Chapter 1: Introduction

1.1 Introduction

In the United States, buildings and their processes for heating, cooling and functional use, account for approximately one-half of all energy consumption. Architects and engineers associated with the fast growing building industry have the responsibility of exploring and trying to integrate various renewable sources of energy in the early stages of the building design. With this approach we might achieve “Positive Energy Architecture” where the role of the building shifts from a net energy consumer to a net energy producer.

One of the most promising renewable energy technologies is photovoltaic (PV) power. PV systems are truly elegant means of producing on-site electricity from the sun without noise, pollution or any moving parts. It is estimated that one hour of solar energy received by the earth is equal to the total amount of energy consumed by humans in one year. By harnessing this renewable source we might reduce our dependence on non-renewable energy sources.

One appealing aspect of photovoltaic power is that by producing electricity at the building site, the distribution becomes distributed thereby shifting power generation away from a regionally located central source. Grid-connected, distributed power systems are gaining popularity and this trend is expected to continue making it a common feature of future buildings.

Some of the advantages of building integrated photovoltaic (BiPV) distributed systems are as follows:

- Serve as both the building envelope material and the power generator
- Provide savings in materials and electricity costs
- Reduce use of fossil fuels
- Add architectural interest to the building.
- Reduces the cost and losses in transmission and distribution of electricity

- Can help reduce peak loads and utility demand
- No site development cost, BIPV is part of the building
- BIPV system provide public expression of environmental commitment
- The system is carbon dioxide neutral once it is paid back

Million Solar Roofs Initiative:

The U.S. Department of Energy Million Solar Roofs initiative is a public-private partnership which aims to increase the market entry of solar technologies. The goal is " to facilitate use of the sun's energy to reduce our reliance on fossil fuels by installing solar panels on 1,000,000 more roofs around our nation by 2010". [1]

The awareness of the benefits of PVs is rapidly increasing but cost and technical issues remain for design and installation that have slowed acceptance and application of these systems. This study aims to provide an understanding of what factors affect the performance of BIPV and to formulate a model which can be applied to predict the performance of the BIPV in a building and thereby give insight as to if the system could be cost effective.

1.2 Goal and objectives

Goal:

The main goal of the study is to create awareness about the economic feasibility of building integrated photovoltaic roofing over conventional non-power generating systems, while considering the performance over the life of the system.

Objective:

- To evaluate the cost-effectiveness of a building integrated photovoltaic roofing system over that of a conventional roofing system in a school building located in

[1] www.millionsolarroofs.org, U.S. Department of Energy, Energy Efficiency and Renewable Energy, Solar Energy Technologies Program

Blacksburg, Virginia while considering the influential parameters including solar radiation, solar altitude, solar azimuth, temperature and utility rates in that region.

1.3 Assumptions

- Life of the building integrated photovoltaic is assumed to be 25 years[2]
- The building integrated photovoltaic is connected in parallel to the utility grid, so there is no cost for batteries or electrical storage.
- The model developed for calculating power using the experimental setup in Blacksburg is suitable for application in other areas for future studies.
- The calculations are based on TMY (Typical Meteorological Year) files and done for a typical school day. Limitations of the model and scope for future improvement are discussed in Chapter 5.

1.4 Hypothesis

The research hypothesis establishes the relationship between power generated per unit area by the PV system and other parameters including solar radiation, solar azimuth, solar altitude and temperature. The hypothetical model is shown in Equation 1.

$$\mathbf{P = b_o + b_1(Sol.\ Rad) + b_2(Sol.\ Az) + b_3\ (Sol.\ Alt) - b_4(Temp)} \qquad \text{Equation 1.1}$$

Where

P = Power generated in watts per square meter

Sol. Rad = Solar radiation incident upon the panels at any particular time in watts per square meter

Sol. Az = Solar azimuth based on the location and season (degree)

Sol. Alt = Solar altitude based on the time of the day (degree)

Temp = Temperature of the panel in degree Fahrenheit

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[2] Energy and economic evaluation of building-integrated photovoltaic by M. Oliver and T. Jackson; Centre for Environmental Strategy, University of Surrey, Guildford, Surrey GU2 7XH, UK

Considering the life of the BIPV and the high utility rates and rebates, it is further hypothesized that over the life of the systems:

Cost (conventional roofing) > Cost (BIPV)

The cost analysis is for a school because of the large roof area available for the installation of the building integrated roofing system, the time of peak demand and peak production match and the need to limit present and future energy cost expenditures for public-sector buildings.

1.5 Research Approach Summary

Chapter 1 introduced the need for the study to develop a model which will give quick insight into the economic feasibility of the system for any building project and provide a description of the goals and objectives, assumptions and hypotheses for this study. In order to formulate the study and focus on the key issues it is necessary to begin with the background knowledge of BIPV. This summary is found in Chapter 2: Literature Review. The experimental setup and the procedures used for collecting the data are described in Chapter 3: Methodology. Chapter 4 summarizes the results. Chapter 5 provides discussion and conclusions drawn from the results and suggests how the Government might advance the use of BIPV by providing rebates and incentives. It also discusses the limitations of the model and the possible further studies.

Chapter 2: Literature Review

2.1 Photovoltaic: Principles and advantages

2.1.1 Solar energy to electricity

Photovoltaic cells, commonly known as solar cells, are converters; they take energy from sunlight and convert it into electricity without any moving parts, noise or pollution. This is possible through the special properties of the semi-conducting materials that the cells are made.

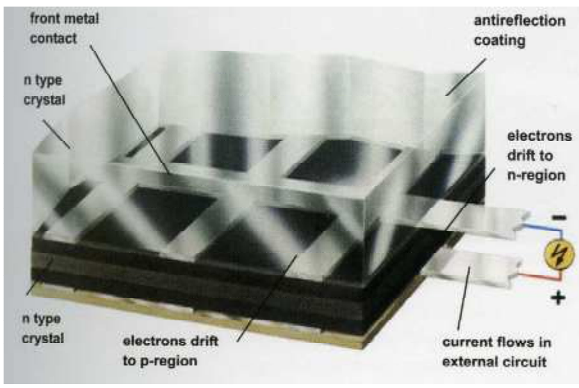

Fig 2.1 – Solar cell operating principles[3]

Most PV cells are made from silicon. Silicon is a "semi-conductor" and has properties of both a metal and an insulator. Atoms in a metal have loosely bound electrons that easily flow when electrical pressure is applied, whereas atoms in an insulator have tightly bound electrons that cannot flow when electric voltage is applied. Atoms in a semi-conducting material bind their electrons tighter than metals, but they may be manipulated to have conductive properties.

PV cells are made by joining two types of semi-conducting material: P-type and N-type. P-type semi-conductors are manufactured to contain negative ions, and N-type semi-conductors are manufactured to contain positive ions. The positive and negative ions

[3] (Figure 3, page 23) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)

within the semiconductor provide the environment necessary for an electrical current to move through a solar cell.

At the atomic level, light is made of a stream of pure energy particles, called "photons." This pure energy flows from the sun and shines on the solar cell. The photons actually penetrate into the silicon and randomly strike silicon atoms. When a photon strikes a silicon atom, it ionizes the atom, giving all its energy to an outer electron and allowing the outer electron to break free of the atom. It is the movement of electrons with energy that we call "electric current." The power produced by the photovoltaic is direct current (DC) power which is converted to AC power using an inverter.[4]

2.1.2 Advantages

Photovoltaics were first used commercially in 1958 to power the Vanguard communications satellite. As a result of declining prices, the practical application for PVs has steadily expanded to include the building industry. PVs can be applied to reduce the peak electrical load and offer the possibility of the building becoming a net energy producer.[5]

Solar electric power offers multiple benefits when compared to conventional power systems including:

- Reliable and low maintenance
- Modular and scalable
- Zero emissions
- Renewable
- No fuel or infrastructure

2.1.3 Photovoltaic systems

There are basically two categories of photovoltaic systems with several types in each category.

[4] Solar integrated technologies
[5] Powerlight Solar Electric Systems

Crystalline Silicon PV systems:

Crystalline PV systems include monocrystalline and polycrystalline silicon which are grown or cast from molten silicon and later sliced into individual “cells”. They are then sandwiched between glass plates and framed with aluminum to form a rigid panel.

Monocrystalline photovoltaic:

This is the oldest and most expensive production technique, but it is also the most efficient sunlight conversion technology commercially available. The output efficiencies average between 10 to 12%. Boules of pure single-crystal silicon are grown in an oven, then sliced into wafers, doped and assembled.

Fig 2.2 – Monocrystalline silicon cell[6]

Polycrystalline photovoltaic:

In this technique, pure molten silicon is cast into cylinders and then sliced into wafers. It is slightly lower in efficiency when compared to monocrystalline PV, but the cost is also lower. Module efficiency averages about 10 to 11%.

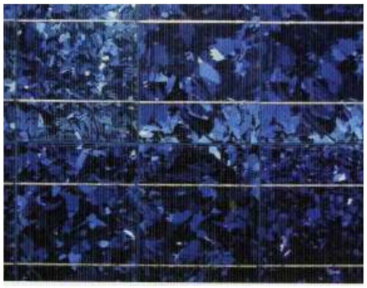

Fig 2.3 – Poly-crystalline silicon cell[7]

[6] (Figure 4, page 23) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)

Flexible PV systems:

Flexible photovoltaic systems are produced in vacuum plasma ovens which deposit a thin layer of silicon material onto a flexible polymer or steel substrate. This technology is commonly known as amorphous silicon thin film. Advantage of this PV technology is that its lightweight and its flexible properties facilitate the integration of the cells into traditional building products and systems such as roofs, facades or windows. The conversion efficiency averages about 5 to 7%.

Fig 2.4 – Amorphous Silicon cell[8]

2.1.4 Applications

Solar generated electricity can serve people living in most isolated areas as well as in the center of densely populated cities. The applications are many as listed below:

Simple PV systems

These systems use the DC electricity as soon as it is generated to power water pumps for irrigation and drinking wells, and ventilation fans for air cooling. They are small systems typically less than 500 watt and weigh less than 150 pounds, which makes them easy to transport and install.

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[7] (Figure 5, page 23) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)

[8] (Figure 9, page 25) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)

PV with battery storage

When coupled with battery storage, PV systems become reliable sources of electric power day and night and when used with an inverter, they can be designed to power DC or AC equipment.

PV with Generators

When power must always be available or when larger amounts than the PV system alone can supply are needed, an electric generator can work effectively with the PV system to supply the needed electricity. If batteries run low, the generator makes up for the difference in electrical demand.

Grid connected PV

Where utility power is available, a grid-connected PV system can supply part of the energy needed. Referred to as a part or partial load systems, this approach typically does not include the expensive battery sub-system. The partial load system reduces the peak electrical demand from the local utility and can be very cost effective in locations with high purchased utility demand charges such as California.

Utility-Scale Power

Large scale utility photovoltaic power plants, consisting of many PV arrays installed together are typically easier and quicker to install and connect than conventional power plants. The PV plants can be incrementally expanded as demand increases and consume no fuel or produce no pollution as they generate electricity.

Hybrid Power Systems

Hybrid systems combine PV systems with wind turbines or small hydro plants to produce electricity. These are ideal for remote applications such as communication stations, military installations and rural villages.

2.2 Building integrated photovoltaic

2.2.1 Introduction

Building Integrated Photovoltaic (BIPV) systems consist of integrating photovoltaic modules into the building envelope. The advantages of BIPV are:

- Serves as the building envelope material and power generator
- Provide savings in material and electricity costs
- Reduces the use of fossil fuels
- Adds architectural interest to the building

2.2.2 BIPV system interfaced with the utility grid

The PV system can be connected in parallel to the utility grid and eliminate the need for the batteries. There are several advantages in a grid connected system:

- Both the building owner and the utility benefit with grid tied BIPV
- On- site production of electricity is typically greatest at or near the time of a building's and utility's peak loads
- Can reduce energy costs for the building owner
- Exported solar electricity helps support the utility grid during the time of its greatest demand and helps the facility to reduce peak loads when the utility rates are highest.

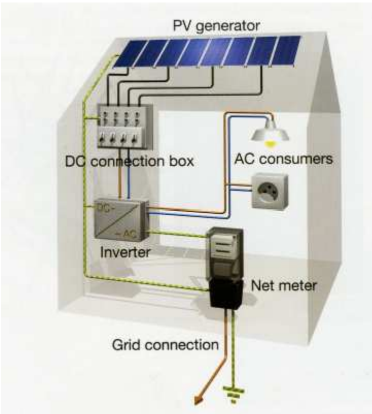


Fig 2.5 - PV connected to utility grid[9]

[9] (Figure 13, page 26) Deo Prasad and Mark Snow, Designing with Solar Power – A source book for Building Integrated Photovoltaic

2.2.3 Power production of BIPV

The production of the BIPV depends on a number of variables mainly:

- Solar radiation (variation due to the rotation of the earth and movement around the sun as well as cloud cover)
- Solar altitude (tilt)
- Solar azimuth (orientation with respect to due south)
- Temperature
- Shading or shadow
- Dirt accumulation
- Cell efficiency

The relationship between the variables, namely solar radiation, solar altitude, solar azimuth and temperature and the power generated per unit area by the BIPV is explored in detail using data collected from this experimental study.

2.3 Examples of BIPV in buildings

Fig 2.6 through 2.8 shows some examples of Building integrating photovoltaic in buildings.

Fig 2.6 – Brundtland Centre[10]

[10](Figure 1, page 70) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)

Brundtland Centre

Location	: Toftlund, Denmark
Size	: 14.25 kWp
PV Type	: Roof and façade system
Building type	: Commercial

Fig 2.7 – Rooftop PV array[11]

J-House

Location	: Tokyo, Japan
Size	: 4.94 kWp
Gross PV Surface Area	: 34.2 m^2
PV Type	: Monocrystalline and polycrystalline silicon cells

Fig 2.8 – Student Housing, Switzerland[12]

[11] (Figure 4, page 98) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovoltaics (BiPV)
[12] (Figure 1, page 147) Deo Prasad and Mark Snow, Designing with solar power – A source book for Building Integrated Photovolatics (BiPV)

Student Housing, Switzerland

Location	: Lausanne, Switzerland
Size	: 14.4 kWp
PV Cell Type	: Polycrystalline silicon
Type of building integration	: Facade

2.4 Application of Literature Review to Research Approach

The literature review provides an understanding of the basic principles, advantages and the different systems and applications available for PVs. Based of the aesthetics, ease of installation and cost, BIPV roofing system connected to the utility grid is chosen for the study. The variables that affect the performance of the PV system were identified for detailed study using the experimental setup. A review of different papers helps to focus on this issue which has not been experimentally established in detail. The research approach and model of study are discussed in detail in Chapter 3: Methodology

The building integrated photovoltaic panel used for the study is discussed in detail in section 3.1. The utility rates and demand charges are discussed in section 4.6.

Chapter 3: Methodology

The study consists of two phases. The first phase involves setting up of the thin film photovoltaic system on the roof at the Research and Development Facility on the campus of Virginia Tech. Then data were collected for the electrical power production of the system. The data collected is used to formulate a model which estimates the relationship between the power generated per unit area of the panel and the independent variables namely temperature, solar radiation, solar altitude and azimuth. In the second phase, the model developed in phase one is applied to Kipps Elementary School building located in Blacksburg, Virginia to estimate the simple payback time for different areas of roof coverage and evaluate the cost-benefit of the system.

Development of the experimental setup

3.1 The Photovoltaic system

From the literature review, when considering factors such as cost, flexibility, ease in handling and integration into the building, the thin film photovoltaic system was chosen for the study. UNI-SOLAR®, a world leader in thin-film solar technologies with years of experience in photovoltaic manufacturing, provided 10 panels of Solar Laminate PVL-series for the study. The panels were connected in combination of parallel and series to form three different circuits labeled as red, blue and white (color coding for easy recognition) for the study.

The thin film photovoltaic used for the study is from UNISOLAR and has the specifications as follows:

Solar Laminate PVL-Series

UniSolar PV laminates (PVL) are flexible and light weight laminates made to be exceptionally durable by encapsulation of the PV cell in UV stabilized polymers. The polymer encapsulation is partially constructed of durable ETFE (eg: Tefzel®, a high light-transmittive polymer). The UniSolar PV cells are produced in a 3-stage spray deposit process with each layer being sensitive to selected wavelengths of light. With this

3-step process, the PV cells are more efficient at both full and partial incident radiation when compared to similar products.

