.

- Battery voltage did not vary greatly during the day but increased with increased PV output in the morning and decreased with increased load in the evening.

4.2.2 Seasonal Variation

Seasonal variation can greatly affect the operation of a system due to differences in solar radiation available. This section explores the effects of changes in solar radiation on battery voltage over the representative months for summer (June) and winter (January).

Fig.21 shows the Battery Voltage Analysis for the winter month of January.

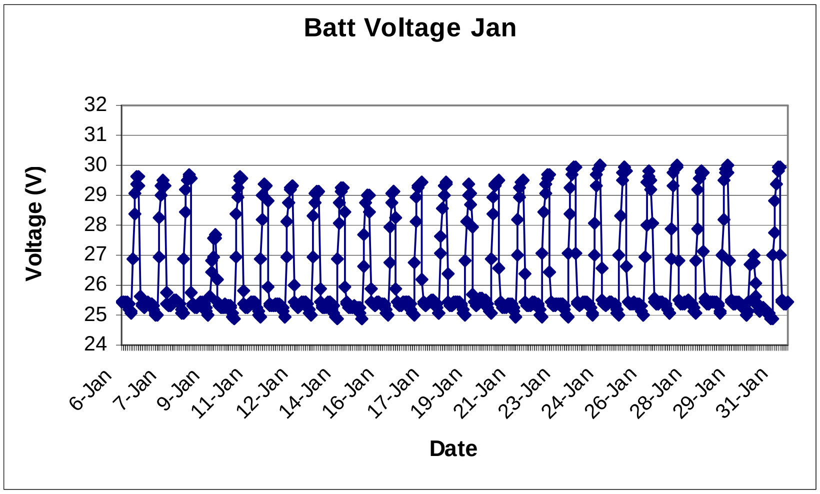

Fig. 21: Daily Battery Voltage for the winter month of January.

As can be seen from Fig. 21:

- The battery voltage in the winter month of January is regularly at the full state of charge.
- There are no sustained periods of low state of charge of the BB.

- There are days where the battery voltage drops down to 25.2 V specifically the 9th and 30th of the month.
- There is evidence of the CC operating, as the battery voltage never gets much higher then 30V. For further evidence of CC operation see Section 4.2.5.

Figure 22 shows the average solar radiation on plane of the array for the winter month of January.

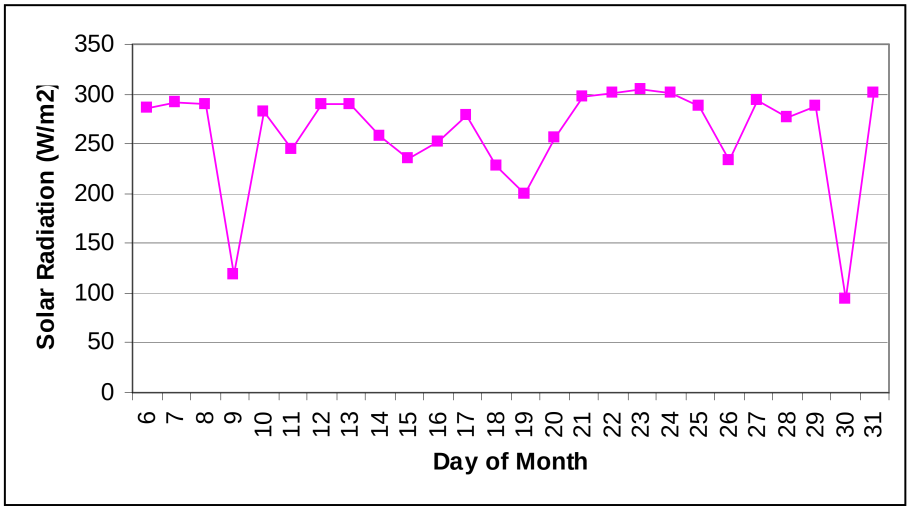

Fig. 22: Average Daily Global Solar Radiation on the POA for the winter month of January.

As can be seen from Fig. 22:

- The days of low battery voltage in Fig. 21 specifically the 9th and 30th correspond to low solar days.
- There is good solar resource even in the winter month. To note whether it is typical for winter to have good solar resource, longer periods of monitored data would be beneficial. This is an aim of the monitoring

project in Tulin but at present there is only one year's worth of data. However, analysis of three years' worth of data from the nearby High Altitude Research Station in Simikot data shows that the year under investigation was an average year. (Zahnd, Alex. 2007)

Figure 23 shows the daily battery voltage for the summer month of August.

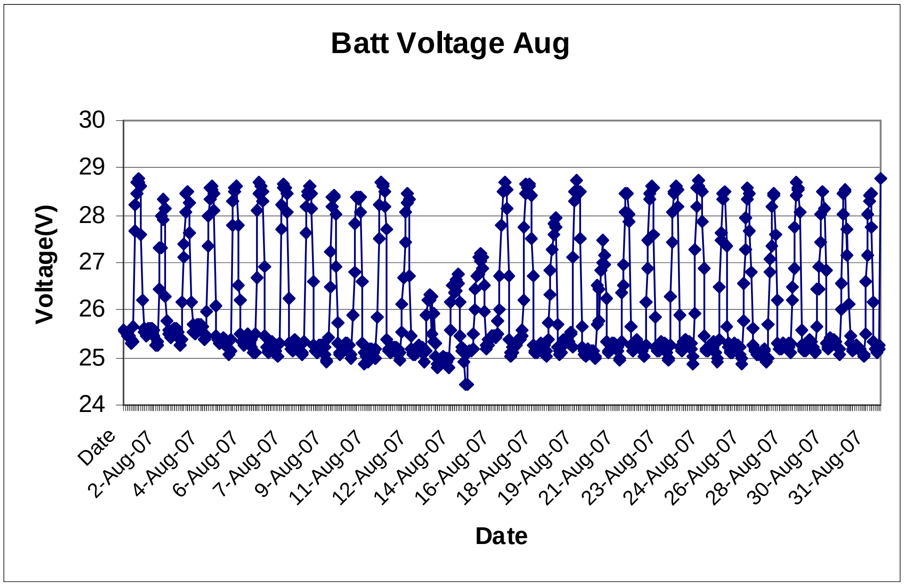

Fig. 23: Daily Battery Voltage for the summer month of August

As can be seen from Fig. 23:

- The battery voltage does not drop below 24V, so there are no periods of sustained low state of charge.
- There are days where the battery voltage drops, specifically the 13th, 14th 15th, 18th and 20th of the month.
- There is evidence of the CC operating as when the battery voltage gets high, i.e. 28.8V the battery is trickle charged and so does not get much higher than the defined maximum voltage. See Section 4.2.5.

- The battery voltage is regularly at the full state of charge.

Figure 24 shows the global solar radiation on the plane of the array for the summer month of August.

