Design and Simulation of a Distributed PV System for Pennsylvania State University

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1. Acknowledgement

We like to thank Mike Prinkey and his staff at The Office of Physical Plant (OPP) for providing tremendous assistance towards the completion of this project.

We would also like to thank Dr. Angela Lueking and Dr. Derek Elsworth for providing valuable feedback throughout the course of this project.

2. Introduction

The Pennsylvania State University is currently the third largest purchaser of RECs (Renewable Energy Credits) among the universities in the United States. Currently around 20% of Penn State's annual electrical demand is met through the purchase of these RECs. However when it comes to percentage of overall demand met by RECs purchased Penn State ranks much lower with several smaller universities meeting 100% of their electricity demand through the purchase of RECs. Penn State's contractual agreement to buy RECs ends in 2011 and the Office of the Physical Plant (OPP) is now looking to explore its onsite renewable energy options. This is being done primarily for two reasons; to check Penn State's ability to comply to Pennsylvania's Alternate Energy Portfolio standards (AEPS) should it make a voluntary commitment and to displace some of the RECs. The prices of RECs fluctuate as per the demand and sometimes end up costing as high as $0.40/kWh. Hence the motivation for OPP to look into onsite renewable energy options to offset these costs. Another reason is that Penn State wants to show its commitment to renewable energy to the student community and the general public. A highly visible onsite power generation would help enhance its image as a "green" university. Although there are other renewable options such as wind and biomass, the scope of this project is to explore Penn State's solar PV potential as a part of the solution to the problems stated above.

This study first explores the roof top potential for solar PV installation of Penn State's buildings. Site survey for several buildings has been conducted using Bing maps and building blue prints. As per their solar PV potential and ease of project implementation, buildings have then been categorized into four Tiers with Tier I being the best category. Rec Hall and Intramural Building of Tier I category have been identified as the best possible candidates for immediate solar PV implementation. Solar PV potential for other buildings has been calculated for future implementation and the total solar PV potential for the University Park campus has been calculated.

As the design process is the same for all the buildings, we have selected the Intramural building to conduct a detailed PV system design and simulation. A solar PV system was designed for the Intramural building and its performance has been simulated using TRNSYS software. Critical parameters such as Power at maximum power point and capacity factor have been calculated for the designed PV system. Financial Analysis was then conducted to check the economic feasibility of the proposed solar PV systems. Environmental impact of the various proposed solar PV projects has also been studied. The results have been presented for OPP's perusal.

3. What Are RECs?

RECs represent the environmental and other non-power attributes of renewable electricity generation and are a component of all renewable electricity products. A REC is created when one (net) megawatt hour of electricity is generated from an eligible renewable energy resource. RECs are unbundled environmental commodity, and therefore may be sold separately, from the underlying electricity generated. RECs embody the positive environmental impacts created by renewable energy production and convey these benefits to the REC owner [1].

The RECs can be used by utilities to show their compliance to their respective alternate energy portfolio standard. The RECs are created to introduce more renewable electricity into the grid. One of its advantages is that it monetizes value of attributes separate from commodity electricity. So when a third party (other than a renewable energy generator and utility) purchases RECs they force more electricity into the grid as the utility has to purchase RECs elsewhere to meet its compliance standards. Another one of its advantages is that can be sold across geographic boundaries. This is beneficial for the renewable energy generator. RECS are not subject to transmission constraints and can be purchased by anyone across the country. RECs also allow consumers to support renewables, even if their suppliers don't provide green power options. They also enable small, distributed projects to benefit by selling RECs.

There is currently a debate as to what extent does the purchase of RECs actually transfer the emission reductions to the buyer. In fact one opinion is that generators that sell RECs are not transferring emission reductions, since they are unlikely to have ownership or the ability to quantify reductions using a commonly accepted standard [2].

4. Penn State's Energy Program

Understanding Penn State's energy consumption is the first step to designing any onsite energy systems that can offset the electricity demand. In this section we looked into the energy consumption figures and trends for Penn State – University Park. We have also looked into the categories of buildings and their energy consumption profile. This section of our literature review has been compiled using Office of the Physical Plant Data [3].

The University Park campus is the largest campus within The Pennsylvania State University system. The University Park campus covers over 15,000 acres of land in the Centre County region. Currently, the enrollment for this campus alone is 44,406 students. The University Park campus has a total of 657 major and minor facilities for academic, research, office, residential, multi-purpose, and other services.

4.1 Penn State's Energy Consumption Facts and Figures

Annual Energy Consumption at all Penn State locations for the 2008/2009 Fiscal Year is 414,000,000 KWH of Electricity, 560,000 MCF of Natural Gas and 74,000 Tons of Coal. However over 75% of electricity consumption is at the University Park campus. The University Park campus alone consumes 315,000,000 KWH of Electricity, 292,000 MCF of Natural Gas and 74,000 Tons of Coal. Our initial goal is to establish the percentage of this electricity demand that can be offset by on site solar PV.

Campus Energy Consumption from all locations is responsible for the following estimated annual quantities of greenhouse gases [3].Penn State emits 650,000 tons of Carbon Dioxide, 2,800 tons of Sulfur Oxides and 1,500 tons of Nitrogen Oxide. It is within the scope of this project to check what percentage of the Carbon Dioxide emission can be reduced by installing onsite PV systems at the University Park campus.

4.1.1 Penn State's Energy Consumption Trends
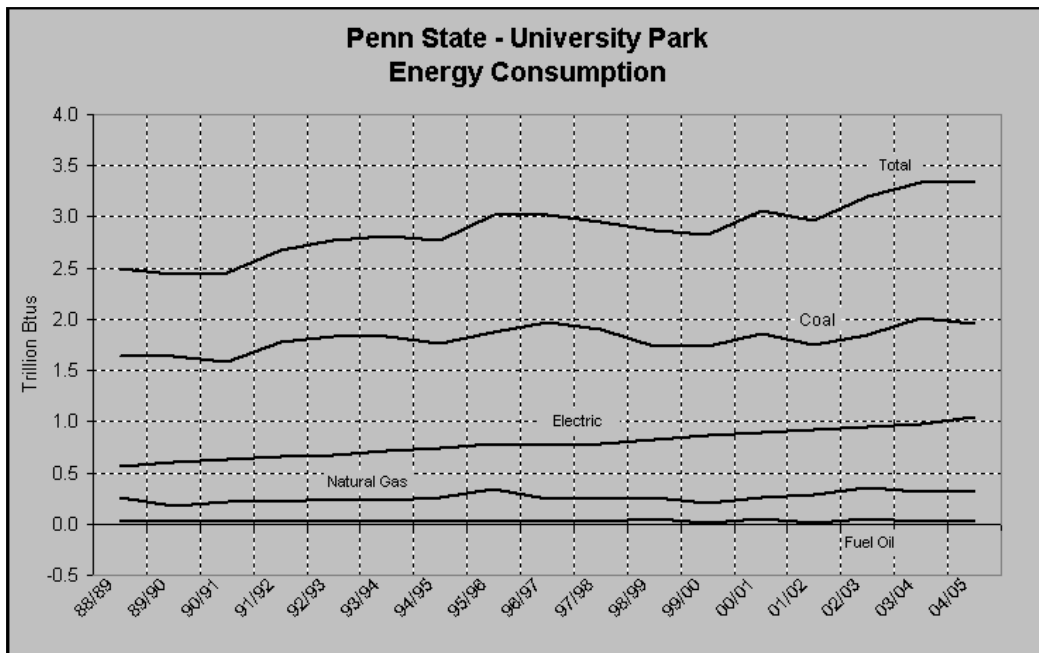
Fig 4.1 Annual trend charts illustrating the growth in energy consumption for the years 1988-89 through 2004-05(Onsite data)
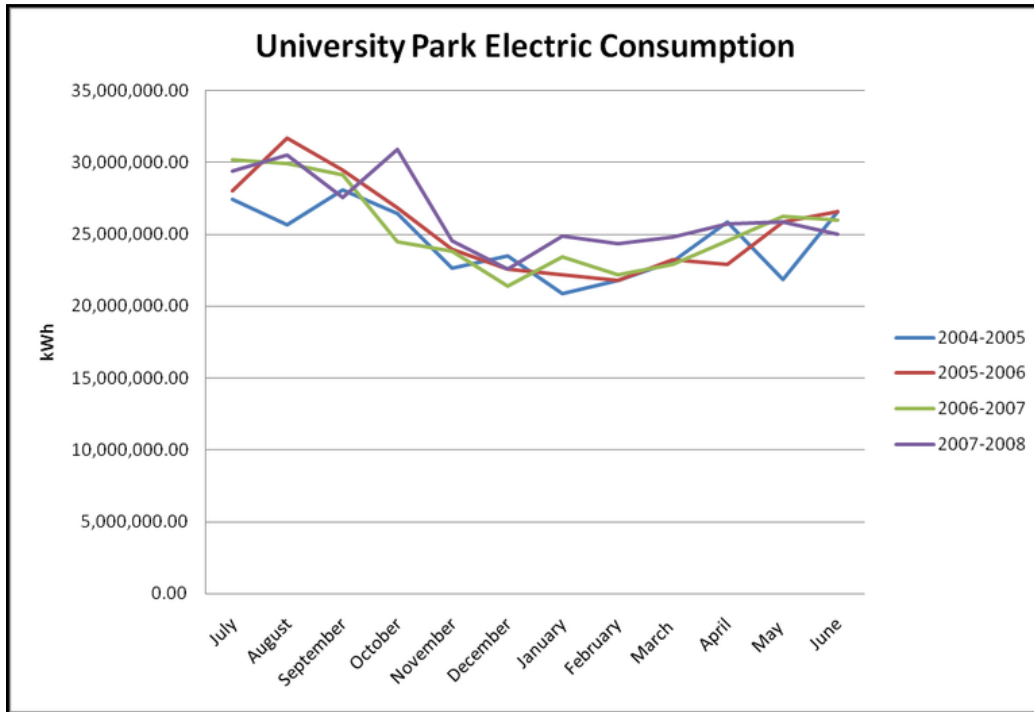
Fig 4.2 University Park Monthly Electricity Consumption Chart

It can be seen that from fig4.1 and fig 4.2 that there is clear growth in Penn State's energy consumption over the past 20 years. Over the recent years the rate of growth has however slowed due to many energy conservation measures put in place by the University.