The UniSolar panels have the following characteristics:

- Thin, light-weight
- Flexible and unbreakable
- Easy to integrate with the roof
- Aesthetically pleasing
- Relatively low installation cost
- High temperature and low light performance
- 20 year warranty on power output at 80%
- Multi-contact connectors or junction box
- Bypass diodes for shadow tolerance

Construction Characteristics

Dimensions: Length: 5486mm (216”), Width: 394mm (15.5”), Depth: 2.5mm (0.1”)

Weight: 7.7kg (17.0 lbs)

Electrical specifications: STC

(at 1000W/m^2, AM 1.5, 25°C cell temperature)

Voltage at Pmax (Vmp):40.0V

Current at Pmax (Imp): 4.1A

Short-circuit Current (Isc): 5.1A

3.2 The Circuit Setup

Using the 10 panels donated by UniSolar, three circuits are setup as shown in the figures 3.1 through 3.2. All the panels and combinations are color coded for ease in setting up the circuits and the data logging device.

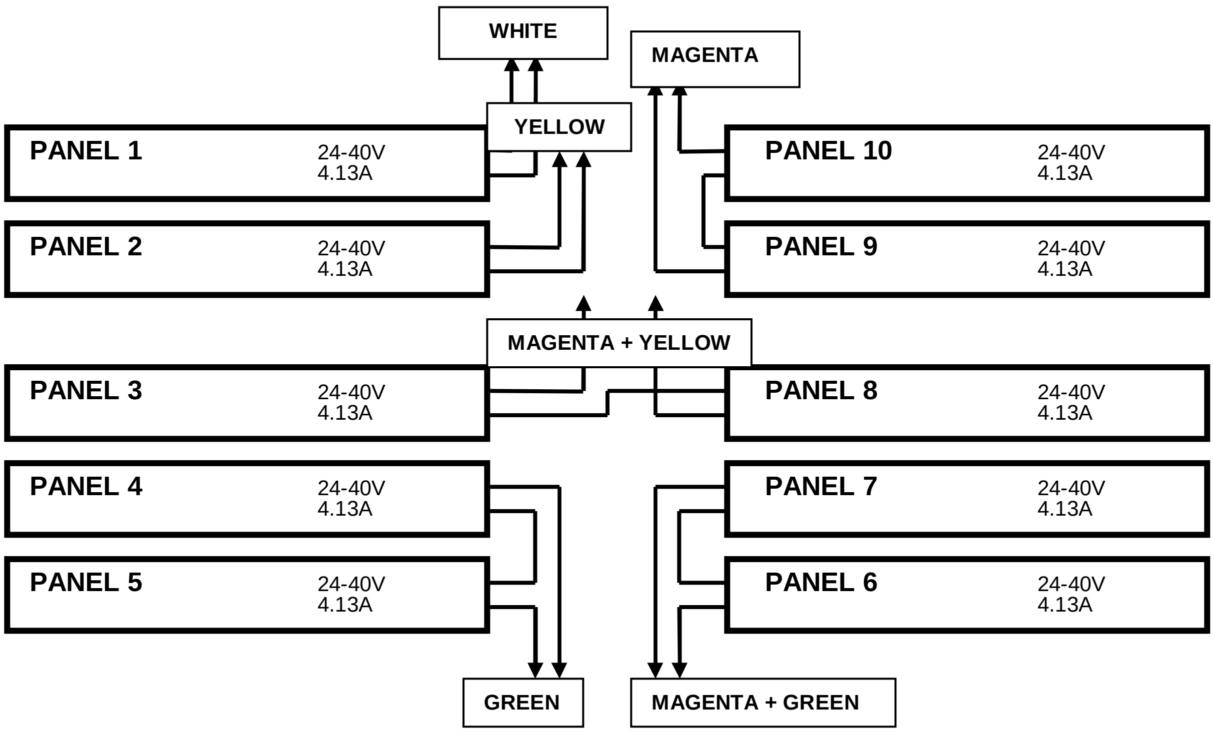
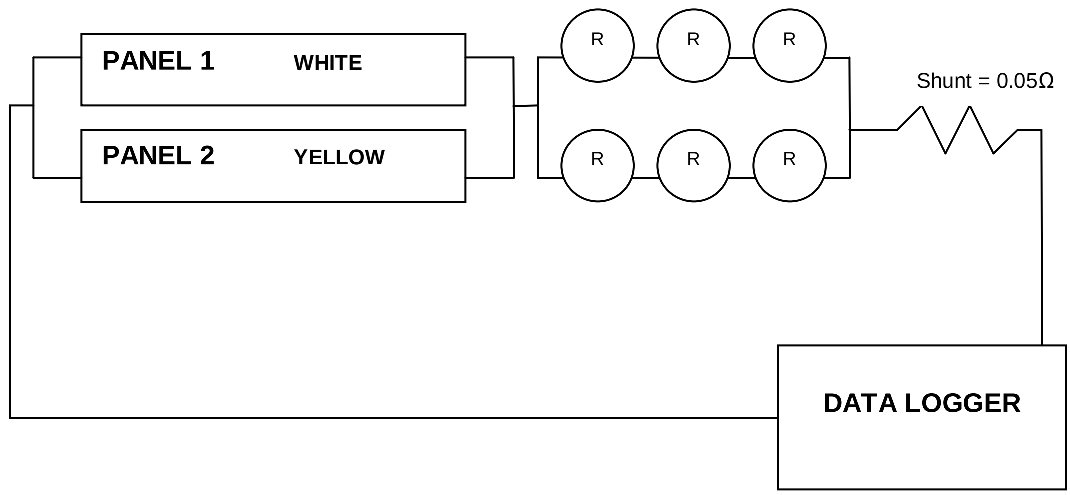


Fig 3.1 – Layout of panels on the roof

Color coding the circuits

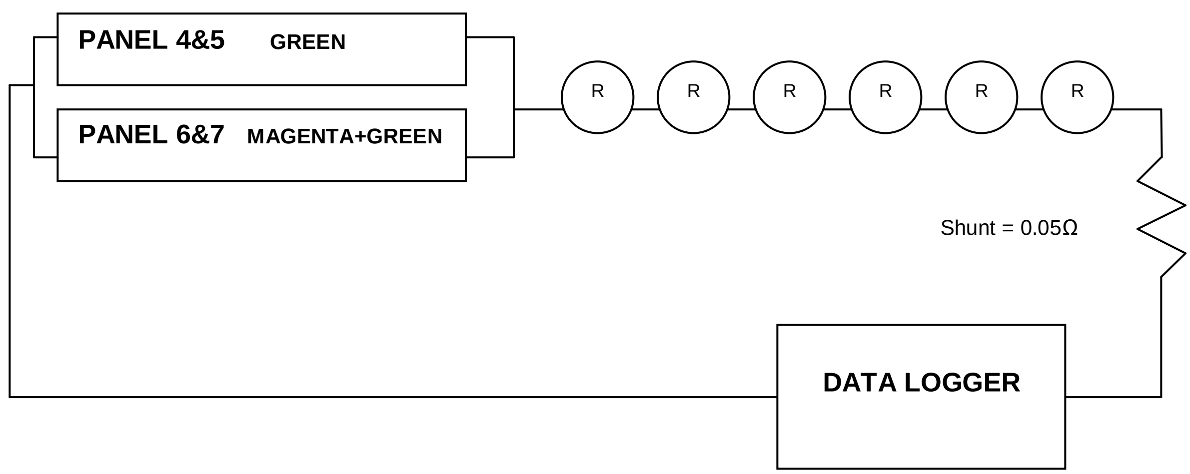
Panels coded white and yellow are connected in parallel to form the red circuit. Panels coded green and magenta + green are connected in parallel to form the white circuit. Panels coded magenta + yellow and magenta are connected in parallel to form the blue circuit. Three different circuits are used to study the effect of connecting the panels in parallel and in series on the power production.

The schematic circuit diagrams for the different setups are shown in the figures 3.2 through 3.4.



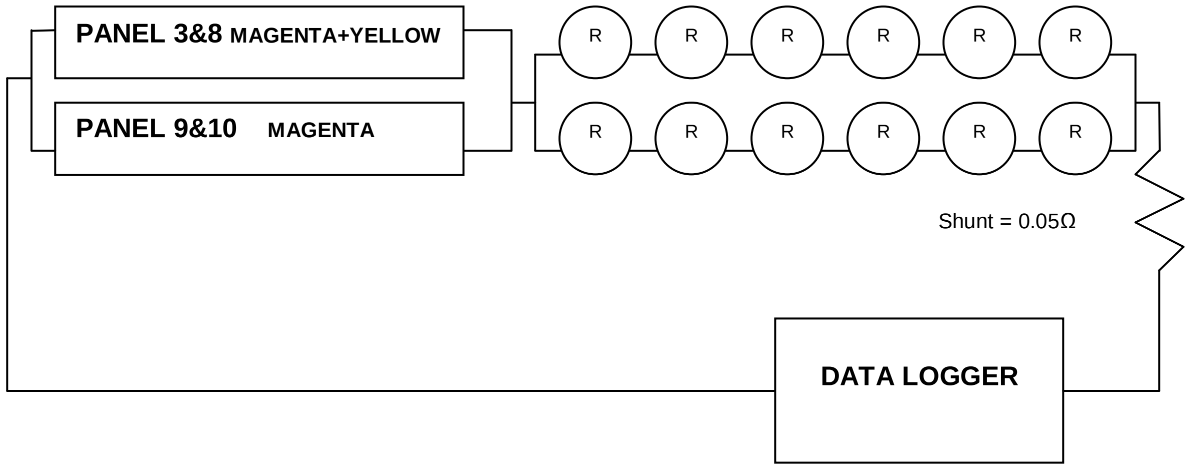
R – Sylvania bulb rated at 25w/12v
Shunt resistance = 0.005Ω

Fig 3.2 - Schematic diagram for the red circuit



R – Sylvania bulb rated at 25w/12v
Shunt resistance = 0.005Ω

Fig 3.3 – Schematic diagram for the white circuit



R – Sylvania bulb rated at 25w/12v
Shunt resistance = 0.005Ω

Fig 3.4 – Schematic diagram for the blue circuit

3.3 The Experimental Setup

To simulate the BIPV system, the panels were setup (as shown in Fig 3.5) on ThermaSteel™ structural insulating panels which were fixed on the flat roof at the Research and Development Facility. The circuits are setup as shown in Fig 3.2 through Fig 3.4.

Fig 3.5 – Layout of the PV panels on the roof

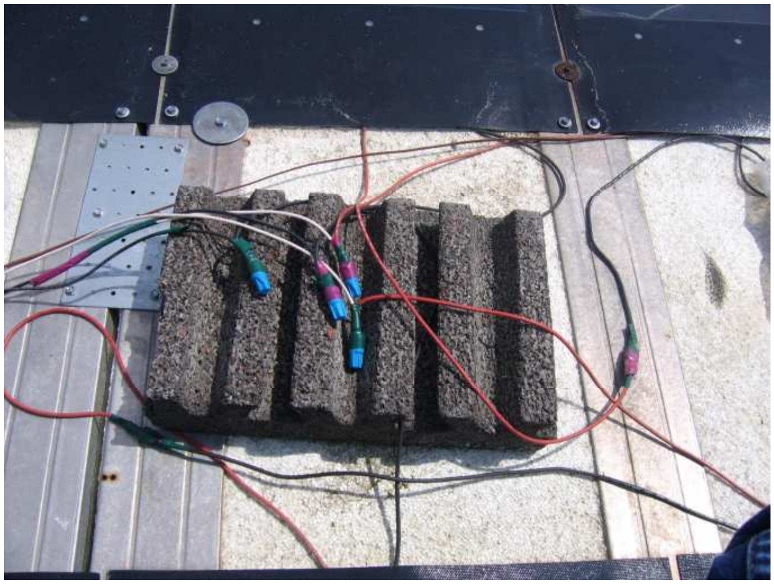


Fig 3.6 – Wiring on the roof

3.4 Parameters for the study

From the Equation 1, it was hypothesized that power production (dependent variable) would be a function of four independent variables, solar radiation, temperature, solar altitude and azimuth.

3.4.1 Solar radiation

Solar irradiance (solar radiation) is the amount of solar energy that falls on a unit area of a surface per unit of time. It is measured in watt/m^2. From the literature review, solar radiation is identified as one of the most important parameters affecting the power production.

For measuring the solar radiation, a glass panel with a wooden frame is setup with LI-COR pyranometers fixed above and below the glass panel. This helps to observe the effect of dirt accumulation on the glass as an indirect indicator of dirt accumulation on the solar panels. The uncovered sensor is used to measure the incident solar radiation.

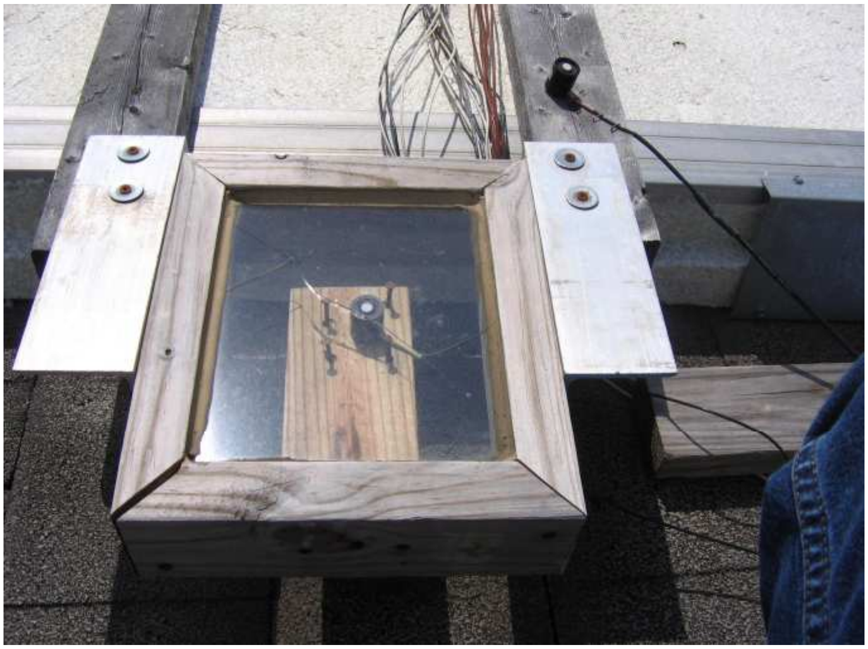


Fig 3.7 – LICOR sensor measuring solar radiation

The sensor used for measuring the solar radiation is a LI-COR Sensor with the specifications as given below:

Model Number: LI-200SZ

Serial Number: PY32791

Output: 91.6 microamps per 1000 watt m^{-2}

The data for solar radiation is measured in millivolts by the datalogger which is converted into watt/m^2 using the following conversion factor.

Conversion

Output: 91.6 microamps per 1000 watt m^{-2}

91.6 microamps = 1000 watt m^{-2}

91.6 millivolt = 1 watt m^{-2}

1 millivolt = 1/91.6 watt m^{-2} = 0.10917 watt m^{-2}

1 volt = 109.17 watt m^{-2}

3.4.2 Temperature

The dry bulb air temperature is measured with a shielded thermocouple. From the literature study as shown in Fig 3.8, temperature is identified as a parameter that affects the power production by photovoltaic.

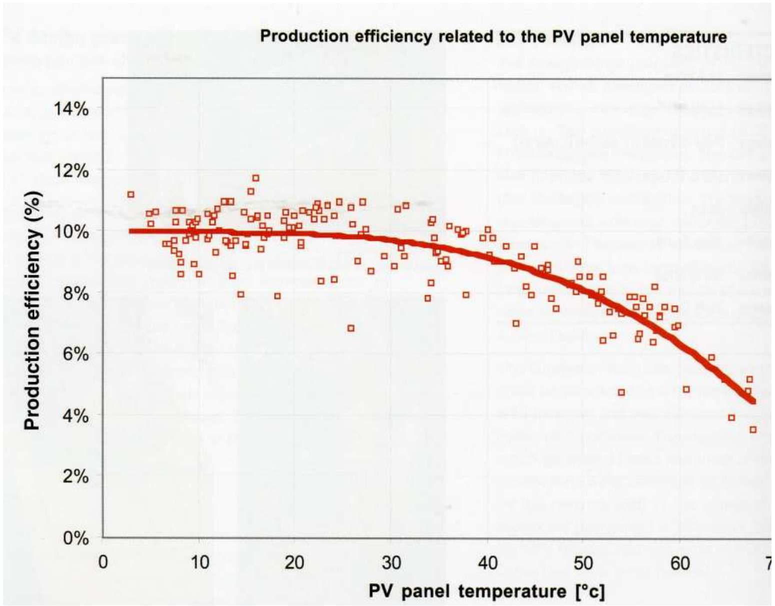


Fig 3.8 – Production efficiency for different PV panel temperatures[13]

Thermal sensors:

Seven copper-constantan thermocouples were laid out on top and below the panels to measure the temperature near the panels. One thermocouple is placed about 6” above the panel to measure the air temperature. All the thermal sensors are color coded and connected to the channels (numbered) in the module of the data logger to record the temperature at one minute intervals throughout the day.