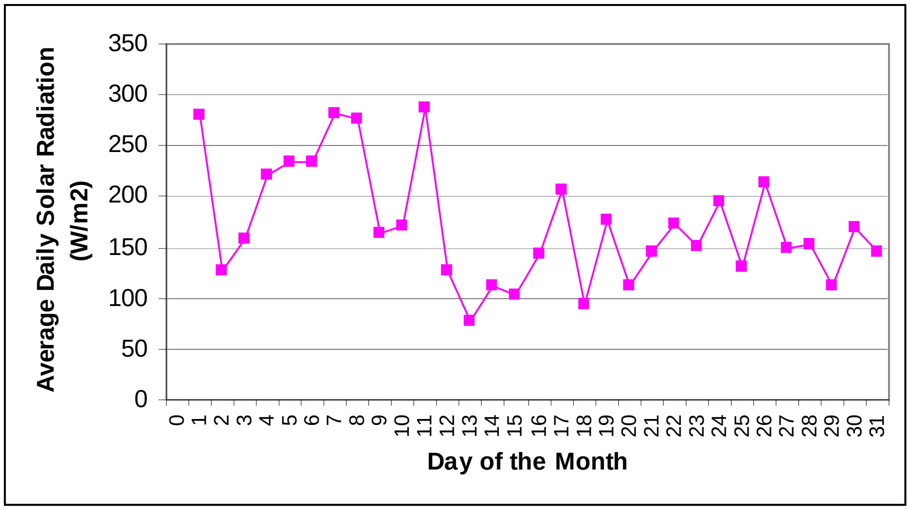

Fig. 24: Average Daily Global Solar Radiation on the POA for the Summer Month of August.

As can be seen from Fig. 24:

- The days with low battery voltage in Figure 23 specifically the 13th, 14th 15th, 18th and 20th of August correspond to low solar radiation days in Figure 24.
- Low radiation days does not necessarily result in low battery voltage, as seen by the low solar radiation on the 2nd and 30th of August.
- There is a similar range of solar radiation in summer and winter, although winter gets higher values on some days (up to 300 W/m^2). This is likely to be due to the monsoon period over summer where there are a large number of unclear cloudy skies.

4.2.3 September

Plots from hourly monitored data have been shown below to investigate the possible reasons for low battery voltage in September 2007.

Figure 25 shows the battery voltage in September.

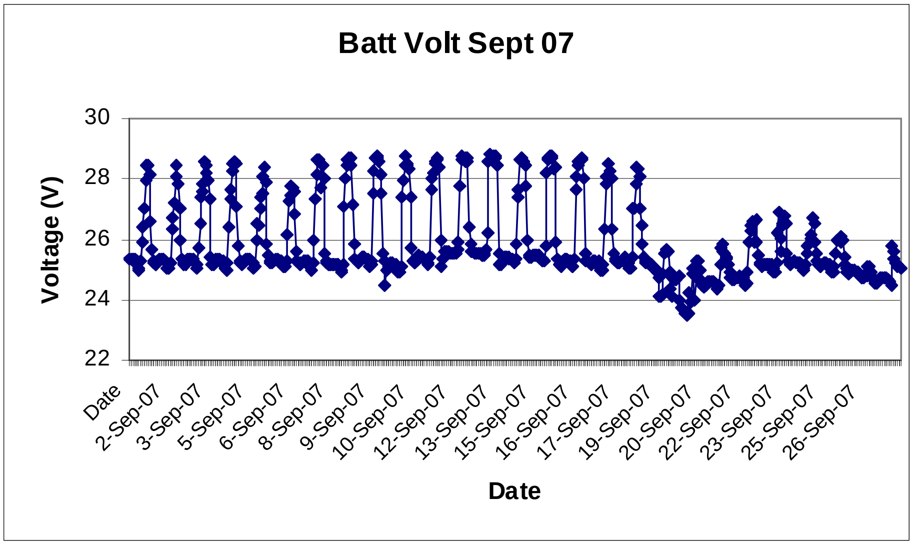

Fig. 25: Battery voltage for September 07

As can be seen from Fig. 25:

- Prior to the 19th Sept the battery voltage was maintaining a constant state between 24.4V and 28.4 V under the daily load pattern, which is an ideal range for the BB.
- The battery voltage makes a significant drop after the 19th September and stays low for the rest of the month.

Figure 26 shows the global solar radiation on the plane of array (POA) for September.

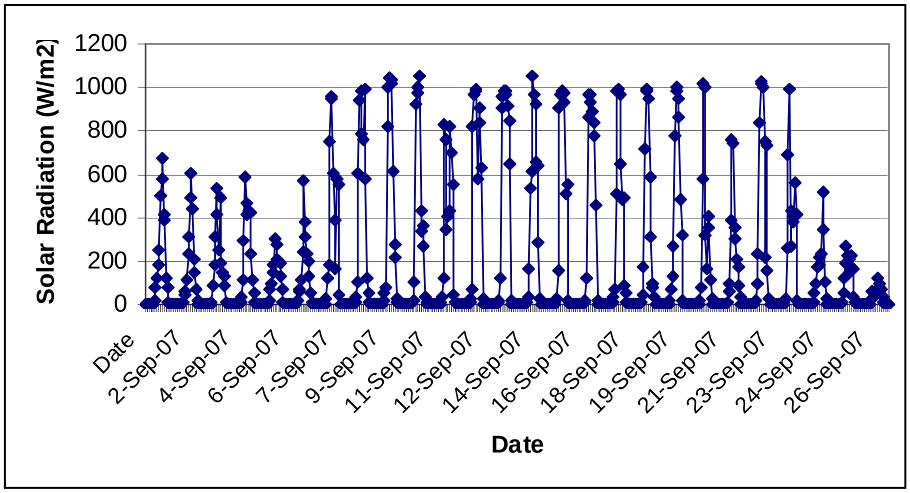

Fig. 26: Solar Radiation on Plane of Array (POA) in September 07

As can be seen from Fig. 26:

- The low periods of solar radiation are at the beginning and end of the month.
- Low solar days at the beginning of the month do not correspond to low battery voltage below 28V.
- However lower radiation days at the end of the month correspond with low battery voltage and explain the inability for the battery voltage to get back to its maximum state of charge after unauthorised high loads on the 19th and 20th seen below in Figure 27.

Figure 27 shows the load profile for September.