4.1.2 Penn State's Top Ten Energy Consuming Buildings

Table 4.1 Buildings Ranked by Energy Consumption in MMBTU (million BTU) for FY 2004/2005

Penn State University Park		Buildings Ranked by MMBTU	
Office of Physical Plant			
Rank Place	Floor Area	MMBTU	MMBTU/SF
1 0050000 : CHEMISTRY BUILDING	190,951	176690	1.017
2 0003000 : PATTEE/PATERNO LIBRARY	486,916	80005	0.164
3 0911000 : WEST CAMPUS STEAM PLANT	31,000	74405	2.794
4 0943000 : WEST CAMPUS CHILLER BUILDING	23,550	62403	2.686
5 0045000 : BRYCE JORDAN CENTER	456,450	56190	0.123
6 0116000 : AG SCIENCE & INDUSTRY	163,762	52443	0.320
7 0910000 : EAST CAMPUS STEAM PLANT	6,078	49726	9.695
8 0275000 : POLLOCK HALL	103,178	48804	0.491
9 0038000 : LIFE SCIENCES BUILDING	159,780	47688	0.298
10 0005000 : HUB-ROBESON CULTURAL CENTER	246,991	46923	0.189

4.1.3 Energy Consumption Sorted by Building Type

Table 4.2 Energy consumption of buildings in each category has been averaged for the year FY 2004/2005

Building Type	Avg MMBTU/SF
Maintenance	102.5
Production	**5.627**
Classroom	0.43
Dining/Student Union	0.342
Multipurpose	0.194
Hotel/Conference	0.191
Athletic	0.181
Libary	0.181
Auditorium	0.165
Research	0.163
Health	0.146
Office	0.117
Museum	0.085
Miscellanous	0.065
Storage/Warehouse	0.058
Residence	0.033

Energy consumption profiles of various categories of buildings have been looked into in order to determine where the majority of the demand lies. It can be seen from fig 4.2 that classrooms have a relatively high consumption average compared to research buildings contrary to our previous assumption. Energy consumption profiles help us determine what fraction of the building's demand can PV systems installed on the respective roofs will power.

4.2 Penn State's Procurement of Renewable Power

Penn State has been purchasing renewable energy since 2001. In 2006, the university executed new contracts for a 5-year term, purchasing an annual supply for 20% of all the campuses' electrical energy consumption [4].

Contracts signed in 2006 include multiple sources of renewable energy with all sources certified by Green-e Standard for Renewable Energy Products. Penn State's Renewable Energy Portfolio currently consists of the following:

- Pennsylvania Based Wind Energy - 17,600 MWH
- National Based Wind Energy - 16,500 MWH
- National Based Biomass - 16,500 MWH
- National Based LIHI Hydro - 33,000 MWH
- Total Purchase - 83,600 MWH

Table 4.3 Current Green Power providers to Penn State

Renewable Energy Type	Provider
Wind Energy	Community Energy Inc.
Wind and Biomass Energy	3 Phases Energy Services
LIHI Hydro Energy	Sterling Planet, Inc.

Penn State as of Jan 5 2010 is the 3rd largest purchaser of Green Power among the Universities. The top two purchasers are University of Pennsylvania and Carnegie Mellon University.

Currently Penn State has only two onsite renewable energy systems producing electricity. One of them is a Solar PV system with capacity 2kW and the second one being a Wind system of capacity 1.7kW [5].

Table 4.4 Summary of Renewable Energy Systems installed on campus [5]

Technology	Collector, Module, Unit Efficiency	System Efficiency	Annual Production	Cost	System Cost Per KWH*
SHW: 64 sq. ft. of collectors + 80 gal. water heater	50%–70%	35%–50%	3,100 kWh	$8,000	$0.09
Grid-tied PV: 2 KW	5%–19%	4%–13%	2,500 kWh	$20,000	$0.27
Grid-tied Wind: 1.7 KW	20%–45%	18%–40%	5,000 kWh	$15,000	$0.10
*Over 30 yrs; maintenance costs not included					

4.3 Pennsylvania Alternate Energy Portfolio Standards

The AEPS law requires EDCs (electric distribution companies) and EGSs (electric generation suppliers) to supply 18.5 percent of electricity using alternative energy resources by 2021. The percentage of Tier I, Tier II and photovoltaic resources that must be included in sales to retail customers gradually increases over this period. By Jan. 1, 2008, the renewable resource requirement is estimated to be 1,215,822 MWHs, representing approximately 0.75 percent of the Commonwealth's annual energy demand. By Jan. 1, 2021, AEPS will provide an estimated 36,639,425 MWHs, or 18.5 percent of Pennsylvania's annual electric requirements [6].

Table 4.5 Overview of AEPS Percentage Sales Requirements

Year*	Tier I	Tier II	Solar PV
Year 01- 2007	1.50%	4.20%	0.0013%
Year 02- 2008	1.50%	4.20%	0.0030%
Year 03- 2009	2.00%	4.20%	0.0063%
Year 04- 2010	2.50%	4.20%	0.0120%
Year 05- 2011	3.00%	6.20%	0.0203%
Year 06- 2012	3.50%	6.20%	0.0325%
Year 07- 2013	4.00%	6.20%	0.0510%
Year 08- 2014	4.50%	6.20%	0.0840%
Year 09- 2015	5.00%	6.20%	0.1440%
Year 10- 2016	5.50%	8.20%	0.2500%
Year 11- 2017	6.00%	8.20%	0.2933%
Year 12- 2018	6.50%	8.20%	0.3400%
Year 13- 2019	7.00%	8.20%	0.3900%
Year 14- 2020	7.50%	8.20%	0.4433%
Year 15- 2021	8.00%	10.00%	0.5000%

❖ Tier I- sources include solar photovoltaic and solar thermal energy, wind power, low-impact hydropower, geothermal energy, biologically derived methane gas, fuel cells, biomass energy, and coal mine methane
❖ Tier II- sources include waste coal, distributed generation systems, demand-side management, large-scale hydropower, municipal solid waste, generation of electricity utilizing by-products of the pulping process and wood manufacturing process including bark, wood chips, sawdust and lignin in spent pulping liquors; and integrated combined coal gasification technology

It can be seen from the table that by the year 2021 an ambitious 0.5% of the total electricity produced must be from Solar PV. In 2007 the solar PV in Pennsylvania produced a total of 756 MWh [6]. By 2021 Solar PV's contribution needs to be 1,017,282MWh which means that the installed capacity has to increase by 1350 times.

4.3.1 Feasibility study for Penn State's Voluntary compliance of Solar PV standards

The Pennsylvania State University is not an EDC or an EGS. Hence it does not have to comply with Alternate Energy Portfolio Standards set forth by the state. However the goal of this project is to investigate Penn State's potential to voluntarily meet the solar PV standards by 2021.

■ Type	Photovoltaic	Solar Thermal	Fuel Cells	Wind	Conventional Hydropower	Geothermal	Municipal Solid Waste - Landfill Gas	Biomass
	41.24	27.63	17.80	7.46	6.91	6.23	5.56	5.30
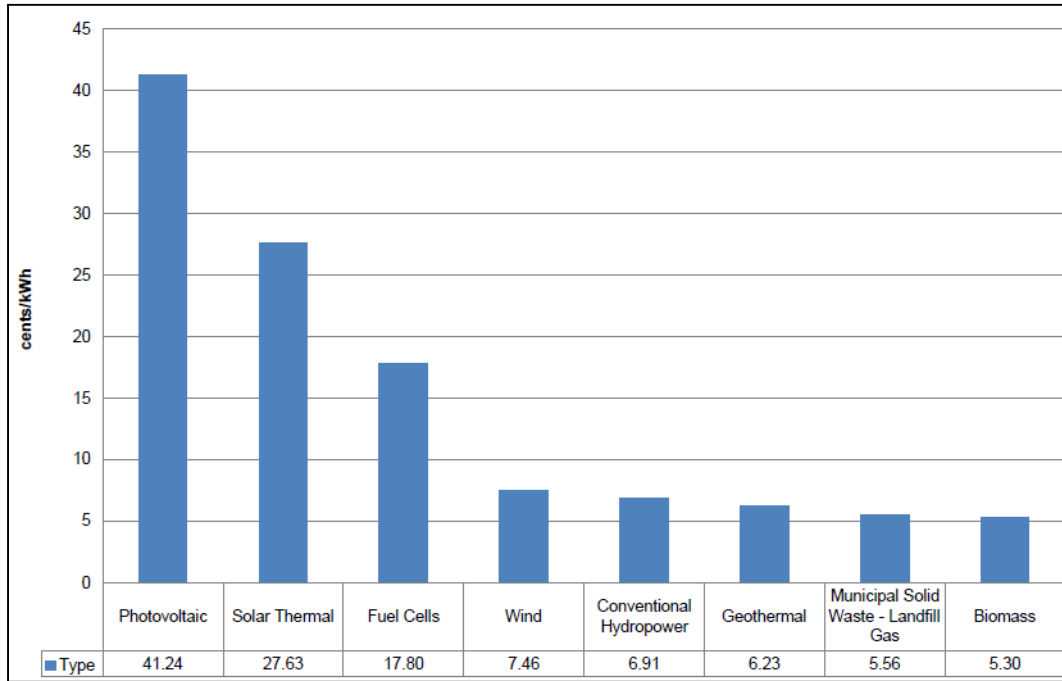
Figure 4.3 Estimated 2007 Installed Plant Costs for Renewable Resources in PA (cents/kWh) [23]

In order for Penn State to meet these standards voluntarily, an estimated solar PV capacity of 2.06 MW needs to be installed by 2021, which can provide upto 1575000 kWh annually which is 0.5% of Penn State's current consumption. This would entail an annual cost of $630000 as per the costs shown in the figure 4.3. This does not include the installation costs.

As mentioned earlier the aim of the project is to check the technical and economical feasibility of implementing solar PV on University Park campus should Penn State make a voluntary commitment to meet these standards in the future for their onsite generation of power.

5. Solar Resource Assessment

Solar Resource information is used to estimate the amount of solar electricity that can be generated in a given area. Solar Resource Assessment is a critical step in the design and simulation of Photovoltaic systems and their interaction with the electric grid. Both historical and forecasted solar resource data are available for power system planning and operations. However further refining of techniques is required in order to forecast solar resources in the hourly or sub hourly intervals at least one to three days in advance to support real-time power system operations. With high penetration of variable renewable energy, long-term solar resource assessment data are required to support generation resource planning [7].

The Solar Resource Information can be obtained in different forms using various resources. A few of them are

- NREL Solar Maps
- SMARTS (The Simple Model of the Atmospheric Radiative Transfer of Sunshine)
- SURFRAD Data (SURFace RADiation Budget Measurement Network): to be used for Penn State.
- TMY(Typical Meteorological Year) data:
- Solar Radiation Models

5.1 NREL data - Solar Maps

Solar maps provide monthly and annual average daily total solar resource information on grid cells. They indicate the amount of insolation available to the photovoltaic panel that is oriented south and at an angle equal to the latitude of the panel location.

Light from the sun has two components, the direct and the diffuse (light that is reflected of clouds, dust particles and other objects). The sum of these two components is the total radiation that is incident on a solar collector. The solar maps presented here give us an annual estimate of the total radiation and direct radiation available. The availability of direct radiation determines the feasibility of concentrated solar systems as they utilize only the direct component of light.