[13] Deo Prasad and Mark Snow, Designing with Solar Power – A source book for Building Integrated Photovoltaic

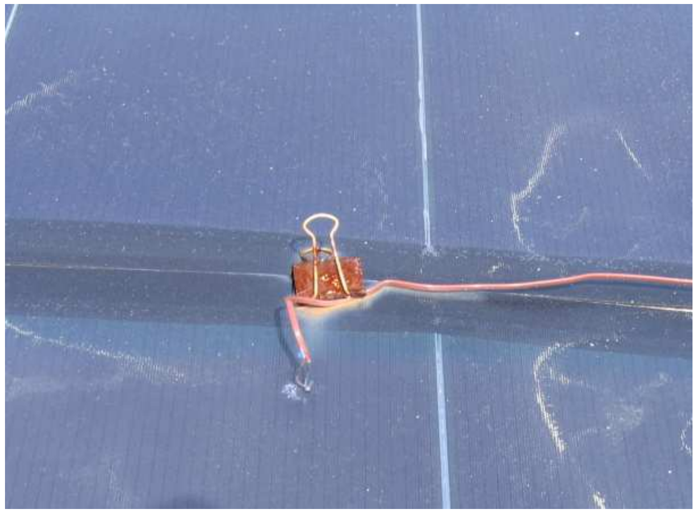


Fig 3.9 – Thermal sensor (Copper-constantan thermocouple)

The layout of the thermocouple sensors above and below the panel is shown in Fig 3.9 and Fig 3.10 and Table 3.1 gives the color code for the sensors.

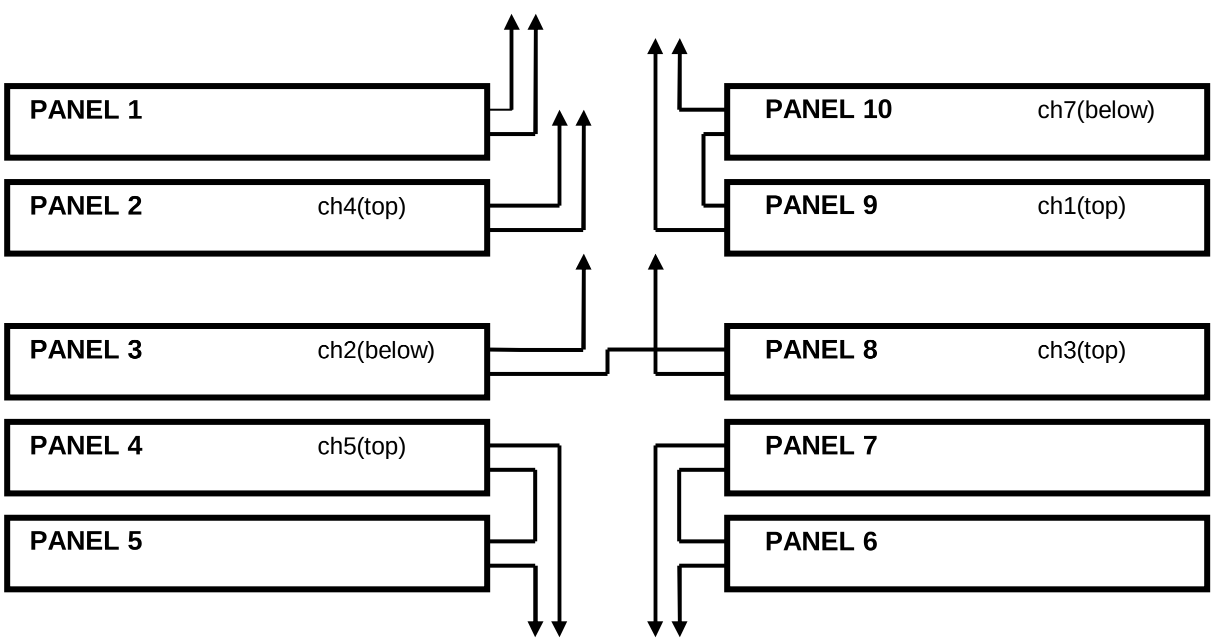


Fig 3.10 – Layout of thermal sensors

Table 3.1 – Color coding for the thermal sensors

Channel number	Location	Color code
Ch0	Air	No color
Ch1	Top Panel 9	Yellow
Ch2	Below Panel 3	Green
Ch3	Top Panel 8	Magenta
Ch4	Top Panel 2	Yellow+ Green
Ch5	Top Panel 4	Magenta
Ch7	Below Panel 10	Green + Yellow + Magenta

3.4.3 Solar Azimuth and Solar Altitude

Solar Azimuth is the angle within the horizontal plane measured from true south (typically) or north. Solar Altitude is the vertical angle between the horizontal and the line parallel to the sun's rays. At sunset/sunrise altitude is 0 and is 90 degrees when the sun is at the zenith. The altitude relates to the latitude of the site, the declination angle and the hour angle.

Based on the date and time, the solar azimuth and altitude are calculated using the sun altitude azimuth table calculator of the day from the Astronomical Applications Department from US Naval observatory. In the calculator used, true north corresponds to 0 degree.

(Courtesy: http://aa.usno.navy.mil/data/docs/AltAz.html)

U.S. Naval Observatory

Astronomical Applications Department

Astronomical Applications

Sun or Moon Altitude/Azimuth Table for One Day

This page provides a way for you to obtain a table of the altitude and azimuth of the Sun or Moon during a specific day, at a time interval that you specify. Simply specify the **object**, **date**, **tabular interval**, and **place** below and click on the "Compute Table" button. The altitude and azimuth values are tabulated as a function of the standard time of the place requested (daylight time is **not** used) on a 24-hour clock.

Use Form A for cities or towns in the U.S. or its territories. Use Form B for all other locations. Both forms are immediately below.

Please read the Notes section for details on the data and definitions of altitude and azimuth.

Form A - U.S. Cities or Towns

Object: ◉ Sun ○ Moon

Year: 2006 **Month:** May **Day:** 3 **Year:** 2004

Month: **Day:** 1

Tabular Interval: 10 minutes (range 1-120 minutes)

State or Territory: D.C.

Place Name:

Fig 3.11 - Input window for Altitude /Azimuth calculator

The place name you enter must be a city or town in the U.S. or its territories. The place's location will be retrieved from a file with over 22,000 places listed. Either upper- or lower-case letters or a combination can be used. Spell out place name prefixes, as in "East Orange", "Fort Lauderdale", "Mount Vernon", etc. The only exception is "St.", which is entered as an abbreviation with a period, as in "St. Louis".

Compute Table | Clear all fields

Alternatively the solar altitude and azimuth can be calculated as described below.

Calculation of Solar Azimuth and Solar Altitude

Solar Altitude:

sin(Alt) = cos(Lat) cos(Decl) cos(HAngle) + sin(Lat) sin(Dec) – Equation 3.1

where

Alt	= Altitude (angle degree)
Lat	= Latitude (angle degree)
Decl	= Declination (angle degree)
HAngle	= Hour Angle

sin_alt_r = cos(lat_r)*cos(decl_r)*cos(hour_r)+sin(lat_r)*sin(decl_r) - Equation 3.2

sin2alt = sin_alt_r * sin_alt_r – Equation 3.3

cos_alt_r = sqrt(1 - sin2alt) – Equation 3.4

altitude = atan(sin_alt_r / cos_alt_r) * TODEGREE – Equation 3.5

where:

sin_alt_r	= Sine of altitude in radians
lat_r	= Latitude in radians
decl_r	= Declination in radians
lat_r	= Latitude in radians
cos_alt_r	= Cosine of altitude in radians
TODEGREE	= Constant equal to 180/pi

Solar Azimuth:

Alt	= Altitude (angle degree)
Azm	= Azimuth (angle degree)
Decl	= Declination (angle degree)
HAngle	= Hour angle (angle degree)
alt_R	= Altitude in radians
azm_R	= Azimuth in radians
lat_R	= Latitude in radians
hour_R	= Hour angle in radians
x_azm	= x component of azimuth
y_azm	= y component of azimuth
TODEGREE	= Constant equal to 180/p

sin(Azm) = cos(Decl) sin(HAngle) /cos(Alt) – Equation 3.6

3.4.4 Voltage and current

For the three circuit setups, DC light bulbs and shunt resistors were used as loads to draw maximum power from the PV circuit. The voltage and current across each circuit was recorded by the data logger and total power per unit area is calculated.

Details of the voltage module and the data logger are explained in 3.5.

Specifications for the load:

Bulb:

Sylvania 25W/12V

Light Output	: 385 lumens
Life	: 1000hours

Shunt resistance	: 0.05Ω

Fig 3.12 – DC light bulbs used as load

3.5 Data Acquisition System

The data acquisition system is an important part of the experimental setup. A good experiment can be completely ruined if the data is not collected with the necessary precision and repeatability. The data acquisition system used is described below.

The datalogger used is a National Instruments Signal Conditioning eXtensions for Instrumentation (SCXI) chassis, modules and associated DAQ devices. SCXI is a high-performance signal conditioning and instrumentation architecture for measurement and automation systems. It consists of multi-channel signal conditioning and data acquisition modules installed in a chassis

SCXI Chassis

The SCXI Chassis used is the SCXI-1001 12-slot chassis. It houses the SCXI modules, supplying power and controlling the SCXIbus. The rugged aluminum SCXI chassis contains an analog bus, a digital bus and a chassis controller that regulates bus operation. The analog bus transfers analog signals from all resident analog modules to the DAQ device using a connection from one of the modules to the DAQ device.

SCXI Modules

The SCXI Module used is the SCXI-1102 which can be used for millivolt, thermocouples and current inputs. The SCXI-1125 is used to measure voltage produced by the circuit. The SCXI-1102 is a 32-channel amplifier module for low voltages. The SCXI-1125 is a jumperless 8-channel amplifier.

SCXI Terminal Blocks

The SCXI-1303 is the terminal block used for collecting data on the current produced, the temperatures and the solar radiation. Feature: Isothermal, signal referencing and open thermocouple detection.

The SCXI -1327 is used for collecting data on the voltage produced by the three different circuits. Features include 100:1 attenuation of voltages to 250 V_{rms}^{2}, switch configurable per channel.

Fig 3.13 – SCXI Chassis with the modules and terminal blocks

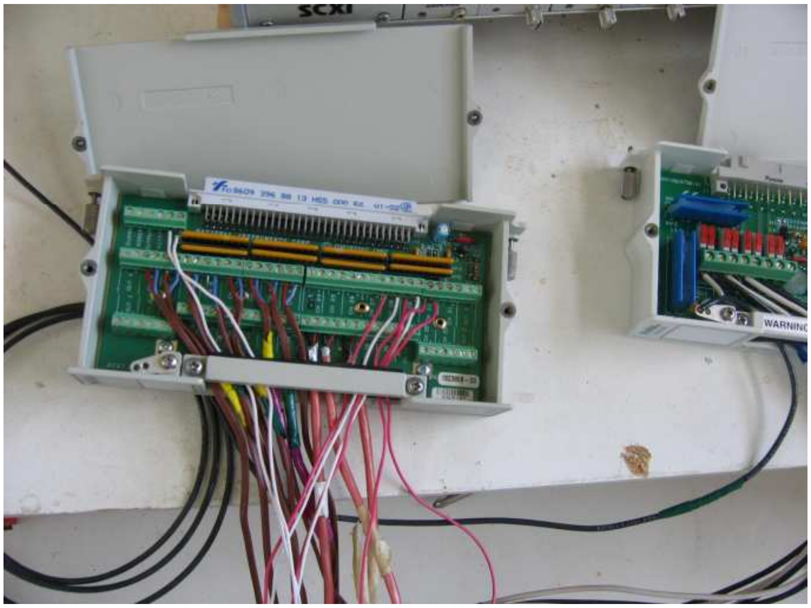


Fig 3.14 – SCXI-1303 Terminal block

Fig 3.15 – SCXI-1327 Terminal Block

Sensors

Description of the sensors used for measuring the various parameters has been stated in Section 3.4 Parameters for the study.

3.6 Datalogging software and data collection

The software used for collecting the data is VirtualBench Version 2.6 for Windows from National Instruments Corporation. The VirtualBench suite of tools is a high-performance, easy to use virtual instruments application program for Windows. The VirtualBench-Logger is used to collect the data by configuring it for temperature, solar radiation, voltage and current at one minute intervals. The Front panel of the VirtualBench-Logger displays the data collected at every minute as shown in Fig 3.14.

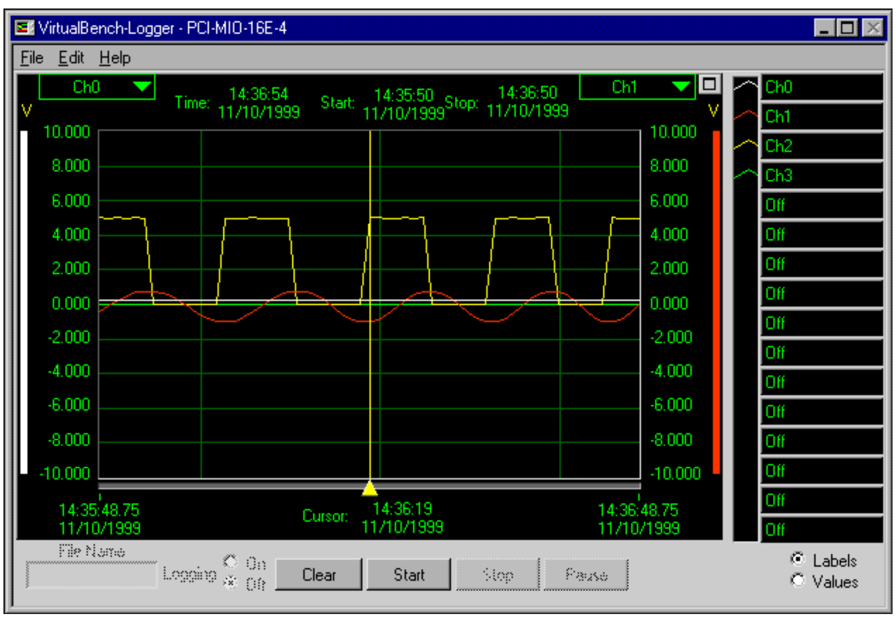


Fig 3.16 - Snapshot of VirtualBench – Logger

Table 3.2 - Sample format for the data

Date	Values
Time	Values
Air Temp (F)	Values
Top Panel 7 (F)	Values
Below Panel 3 (F)	Values
Top Panel 8 (F)	Values
Top Panel 2 (F)	Values
Top Panel 4 (F)	Values
Below Panel 8 (F)	Values
White A (A)	Values
Blue A (A)	Values
Red A (A)	Values
Pyranometer (w/m2)	Values
Blue volt (V)	Values
White volt (V)	Values
Red Volt (V)	Values

The power produced by each circuit is calculated using Equation 3.7

Power = Voltage * Current – Equation 3.7

The power per unit area was calculated by dividing by the total area of the panels in the circuit setup. The calculations and results of the regression analysis are presented in Chapter 4.

3.7 Model for study in Phase 2

The Kipps Elementary School was chosen to evaluate the cost effectiveness of the system for full, half and quarter roof area. Data on energy consumption and utility bills for the year of 2005 was used to develop load profiles for different months to evaluate the cost-benefit of the system as discussed in detail in 4.6.2. The roof of the school is assumed to be flat. The data was collected from June 2005 to January 2006. Only day time values were used for the regression model.

3.8 Summary of Methodology

The study starts with identifying the parameters affecting performance explained in Chapter 2. The experimental setup is constructed and the data acquisition system is chosen based of the requirements of data collected. The data collected is analyzed and studied through charts and the regression models as explained in chapter 4.

Chapter 4: Results

4.1 Relationship between power and the independent variables

The data collected from the experimental setup was plotted to check if the relationship between the dependent variable and the independent variables were linear. This is one of the assumptions for multiple linear regression analysis. Wherever major deviations from linearity were observed, the independent variable was transformed to satisfy the condition of linearity. X-Y plots are shown in Fig 4.1 to 4.3.