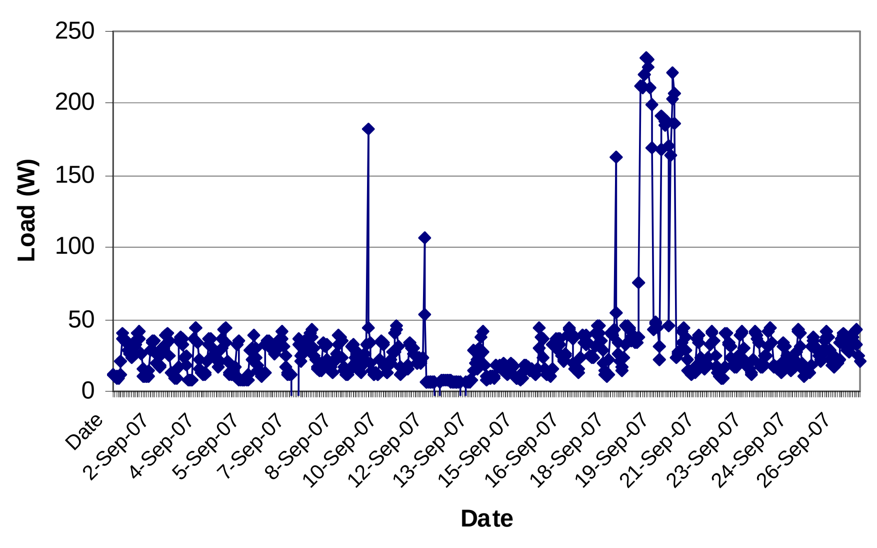

Fig. 27: Load Profile for September from average hourly data.

As can be seen from Fig. 27:

- There are identified loads far over the system design load maximum of 84W on the 9th, 11th, 19th and 20th September.
- The high loads are far greater then 84W, reaching a maximum power drawn from the battery of 225W.
- There is a correlation between high loads for extended periods and low battery voltage seen in Figure 25 for the days of extremely high loads.
- The system was not designed to draw such high loads and thus the BB cannot provide for such high loads for long periods. Table 10 investigates these high loads further.

Possible reasons for loads far greater then 84W include:

- Villagers have added an impermissible high load to system.
- The air heater has drawn more direct power from the BB, then it is designed to use, due to an internal short circuit in the CC.

Table 10: September hourly data for high loads period.

Date	Time	Tilt	PV Power	CC-BB Volt	Power Into BB	Load
9-Sep-07	20:00	0.00	0.00	24.50	184.3	182.75
11-Sep-07	19:00	4.54	0.11	25.08	103.5	106.65
18-Sep-07	11:00	992.36	294.22	27.00	177.1	162.63
19-Sep-07	8:00	69.24	16.44	24.08	216.2	212.19
19-Sep-07	9:00	130.17	33.34	24.10	216.4	212.19
19-Sep-07	10:00	266.20	71.15	24.18	216.5	211.40
19-Sep-07	11:00	779.11	217.48	24.84	233.4	220.58
19-Sep-07	12:00	1002.96	293.43	25.56	251.0	232.42
19-Sep-07	13:00	984.48	293.40	25.66	250.4	231.48
19-Sep-07	14:00	946.88	289.05	25.69	248.6	230.44
19-Sep-07	15:00	861.78	265.57	25.60	241.5	225.87
19-Sep-07	16:00	487.17	141.30	24.91	218.6	211.27
19-Sep-07	17:00	320.79	88.07	24.34	203.7	199.01
19-Sep-07	18:00	19.81	3.54	24.09	171.6	169.39
20-Sep-07	1:00	0.00	0.00	23.96	169.5	167.68
20-Sep-07	2:00	0.00	0.00	23.75	194.6	190.90
20-Sep-07	3:00	0.00	0.00	23.70	194.3	190.53
20-Sep-07	4:00	0.00	0.00	23.65	190.6	187.03
20-Sep-07	5:00	0.01	0.00	23.58	188.5	184.99
20-Sep-07	6:00	0.03	0.00	23.49	191.1	187.35
20-Sep-07	7:00	2.19	-0.26	23.51	173.2	170.81
20-Sep-07	9:00	75.78	18.73	23.55	165.1	163.74
20-Sep-07	10:00	582.72	155.09	23.92	211.6	202.98
20-Sep-07	11:00	1018.54	290.44	24.86	240.2	221.23
20-Sep-07	12:00	1004.18	289.33	25.06	224.2	207.23
20-Sep-07	13:00	320.71	85.57	24.00	189.5	186.22

As can be seen from Table 10:

- There are isolated high loads for no longer than one hour periods on the 9th, 11th, and 18th September. These are likely to be impermissible loads added by villagers.
- These early dates have not affected the BB voltage negatively.
- The 19th and 20th are the days that are of most interest, when the high loads are for longer periods and correspond to low BB voltage.
- The daily WLED load consumption for the 19th September is 2752Wh and the power into the battery on this day is only 149 Wh.

2752Wh – 149Wh = 2603Wh.

If that energy was drawn at an average voltage of 24V, this amounts to 108.5Ah, which is 36.1% of its full (300Ah) BB capacity in one day.

- The daily load consumption for the 20th September is 2492Wh and the power into the battery on this day is only 308Wh Wh. 2492Wh – 308Wh = 2184Wh.

  If that energy was drawn at an average voltage of 24V, this amounts to 91Ah, which is 30% of its full (300Ah) BB capacity in one day.
- Thus the 19th and 20th of September amounts to a DoD of approximately 67% of the BB's total capacity over just two days, explaining the observed drop in BB voltage.
- As can be seen above, the power drawn from the BB was much higher than the power into the BB, which is why low battery voltages are observed at this time.
- There exists a potential danger for the BB lifetime if sustained periods of low batter bank voltage are experienced.

Further investigation, by email correspondence, into the high loads incident on the 19th and 20th September uncovered that these high load periods were followed shortly after by damage to the air heater. On September 10th the air heater was connected to the system as part of the research in Tulin. No recordings for air heater voltage or current were observed at this time. It is hypothesized that the air heater may have been drawing a large current prior to it burning down, due to an internal short circuit. At the end of the high load days 19th and 20th September the air heater burnt down and caused damage to the current transducers in the DT80.

This subsequently caused the monitoring system to be down until the problem was rectified on the 4th October. The electrification system was not affected by the problem only the monitoring system.

4.2.4 February

Fig. 28 shows the average daily load diagram for February

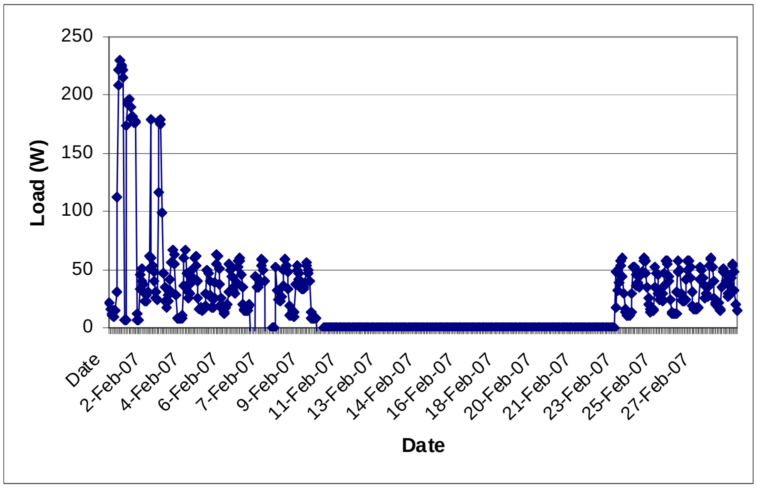

Fig. 28: Average Daily Load for February

As can be seen from Fig. 28:

- The first two days of February have very high loads.
- For the remainder of the month there is a relatively stable load within the expected range, i.e. 10 –70W.