5.1.1 Photovoltaic Solar Resource in US(Total Radiation)
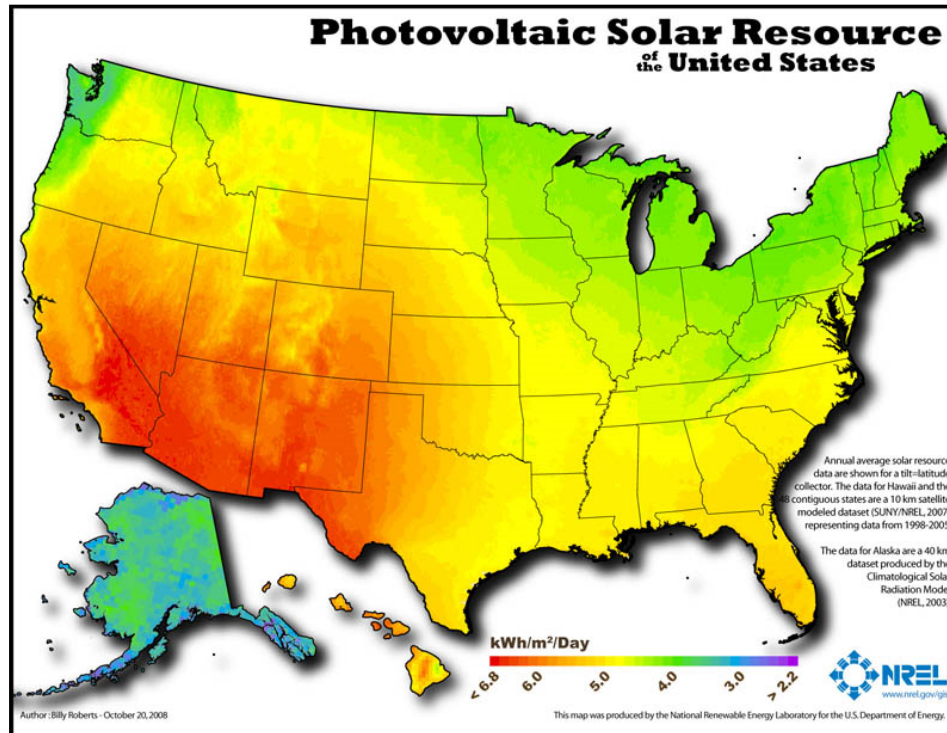
Fig 5.1 Annual Average Photovoltaic Solar Resource of the United States

It can be seen that Pennsylvania receives an annual average of 4-4.5 kWh/m^2/day [8]. There is general perception that the solar resource in Pennsylvania is insufficient. In order to dispel that myth let us consider the solar resource for Germany, the world leader in PV market. It is around 2.6 – 3.6 kWh/m^2/day [9]. Freiburg, world's first solar city, receives around 3 kWh/m^2/day and has an installed capacity of 3,200 kW (3.2 MW) in December 2003[10].Clearly Pennsylvania receives more global irradiation than Germany thereby dispelling the myth that solar resource for PV systems is not sufficient in Pennsylvania.

5.1.2 Concentrated Solar Resource in US (Direct Normal Radiation):

Fig 5.2 Annual Average concentrated Solar Resource of the United States

5.1.3 Concentrated Solar Resource in Pennsylvania:

Fig 5.3 Annual Average concentrated Solar Resource of the Pennsylvania

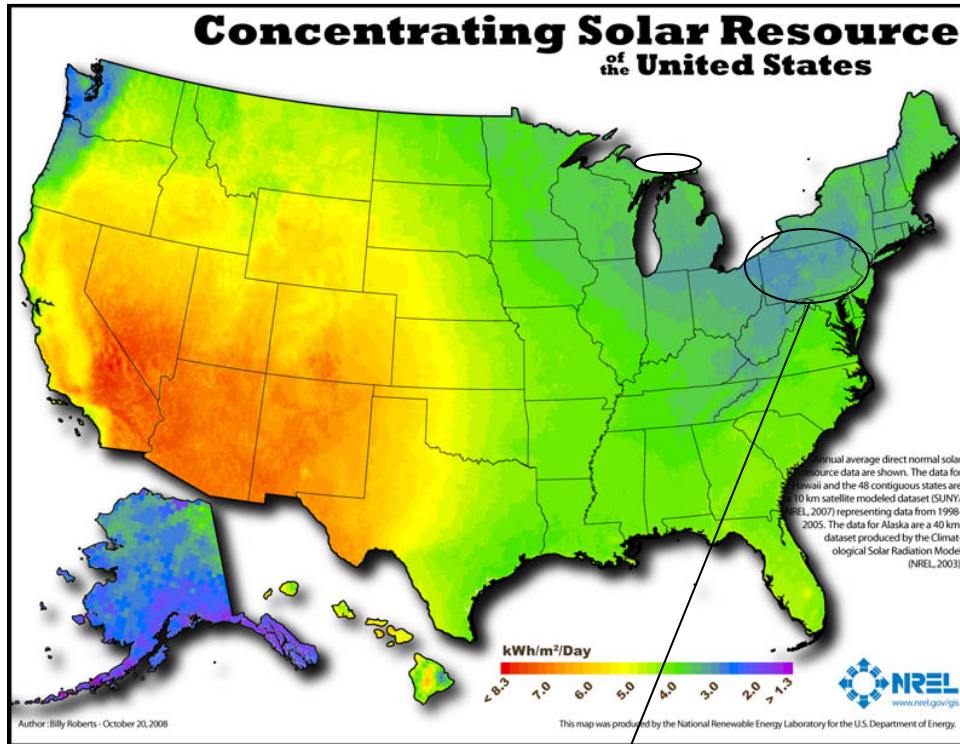It can be seen that Pennsylvania has relatively poor concentrated solar resource as compared to other states in the US. Pennsylvania receives between 3.2 - 3.5 kWh/m^2/day as compared to 5 – 8.3 kWh/m^2/day that the south western part of US receives [10]. Northern States like Minnesota, North Dakota and Montana receive an annual average between 4-5 kWh/m^2/day which is more than what Pennsylvania receives.

5.2 SMARTS

The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) was developed by Dr. Christian Gueymard for NREL. SMARTS can be used to predict clear-sky spectral irradiances. SMARTS computes how changes in the atmosphere affect the distribution of solar power or photon energy for each wavelength of light.

It computes clear sky spectral irradiances including direct beam, circumsolar, hemispherical diffuse, and total on a tilted or horizontal receiver plane for specified atmospheric conditions. The main applications of SMARTS are the testing the performance of spectroradiometers, development reference spectra, establishment of uniform testing conditions for materials research, optimization of daylighting techniques and verification of broadband radiation models. Researchers also use SMARTS in the fields of architecture, atmospheric science, photobiology, and health physics. SMARTS 2.9.2 is the basis for American Society of Testing and Materials (ASTM) reference spectra (ASTM G-173 and ASTM G-177) used for photovoltaic performance testing and materials degradation studies [11].

However for PV system design and simulation we do not need the spectral irradiances but rather the global irradiance which is nothing but the integral of the individual spectral irradiances. Hence the SMARTS tool will not be employed for our PV System Design.

5.3 SURFRAD Solar Radiation Network:

Hourly solar radiation data can be obtained from several solar radiation networks across the United States. Some of these networks are regional in scope, while others provide data on a national level.

Table 5.1 Solar Radiation Networks in United States [12]

Solar radiation network	Station coverage	Global	Direct
AZMET	Arizona	×	
CONFRRM	National	×	×
ISIS	National	×	×
HPRCC-AWDN	High Plains	×	
PAAWS	Indiana	×	
SCAN	National	×	
SURFRAD	National	×	×
TSRD	Texas	×	×
UO_SRML	Northwest US	×	×

These networks have a combined 53 measuring stations all over the United States [12]. Our literature survey revealed that the SURFRAD network has a station in Pennsylvania State University. The Penn State University SURFRAD station is located on the grounds of PSU's agricultural research farm. It is in a broad Appalachian valley between Tussey and Bald Eagle Ridges, and is hosted by the Meteorology Department.

Show below are a few details of the station

Latitude: 40.72 degrees North

Longitude: 77.93 degrees West

Elevation: 376 meters

Time Zone: Local Time + 5 hours = UTC

Installed: June 1998

The SURFRAD Station records hourly solar radiation data that can be used for PV system design and Simulation. Applications of this data also include the usage as an input to the real-time simulation model that needs to be developed after the actual installation of the PV system. Disparities between the physical system and the model can be identified and thereby leading to eventual improvement of the simulation model.

5.4 TMY (Typical Meteorological Year) data

A typical meteorological year (TMY) data set provides designers and other users with a reasonably sized annual data set that holds hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years. TMY data sets are widely used by building designers and others for modeling renewable energy conversion systems [13].

TMY data can simply be defined as an average of meteorological data collected over a number of years for a particular location. .However, a simple average of the yearly data underestimates the amount of variability, so the month that is most representative of the location is selected. For each month, the average radiation over the whole measurement period is determined, together with the average radiation in each month during the measurement period. The data for the month that has the average radiation most closely equal to the monthly average over the whole measurement period is then chosen as the TMY data for that month. The months are added together to give a full year of hourly samples.

TMY: Derived from the 1952-1975 SOLMET/ERSATZ data base

TMY2: Derived from the 1961-1990 National Solar Radiation Data Base (NSRDB).TMY2 Data is available for 239 US locations.

TMY3: Derived from the 1961-1990 and 1991-2005 National Solar Radiation Data Base (NSRDB) archives. TMY3 data is available for 1020 US locations.

The intended use for TMY data is computer simulations of solar energy conversion systems and building systems. The TMY data represents typical and not extreme conditions and hence are not suited for designing systems to meet the worst-case conditions occurring at a location [13]

6. PV Literature review

6.1 What are solar cells?

A solar cell represents the fundamental power conversion unit of a photovoltaic system. It is a simple and elegant device that converts light directly into electrical energy. Solar cells are made from semiconductors such as silicon, and have much in common with other solid-state electronic devices, such as diodes, transistors and integrated circuits. The electrical output of a single solar cell is usually small, on the order of 1W or less; Hence, cells are connected together to form modules in order to generate greater power output.

The range of solar cells spans different materials and structures in the quest to extract maximum power from the device while keeping the cost to a minimum. Devices with efficiency exceeding 30%-40% have been demonstrated in the laboratory [14, 15]. The efficiency of commercial devices, however, is usually less than half this value.

6.1.1 First Generation Photovoltaic

First generation photovoltaic cells are the dominant technology in the commercial production of solar cells, accounting for more than 86% of the solar cell market. First generation PV cells are classic *p-n junctions,* which are based on the elemental semiconductor silicon, either single crystalline or multi-crystalline. The efficiency of silicon solar cells lie in the range of 20-25% [16,17,18]. Cell and module-fabrication technology is well established and reliable with a life time of around 25-30 years. Furthermore, it has broad spectral absorption range and high carrier mobility. However, much of the energy of higher energy photons, at the blue and violet end of the spectrum, is not absorbed and becomes waste heat. In addition, a substantial amount of silicon is needed to produce a functional cell, leading to an increase in cost.