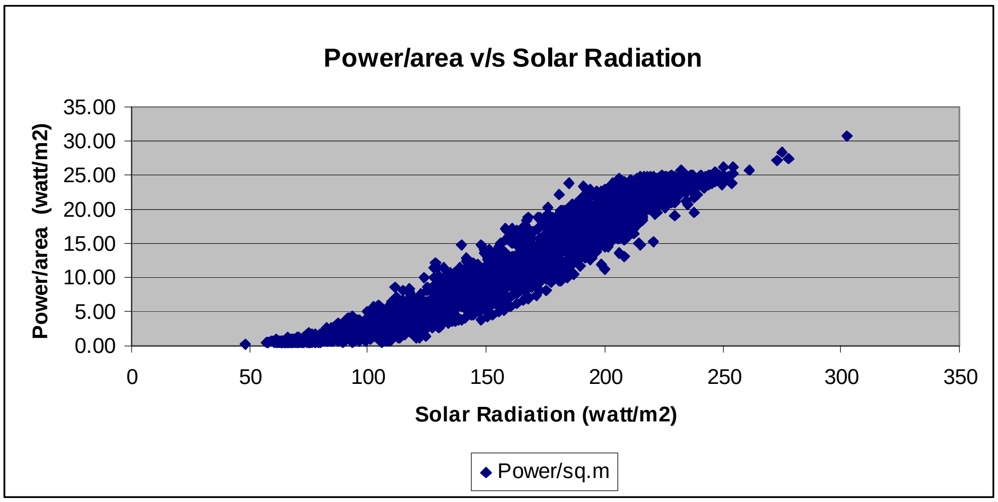


Fig 4.1 – Power per unit area, for different solar radiations

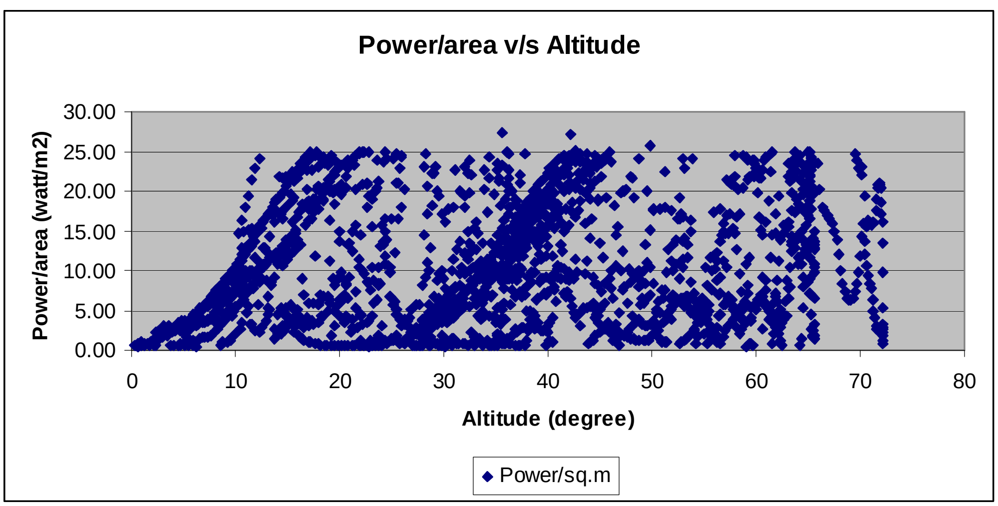


Fig 4.2 – Power per unit area, for different altitudes

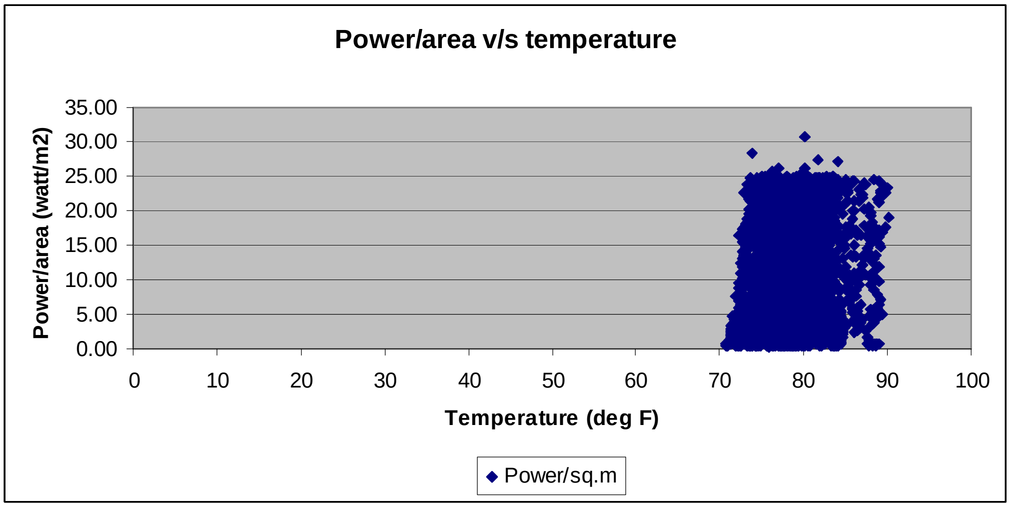


Fig 4.3 – Power per unit area, for different temperatures

4.2 Multiple Linear Regression Analysis

Multiple linear regression analysis was used to establish an estimate for the relationship between the independent variables (solar radiation, temperature, altitude, and azimuth) and the dependent variable, power produced per unit area. The model developed was used to predict the electrical power production for each month for different roof coverage areas in the Kipps Elementary School located in Blacksburg, Virginia.

Assumption and Limitation

The relationship between the variables is assumed to be linear from the plots. In practice this assumption is difficult to be confirmed, but fortunately multiple regression procedures are not greatly affected by minor deviations from this assumption. If the bivariate plots indicate curvature in relationship, we may consider transforming the variables.

The major conceptual limitation of regression techniques is that we can only ascertain relationships, but never be sure about the underlying casual mechanism, this must come theory and the knowledge of the system under study.

4.3 Regression Model using Statview

Statview is used for the Multiple Linear Regression Analysis. Statview statistics software helps to visualize and uncover data patterns that may impact the research, development, and production activities. The detailed output for the models is available in the Appendix A.

Regression Model

The hypothesized model from Chapter 1 is shown in Equation 4.1.

$$\mathbf{P = b_o + b_1 * Rad + b_2 * Azimuth + b_3 * Altitude - b_4 * Temp} \quad \text{– Equation 4.1}$$

where P is power produced per unit area (watt/sq.m)

Rad is the solar radiation incident at that time (watt/sq.m)

Temp is the temperature of the panel (deg F)

Azimuth and Altitude are calculated based on the time of the day (deg)

Output from the Multiple Linear Regression Analysis using Statview is given below:

Regression Summary
Power/sq.m vs. 4 Independents

Count	4004
Num. Missing	0
R	.971
R Squared	.942
Adjusted R Squared	.942
RMS Residual	1.838

ANOVA Table
Power/sq.m vs. 4 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	4	221542.761	55385.690	16385.968	<.0001
Residual	3999	13516.893	3.380		
Total	4003	235059.654			

Regression Coefficients
Power/sq.m vs. 4 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	-17.619	.708	-17.619	-24.892	<.0001
Rad	.147	.001	.950	237.744	<.0001
Azimuth	.011	.001	.106	21.342	<.0001
Altitude	.031	.002	.075	16.413	<.0001
Temp	.032	.010	.014	3.304	.0010

Fig 4.4 – Sample output of Regression Analysis from Statview

Regression Summary
Power/sq.m vs. 3 Independents

Count	4004
Num. Missing	0
R	.967
R Squared	.936
Adjusted R Squared	.936
RMS Residual	1.940

ANOVA Table
Power/sq.m vs. 3 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	3	220003.164	73334.388	19482.466	<.0001
Residual	4000	15056.490	3.764		
Total	4003	235059.654			

Regression Coefficients
Power/sq.m vs. 3 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	-21.521	.722	-21.521	-29.824	<.0001
Rad	.147	.001	.950	225.331	<.0001
Altitude	.011	.002	.027	6.344	<.0001
Temp	.119	.009	.054	12.995	<.0001

Correlation Matrix

	Altitude	Azimuth	Temp	Rad
Altitude	1.000	-.526	-.175	.223
Azimuth	-.526	1.000	.457	-.034
Temp	-.175	.457	1.000	.180
Rad	.223	-.034	.180	1.000

Fig 4.5 – Final output of Regression Analysis from Statview

The regression models were developed with and without considering Azimuth. Azimuth was observed to have a strong correlation with Altitude. Also eliminating Azimuth from the model did not affect the model significantly.

Other regression models were developed using different combinations of Rad, Temp, Rad2, Temp2, Altitude, Azimuth, Modified Azimuth (180-Azimuth). The best model developed considering the R-square values and t-values is:

$$\textbf{Power/m2} = -21.521 + 0.01{*}\textbf{Altitude} + 0.119{*}\textbf{Temp} + 0.147{*}\textbf{Rad} \quad \text{– Equation 4.2}$$
$$(-29.824) \quad (6.3444) \quad (12.995) \quad (225.331)$$

This model could then be used to estimate power production per unit area for any combination of levels for the independent variable set. Using the TMY weather data and given month, day and time, the model can be applied to estimate power production for a given roof area.

4.4 Cost analysis case study

Kipps Elementary School located on Prices Fork Road in Blacksburg, Virginia was chosen as the building to study the cost-benefit of the thin film photovoltaic roofing system compared to a non-electricity producing conventional roof. The school houses approximately 500 students from grades K-5. The roof of the school building was assumed to be flat. The usable roof area is about 20,000sq.ft.

Fig 4.6 – Kipps Elementary School

4.5 Simple Payback Analysis

A simplified form of cost/benefit analysis is the simple payback technique. In this method, the total first cost of the improvement is divided by the first-year energy cost savings produced by the improvement. This method yields the number of years required for the improvement to pay for itself. For new construction, it can be used to evaluate conventional construction to energy-efficient design alternatives.

In simple payback analysis, you are assuming that the service life of the energy efficiency measure will equal or exceed the simple payback time. Simple payback analysis provides a relatively easy way to examine the overall costs and savings potentials for a variety of project alternatives. While the payback period analysis does not take into consideration the time dependent value of money, nor the total accumulated cost or savings over the life of the system, for systems with equal expected lives, simple payback period can be applied to determine relative performance among alternatives.

Simple Payback time (years) = Total cost of the system/ Annual Savings

– Equation 4.3

4.6 Simple Payback Time Calculator

A spreadsheet was developed in Excel to calculate the simple payback time for the BIPV roofing system based on the energy consumption data entered, the area of roof coverage, utility rates and demand charge. This spreadsheet was developed considering the TMY files for a typical day of the month and using the load profile for a typical school day. The limitation of this model and scope for future improvement is discussed in Chapter 5 in detail.

4.6.1 Energy Consumption data

The energy consumption data from year 2005 for Kipps Elementary School provided by Montgomery County Public Schools was used for this study and is shown in Table 4.1

Table 4.1 – Energy consumption data for Kipps Elementary School, year 2005

Energy consumption data			
Month	**Electricity/day (kWh/day)**	**No. of days**	**Electricity (kWh)**
Jan	2003	31	62100
Feb	2357	28	66000
Mar	2187	31	67800
Apr	2640	30	79200
May	2274	31	70500
Jun	2510	30	75300
Jul	2303	31	71400
Aug	2303	31	71400
Sep	3100	30	93000
Oct	2487	31	77100
Nov	2510	30	75300
Dec	2032	31	63000

4.6.2 Load profile for typical school day

The load profile for a typical school day from Marion County, Florida is shown below and is proportionately altered to estimate the load profiles for the different months based on the Kipps Elementary school data for year 2005.

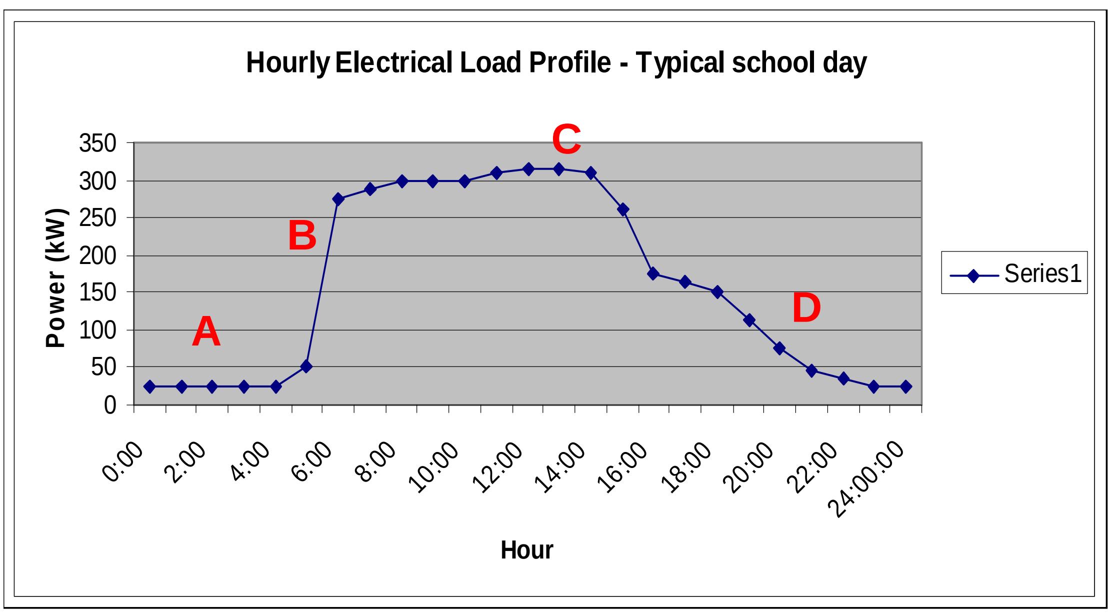


Fig 4.7 – Load profile for a typical school day

In the chart above,

Area A depicts the base load during the non-operational hours.

Area B depicts the HVAC and other equipment starting at the same time creating an unnecessary peak load and raising the demand charge.

Area C depicts the peak load.

Area D depicts the equipment left running after the class.

The load profile for different months of the year for Kipps Elementary School located in Blacksburg was obtained by scaling the above profile using the utility records obtained from Montgomery County Public School. The load profiles are shown in Fig 4.8 through 4.19.