Table 11: February High Loads and the consequent affect on Battery voltage

Date	Time	2-Axis Tracking	PV Power	Batt Volt	Batt Power In	Load
1-Feb-07	0:00	0.00	0.00	25.49	-2.63	20.77
1-Feb-07	1:00	0.0	0.0	25.5	1.5	16.5
1-Feb-07	2:00	0.0	0.0	25.5	5.7	12.2
1-Feb-07	3:00	0.0	0.0	25.5	7.0	10.9
1-Feb-07	4:00	0.0	0.0	25.5	7.9	9.9
1-Feb-07	5:00	0.0	0.0	25.5	3.8	14.2
1-Feb-07	6:00	0.0	0.0	25.5	2.9	15.1
1-Feb-07	7:00	0.0	0.0	25.3	-12.9	31.3
1-Feb-07	8:00	9.1	0.5	25.0	-91.9	112.5
1-Feb-07	9:00	24.6	4.3	24.5	-185.7	208.8
1-Feb-07	10:00	866.3	232.7	25.6	10.6	222.5
1-Feb-07	11:00	1061.4	295.5	26.3	59.5	229.5
1-Feb-07	12:00	1077.7	299.2	26.4	67.8	224.5
1-Feb-07	13:00	1070.8	295.3	26.4	62.5	226.6
1-Feb-07	14:00	1010.2	275.2	26.3	49.9	222.0
1-Feb-07	15:00	904.4	240.1	26.1	25.6	214.8
1-Feb-07	16:00	837.3	226.0	27.4	216.5	7.1
1-Feb-07	17:00	174.0	42.8	26.5	52.9	6.8
1-Feb-07	18:00	11.1	0.9	25.2	-153.5	173.9
1-Feb-07	19:00	0.2	0.0	24.7	-175.2	193.1
1-Feb-07	20:00	0.0	0.0	24.4	-177.4	195.3
1-Feb-07	21:00	0.0	0.0	24.4	-178.8	196.4
1-Feb-07	22:00	0.0	0.0	24.4	-172.7	190.3
1-Feb-07	23:00	0.0	0.0	24.3	-162.8	180.5
2-Feb-07	0:00	0.0	0.0	24.3	-164.5	181.5
2-Feb-07	1:00	0.0	0.0	24.2	-162.5	179.3
2-Feb-07	2:00	0.0	0.0	24.2	-160.1	177.0
2-Feb-07	3:00	0.0	0.0	24.1	-160.7	177.5
2-Feb-07	4:00	0.0	0.0	24.1	-160.1	176.9
2-Feb-07	5:00	0.0	0.0	24.8	4.4	11.4
2-Feb-07	6:00	0.0	0.0	24.9	9.3	6.5
2-Feb-07	7:00	0.0	0.0	24.9	9.4	6.5
2-Feb-07	8:00	9.5	0.6	24.7	-15.9	33.7
2-Feb-07	9:00	25.3	4.4	24.6	-23.7	45.4
2-Feb-07	10:00	854.1	229.3	25.8	176.0	50.8
2-Feb-07	11:00	1050.3	293.4	26.3	242.5	40.4
2-Feb-07	12:00	1076.9	301.2	26.5	252.8	37.0
2-Feb-07	13:00	1068.2	296.3	26.6	255.8	29.6
2-Feb-07	14:00	1027.8	283.1	26.7	251.2	22.6
2-Feb-07	15:00	959.0	261.1	26.8	226.5	28.7
2-Feb-07	16:00	861.3	231.0	26.9	206.5	22.3
2-Feb-07	17:00	205.4	50.6	26.1	36.0	30.8
2-Feb-07	18:00	11.8	1.0	25.6	-30.7	51.4
2-Feb-07	19:00	0.2	0.0	25.4	-42.0	61.4
2-Feb-07	20:00	0.0	0.0	25.0	-159.1	178.6
2-Feb-07	21:00	0.0	0.0	25.2	-42.3	60.5
2-Feb-07	22:00	0.0	0.0	25.2	-35.5	53.7
2-Feb-07	23:00	0.0	0.0	25.2	-30.3	48.3
3-Feb-07	0:00	0.0	0.0	25.2	-21.8	39.6
3-Feb-07	1:00	0.0	0.0	25.2	-13.3	30.9
3-Feb-07	2:00	0.0	0.0	25.2	-8.5	25.9
3-Feb-07	3:00	0.0	0.0	25.2	-6.2	23.6
3-Feb-07	4:00	0.0	0.0	24.8	-97.8	116.9
3-Feb-07	5:00	0.0	0.0	24.5	-159.6	178.2
3-Feb-07	6:00	0.0	0.0	24.4	-156.9	175.4
3-Feb-07	7:00	0.1	0.0	24.3	-160.2	178.5
3-Feb-07	8:00	10.2	0.8	24.5	-79.9	99.5
3-Feb-07	9:00	29.1	5.3	24.6	-23.8	46.9
3-Feb-07	10:00	780.8	208.3	25.8	161.9	46.3
3-Feb-07	11:00	998.5	277.9	26.3	234.7	34.5
3-Feb-07	12:00	1020.5	284.4	26.6	251.5	23.2
3-Feb-07	13:00	1020.8	283.0	26.7	255.7	17.7
3-Feb-07	14:00	989.4	272.6	26.9	242.3	22.5
3-Feb-07	15:00	881.1	239.2	26.9	208.6	27.7
3-Feb-07	16:00	505.9	131.0	26.5	108.0	32.3
3-Feb-07	17:00	146.9	34.7	25.9	10.1	42.0
3-Feb-07	18:00	14.9	1.9	25.5	-35.6	56.7
3-Feb-07	19:00	0.2	0.0	25.4	-47.8	67.0
3-Feb-07	20:00	0.0	0.0	25.3	-47.5	66.2
3-Feb-07	21:00	0.0	0.0	25.3	-44.4	62.9
3-Feb-07	22:00	0.0	0.0	25.2	-35.9	54.3
3-Feb-07	23:00	0.0	0.0	25.3	-10.3	27.9
4-Feb-07	0:00	0.0	0.0	25.4	9.4	7.6
4-Feb-07	1:00	0.0	0.0	25.4	9.4	7.6

Table 11 shows the hourly data for the 1st-4th February and gives a good example of the hourly responses of the BB's' voltage to the load and solar radiation. High loads for short periods have not affected the battery voltage negatively.