6.1.2 Second Generation Photovoltaic

The move towards the use of thin-films solar cells is driven by the need to reduce module costs. The cells must therefore be capable of being manufactured in large volumes at low cost. These cells are formed by depositing thin films of photon-absorbers on layered stacks of a substrate such as glass.

Four types of thin-film cells have emerged to be of commercial importance. These are the amorphous silicon cell, thin multi-crystalline silicon films on a low-cost substrate, the copper indium diselenide/cadmium sulphide heterojunction cell (or variants of it), and the cadmium telluride heterojunction cell. Also, there are some studies about organic solar cells at The Pennsylvania State University but they are not in commercial production yet [19].

6.1.2.1 Amorphous silicon cells

Amorphous silicon panels are a thin-film technology. They contain less silicon than crystalline panels, which can lower costs. Another advantage of reducing the silicon used in a solar panel is that it takes less time for the panel's output to match the energy used in its construction – its energy payback time [20].

Amorphous silicon is a direct-gap material with an optical energy gap of about 1.75 eV. The

efficiency is around 10% [21]. Good results can be achieved in the laboratory on small-area cells, but achieving similar results reliably and repeatedly in commercial production on large-area modules is a major challenge. Although these cells are inexpensive, they don't use considerable part of solar spectrum because of band gap.

6.1.2.2 Thin polycrystalline silicon

There is good theoretical justification for using thin base layers in silicon solar cells because the dark saturation current decreases with decreasing base-layer thickness, leading to higher open-circuit voltage values for thin cells. There are other benefits to such thin cells. The diffusion length needs to be only 50-80 μm, so lower quality material can be used, and higher doping levels can be tolerated giving higher open-circuit voltage [22]. This is therefore a very promising route for the production of efficient cells at low cost. Efficiencies up to 16% have been observed in small-area cells [23]. The challenges of these cells are problems that occur during the chemical process their production.

6.1.2.3 Cadmium Telluride (CdTe)

CdTe cells are manufactured by depositing the absorbing layer of CdTe on a glass substrate with a transparent conductive oxide (TCO) layer as the front contact. The commercial efficiency of these modules is around 8.5-10% [23].

CdTe technology has the lowest production costs among the current thin-film modules and mass production may help to further decrease the cost [24]. However, an important issue of debate is the use of cadmium, which is a heavy metal. Research has shown that processing cadmium into CdTe modules is not harmful.

6.1.2.4 Copper Indium Gallium Selenide (CIGS)

The active semiconductor material used is copper indium gallium diselenide. These cells are fabricated by initially coating a thin molybdenum layer on a glass substrate, and then sputtering the individual elements as individual layers at room temperature, and then combine them to form CIGS by briefly heating to 500°C [24]. The commercial efficiency is between 9 to 11% [23].

These cells are currently the most efficient of all thin-film technologies and lower costs in production can be expected with expansion in mass manufacturing

6.1.3 Concentrating Photovoltaic System (CPV)

Concentrating photovoltaic (CPV) systems use lenses or mirrors to focus and magnify sunlight onto high-efficiency solar cells. These mirrors or lenses are located between the sun and the solar cells. These solar cells are typically more expensive than conventional cells but CPV reduces the area of solar cell while increasing its efficiency. Also, CPV provides some advantages such as no moving parts and intervening heat transfer surface.

CPV technology however is only suitable for locations with high Direct Normal Irradiation (DNI). A recommendation for High Concentrated Photovoltaic (HCPV) is an annual average

daily DNI of about 6 kWh/m^2/day. 5 kWh/m^2/day is recommended for Low Concentrated Photovoltaics (LCPV) [25]. However, Pennsylvania has a DNI of 3.2 - 3.5 kWh/m^2/day making it a poor location for the implementation of CPV.

6.2 Factors affecting PV choice

We have decided to use cadmium telluride (CdTe) modules for this project. There are number of factors that affected our decision to select cadmium telluride PV. The three major factors that guided our decision are the module cost, the performance, and the quality of the brand. These factors may have varying impacts depending on the applications and the location of installation.

6.2.1 Cost

Cost is a major factor to consider when designing a PV system, and in many cases it is the most important factor. The capital investment cost of implementing PV can be very high, and utmost consideration must be given in order to reduce cost and get the best value for the money spent. There are no standard costs for PV modules as the prices vary based on the technology used and the reputation of the module brand. First generation (silicon) modules, though dominant in the market, are generally more expensive thin film modules [26]. In addition to this, mark ups instituted by various retailers are usually different. As stated earlier, CdTe modules have the lowest production costs, making it the lead choice for this consideration.

6.2.2 Performance/Efficiency

The efficiency of solar cells varies with the technology type. Amongst all the cells being mass produced, silicon cells have the highest efficiency [23]. However, efficiency of a module is not necessarily a show stopper. Although, thin-film modules may have lower efficiencies, they may still be ideal candidates for certain locations and applications. For instance, research shows that thin-film modules are well suited for locations that receive substantial amount of diffuse sunlight. According to our weather resource assessment, State College is an example of an area with considerable diffuse sunlight.

Another important consideration is the temperature coefficients given by the manufacturers. Once the PV temperature increases past a certain point, the module's performance would deteriorate by a certain percentage [27]. This figure is described and given as the temperature coefficient. In locations with very high temperature, it may be better to choose a module that has a low temperature coefficient.

6.2.3 Brand Quality

Brand quality is also another important factor that affects the selection of appropriate PV modules. Modules differ by technical attributes and certifications, and in order to make the right decision, these facts must be considered [28].

The lifetime and guarantee of most solar panels are in the 15-20 years range. There is a possibility of a manufacturer collapsing in this time period, and if this happens the product may not be replaced in case of failure. While it is impossible to accurately predict the companies that would collapse in the future, we can make smarter decisions by observing the economic health of

the manufacturing company and the reputation of their products. For instance, First Solar, a manufacturer of CdTe modules, is an industry leader and a very reputable company [29]. We will generally feel safer recommending their modules than a smaller start-up company with no track record.

	Silicon PV	Thin Film	Conventional Concentration
Low silicon consumption	☒	☑	☑
Low cost	☒	☑	☑
High efficiency	☑	☒	☑
Low maintenance	☑	☑	☒
All climates	☑	☑	☒

Table 6.1 Comparison of Silicon PV, Thin-film PV, and CPV

7. Site Survey

Site Survey is the first and a critical step in PV system design. Improper site survey, for instance improper shading analysis, can lead to the PV system working much below its rated power there by lowering its capacity factor. Traditional method of a site survey is an onsite physical analysis [30]. However it is impractical to conduct an onsite physical survey for all the buildings on the University Park campus. We have thus indentified two alternate methods. First method is a two stage process in which the first stage is the visual inspection of the rooftops using aerial images. In this stage buildings with negligible usable area are eliminated. In stage two shading analysis is done for all the selected buildings utilizing their blue prints and usable area determined. The second method is Aerial Imaging. In this method an image processing software automatically determines the usable area. Since this is an automated process it can be done for many buildings in a short period of time and suitable for a site survey of University Park campus. The Aerial Imaging technique is upto 97.8% accurate with the reference being the onsite physical analysis [30]. Shown below are the pictures and results of a case study conducted for a school building in California using the Aerial Imaging technique [30].

Figure 7.1 Processed Aerial Images for perimeter detection

Table 7.1 Comparison of Aerial Imaging and physical site Inspection

Parameters	Aerial Imaging	Physical Site Inspection	Accuracy
Usable Roof Area (Ft)	78,257.0	80,100.0	97.8 %
Power Capacity KW CEC	377.5	380.6	99.2 %

8. Dynamic Simulation of PV systems

Dynamic Simulation is done to predict the performance of the designed PV systems. It allows us to check the load meeting capabilities of the PV systems in case of standalone systems and check the fraction of demand offset in case of grid-connected systems. Essential parameters such as capacity factor, total output, and hourly variation of insolation can be calculated for the entire year by the PV designers. These parameters play a vital role in the feasibility analysis of the PV project.

Various simulation tools are currently available to perform PV simulation. Some of them are TRNSYS [31], RETScreen [32], PVSYST [33], PVSIM [34], PVFORM [35], PV f-Chart [36], ENERGY-10 PV [37], PVNet [38], PVSS [39], SOLCEL-II [40], Renew [41] and SimPhoSys [42].

We have selected TRNSYS for our purposes due its availability, ease of use and built in weather data. Developed correctly, TRNSYS models have proven to be in good agreement with measured data [43]. Given below are the results of a TRNSYS simulation study that was performed for a 13kW grid connected PV system in the Northern Ireland (latitude $54^o52'$N and longitude $6^o17'$W). The predicted output of the TRNSYS model was compared to the performance data measured from April 2001 to December 2003[43].
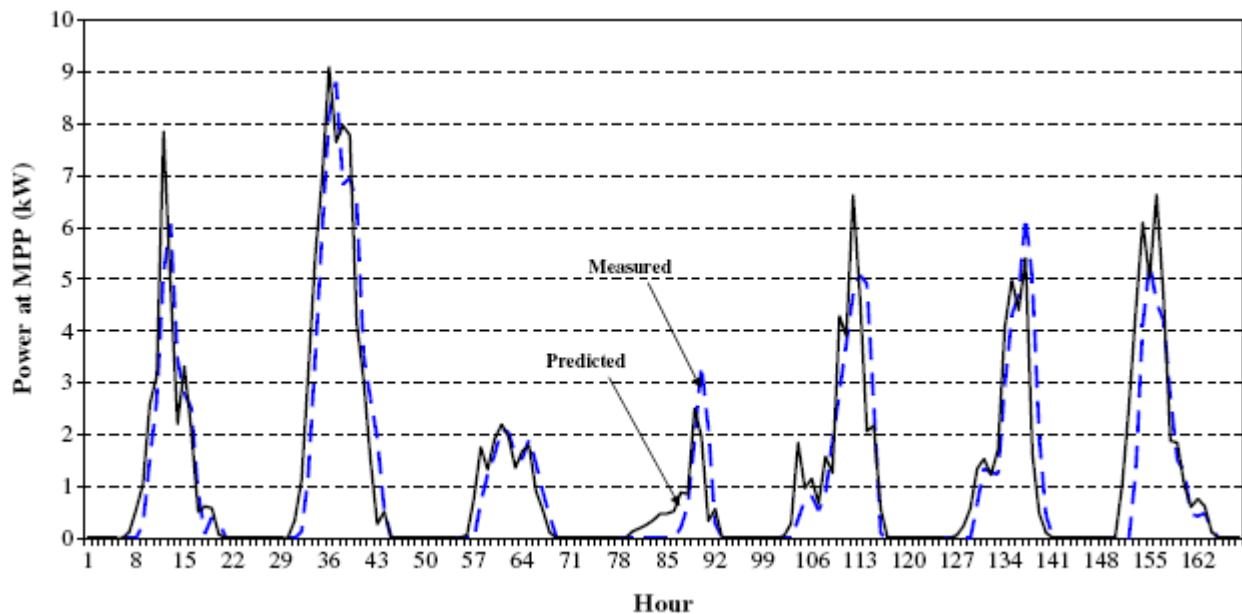

Figure 8.1 Comparison between predicted and measured MPP power for 7 days.