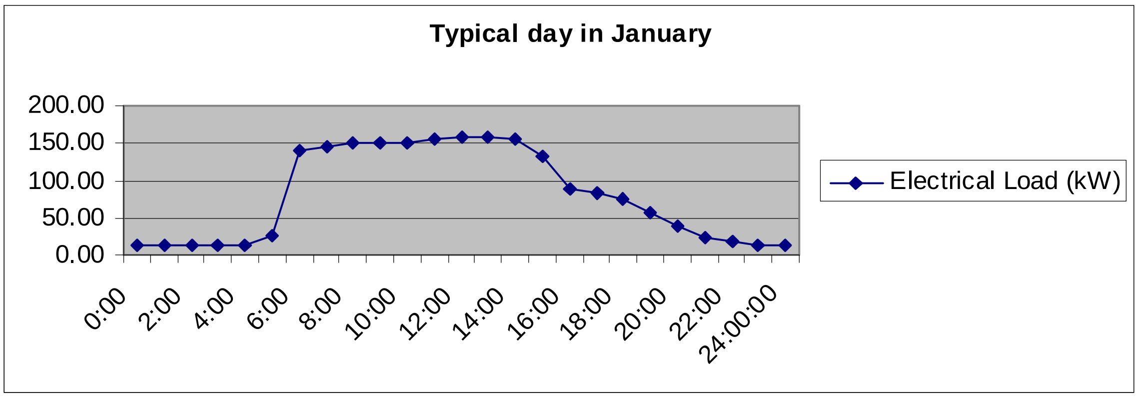


Fig 4.8 – Electricity Load Profile for typical day in January

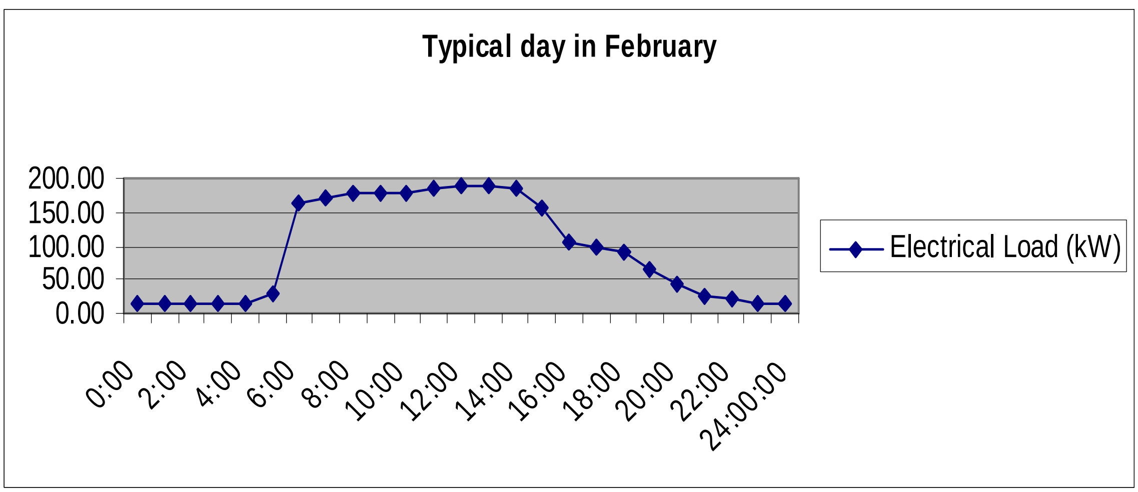


Fig 4.9 – Electricity Load Profile for typical day in February

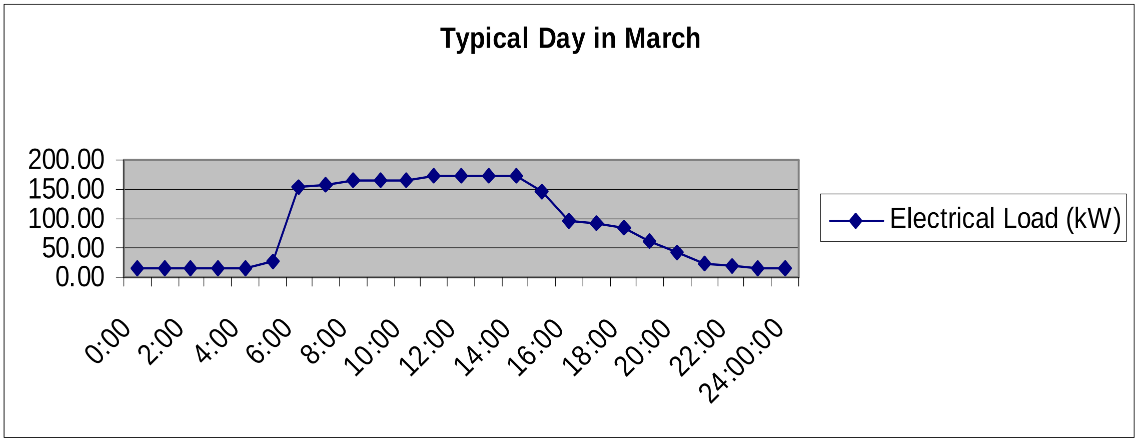


Fig 4.10 – Electricity Load Profile for typical day in March

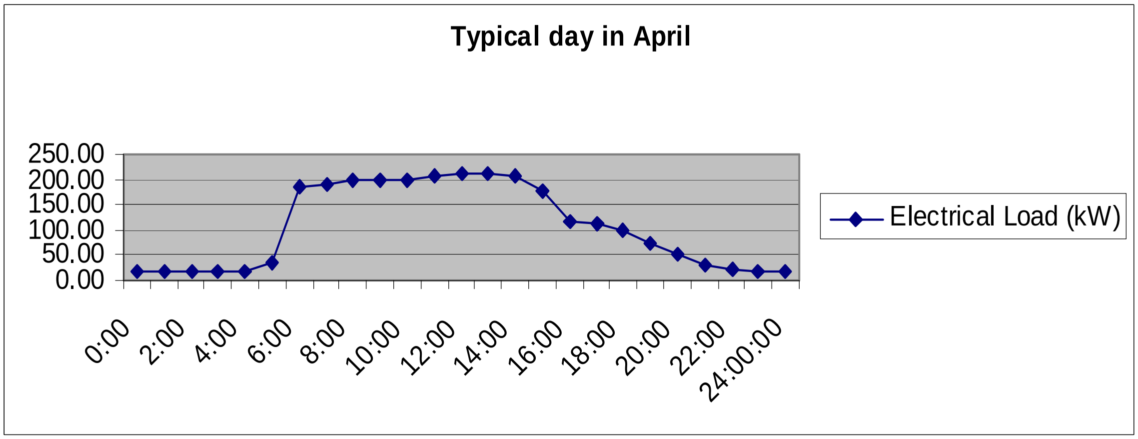


Fig 4.11 – Electricity Load Profile for typical day in April

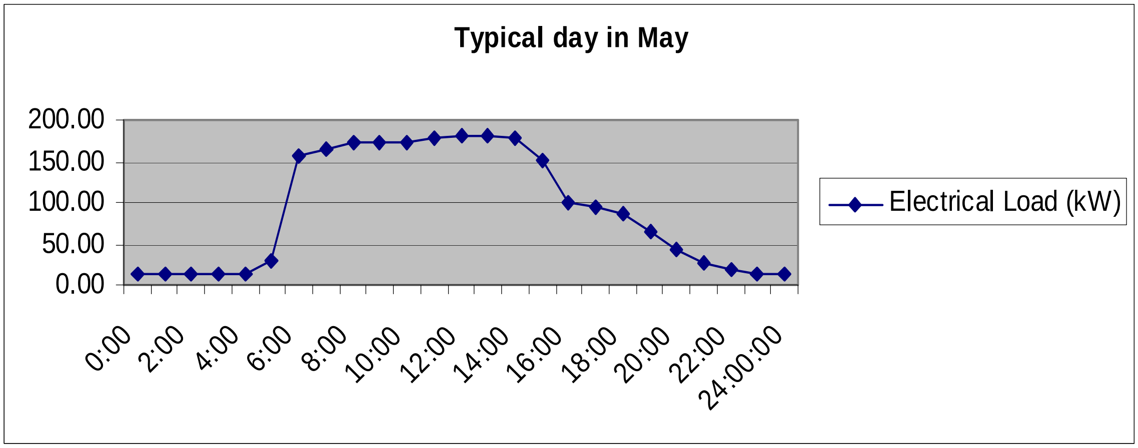


Fig 4.12 – Electricity Load Profile for typical day in May

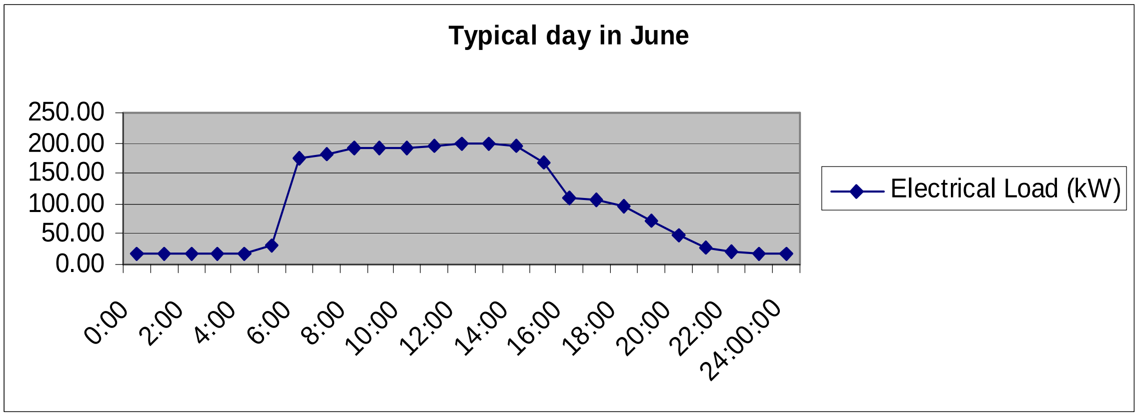


Fig 4.13 – Electricity Load Profile for typical day in June

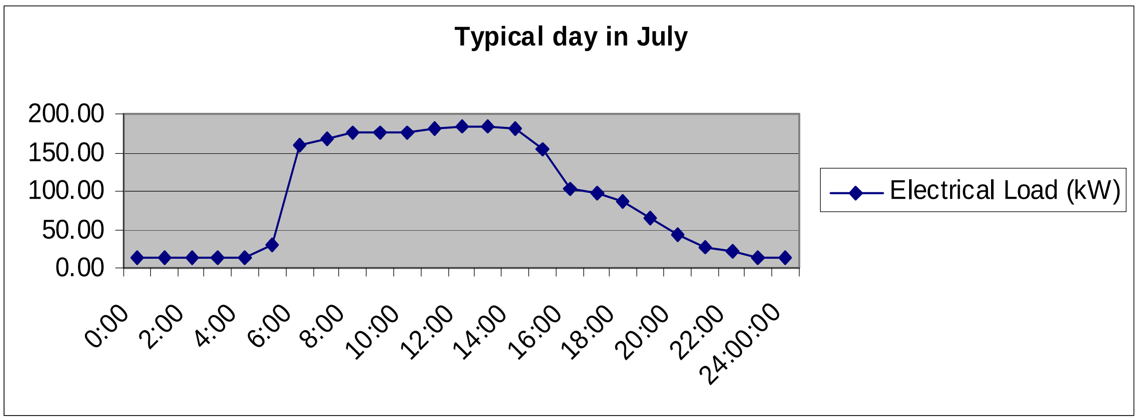


Fig 4.14 – Electricity Load Profile for typical day in July

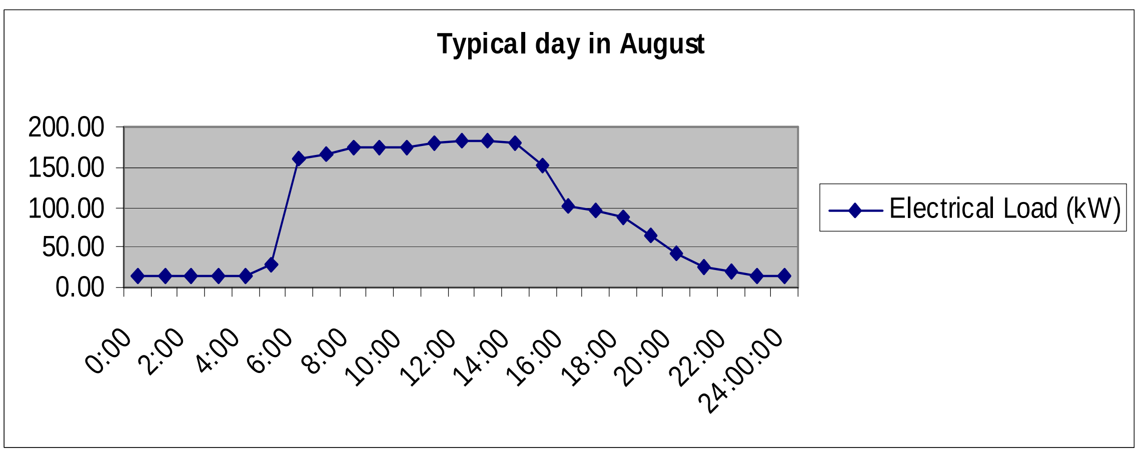


Fig 4.15 – Electricity Load Profile for typical day in August

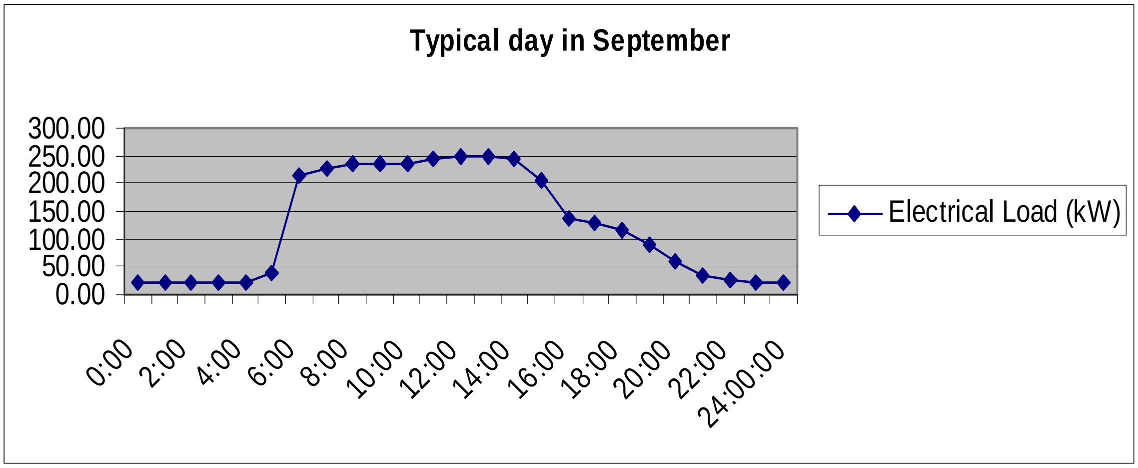


Fig 4.16 – Electricity Load Profile for typical day in September

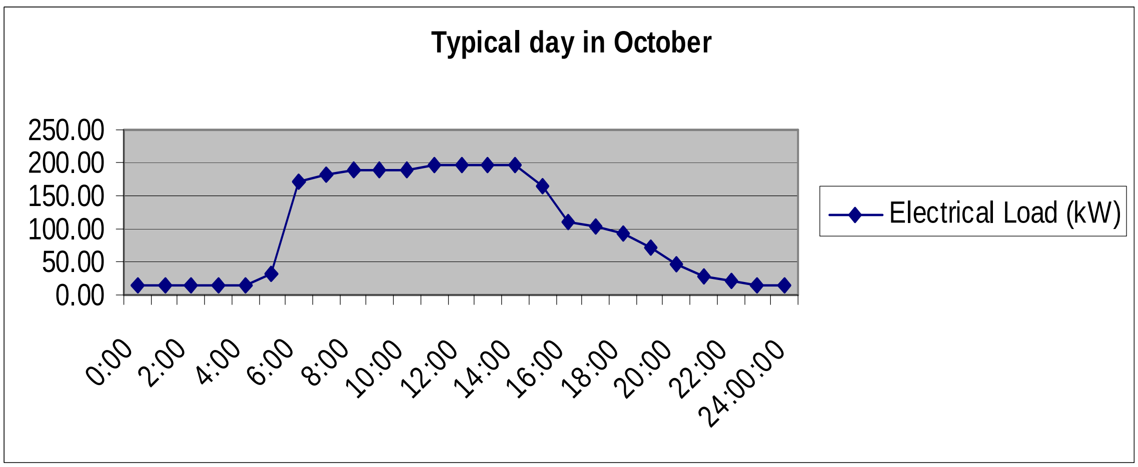


Fig 4.17 – Electricity Load Profile for typical day in October

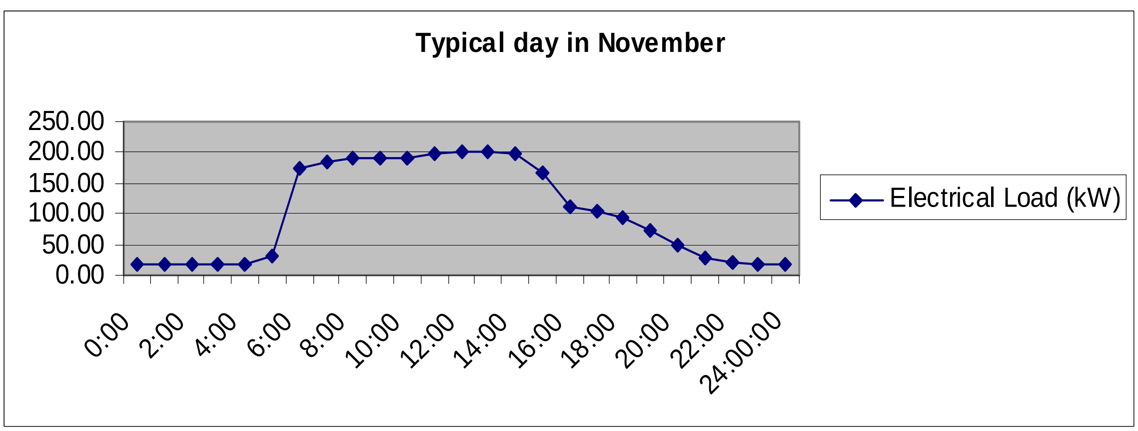


Fig 4.18 – Electricity Load Profile for typical day in November

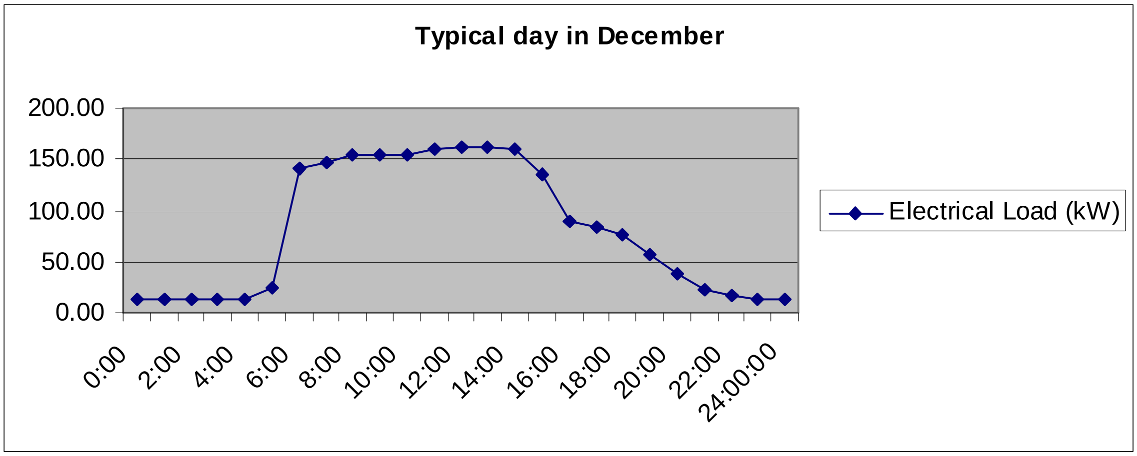


Fig 4.19 – Electricity Load Profile for typical day in December

4.6.3 Electricity production prediction using the Regression Model

The electricity production per unit area for each month was calculated using the Regression Model (Equation 4.2) and is shown below.

$$\mathbf{Power/m^2 = -21.521 + 0.01*Altitude + 0.119*Temp + 0.147*Rad} \text{ – Equation 4.2}$$

where,

Power/m^2 = Power produced per sq.m area of panel (watt/m^2)

Altitude = Solar altitude based on time of the day (degree)

Temp = Temperature of the panel (degree F)

Rad = Solar radiation incident upon the panels at any particular time (watt/m^2)

Using the model, electricity production per unit area for each hour of the 15^{th} day in each month was calculated. The tables are included in Appendix B.