A possible explanation for these high loads at the beginning of February is that the villagers charged a battery or used some other load by cutting wires and plugging into the system, which the system has not been designed for. It is uncertain whether there is any physical evidence of this occurring.

4.2.5 Operation of charge controller (CC)

Evidence of the CC operating effectively to protect the batteries by reducing the PV array voltage and hence reducing the PV array power output is investigated in this section. Figures 29 and 30 show evidence of the charge controller operating well for a representative day for summer and winter.

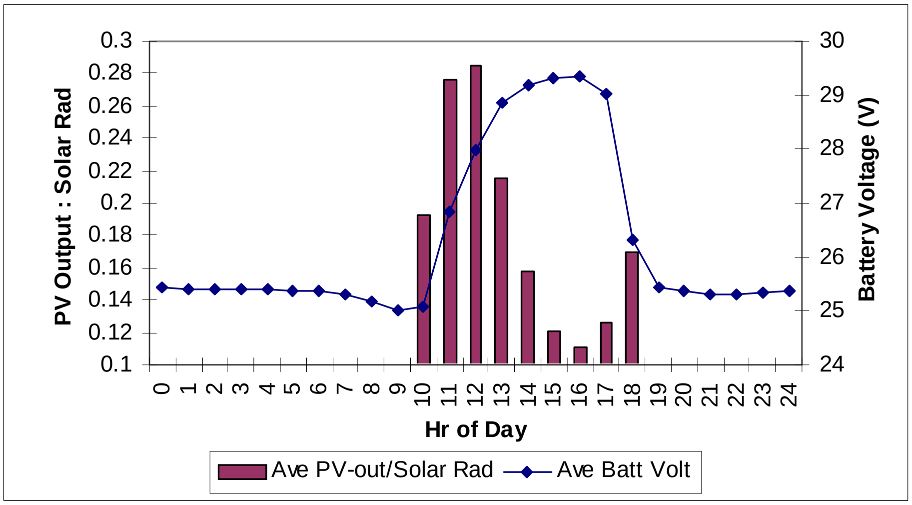

Fig. 29: Average PV Array Power Output / Solar Radiation (on the POA) for the Winter Month of January

As can be seen from Fig. 29:

- The ratio of the PV array power output to the global solar radiation decreased after midday, as the BB is full. This is evidence that the CC was operating, to trickle charge the BB, by decreasing the PV array power output, by reducing the PV array voltage.

- Later in the day as the BB voltage decreased the CC allowed the PV array voltage to increase again and the PV array power output increased, resulting in an increased ratio of PV output to the global solar radiation as was observed at approximately 6pm in Figure 29.

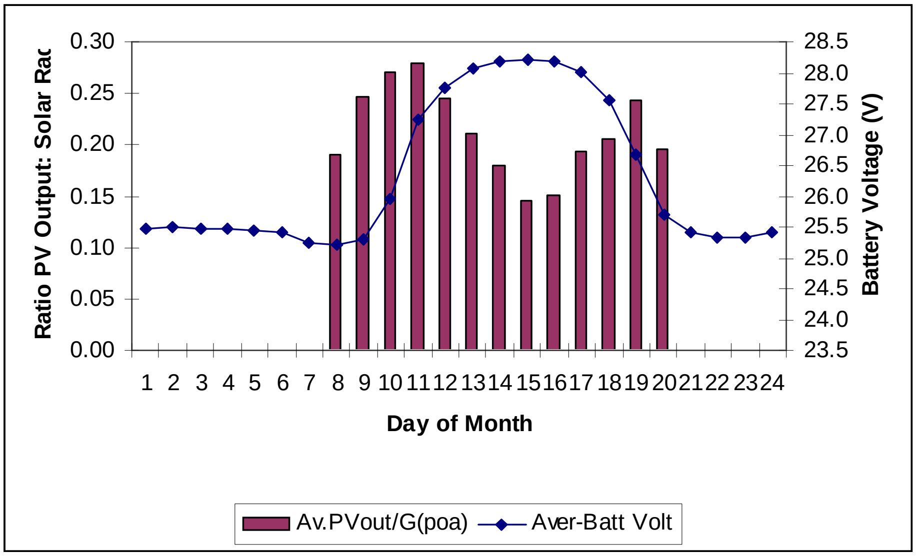

Fig. 30: Average PV Array Power Output / Solar Radiation (POA) for the Summer Month of June.

As can be seen from Fig. 30:

- The ratio of PV array power output to the global solar radiation decreased after approximately 11am, when the BB was approaching full. Again this is evidence that the CC was operating to reduce the PV array power output, by reducing the PV voltage and hence the BB was trickle charging.
- This coincided with a high battery voltage of over 28V.

- Again later in the day as the BB voltage decreased the CC allowed the PV array voltage to increase again and the PV array power output increased thus resulting in an increased ratio of PV array power output to the global solar radiation as was observed at approximately 4pm in Fig. 30.
- The average daily load in June the summer month was only 524Wh/day compared with the average daily load in January of 654Wh/day, which could explain why the charge controller operated more in winter than in summer. With a higher load in winter the BB was not as fully charged as in summer.

Figure 29 and 30 show the CC working well to protect the BB from being overcharged by reducing the PV array power output. There are other months when the CC does not seem to have been functioning as well, if at all. Figures 31 and 32 look at these months and provide possible explanations.

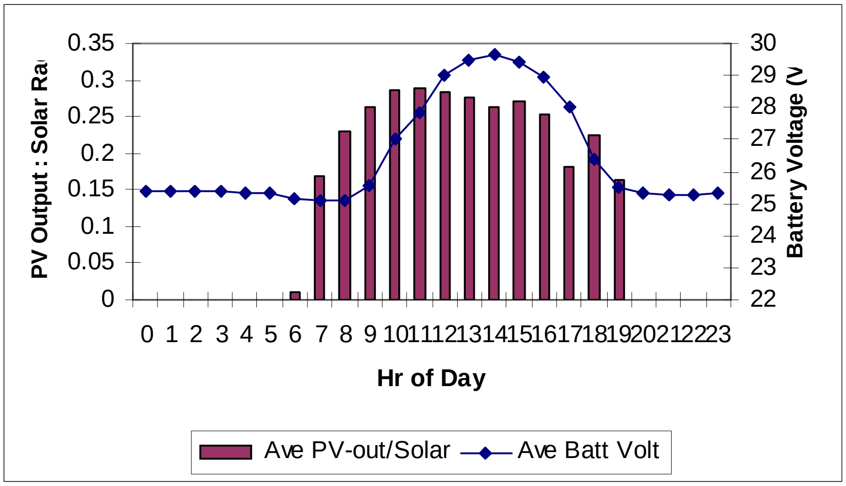

Fig. 31: Average PV Array Power Output / Solar Radiation (POA) for the Spring Month of May.