9. Utility Interconnection

The use of Interactive distributed generation of electrical power is a very useful supplement to traditional central power generation. Grid connected PV systems are becoming a popular choice for distributed generation[27]; in fact a majority of the newly installed systems over the last decade have been grid connected as shown in figure 9.1.

Connecting a PV system to the grid allows for two way interaction between the utility and the PV system. Customers benefit from obtaining power to on-site loads and some backup power in case of utility outage. For utilities, they can increase their capacity to serve customers without building new power plants.

The electric utility system consists of hundreds or thousands of interconnected generators operating in parallel. These generators must be synchronized with each other to prevent damaging themselves. Synchronizing is the process of connecting a generator, in this case a PV system, to an energized electrical system. This is an extremely critical process and it involves precisely matching the phase sequence, frequency, voltage, and phase balance of the PV system to the rest of the electrical system [27].

Therefore, before installing a grid connected PV system, careful considerations must be made with regards to the technical, procedural, and contractual requirements needed in making interconnections with the grid utility. These considerations ensure the safety and reliability of the connections. In addition, they also ensure that the connections do not adversely impact the rest of the electricity distribution system. These requirements and issues are discussed in this section.

9.1 Issues with Grid connection

Electricity utilities are responsible for the safety and quality of supply to their customers. The major DC and grid connected issues are listed below

9.1.1 Power Quality

One of the most important technical issues of the grid connection of generation plants is the Power Quality. For any grid-connected system, power factor and harmonic consideration are important [44]. The power quality is influenced by the performance of the electrical generation and distribution equipment, as well as electrical loads operating on the system.

Overvoltage is an important issue affecting power quality [45]. When installed PV systems feed power to the utility grid, the electricity current flow reverses direction and this leads to an increase in voltage. As a result of this increase in voltage, a condition known as overvoltage may occur. Overvoltage can cause serious problems for utilities and consumers since electrical loads

are designed to operate at particular voltage conditions to prevent damage to electrical loads and utility system equipment.

This issue can be corrected by using power conditioners designed to limit voltage rise, however, the implication is that PV power output may be dumped so as to limit or control the voltage [45]. This may affect the return on investments for the installed system since owners can receive no credit or payment for power that is dumped instead of fed back into the grid.

9.1.2.2 Islanding

Islanding is an undesirable condition where an interactive inverter continues to transfer power to the utility grid during a utility outage [46]. When the utility grid experiences an outage, transferring power to it can be detrimental because it is a serious safety hazard (electric shock) for utility workers trying to restore power after an outage.

Although Islanding can be a serious issue, it can only possibly happen when the following three conditions occur simultaneously [45].

1. Power supply from the grid is interrupted
2. Power generated from PV systems accidentally matches load
3. Islanding protection functions in the inverter fail to detect the islanding conditions

For this project, it is essential to use non-islanding interactive inverters. The inverter detects power outages and discontinues power transfer when it does so. This is very important in order to limit or prevent damage or electric shock. Islanding can also damage utility equipment by interfering with the utility's normal procedures for restoring service following an outage because the islanded system is no longer in phase with the utility system. We must use non-islanding interactive inverters.

9.1.3 Disconnection time of Intersystem fault

High voltage winding and low voltage winding are insulated from each other in a transformer box. An intersystem fault occurs when an abnormal voltage flows into the transformer and the insulation breaks down [45]. When this occurs, the power plants must stop operation and disconnect from the grid. The problem, however, is that PV systems cannot detect this fault until the islanding effect occurs. Electronic devices cannot withstand the increase in voltage which may lead to an increase in the chances of electric shock or fire.

The remedy to this is using inverters that are designed to react faster in detecting the islanding effect in order to minimize risk.

9.2 Interconnection Policies

This section covers the regulations and policies that must be met before a PV system can be successfully commissioned and fully operational.

9.2.1 Pennsylvania's Net Metering Policy

In Pennsylvania, investor-owned utilities must offer net metering to residential customers that generate electricity with systems up to 50 kilowatts (kW) in capacity; nonresidential customers with systems up to three megawatts (MW) in capacity [47]; and customers with systems greater than 3 MW but no more than 5 MW who make their systems available to the grid during emergencies, or where a micro grid is in place in order to maintain critical infrastructure. Net metering is available when *any portion* of the electricity generated is used to offset on-site consumption (i.e., system size is not limited by the customer's on-site load).

Net metering is achieved using a single, bi-directional meter that can measure and record the flow of electricity in both directions at the same rate. Net excess generation (NEG) is carried forward and credited to the customer's next bill at the full retail rate. Customer-generators are compensated for remaining NEG at the utility's "price-to-compare" at the end of the year. The price-to-compare includes the generation and transmission components -- but not the distribution component -- of a utility's retail rate. In order to reconcile net metering with Pennsylvania's broader renewable energy goals, the "year" referenced above is defined to coincide with the compliance year (June 1 - May 31) used for Pennsylvania's Alternative Energy Portfolio Standard (AEPS)[47].

9.2.2 Public Utilities Regulatory Policy Act (PURPA)

PURPA was passed by the U.S congress in 1978 to help decrease U.S dependence on foreign oil [27]. The legislation requires electric utilities to purchase power from independent power producers, and also establish the technical requirements for their interconnection to the utility system.

9.2.2.1 Qualifying Facility

A qualifying facility, as defined by PURPA, is a non-utility large-scale power producer that meets the technical and procedural requirements for interconnection to the utility system. The legislation mandates that utilities purchase power from these facilities at its avoided cost, which is the cost the utility avoids by not generating the power itself.

9.2.2.2 Interconnection Agreements and Fees

Qualifying-facility agreement is a contract between a qualifying-facility and a utility that establishes the terms for interconnection and the rates that apply. These agreements will include the commitments regarding prices and expected levels of power generation.

Interconnection agreement is a contractual agreement between a qualifying facility and an electric utility that establishes the terms and conditions for the interconnection that include size restrictions, liability insurance, and system maintenance.

Interconnection application fees are imposed in order to offset the additional costs of inspecting, monitoring, billing and completing paperwork for interconnecting systems [47]. The agreement may also include a schedule of fees for other services and equipment needed to interface the utility with the PV system.

9.2.3 IEEE 1547, Standards for Interconnecting Distributed Resources with Electric Power Systems

The interconnection of distributed generation to the electric utility grid is governed by IEEE 1547, *Standard for Interconnecting Distributed Resources with Electric Power Systems*. This standard of the Institute of Electrical and Electronics Engineers (IEEE) establishes uniform criteria for safety, operation, performance, testing and maintenance of interconnected distributed generation systems.

IEEE 1547 Requirements

IEEE 1547 outlines numerous technical requirements for safely and reliably connecting distributed generation to the electric utility grid [48]. These technical requirements include:

- Voltage regulation
- Power monitoring
- Grounding
- Synchronization
- Connection to network distribution systems
- Back-feeds
- Disconnecting means
- Coordinated equipment ratings
- Abnormal operating conditions
- Power quality
- Islanding

10 Environmental Impact

10.1 Chemicals used in the Production of Photovoltaic Cells

The production of photovoltaic devices involves the use of a variety of chemical and materials. The amounts and types of chemicals used will vary depending on the type of cell being produced.

Table10.1.1 Chemicals and Materials Used in the Manufacturing Process of Various Photovoltaic Cells [49]

Crystalline Silicon Cells*	Polycrystalline Silicon Cells**	Amorphous Silicon	Cu$_2$S/CdS Cells**	CdTe/CdS	CIS Cells	CIGS Cells	GaAs Cells
Aluminum	Aluminum	Acetone	Ammonium chloride	Cadmium chloride	Cadmium	Cadmium	Arsenic
Ammonia	Ammonia	Aluminum	Ammonium fluoroborate	Cadmium	Copper	Copper	Arsine
Ammonium fluoride	Arsine	Chloro-silanes	Cadmium sulfide	Molybdenum	Hydride gas	Gallium	Gallium
Hydrochloric acid	Boron trichloride	Diborane	Chromate coating	Nickel	Hydrogen sulfide	Indium	Hydrochloric acid
Hydrofluoric acid	Copper catalyst	Germanium (used in some)	Copper	Sulfur	Hydrogen selenide	Molybdenum	Methane
Hydrogen fluoride	Diborane	Germanium tetrafluoride (used in some)	Cuprous chloride	Tellurium	Indium	Selenium	Phosphine
Isopropyl alcohol	Ethyl acetate	Hydrochloric acid	Gold	Thiourea	Molybdenum	Zinc	Trichloroethylene
Nitric acid	Ethyl vinyl acetate	Hydrofluoric acid	Hydrochloric acid	Tin	Selenium		Triethyl gallium
Nitrogen	Hydrochloric acid	Hydrogen	Hydrogen sulfide		Zinc		Trimethyl gallium
Oxygen	Hydrogen	Isopropanol	Methanol				
Phosphorus	Hydrogen fluoride	Nitrogen	Nickel				
Phosphorus oxychloride	Hydrogen peroxide	Phosphine	Nitrogen				
Silane	Ion amine catalyst	Phosphoric acid	Polyvinyl butyrol				
Silicon	Isopropyl alcohol	Silane	Silicon monoxide				
Silver	Nitric acid	Silicon tetrafluoride	Sodium chloride				
Sodium hydroxide	Nitrogen	Silicon	Tantalum pentoxide				
Sulfuric acid	Phosphine	Sodium hydroxide	Zinc				
Tin	Phosphorus trichloride	Tin	Zinc fluoroborate				
	Silicon						
	Silicon dioxide						
	Silane						
	Silicon trioxide						
	Silicon tetrachloride						
	Silver						
	Sodium hydroxide						
	Stannic chloride						
	Sulfuric acid						
	Tantalum pentoxide						
	Titanium						
	Titanium dioxide						
	Trichlorosilane						

During the manufacturing process, a variety of acids and corrosive are used fairly large quantities. These are hydrochloric acid, sulfuric acid, nitric acid, and hydrogen fluoride. These chemicals used for cleaning of wafers or to remove impurities from raw semiconductor materials. Etching compounds such as sodium hydroxide and cleaning compounds such as trichloroethane and acetone also used in relatively large quantities [49].

Hazards in PV manufacture differ for different thin-film technologies and deposition processes. The main hazards associated with specific technologies are shown in the table below.

Table10.1.2. Major Hazards in PV Manufacturing [53]

Module Type	Types of Potential Hazards
x-Si	HF acid burns SiH_4 fires/explosions Pb solder / module disposal
a-Si	SiH_4 fires/explosions
CdTe	Cd toxicity, carcinogenicity, module disposal
CIS, CGS	H_2Se toxicity, module disposal
GaAs	AsH_3 toxicity, As carcinogenicity, H_2 flammability, module disposal

10.2 CdTe Environmental Impact

Table10.2.1. CdTe, Cd and $Cd(OH)_2$ physical properties [50]

Compound	T melting (^0C)	T boiling (^0C)	Solubility (g/100cc)	Toxic/Carcinogen
Cd	321	765	Insoluble	yes
$Cd(OH)_2$	300	-	2.6e-4	yes
CdTe	1041	-	Insoluble	??