4.6.4 Electricity production for different roof areas

Based on the area of the roof covered with the PV panels (full, half, quarter roof), the electricity production was calculated and compared to the electricity consumption as shown in the following figures. For calculation of the energy production per unit area using the regression model developed, TMY files were used for a typical day in each month.

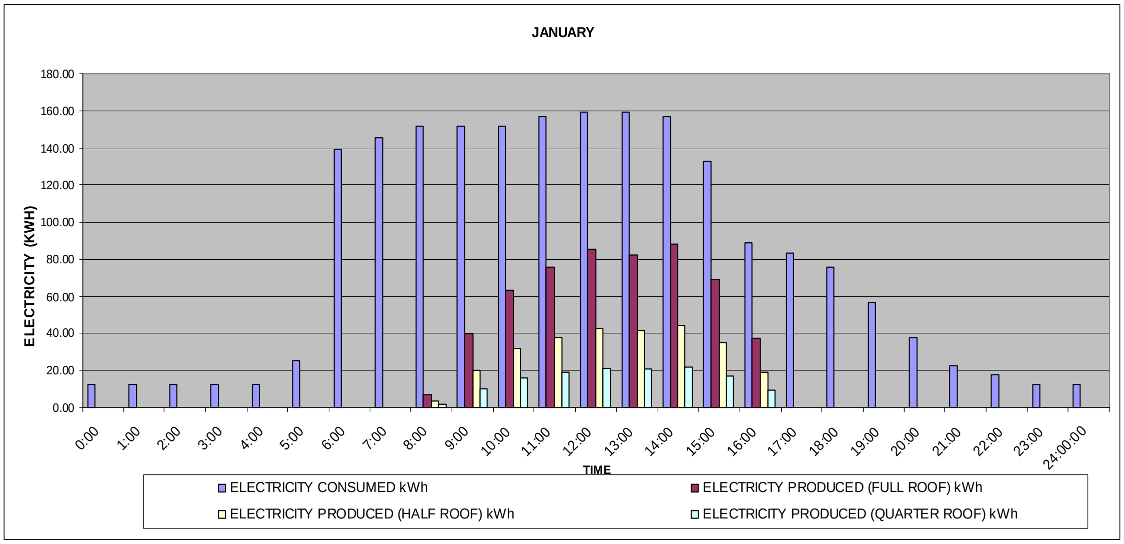


Fig 4.20 – Electricity chart for January

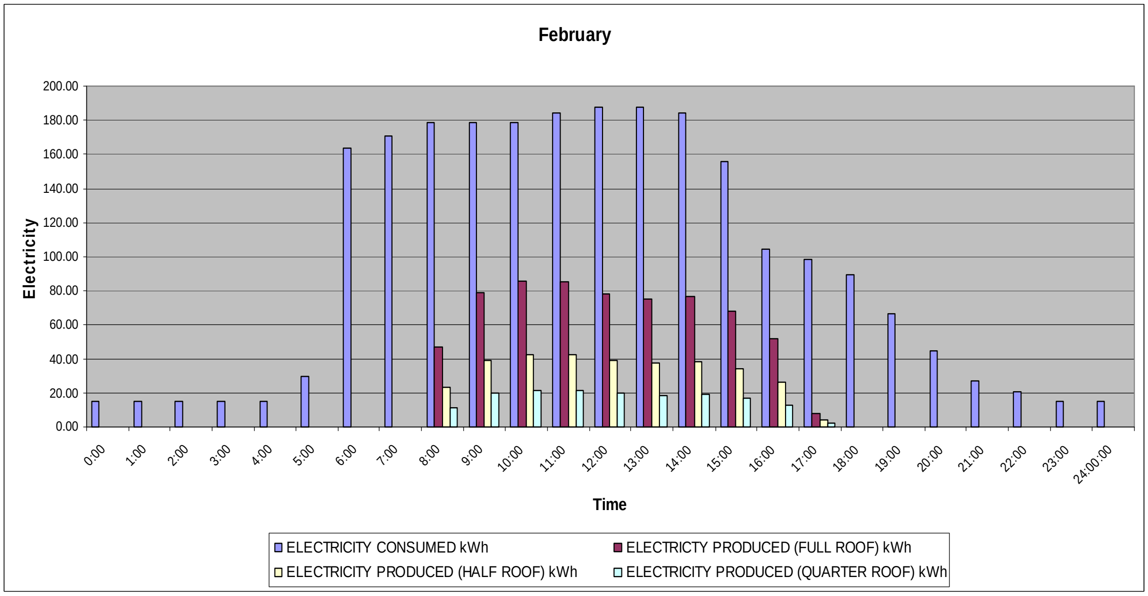


Fig 4.21 – Electricity chart for February

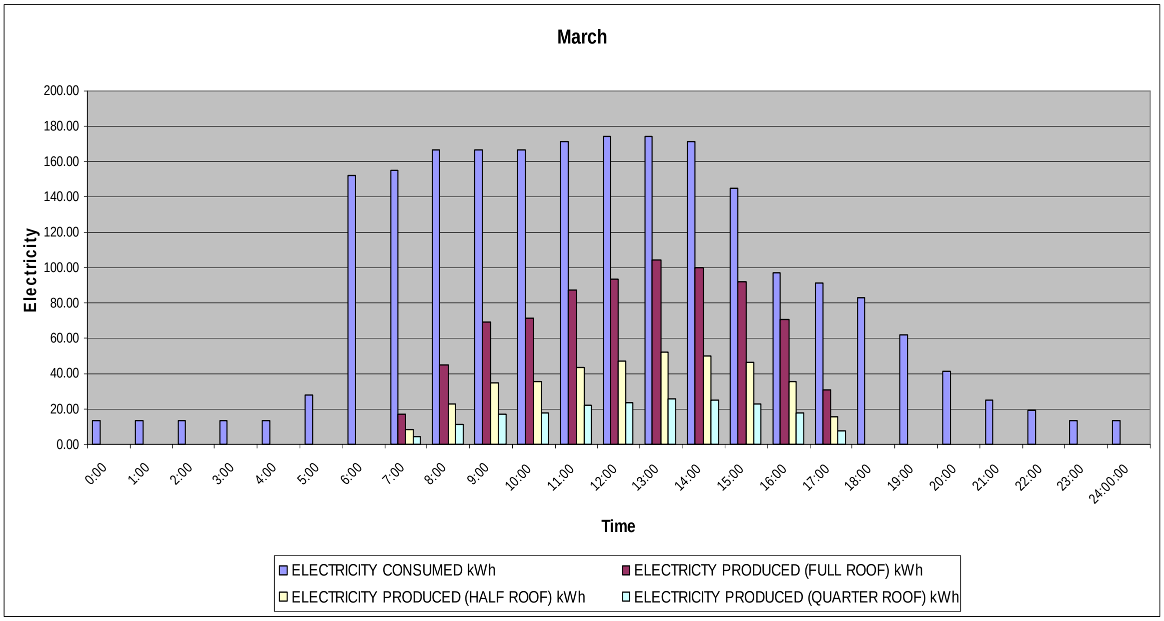


Fig 4.22 – Electricity chart for March

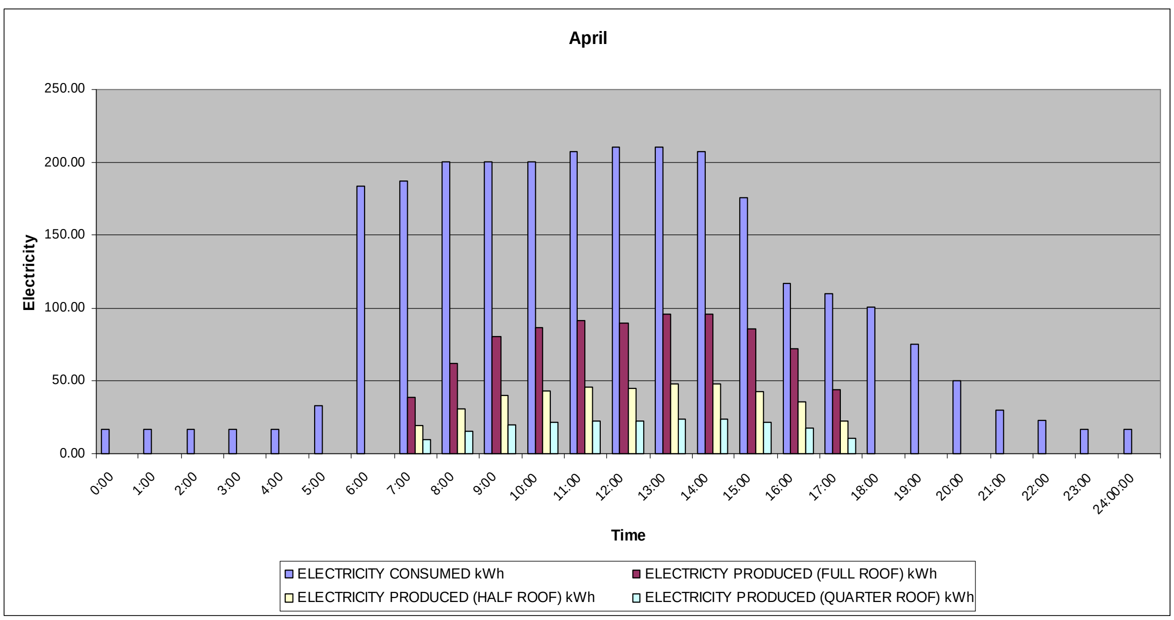


Fig 4.23 – Electricity chart for April

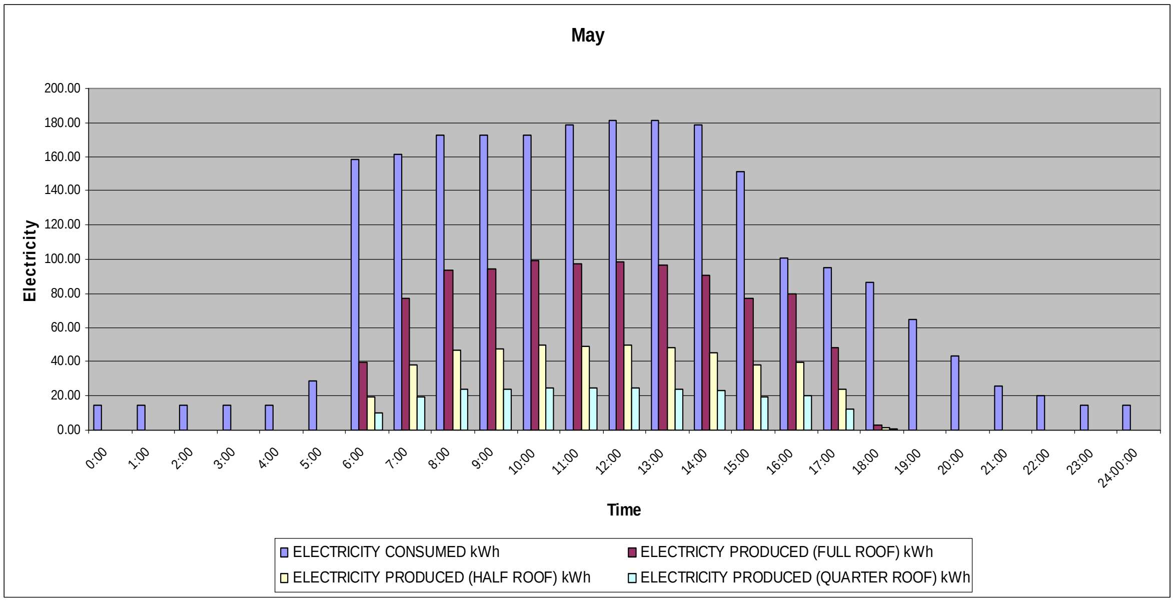


Fig 4.24 – Electricity chart for May

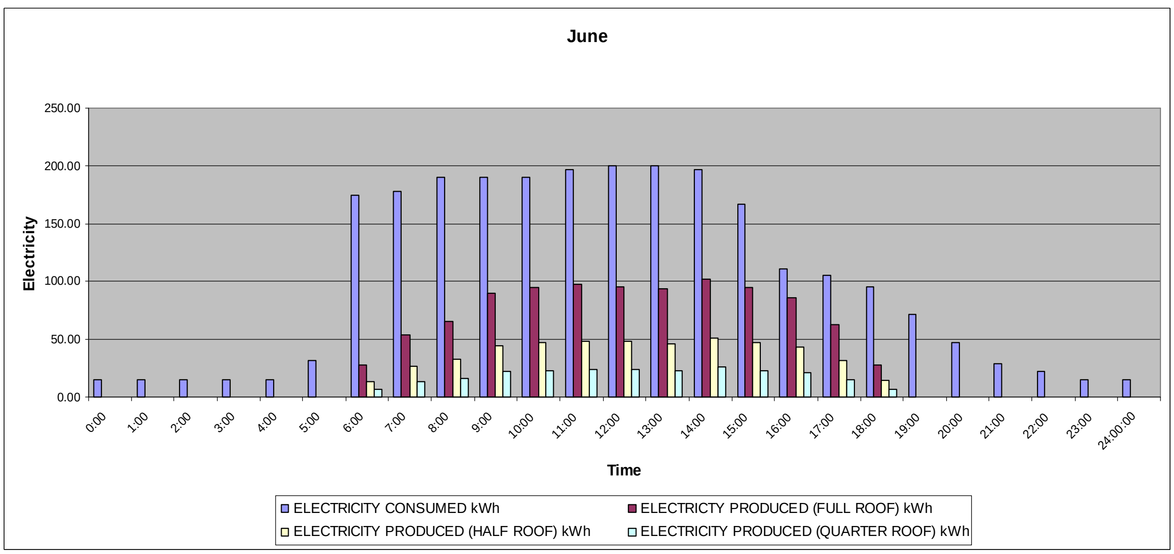


Fig 4.25 – Electricity data for June

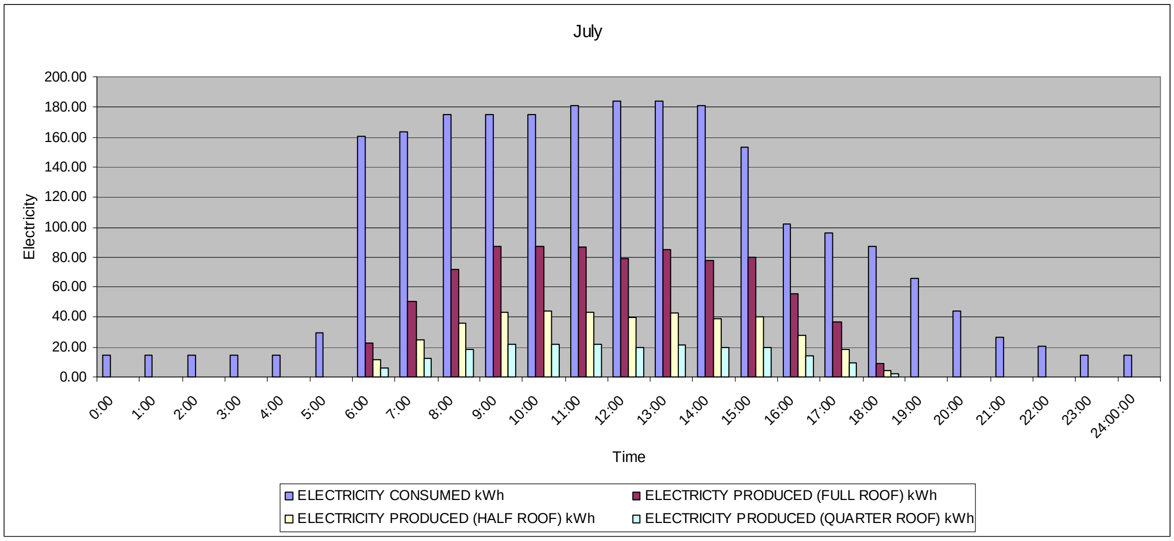


Fig 4.26 – Electricity data for July

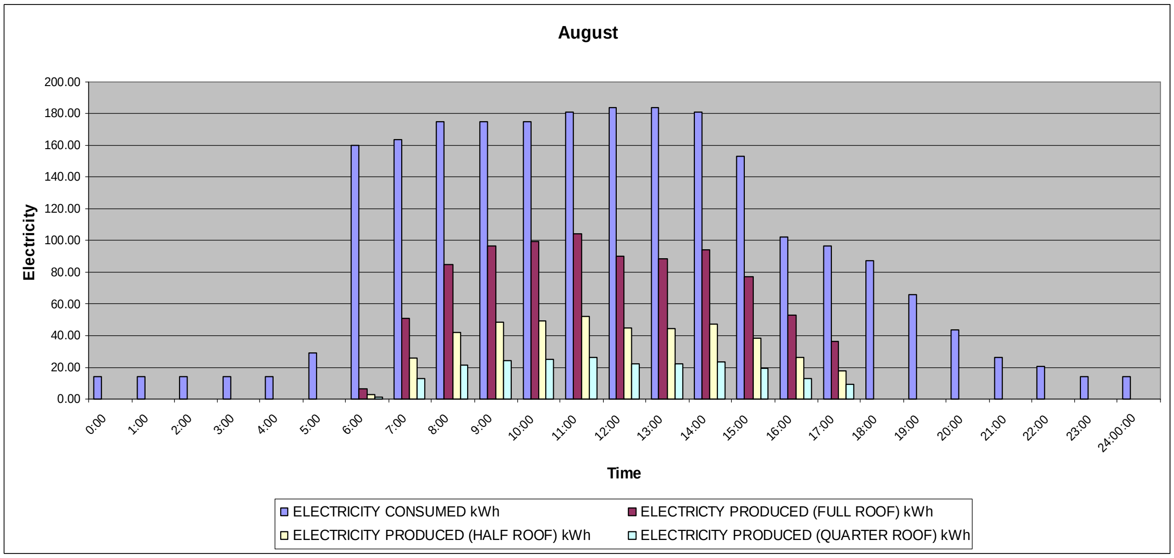


Figure 4.27 – Electricity data for August

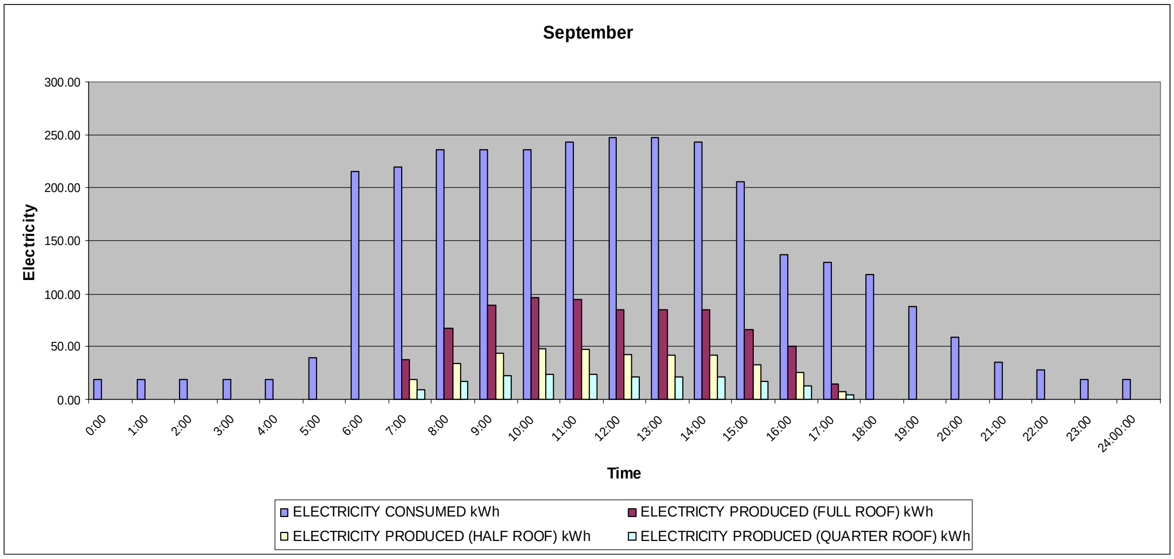


Figure 4.28– Electricity data for September

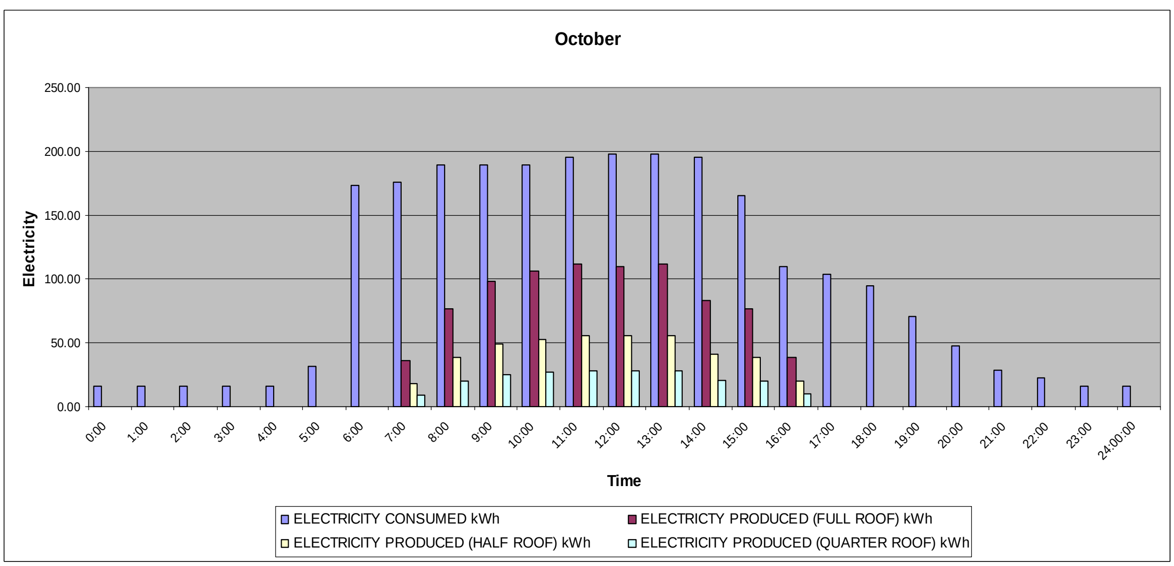


Figure 4.29 – Electricity data for October

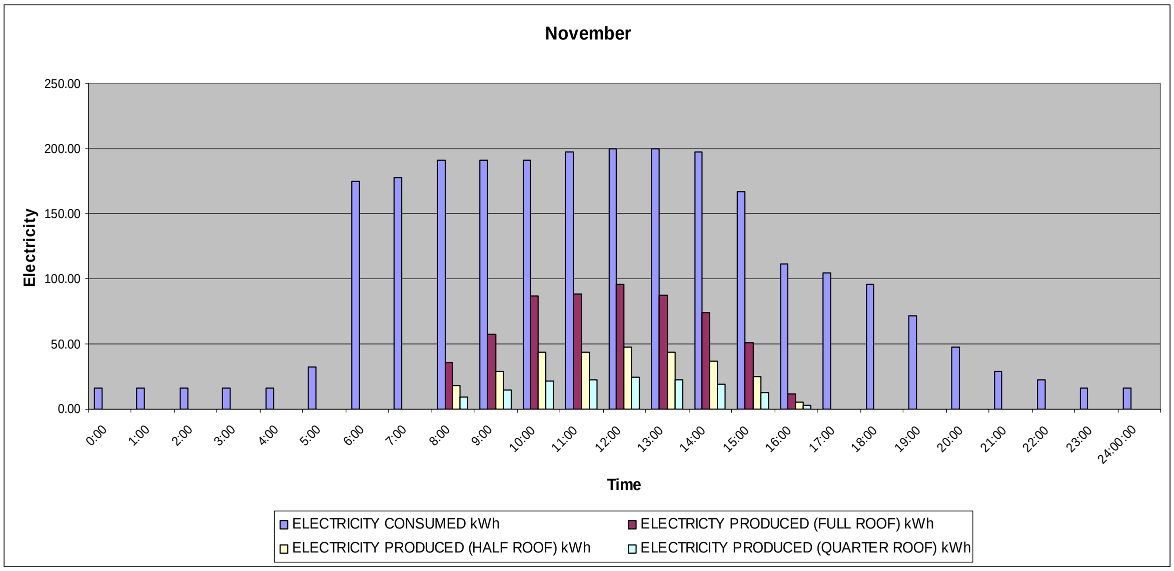


Figure 4.30– Electricity data for November

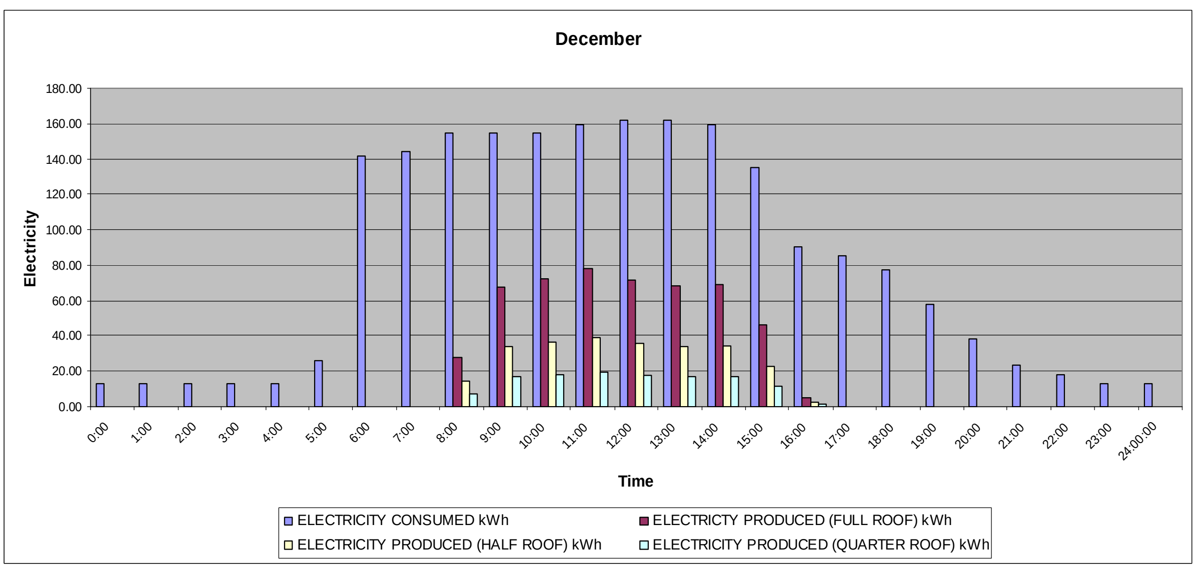


Figure 4.31 – Electricity data for December

Note: It has been observed that the peak load occurs when all the equipment is switched on in the morning. At this time, the power production is low or almost zero. By changing the pattern of equipment operation, huge savings can be made in electricity bills by cutting down the peak load and demand charges.

The detailed tables showing calculation of electricity drawn from the utility at each hour of the day in each month, the peak load, the electricity bills, demand charges and savings is presented in Appendix B.

4.6.5 Simple Payback time

The total electricity bills and savings are given below. Detailed calculations are in Appendix B.

Data :

Area of full roof: 1810.33 sq.m (approx.)

Area of panel: 2.16 sq.m

Cost of panel: $748

Demand charge: $8/kW

Utility rate: $0.08/kWh

Table 4.2 – Electricity bills for different roof coverage

	WITHOUT PV	**FULL ROOF**	**HALF ROOF**	**QUARTER ROOF**
MONTH	**Total Electricity Bill**	**Total Electricity Bill**	**Total Electricity Bill**	**Total Electricity Bill**
January	$6,246.01	$4,766.17	$5,475.66	$5,830.40
February	$6,783.80	$5,151.27	$5,883.99	$6,267.76
March	$6,819.31	$4,702.35	$5,672.24	$6,177.91
April	$8,020.25	$5,784.07	$6,795.23	$7,334.76
May	$7,090.88	$4,124.83	$5,515.74	$6,282.24
June	$7,625.32	$4,817.16	$6,119.57	$6,842.46
July	$7,181.40	$4,757.10	$5,875.95	$6,509.84
August	$7,181.40	$4,759.75	$5,877.28	$6,458.48
September	$9,417.72	$7,315.82	$8,241.20	$8,786.24
October	$7,754.70	$5,450.96	$6,502.09	$7,038.53
November	$7,625.32	$6,036.77	$6,742.08	$7,124.38
December	$6,336.53	$4,938.28	$5,565.38	$5,905.27

Table 4.3 – Savings for different roof coverage

	FULL ROOF	HALF ROOF	QUARTER ROOF
MONTH	**savings**	**savings**	**Savings**
January	$1,479.84	$770.35	$415.61