As can be seen from Fig. 31:

- Once the BB voltage rose over 28V, the PV output to global solar radiation ratio did decrease, although only slightly.
- This decrease had minimal effect on the BB's voltage which continued to increase, reaching almost 30V due to trickle charging.
- The BB voltage did not get back to below 28V until the PV array power output to global solar radiation ratio decreased to below 0.2, which considering the time of day, i.e. 5pm is likely to have been a result of lower global solar radiation.
- It seems from this graph that the CC was not operating as specified, as the PV array power output did not decrease. The BB is remained at below 30V and may have been as a result of trickle charging from the CC. Three different charge controllers were used during the monitoring period and it is unclear whether the CC had different operating specifications, which may have resulted in different graphs, seen from May and June.

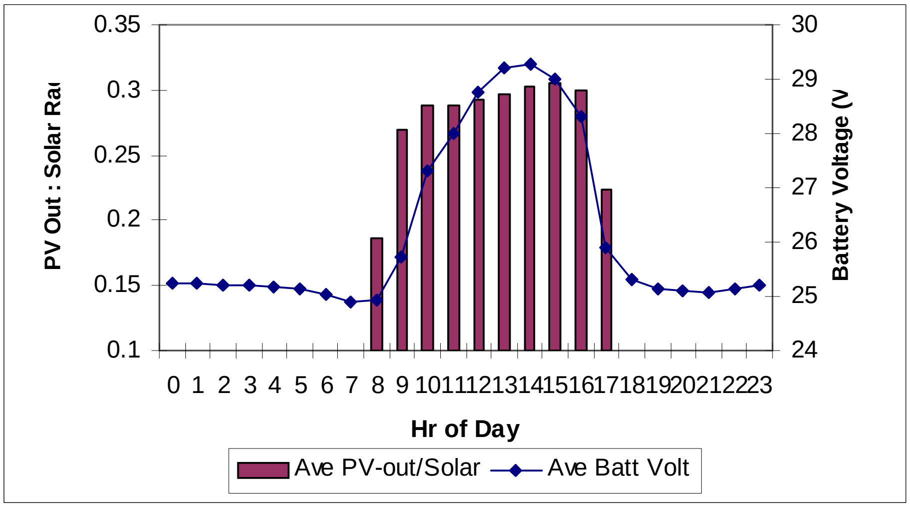

Fig. 32: Average PV Array Power Output / Solar Radiation (POA) for Autumn Month of October.

As can be seen from Fig. 32:

- There was no reduction in the PV array power output to global solar radiation ratio during the day.
- When the ratio fell, this is likely to have been due to the decreasing global solar radiation in the evening.
- The BB voltage during this month was well over the maximum cut-off voltage for the CC of 28.8V.
- It is clear from this graph that the CC was definitely not operating and this is demonstrated further by the CC history given below.

The history of the charge controllers is as follows. In November 2006 a pulse width modulator (PWM) CC was installed, during the second week of March 2007 a PWM CC with air heater (AH) channel was installed. The air heater was not connected as it was still in its testing phase and was not performing as expected. On September 10th 2007 a non PWM CC with air heater was installed as a dump load when the BB is full as part of an academic research project, so that the PV array power output could be better analysed. On September 27th the AH burnt down, perhaps as a result of drawing too much current, as high loads were also observed at this time. Since then there has been a Non-PWM CC installed but with the CC channel short-circuited. (Malla, Avishek. 2008). Thus in October 2007 there is no CC operating as is seen in Figure 32 above. For this reason the BB was not protected from being overcharged, as was the initial design. It is planned to install a Plasmatronic CC to once again protect the BB and have a dump load so that the PV array power output can be measured at its full power under the prevailing meteorological conditions. (Zahnd, Alex. 2007)

5 Discussion of Results

5.1 Comparison of results with expected performance

Table 12: Expected Performance Compared with Measured Performance

Parameter	**Projected by PVSyst or BOE Design**	**Measured Results**
Global solar radiation on the horizontal surface (H)	3.79Wh/m^2/day	3.950kWh/m^2/day
Global solar radiation on the plane of array (POA)	5.04kWh/m^2/day	5.510 kWh/m^2/day
Difference in global solar radiation (POA-H)	1.25 kWh/m^2/day	1.560 kWh/m^2/day
Battery bank voltage	25.9 V	26.2 V
Load for WLED lights	700Wh/day	556Wh/day
PV array power output	940.5Wh/day	1260Wh/day
Performance ratio (PR)	0.39	0.37

As can be seen from Table 12 the measured results were in most cases slightly higher than the expected performance, demonstrating that on a whole, the system is operating remarkably well. There is a difference in the PVsyst4.1 forecasted and the measured PV array power output. This may be because of the inconsistencies experienced with the charge controllers in the monitored system. This resulted in PV output not always being reduced when the batteries were full. Each parameter is discussed further below.

5.2 Global Solar Radiation

Tulin is subject to monsoon periods and as a result the best solar months were the mid season months of April to June. This seasonal variation is further emphasized through the high horizon due to the surrounding mountain ranges between 4500-6500 metres high around Tulin village. (Zahnd, Alex. 2007)

The solar resource is as expected with the available global solar radiation on the POA having a yearly average of 5.510kW/m^2/day. The BOE calculations used an approximation of 5.3kWh/m^2/day. The benefit of using a tracking system is irrefutable with an average yearly increase in solar radiation of 39.5%. The adjustments were not carried out through some of the winter months according to RIDS-Nepal staff perhaps because of heavy snowfall (Malla, Avishek, 2007.) This could even be improved if the weekly adjustment of the north-south tracker is routinely carried out by the local trained users, which could increase the system's annual solar radiation by 5 –10%. (Zahnd, Alex. 2007) This demonstrates the importance of training staff and perhaps the need to check to ensure local people in charge of the O&M are carrying out responsibilities.

Both the global solar radiation on a horizontal surface and on the POA are higher by approximately 10% than the expected average yearly global solar radiation values predicted by PVSyst4.1 as can be seen in Table 12 in Section 5.1 above. It is not sufficient to only compare real data with a design average. It is also important to compare the global horizontal solar radiation with the projected real data from Simikot as seen in Figure 10 in Section 4.1.1, which shows that the measured global solar radiation on a horizontal surface is actually better than the estimated solar radiation values made for Tulin by using the real data from Simikot and reducing it by 20% to take into account the high horizon.

5.3 Battery Bank Voltage

Overall the batteries are performing well with a yearly average BB voltage of 26.2V, with no sustained periods of low state of charge. The yearly average BB voltage is very close to the predicted PVSyst4.1 value of 25.9V as seen in Table12 in 5.1. The variation in monthly average battery voltage is within 1V indicating that the BB is maintaining a good state of charge. The BB voltage is most affected by exceptionally high (unauthorised) loads in September. This is the only time during the analysis period that the BB voltage goes below the specified minimum state of charge of 23.8V.