CdTe's physical properties, including its extremely low vapor pressure and high boiling and melting points, along with its insolubility in water, limit its mobility. CdTe is much more stable than Cd and $Cd(OH)_2$ used in batteries [50]. The amount of Cd in CdTe solar cells is very small, and could be reduced even further as the cells become thinner; a NiCd flashlight battery has more Cd (7g) than a square meter of today's CdTe PV module [52].

The potential EHS risks related to the cadmium content of CdTe PV modules are; Cd mining, CdTe PV manufacture, CdTe PV use and CdTe PV decommissioning. Cadmium is produced primarily as a by-product of zinc production; also Tellurium is a by-product of copper mining. The very thin layer of CdTe in PV modules is encapsulated between two protective sheets of glass. As a result, the risk of health or environmental exposure in fires, from accidental breakage or from leaching is almost non-existent [49, 50, 51]. The only environmental issue is what to do with the modules about 30 years later, if they are no longer useful. PV industry is considering recycling of these modules at the end of their useful life. Recycling will resolve any environmental concerns.

10.3 CdTe PV Module Recycling

Recycling of CdTe PV modules and manufacturing waste aims to optimize the separations and recovery of glass, cadmium and tellurium while minimizing life-cycle emissions and energy use, under the constraint of low cost. The major processes are:

- Cleaning of glass from the metals and recycling of glass;
- Separation of Te from Cd and other metals and recovery of Te for its value;
- Recovery of Cd for re-use or effective sequestration [54].

Cd and Te can be effectively leached from fragments of PV modules with a dilute solution of H_2SO_4 and H_2O_2; this can be re-used with a small amount of H_2O_2 make-up [55]. The recovery of tellurium is 80% or better, and it can be sold as commercial grade (99.7% Te). The remaining metals (e.g., Cd, Te, Sn, Ni, Al, Cu) are contained in a Cd-rich sludge used as feedstock for NiCd batteries.

CdTe PV modules do not present any risks to health and the environment during their use, and environmental benefits of recycling products provide savings in landfill space, energy, emissions and raw materials [52,56].

11. Site Selection and Building categorization

One of the important goals of our project is to estimate the solar PV potential of the rooftops of buildings on the University Park campus. As described in the literature review the Aerial Imaging method would have been ideal for University Park which has 657 buildings. However the lack of availability of the required Aerial Imaging Software and the lack of expertise to develop one has led us to use method one described in the literature review. This method has two stages. In the first stage we used Bing maps to eliminate buildings with very little roof area to implement solar PV at this stage. The remaining buildings were categorized into different tiers based on their suitability to have solar PV installed on their rooftops. The categorization was done based on parameters such as preplanned roof replacement, roof area, roof type, roof pitch and orientation. The two parameters that are given highest priority are roof area and preplanned roof replacement. For instance, buildings with large roof area and preplanned roof replacement are categorized under Tier I as being most suitable for PV installations. Roof type also played an essential role in the categorization in that buildings with metal roofs are not considered due to complexity of the mounting structures which will lead to higher costs. Similarly buildings with horizontal roofs are given higher preference over those with a curvature. Sports buildings such as the Holuba Hall and Track and field stadium that have large roof areas and curved metal roofs are not considered. Most of the buildings on University Park campus are oriented in the same direction hence orientation did not play a major role in this categorization. Shown below are aerial images of buildings from each category.
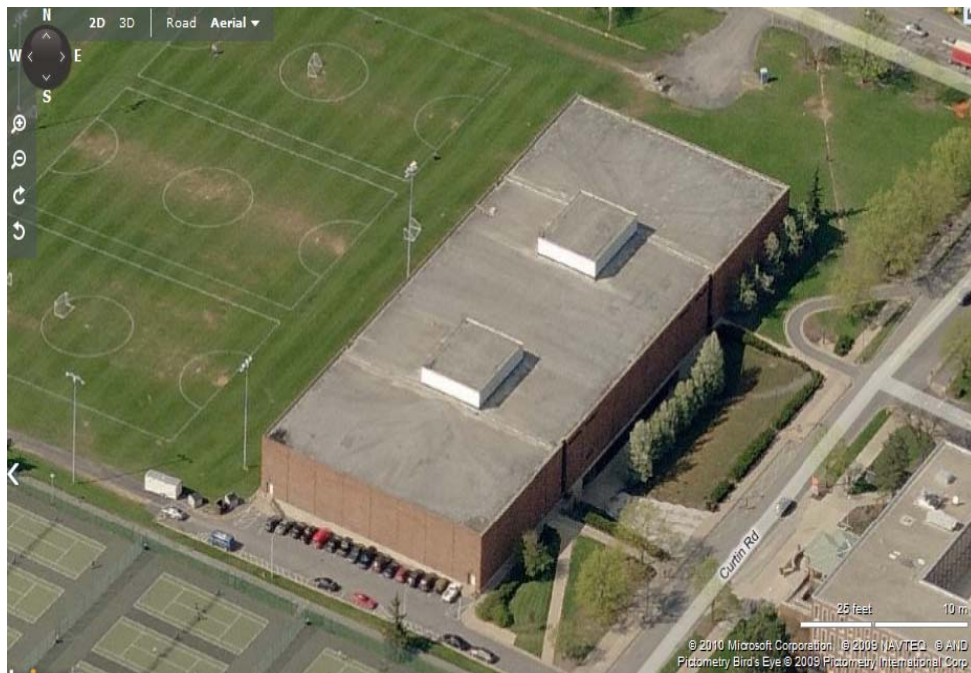

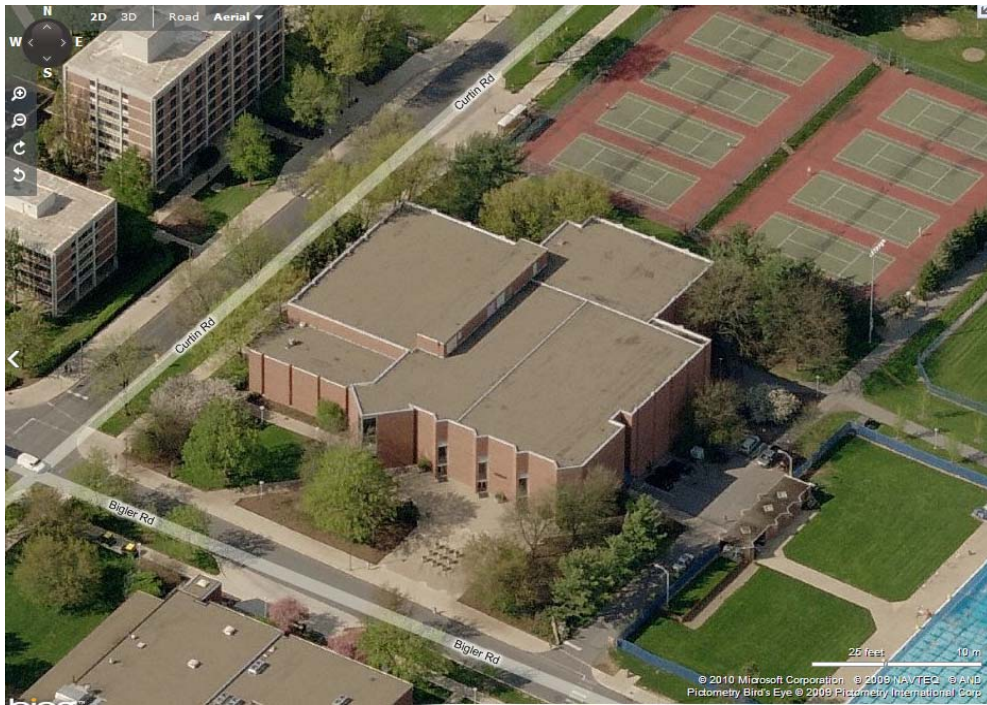Fig 11.1 Example of Tier I building- Intramural Building (*courtesy* – Bing Maps)

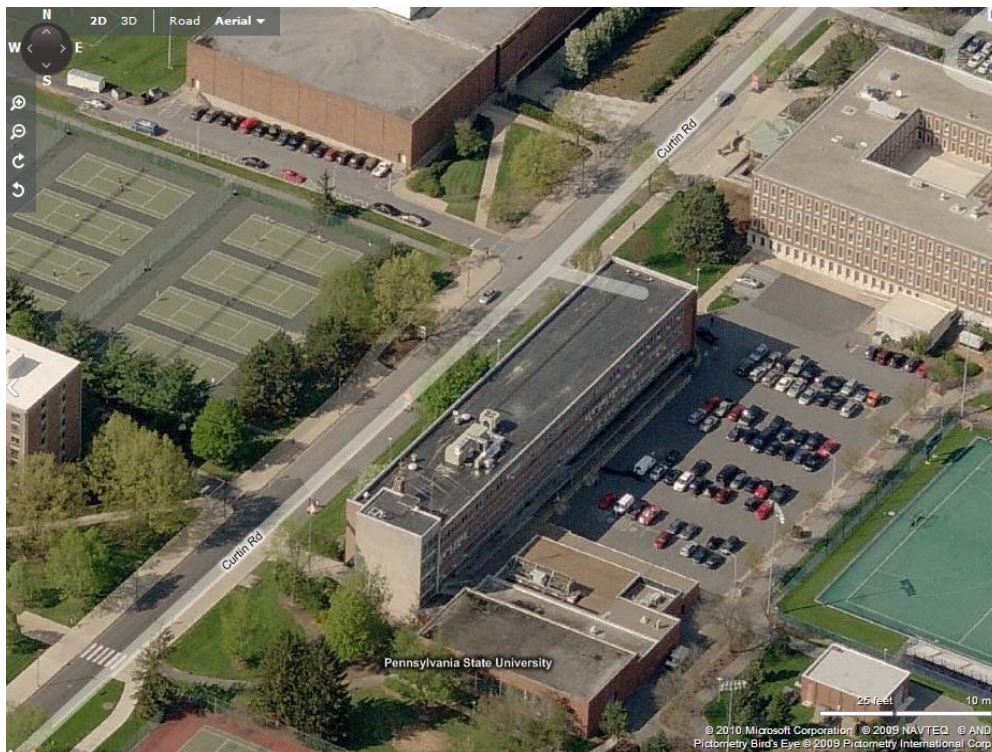Fig 11.2 Example of Tier II building – McCoy Natatorium (*courtesy* – Bing Maps)

Fig 11.3 Example of Tier III building – Wagner Building (*courtesy* – Bing Maps)

Fig 11.4 Example of Tier IV building – Walker Building (*courtesy* – Bing Maps)

Table 11.1 Building Categorization (with Tier I being most suitable for solar PV)

Tier I	Tier II	Tier III	Tier IV
Recreation Hall Intramural Building	Eisenhower Parking Deck Eisenhower auditorium McCoy Natatorium Rec Hall Research A,B and C Greenberg Ice pavilion White Building The Penn Stater Hammond Building	IST Building Physical Plant building Earth and Engineering sciences building Wagner Building Pond Laboratory Agriculture engineering building Shields Building Multisport indoor facility MRL building Penn State Gym and biomechanics lab Transportation Institute Land and water building Thomas Building Kern Building Coal Utilization laboratory	Stiedle Building Fenske Lab Burrowes Building Walker Building Buckout Laboratory James Building Tyson Building Henderson North and south Etc.