February	$1,632.53	$899.81	$516.04
March	$2,116.96	$1,147.07	$641.40
April	$2,236.18	$1,225.02	$685.49
May	$2,966.05	$1,575.14	$808.64
June	$2,808.16	$1,505.75	$782.86
July	$2,424.30	$1,305.45	$671.56
August	$2,421.65	$1,304.12	$722.92
September	$2,101.90	$1,176.52	$631.48
October	$2,303.74	$1,252.61	$716.17
November	$1,588.55	$883.24	$500.94
December	$1,398.25	$771.15	$431.26
ANNUAL	**$25,478.11**	**$13,816.23**	**$7,524.37**

Cost of the system:

Full roof area: $ 627,572.00

Half roof area: $ 314,160.00

Quarter roof area: $ 157,080.00

Simple payback time = Total cost of system / Annual savings –Equation 4.3

For different roofs areas:

Full Roof Area : Simple Payback time = 24.63 years

Half Roof Area : Simple Payback time = 22.74 years

Quarter Roof Area : Simple Payback time = 20.88 years

4.6.6 Simple Payback time for different utility rates and rebates

The simple payback period was calculated for different utility rates and rebate amounts to observe at what point the system appears cost-effective compared to the conventional non-electricity producing roofing system. The results are summarized in tables 4.4 through 4.6.

Table 4.4 – Simple Payback period for full roof coverage

FULL ROOF AREA									
simple payback time for different utility rates and rebates									
	Rebate								
Utility rate	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
$ 0.06	31.61	28.45	25.29	22.13	18.97	15.80	12.64	9.48	6.32
$ 0.08	24.63	22.17	19.71	17.24	14.78	12.32	9.85	7.39	4.93
$ 0.10	20.18	18.16	16.14	14.12	12.11	10.09	8.07	6.05	4.04
$ 0.12	17.09	15.38	13.67	11.96	10.25	8.54	6.84	5.13	3.42
$ 0.14	14.82	13.34	11.85	10.37	8.89	7.41	5.93	4.45	2.96
$ 0.16	13.08	11.77	10.46	9.16	7.85	6.54	5.23	3.92	2.62
$ 0.18	11.71	10.54	9.37	8.20	7.03	5.85	4.68	3.51	2.34
$ 0.20	10.60	9.54	8.48	7.42	6.36	5.30	4.24	3.18	2.12

Table 4.5 – Simple Payback period for half roof coverage

HALF ROOF AREA									
simple payback time for different utility rates and rebates									
	Rebate								
Utility rate	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
$ 0.06	28.55	25.69	22.84	19.98	17.13	14.27	11.42	8.56	5.71
$ 0.08	22.74	20.46	18.19	15.92	13.64	11.37	9.10	6.82	4.55
$ 0.10	18.89	17.00	15.11	13.23	11.34	9.45	7.56	5.67	3.78
$ 0.12	16.16	14.54	12.93	11.31	9.70	8.08	6.46	4.85	3.23
$ 0.14	14.12	12.71	11.29	9.88	8.47	7.06	5.65	4.24	2.82
$ 0.16	12.53	11.28	10.03	8.77	7.52	6.27	5.01	3.76	2.51
$ 0.18	11.27	10.14	9.02	7.89	6.76	5.63	4.51	3.38	2.25
$ 0.20	10.24	9.12	8.19	7.17	6.14	5.12	4.09	3.07	2.05

Table 4.6 – Simple Payback period for quarter roof coverage

QUARTER ROOF AREA									
simple payback time for different utility rates and rebates									
	Rebate								
Utility rate	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
$ 0.06	25.67	23.11	20.54	17.97	15.40	12.84	10.27	7.70	5.13
$ 0.08	20.88	18.79	16.70	14.61	12.53	10.44	8.35	6.26	4.18
$ 0.10	17.59	15.83	14.07	12.31	10.55	8.79	7.04	5.28	3.52
$ 0.12	15.20	13.68	12.16	10.64	9.12	7.60	6.08	4.56	3.04
$ 0.14	13.38	12.04	10.70	9.36	8.03	6.69	5.35	4.01	2.68
$ 0.16	11.95	10.75	9.56	8.36	7.17	5.97	4.78	3.58	2.39
$ 0.18	10.79	9.71	8.63	7.55	6.48	5.40	4.32	3.24	2.16
$ 0.20	9.84	8.86	7.87	6.89	5.90	4.92	3.94	2.95	1.97