There are numerous times when the BB voltage goes above the specified maximum state of charge of 28.8V. Various prototype charge controllers developed and manufactured in Nepal by PPN have been installed and tested and they have not always performed as expected. Thus the BB was not always well protected from overcharging; this is explored further in Section 5.7.

The fact that the batteries are often full and hence are relying on the CC to reduce the PV array power output indicates that the PV system is oversized for the present load requirements. The PV system has been oversized on purpose to allow all the daily lighting services to be met in up to 4-5 years time, when the village population has increased (currently at the rate of 2% p.a.) and energy demand has increased by an expected 5-10 % p.a.(Zahnd, Alex. 2007)

5.4 Load

The daily load profile is different to what was initially planned in the design stage. The designed load was for 7 hours over the morning and evenings. But after the village community requested to have the option for light all the time, it is observed that there is a baseline load with low loads all night and peak loads in the morning and evening. Higher than predicted loads of 90W max were observed.

Two things are clear form observing the loads. Firstly as the villagers grow accustomed to using lights, they want them on for longer than they originally perceived they would. What is especially interesting is the observation of some low loads all night. This has a cultural explanation and was similarly observed in the Sukatani project in Indonesia (A.H.M.E. Reinders et al. 1999.) Locals have a belief in evil spirits, and they often have a fire going, but now with the WLED lamps, they leave some lamps on all night to provide protection from the evil spirits. This use of the lights at night was actually at the local users' request after the first few months' installation and with the project implementers' agreement when it was checked that the PV system could meet the increased load. (Zhand, Alex. 2007) Secondly as the villagers get more comfortable with the technology they have been provided with, villagers will begin to add on new loads and use the system, not as it was designed but never the less ingeniously to provide other services they may need, (e.g. charging batteries). This was also observed in the Sukatani project. (A.H.M.E. Reinders et al, 1999)

With these experiences in mind over-sizing the PV array appears to be beneficial especially in a developing country context when it is a first time experience with PV technology.

5.5 PV power

The charge controller is designed to cut the PV array power as observed in Sections 4.3.3 and 4.3.4 once the state of charge of the batteries is reaching its full state. This is occurring for approximately half the solar day in the months when the CC is operating well, as described in Section 4.2.5. Thus the PV array power output is not fully utilized in relationship to what it could produce. A lot of power is being lost due to full batteries. This is expected for the fist few years of the Tulin PV system as it is designed to provide the full energy demand by the local community after 5 years of population and demand growth. The PV power measured is higher than the PV power expected in the PVSyst4.1 simulation. This difference may be as a result of the charge controller not always operating as specified.

5.6 Performance Ratio (PR) comparison

The performance ratio observed in the measured data is very close to the performance ratio predicted by PVSyst4.1, indicating that the overall the system is operating well and close to what was expected.

Also from the analysis of data in the IEA-PVPS database of 260 PV plants the following annual performance ratios can be expected for the stand-alone systems without back-up PR = 0.1 -0.6. (IEA-PVPS Task 2, 2000). Hence the Tulin PR is well within this range and closer to the high end.

The performance ratio (PR) is used to indicate the overall effect of losses on the array's rated output due to array temperature, incomplete utilization of the irradiation, and system component inefficiencies or failures. (IEA PVPS Task 2, 2000) Since the Tulin central tracking PV system is oversized to allow for population/load growth for the next 5 years, the performance ratio of the system is likely to improve over time with increasing loads. Thus it could reach values of between 0.5-0.7 which are considered very good. (Poissant, 2008).

Performance ratio observations for individual days show that the lower the global solar radiation the higher the performance ratio. This could be taken as further evidence that the PV system is oversized, which has been confirmed by the designer Alex Zahnd. (Zahnd, Alex. 2007)

5.7 Limitations of results

Limitations included that at times, data was missing. This is unavoidable when monitoring real data especially in a very remote location in a harsh environment. Also the project was designed to be a prototype and research project; therefore it is still at an experimental stage.

Another limitation was the ill-success of the air heater, designed initially as a dump load to increase the PV power output values so that they may better represent the true systems performance. However it never met its expectations and instead was the cause of some faults and eventually burnt down damaging the CT in the DT80 and causing 7 days of data loss and the system to run without a charge controller from September 27th onwards. Hence the BB is not protected from overcharging. The village is still waiting on the new CC, a Plasmatronic PL20 to come from Australia. This emphasizes the importance of availability of spare parts especially in the rural context. Locally manufactured charge controllers are available, but it is now preferred to use an Australian-produced charge controller in order to gain experience with an approved product before another, locally produced CC is developed and installed. (Zahnd, Alex. 2007)

At times the three different charge controllers developed were not operating as well as expected. Project staff have confirmed this, as new developed models were tested throughout the monitoring period and various shortcomings were experienced and at times, the batteries were not protected from being overcharged.

5.8 Lessons Learnt

The lessons learnt include the need for reliable equipment, especially if the system is being monitored. The difficulties with the charge controllers made conclusions about PV array power output difficult.

Another lesson was that unauthorised exceptionally high loads can, if unnoticed for longer time periods, result in significant lower life expectancy of the BB. Thus it is an important lesson of the monitoring system that to avoid this, protection and measurements for recognizing low battery voltage and/or high loads for prolonged periods are needed.

Another lesson is that over sizing a PV array for a remote village provides a very reliable system and, if cost permits, it is a desirable aim in very remote locations.

Finally the difficulty in obtaining reliable monitored data from a remote, rural location is a lesson to be aware of when monitoring remote PV systems. This difficult task is achievable and a better understanding of the system is likely after a longer analysis period.

5.9 Significance of results

The consistent battery voltage indicates that, if affordable, an oversized PV array allows exceptional circumstances to occur such as seen in the September high loads without reducing the BB’s voltage dramatically, and also allows room for population and load growth and changes in users’ needs as they grow accustomed to the technology, This is very important for sustainable Holistic Community Development. (HCD)

This is ideal for a testing village, such as Tulin, or very remote villages. The disadvantage of over sizing is that the system PV array output is often higher than needed and the produced power is lost due to a fully charged BB. This will be reflected by the performance ratio, which will be lower on average than it could be if the system was sized smaller. Not to mention that an oversized system is not as cost effective as a smaller system. A relationship could be determined so that PV size is still large enough to meet all the loads but is as small as possible to save on costs.