12. Shading Analysis

Shading analysis is an important step in the PV design process. It is used to select the optimum location for panels and ensure sufficient energy production. The PV array characteristic current-voltage (I-V) curve changes as a result of shading. This causes the maximum power point (MPP) to shift. The change of MPP determines the power reduction relative to the un-shaded array [57].

The roof must be analyzed for year round shading. Note that the casting of shadows due to seasonal rise and fall of the solar angle must be taken into account as it has a significant impact on the direction of the shadow and surface area. Shadows cast by structures vary in length and direction throughout the day and from season to season.

We used Google-SketchUp Program to perform the shading analyses [58]. Google-SketchUp is a software that can be used to create, share and present 3D models. This program, through its shading toolbar, allows a PV designer to observe the shading areas around a building at different times during the day. The sizes of the roofs were accounted for using the blueprints provided by the office of physical plants (OPP).

We selected two dates, December 21 and June 21, because it would be extremely difficult to perform shading analyses for every day of the year. Shadow lengths increase during the "low sun" or winter season and are longest on December 21-22, the winter solstice. The winter solstice, therefore, represents the worst-case shadow condition and representing the greatest potential for loss of access to sunlight. Shadow lengths are shortest on June 21-22, the summer solstice.

We also considered three times in a day, an hour after the sun rises, noon and one hour before sunset. Of the total amount of the sun's energy available during a daylight period, approximately 85% of it reaches the earth between 9:00 a.m. and 3:00 p.m. The California Energy Commission defines this time period as the useable solar sky-space [59].The sun must rise a little in the sky for a PV array to capture the sun light. Moreover, the shadow is longer in the morning and in the evening whereas it is shorter in the noon. We calculated shading areas at these times. Also, we dedicated about 1.5 m from the all edges of the roofs as free space to enable installation and maintenance crews to work at ease. Finally, we subtracted the shaded areas and areas that we dedicated as workspace from the total roof area to achieve usable area. The blue area in the fig 12.1 represents the morning shadow with the pink and the green areas representing the shadows at noon and evening.
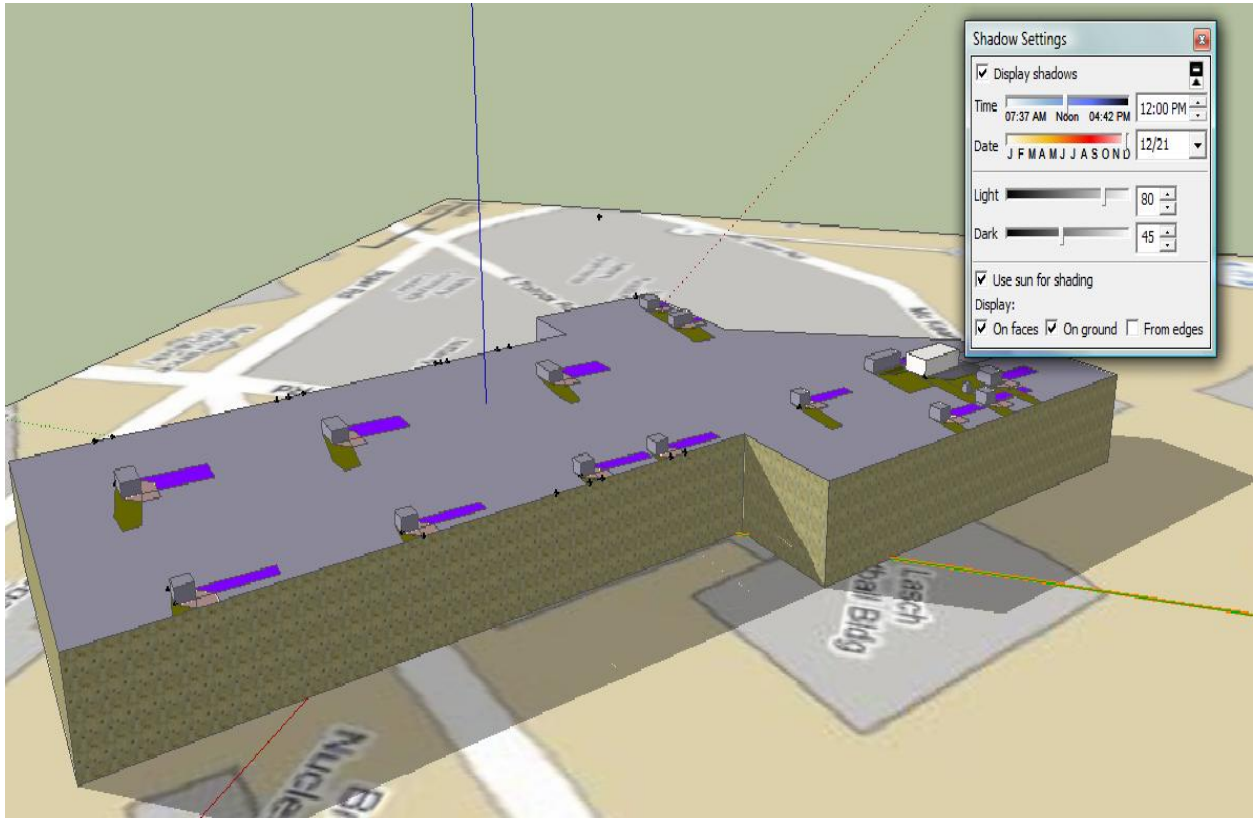
Figure 12.1: Shading areas from Greenberg Ice Pavilion

Table12.1: Usable areas of buildings.

Building	Total Area (m2)	Usable Area (m2) (Dec21)	Usable Area (m2) (June21)
IM Building	4998.06	4438.83	4192.22
Rec Hall	3925.274	2038.682	2702.947
Greenberg Ice Pavilion	3752	3325.93	3300
McCoy Natatorium	2000.84	1646.99	1594.54
White Building	2665.64	1279.56	1279.56
Research A,B,C Buildings	3776	3050.49	3052.67
Eisenhower Auditorium	2462.16	1525.97	1255.80
Eisenhower Parking	5169.28	4511.28	4511.28
Wagner Building	1350.17	689.28	689.28
Kern Building	2412.17	927.67	336.75
Hammond Building	2760	1778	1710
Thomas Building	2060.61	1057.39	1263.39
The Penn Stater	6178.74	4785.98	2695.03
Shields	1804.01	1472	1391.51
MRL	1985.14	1467	1666.30
OPP	1855	1510	1560
Rec Hall(small building)	791.65	590.23	590.23
EES	1600	705	728.97
Warwick Lab	780	462.70	350.00

13. PV System Design

13.1 Power Capacity Calculations

Solar PV potentials for various buildings have been calculated given the useful roof area for each building. The calculations made are tabulated in table 13.5. A total of 3.56MW solar PV capacity has been estimated for the selected buildings.

13.2 IM Building Design

We performed detailed roof top analyses of the selected buildings as shown in section 12. However, we will use the IM building to illustrate our design approach since the system design is very similar for all the buildings in this study.

13.3 System overview

The proposed design is a grid interactive photovoltaic (PV) system that works without a battery backup. There is no need for a battery backup system since the electric grid will also supply electricity. A general overview of what a functioning grid interactive system looks like is shown in fig 13.1. The PV array and the inverter are the two most important components of this system [27].
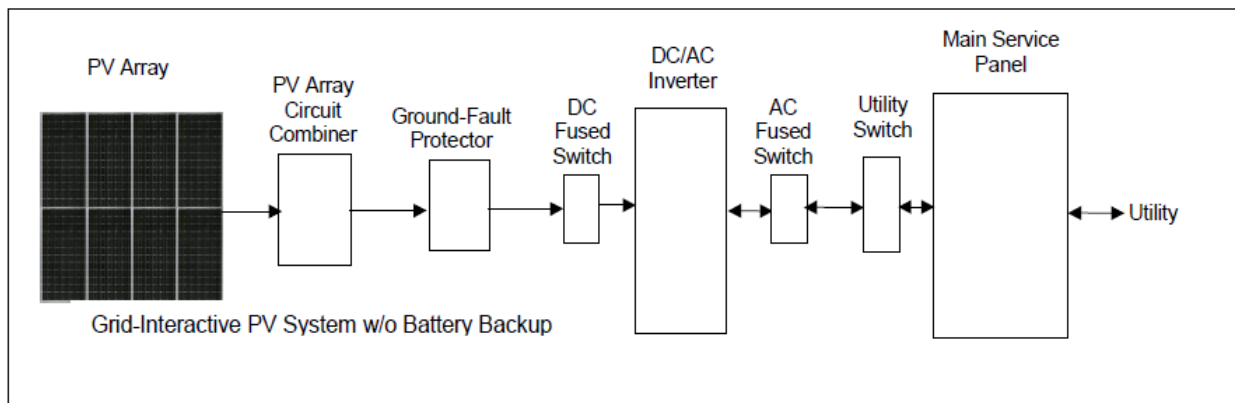

Fig 13.1 Block Diagram showing the system overview

13.3.1 Module Selection

The First Solar FS-277 Module was selected for this project. The FS-277 is a thin film cadmium telluride (CdTe) module that produces 77.5 W_p and has an open circuit voltage (V_{oc}) of 90.5 V [61]. In our literature review, we outlined the reasons why we picked cadmium telluride modules and these reasons include low cost, good efficiency, and the reliable brand strength of the manufacturer, First Solar Inc.

13.3.2 System size

The primary constraint for the size of the PV system was the available roof space. In our roof top analysis, we calculated the amount of total roof space on the IM building. The shading analysis was then performed to show the useable area for a PV installation.

This data was used to calculate the number of modules to be installed on the roof of the IM building and its total power capacity.

Table 13.2 Roof area and Power capacity of IM building

Roof Area (m²)	Useable Area (m²)	Number of Modules	Power Capacity(kW$_p$)
4998.06	4438.83	5640	437.1

13.3.3 Power Conditioning Unit (PCU)

The power conditioning unit performs power processing functions such as rectification, transformation, and DC-DC conversion. It is also responsible for inverting the DC current produced by the PV array to AC current used by the loads [27].