4.6.7 Simple Payback period for different utility rates and demand charge

Table 4.7 – Simple payback period for Utility rate = $0.08/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.08	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/ kW**	**$24/ kW**
FULL ROOF	24.63	22.05	19.96
HALF ROOF	22.74	19.17	16.58
QUARTER ROOF	20.88	16.67	13.87

Table 4.8 – Simple payback period for Utility rate = $0.10/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.10	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/ kW**	**$24/ kW**
FULL ROOF	20.18	18.41	16.93
HALF ROOF	18.89	16.37	14.43
QUARTER ROOF	17.59	14.5	12.34

Table 4.9 – Simple payback period for Utility rate = $0.12/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.12	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/ kW**	**$24/ kW**
FULL ROOF	17.09	15.8	14.7
HALF ROOF	16.16	14.27	12.78
QUARTER ROOF	15.2	12.84	11.11

Table 4.10 – Simple payback period for Utility rate = $0.14/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.14	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/kw**	**$24/kw**
FULL ROOF	14.82	13.84	12.99
HALF ROOF	14.12	12.66	11.47
QUARTER ROOF	13.38	11.51	10.11

Table 4.11 – Simple payback period for Utility rate = $0.16/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.16	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/kw**	**$24/kw**
FULL ROOF	13.08	12.32	11.64
HALF ROOF	12.53	11.37	10.4
QUARTER ROOF	11.95	10.44	9.27

Table 4.12 – Simple payback period for Utility rate = $0.18/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.18	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/kw**	**$24/kw**
FULL ROOF	11.71	11.09	10.54
HALF ROOF	11.27	10.32	9.52
QUARTER ROOF	10.79	9.55	8.56

Table 4.13 – Simple payback period for Utility rate = $0.20/kWh

SIMPLE PAYBACK PERIOD FOR DIFFERENT DEMAND CHARGES			
Utility rate =	$ 0.20	WITH NO REBATES	
	DEMAND CHARGE		
	$8/kW	**$16/kw**	**$24/kw**
FULL ROOF	10.6	10.09	9.63
HALF ROOF	10.24	9.45	8.77
QUARTER ROOF	9.84	8.79	7.95

4.7 Summary of Results

The calculation of simple payback periods for different utility rates and demand charges for different roof coverage shows that at present the system is not economically feasible because of the high cost. The load profile reveals that a peak load occurs at around 5:00 – 6:00A.M in the morning when all the equipment is switched on simultaneously. At this hour of the day, the electricity production by the PV panel is very low and almost zero so the effect of the PV system on reducing the demand charge is not observed. The system can prove economical feasible if this load is distributed more evenly during the course of the day. Limitations of the model and scope for future improved models are discussed in Chapter 5. The rebates necessary to make the system cost-effective is also discussed in chapter 5.

Chapter 5: Conclusions and Discussion

5.1 Conclusions

The model was developed to predict the electricity power production for the system for any building when the levels of the variables (solar radiation, solar altitude, azimuth and temperature) are known.

The model was applied to the Kipps Elementary School located in Blacksburg, Virginia. From the results, it can be concluded that at current utility rate of about 8 cents/kWh and a demand charge of $8/kW, the system is not economically feasible. However with a rebate of about 80%, the simple payback period drops to about 4.93 years for full roof, 4.55 years for half roof and 4.18 years for quarter roof area. Not much difference is noticed in the three different roof coverage because the peak load occurs early in the morning when the PV panel production is low. By distributing this load evenly throughout the day, big savings can be made in the demand charge. At higher utility rates like 18 cents/kWh and 20 cents/kWh, the system appears cost-effective with about 50% rebates from the Government or utilities. With rebates, the demand for the PV panels will rise gradually leading to more production of panels and a likely drop in price thereby making the system more cost-effective. The study has a few limitations which can be improved in future as mentioned in 5.2.

5.2 Limitation of the study and recommendations

The model developed using multiple linear regression analysis, shows a positive relationship between temperature and the power produced by the panel. From the literature study, it was noted that at very high temperatures, the power production by the panel drops. This was not observed in the data collected since extremes temperatures were not experienced during the time of collection. The study can be improved by developing separate models for very warm, cold, clear and cloudy days to make the prediction more accurate.

The electricity load profiles for a typical school day were used in the study after scaling it to the electricity consumption data for each month for Kipps Elementary School obtained for year 2005 from the Montgomery County Public School. The load profiles vary for warm, cold and moderate days. Accurate predictions can be made using the actual load profile for the building. However due to unavailability of data, typical day load profile was used.

For calculation of the energy production per unit area using the regression model developed, TMY files were used for a typical day in each month. The prediction can be made more accurate using different data for warm, cold and moderate days.

As mentioned in earlier chapter, the peak load that occurs in the morning was responsible for not making the system appear economically feasible. By distributing this load, the system can appear cost-effective at lower rebates and utility rates.

The BIPV roofing system can be made economically feasible with rebates from the Government initially and also by distributing the loads throughout the day.

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Appendix A – Regression Analysis

Dependent variable : Power/m^2

Independent variables : Solar Radiation (Rad);

Solar Altitude (Altitude);

Temperature (Temp)

Solar radiation greater than 1watt/m^2 and less than 50 watt/m^2 were used for the analysis; at very high solar radiations the peak power was observed.

Statview summary

Regression Summary
Power/sq.m vs. 3 Independents

Count	4004
Num. Missing	0
R	.967
R Squared	.936
Adjusted R Squared	.936
RMS Residual	1.940

ANOVA Table
Power/sq.m vs. 3 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	3	220003.164	73334.388	19482.466	<.0001
Residual	4000	15056.490	3.764		
Total	4003	235059.654			

Regression Coefficients
Power/sq.m vs. 3 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	-21.521	.722	-21.521	-29.824	<.0001
Altitude	.011	.002	.027	6.344	<.0001
Temp	.119	.009	.054	12.995	<.0001
Rad	.147	.001	.950	225.331	<.0001

Correlation Matrix

	Altitude	Azimuth	Temp	Rad
Altitude	1.000	-.526	-.175	.223
Azimuth	-.526	1.000	.457	-.034
Temp	-.175	.457	1.000	.180
Rad	.223	-.034	.180	1.000

4004 observations were used in this computation.

Appendix B – Electricity production

Note: The calculations are based on TMY files for a typical day in each month. The panel used is PVL series from UniSolar.

B-1 Electricity production in each month using the Regression Model

REGRESSION MODEL:

Power/m2 = -21.521 + 0.01*Altitude + 0.119*Temp + 0.147*Rad

where Power/m2 = Power produced per sq.m area of panel (watt/m2)
Altitude = Solar altitude based on time of the day (degree)
Temp = Temperature of the panel (degree F)
Rad = Solar radiation incident upon the panels at any particular time (watt/m2)

Table B-1-1

JANUARY						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
8:00	3.6	33.3	146	3.93	0.0039	
9:00	12.9	34.5	267	21.96	0.0220	
10:00	20.8	36.1	354	35.03	0.0350	
11:00	26.6	37.8	399	41.89	0.0419	
12:00	29.5	39.2	433	47.09	0.0471	
13:00	29.3	39.6	422	45.51	0.0455	
14:00	25.9	39.7	445	48.88	0.0489	
15:00	19.7	40.1	374	38.43	0.0384	
16:00	11.6	38.3	255	20.64	0.0206	
			Energy/m2/day		0.3034	kWh/m2/day
			Energy/m2/month		**9.4043**	**kWh/m2**

Table B-1-2

FEBRUARY						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
8:00	5.8	33.08	294	25.69	0.0257	
9:00	15.9	35.60	412	43.44	0.0434	
10:00	24.7	37.40	436	47.27	0.0473	
11:00	31.4	39.38	433	47.13	0.0471	
12:00	35.2	41.36	405	43.29	0.0433	
13:00	35.6	42.26	391	41.34	0.0413	
14:00	32.3	43.16	398	42.44	0.0424	
15:00	26.1	44.06	365	37.64	0.0376	
16:00	17.6	42.08	307	28.79	0.0288	
17:00	7.7	40.10	143	4.35	0.0043	
			Energy/m2/day		0.3614	kWh/m2/day
			Energy/m2/month		**10.1186**	**kWh/m2**

Table B-1-3

MARCH						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
7:00	1.0	42.62	176	9.43	0.0094	
8:00	12.3	45.32	278	24.86	0.0249	
9:00	23.1	48.56	366	38.29	0.0383	
10:00	32.7	51.26	372	39.59	0.0396	
11:00	40.3	53.60	428	48.18	0.0482	
12:00	44.7	55.22	451	51.79	0.0518	
13:00	45.0	57.20	488	57.47	0.0575	
14:00	41.1	58.28	472	55.21	0.0552	
15:00	33.9	58.46	444	51.04	0.0510	
16:00	24.5	57.74	364	39.10	0.0391	
17:00	13.8	55.22	217	17.09	0.0171	
			Energy/m2/day		0.4321	kWh/m2/day
			Energy/m2/month		**13.3938**	**kWh/m2**

Table B-1-4

APRIL						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
7:00	9.8	53.42	249	21.54	0.0215	
8:00	21.6	56.30	333	34.35	0.0343	
9:00	33.1	59.00	399	44.48	0.0445	
10:00	43.6	60.98	419	47.76	0.0478	
11:00	52.1	62.96	434	50.29	0.0503	
12:00	57.0	64.94	428	49.69	0.0497	
13:00	56.6	65.30	450	52.97	0.0530	
14:00	51.0	65.84	449	52.83	0.0528	
15:00	42.1	66.20	412	47.34	0.0473	
16:00	31.4	64.58	362	39.69	0.0397	
17:00	19.9	62.78	261	24.52	0.0245	
			Energy/m2/day		0.4655	kWh/m2/day
			Energy/m2/month		**13.9637**	**kWh/m2**

Table B-1-5

MAY						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
6:00	5.6	58.64	247	21.82	0.0218	
7:00	17.3	62.42	383	42.38	0.0424	
8:00	29.2	65.84	443	51.73	0.0517	
9:00	41.0	68.00	443	52.10	0.0521	
10:00	52.3	70.16	459	54.82	0.0548	
11:00	61.9	71.78	450	53.79	0.0538	
12:00	67.6	73.04	454	54.58	0.0546	
13:00	66.2	74.12	443	53.08	0.0531	
14:00	58.6	74.48	423	50.11	0.0501	
15:00	48.2	74.48	372	42.51	0.0425	
16:00	36.6	73.58	384	44.05	0.0440	
17:00	24.8	71.78	267	26.52	0.0265	
18:00	12.9	69.44	101	1.72	0.0017	
			Energy/m2/day		0.5492	kWh/m2/day
			Energy/m2/month		**17.0257**	**kWh/m2**

Table B-1-6

JUNE						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
6:00	9.6	65.30	197	15.30	0.0153	
7:00	21.0	68.54	292	29.77	0.0298	
8:00	32.8	71.06	335	36.51	0.0365	
9:00	44.7	72.86	420	49.34	0.0493	
10:00	56.4	75.02	437	52.21	0.0522	
11:00	67.2	76.64	446	53.83	0.0538	
12:00	74.3	78.08	439	53.05	0.0530	
13:00	72.6	78.98	429	51.67	0.0517	
14:00	63.6	78.98	463	56.57	0.0566	
15:00	52.4	79.34	434	52.24	0.0522	
16:00	40.5	78.62	404	47.63	0.0476	
17:00	28.6	77.54	319	34.89	0.0349	
18:00	17.0	75.02	190	15.51	0.0155	
			Energy/m2/day		0.5485	kWh/m2/day
			Energy/m2/month		**16.4553**	**kWh/m2**

Table B-1-7

JULY						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
6:00	9.1	69.62	175	12.58	0.0126	
7:00	20.4	72.68	276	27.90	0.0279	
8:00	32.1	75.74	353	39.70	0.0397	
9:00	44.0	78.62	407	48.10	0.0481	
10:00	55.8	80.24	406	48.27	0.0483	
11:00	66.8	81.86	401	47.84	0.0478	
12:00	74.8	83.48	370	43.55	0.0436	
13:00	74.0	83.30	393	46.90	0.0469	
14:00	65.3	82.94	367	42.95	0.0430	
15:00	54.0	82.76	376	44.14	0.0441	
16:00	42.2	81.32	287	30.77	0.0308	
17:00	30.3	80.06	218	20.36	0.0204	
18:00	18.6	78.62	114	4.78	0.0048	
			Energy/m2/day		0.4578	kWh/m2/day
			Energy/m2/month		**14.1930**	**kWh/m2**

Table B-1-8

AUGUST						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
6:00	5.6	66.02	116	3.44	0.0034	
7:00	17.0	69.26	281	28.20	0.0282	
8:00	28.9	72.50	405	46.93	0.0469	
9:00	40.8	75.74	445	53.32	0.0533	
10:00	52.3	77.36	452	54.65	0.0547	
11:00	62.7	78.98	471	57.74	0.0577	
12:00	69.7	80.60	414	49.63	0.0496	
13:00	69.4	80.96	408	48.78	0.0488	
14:00	62.0	81.14	430	51.96	0.0520	
15:00	51.5	81.50	368	42.79	0.0428	
16:00	39.9	79.16	278	29.16	0.0292	
17:00	28.0	77.00	219	20.12	0.0201	
			Energy/m2/day		0.4867	kWh/m2/day
			Energy/m2/month		**15.0884**	**kWh/m2**

Table B-1-9

SEPTEMBER						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy Wh/m2)**	**Energy (kWh/m2)**	
7:00	12.6	63.86	236	20.90	0.0209	
8:00	24.5	67.10	345	37.42	0.0374	
9:00	36.0	70.34	420	48.95	0.0489	
10:00	46.7	73.04	446	53.20	0.0532	
11:00	55.5	75.02	438	52.35	0.0523	
12:00	60.4	75.92	399	46.77	0.0468	
13:00	59.6	77.18	397	46.62	0.0466	
14:00	53.3	76.64	397	46.49	0.0465	
15:00	43.8	76.46	332	36.82	0.0368	
16:00	32.7	75.38	273	27.91	0.0279	
17:00	21.0	73.04	144	8.55	0.0085	
			Energy/m2/day		0.4260	kWh/m2/day
			Energy/m2/month		**12.7792**	**kWh/m2**

Table B-1-10

OCTOBER						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
7:00	7.7	53.96	236	19.67	0.0197	
8:00	19.2	57.92	387	42.45	0.0425	
9:00	29.9	61.16	465	54.41	0.0544	
10:00	39.2	63.86	490	58.50	0.0585	
11:00	46.1	65.84	508	61.45	0.0615	
12:00	49.3	67.10	502	60.75	0.0608	
13:00	47.8	68.00	507	61.58	0.0616	
14:00	42.1	68.36	399	45.69	0.0457	
15:00	33.5	67.64	378	42.43	0.0424	
16:00	23.2	65.30	237	21.32	0.0213	
			Energy/m2/day		0.4683	kWh/m2/day
			Energy/m2/month		**14.5158**	**kWh/m2**

Table B-1-11

NOVEMBER						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
8:00	12.70	48.02	242	19.89	0.0199	
9:00	22.40	50.90	319	31.65	0.0317	
10:00	30.40	52.88	427	47.84	0.0478	
11:00	36.00	55.04	431	48.75	0.0487	
12:00	38.20	57.02	456	52.68	0.0527	
13:00	36.60	57.20	428	48.57	0.0486	
14:00	31.50	57.38	376	40.89	0.0409	
15:00	23.90	57.38	289	28.03	0.0280	
16:00	14.40	55.22	144	6.36	0.0064	
			Energy/m2/day		0.3247	kWh/m2/day
			Energy/m2/month		**9.7401**	**kWh/m2**

Table B-1-12

DECEMBER						
Time	**Altitude**	**Temp (degree F)**	**Rad (Wh/m2)**	**Energy (Wh/m2)**	**Energy (kWh/m2)**	
8:00	6.7	35.96	222	15.46	0.0155	
9:00	15.8	38.12	369	37.42	0.0374	
10:00	23.4	40.64	384	40.00	0.0400	
11:00	28.6	42.26	403	43.03	0.0430	
12:00	30.8	44.24	377	39.47	0.0395	
13:00	29.8	45.68	363	37.57	0.0376	
14:00	25.6	46.58	365	37.93	0.0379	
15:00	18.8	46.22	281	25.47	0.0255	
16:00	10.1	43.34	131	2.99	0.0030	
			Energy/m2/day		0.2794	kWh/m2/day
			Energy/m2/month		**8.6600**	**kWh/m2**