Possible effects and benefits from electrification of the Tulin village include a teaching book, which has been developed by RIDS-Nepal. It is now used in the Tulin for Non-Formal-Education of mothers and out-of-school children and shows that with more light the village has a greater opportunity to learn and read. (RIDS, 2007). Also the ability for the villagers to add loads on although not allowed shows they are learning about the technology and are adapting the system to their needs. The system has also been the responsibility of the village, along with periodical field visits from RIDS-Nepal staff and hence all those involved have learnt about the technology and the required maintenance and limitations of the technology.

6 Conclusion

The electrification of the remote rural village of Tulin in one of the Himalayan villages of Nepal has been a successful project providing basic electric light with WLED lamps for 28 homes continuously since its installation in 2005. The extensive monitoring program allowed this study to investigate how the system components operated in a harsh, rural, remote context. It was found that the design expectations were met and the system components operated well together. The system was always able to meet the load, even exceptionally high loads. There were some difficulties with the charge controller which is being rectified and this demonstrated the importance of a CC to allow proper charging/discharging and protection of the batteries. The central PV array has been oversized but this was a conscious decision during the design stage to allow for growth and to ensure the remote village could be provided with light, even in the worst situations of low global solar radiation or very high loads. Prolonged periods of high loads could reduce the battery bank’s lifetime. Difficulties in obtaining reliable data in remote areas were encountered, yet the success of this project shows the potential for small scale solar PV village electrification systems in rural and remote communities to provide a basic energy service, which helps the life of the poor in developing countries. This project could in fact be used as a template to help other communities with similar needs to achieve the basic energy service of lighting.

7 Further Work

Tulin is not an isolated village in regards to the RIDS–Nepal community projects. There are indeed many villages in both Humla and Jumla districts that have been fortunate enough to benefit from the RIDS-Nepal community projects that provide the ‘Family of Four’ HCD concept to impoverished villages. A similar analysis of other villages with different solar PV systems, such as in Pamlatum, a cluster system including up to 12 homes in one cluster and in Darpari village with each individual home having its own small solar PV system or SHS (Solar Home System) would be important to determine the design success of similar but structurally different systems. Ultimately the identification of the successful parameters of these village electrification systems could aid the development of a design tool to allow other non-Governmental Organizations’ with community aid intentions to utilize the engineering expertise and practical experience that these villages provide. A design tool for implementing small scale solar PV village electrification systems in rural and remote villages would benefit some of the nearly two billion people in the world without access to electricity and help reduce environmental degradation simultaneously.

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Appendices

Appendix 1: BP275F Specifications.

BP280F & BP275F

Module Catalogue Number BP280 BP275

Nominal Peak Power (Pmax) **80.00W 75.00W**

Voltage @ maximum power (V mp) **17.00V 17.00V**

Current @ maximum power (I mp) **4.70A 4.45A**

Short-circuit current (I sc) **5.0A 4.75A**

Open-circuit Voltage (V oc) **21.8V 21.40V**

Dimensions F=Framed L=Laminate

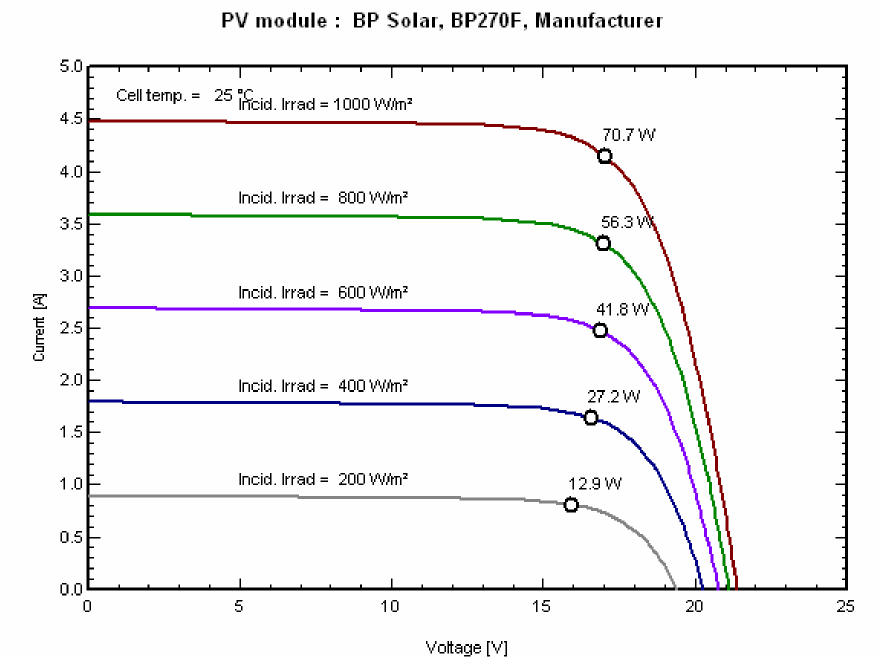
BP275/280F Length 1188 mm Width 530 mm

Depth 43.5 mm Weight 7.5 kg

BP275/280L Length 1183 mm Width 525 mm

Depth 4 mm (±1 mm) Weight 5.5 kg

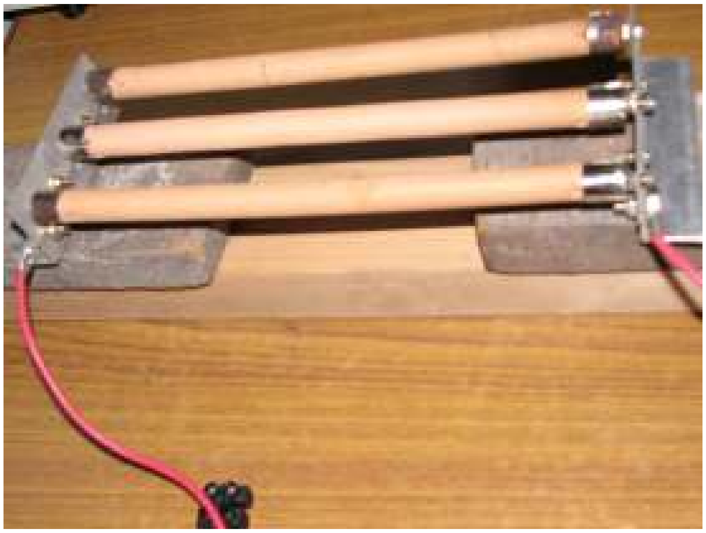
Appendix 2: PV Irradiation graph



Appendix 3: Photo of Charge Controller (photo courtesy of Alex Zahnd)

Appendix 4: WLED Photo (Photo courtesy of Alex Zahnd)

Appendix 5: Photo of Air Heater. (Photo courtesy of Alex Zahnd)



Appendix 6: Representative Day criteria given by the monthly averages:

Parameter	Summer (June)	Winter (Jan)
Load(Wh/day)	523.8	653.7
BB (V)	26.32	26.33
POA Solar Radiation(Wh/m2/day)	5321.7	6253.3
PV Power(Wh)	999.6	1129.4