The PV capacity for the IM building is rated at approximately 437 kW$_p$; hence the chosen PCU must have a greater power rating. We selected the PowerGate® Plus 500 kW PCU designed by Satcon. This device meets all the required standards such as UL 1741 and IEEE 929 [62]. A more detailed explanation of the implications of these standards can be seen in the literary review. It should be noted that the PCU is not noise free and it is best mounted in an area where noise is not a serious issue.

Table 13.3 Important Parameters of the PCU

PowerGate Plus 500 kW Specifications			UL/CSA	CE
Input Parameters				
Maximum Array Input Voltage	600 VDC		•	
	900 VDC			•
PV Array Configuration	Positive Ground		○	○
	Negative Ground		•	○
	Floating			•
Input Voltage Range (MPPT; Full Power)	320/333–600 VDC	200/208 VAC¹	•	
	420–850 VDC	265 VAC¹		•
	320–600 VDC	480 VAC	•	
Maximum Input Current	1,628 ADC/ 1,565 ADC	200/208 VAC¹	•	
	1,228 ADC	265 VAC¹		•
	1,628 ADC	480 VAC	•	
Output Parameters				
Output Voltage Range (L-L)	176–220 VAC/ 183-229 VAC	200/208 VAC¹	•	
	233–292 VAC	265 VAC¹		•
	422–528 VAC	480 VAC	•	

13.3.4 Array Configuration

The next step after selecting an ideal power conditioning unit and PV modules is to decide the best way to assemble the PV array. NEC Table 690.7 requires division of the maximum input voltage of the PCU by 1.13 to correct for the -10ºC input temperature [60]. Thus, the maximum V_{OC} of the PV array is limited to 531 V in order to keep the PV array output voltage below 600 V. In addition, short circuit current (I_{SC}) of the array must be limited so that 1.25 I_{SC} is less than the PCU rated input current. Thus the I_{SC} should be less than 1302 A.

Using this information, 1128 strings or "source circuits" can be connected with 5 modules connected in series for every string, giving a total voltage of 452.5 V. The 1128 strings can be connected in parallel using panel combiner boxes. The output of the combiner boxes can be fused and connected as an input to the PowerGate® Plus 500 kW PCU. A revenue grade meter should be used to monitor the PCU and the main power distribution center. In addition, the modules can be mounted securely in a south-facing direction at the angle of latitude of state college (40.7º).

Table 13.4 Array Configuration Table

Number of Modules	Number of strings	Number of modules in series
5640	1128	5

Appropriately sized cables must be picked as per the NEC requirements. The essential criteria for sizing cables are the cable voltage ratings, the current carrying capacity of the cable, and the minimizing of cable losses [24]

13.3.5 Grounding, surge protection and disconnects

A utility interface disconnect switch is a manual, lockable, load-break disconnect switch that is visible and accessible to utility workers [27]. Disconnects and ground fault protection are generally required by utilities, however they are not required in our design since the manufacturer of the selected PCU already incorporated the functions into the product[62]. However, the negative PV output conductor should be grounded at a single point at the PCU. This will ensure proper operation of the ground fault circuit

Table 13.5 Power capacity of selected buildings.

Building	Total Area(m^2)	PV capacity (kW$_p$)
Rec Hall	3925.274	266.4
Greenberg Ice Pavilion	3752	369.8
McCoy Natatorium	2000.84	162.3
White Building	2665.64	124.1
Research A,B,C Buildings	3776	300.8
Eisenhower Auditorium	2462.16	150.4
Eisenhower Parking	5169.28	509.4
Wagner Building	1350.17	67.9
Kern Building	2412.17	91.4
Hammond Building	2760	175.3
Thomas Building	2060.61	124.5
Penn Stater	6178.74	471.7
Shields	1804.01	145.1
MRL	1985.14	164.2
OPP	1855	153.7
EES	1600	71.8
Warwick Lab	780	45.6

14. TRNSYS Simulation

14.1 Methodology:

The PV system designed for Intramural Building (437.6kW) has been chosen for simulation in TRNSYS. TRNSYS has several built-in mathematical models for components such as photovoltaics panels, weather data processor, inverter and power conditioning unit that comprise a PV system. TRNSYS has a user interface which enables the users to interconnect these components as shown in FIG 14.1 and develop a virtual PV system. A simple PV system was developed utilizing the weather data sets which provides input to components such as the thin film modules and the inverter.
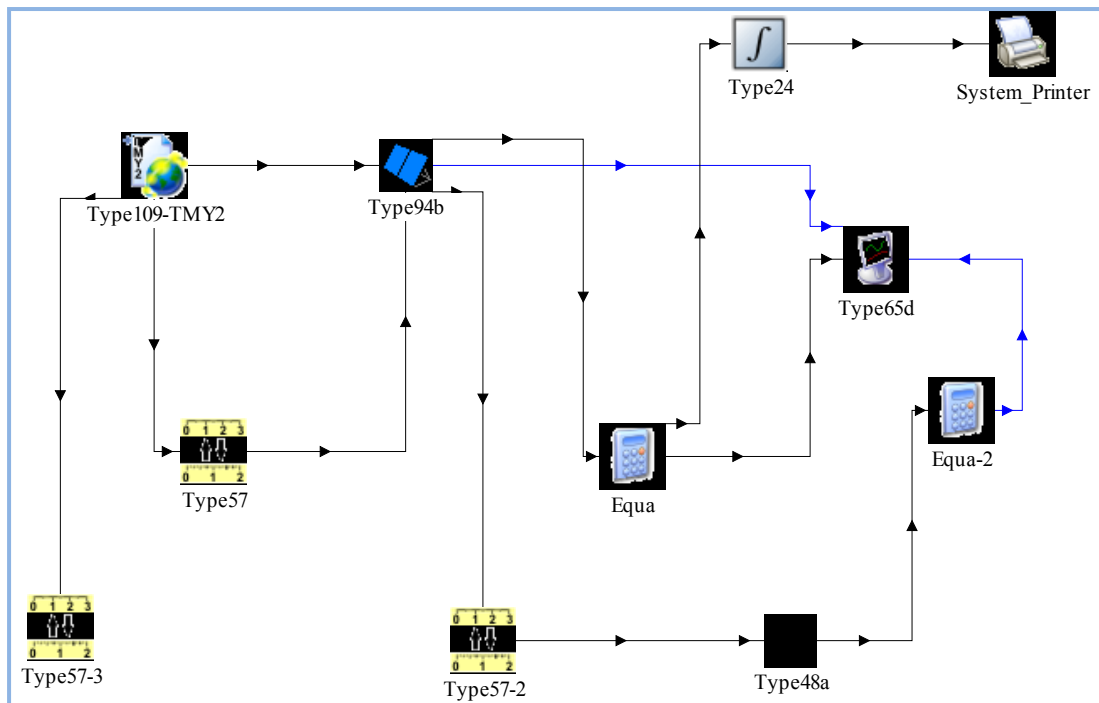
Fig 14.1 Schematic of TRNSYS simulation for a PV system

14.1.1 Weather data:

TRNSYS employs TMY 2 data for its simulations. TMY 2 data sets contain the typical meteorological year data for 237 U.S locations derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The data set is known as "TMY2" to distinguish it from the earlier TMY data set derived from the 1952-1975 SOLMET/ERSATZ data base. TMY 2 data sets does not contain insolation data for State College hence weather data for Pittsburgh,PA was chosen for this simulation. Hence an assumption that Pittsburgh closely represents State College's weather has been made.

14.1.2 Photovoltaic Model:

TRNSYS employs equations for an empirical equivalent circuit model to predict the current-voltage characteristics of a single thin film module which in our case is the CdTe module. This circuit consists of a DC current source, diode, and two resistors. This model is termed the "five parameter model" and is a derivative of the "four parameter model" developed by Townsend [63]. The algorithms and behavior of the five-parameter model are discussed in detail by Fry [64].
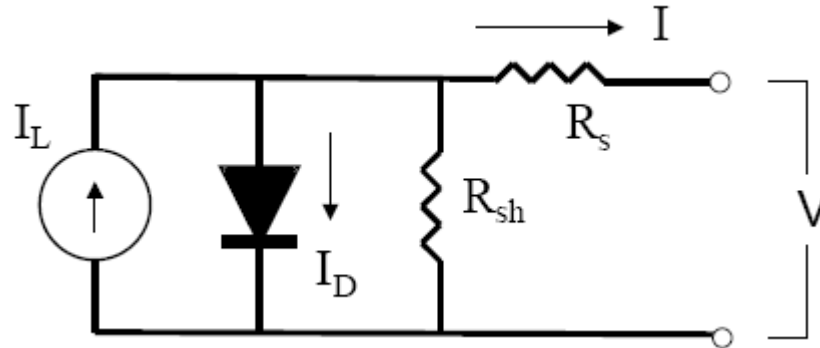
Fig 14.2 Equivalent electrical circuit of the 5-parameter model

The current-voltage equation for the equivalent circuit,

$$I = I_L - I_o \left[\exp\left(\frac{q}{\gamma k T_c} (V + IR_s) \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

Where,

I	Current
k	Boltzmann constant [J/K]
IL	Module photocurrent
Io	Diode reverse saturation current
Rs	Module series resistance [Ω]
Rsh	Module shunt resistance [Ω]
V	Voltage
γ	Empirical PV curve-fitting parameter

Table 14.1 Module Parameters used for simulation (source: FS 277 data sheet)

Nominal Values		FS-270	FS-272	FS-275	FS-277
Nominal Power(+/-5%)	P_{MPP}(W)	70	72.5	75	77.5
Voltage at P_{MAX}	V_{MPP}(V)	65.5	66.6	68.2	69.9
Current at P_{MAX}	I_{MPP}(A)	1.07	1.09	1.10	1.11
Open Circuit Voltage	V_{OC}(V)	88.0	88.7	89.6	90.5
Short Circuit Current	I_{SC}(A)	1.23	1.23	1.23	1.22
Maximum System Voltage	V_{SYS}(V)	1000			
Temperature Coefficient of P_{MPP}	$T_K(P_{MPP})$	-0.25%/°C			
Temperature Coefficient of V_{OC}, high temp (>25°C)	$T_K(V_{OC, high\ temp})$	-0.25%/°C			
Temperature Coefficient of V_{OC}, low temp (-40°C to + 25°C)	$T_K(V_{OC, low\ temp})$	-0.20%/°C			
Temperature Coefficient of I_{SC}	$T_K(I_{SC})$	+0.04%/°C			
Limiting Reverse Current[2]	I_R(A)	2			
Maximum Source Circuit Fuse	I_{CF}(A)	10 (2 IEC61730[3])			

14.2 Results and Discussion

A PV system, designed for the Intramural Building, was developed in TRNSYS and its performance was simulated. Critical parameters such as power at maximum power point (operational point on the IV curve of PV module at which maximum power is delivered) and capacity factor (The ratio of the average load on (or power output of) an electricity generating system to the capacity rating of the system over a specified period of time) were calculated and are presented below. Plots for available Incident Radiation for the months of June and December have been attached in the Appendix.

14.2.1 Power at Maximum Power Point:

Predicted Performance of the PV system – Intramural Building (437.6 kW)
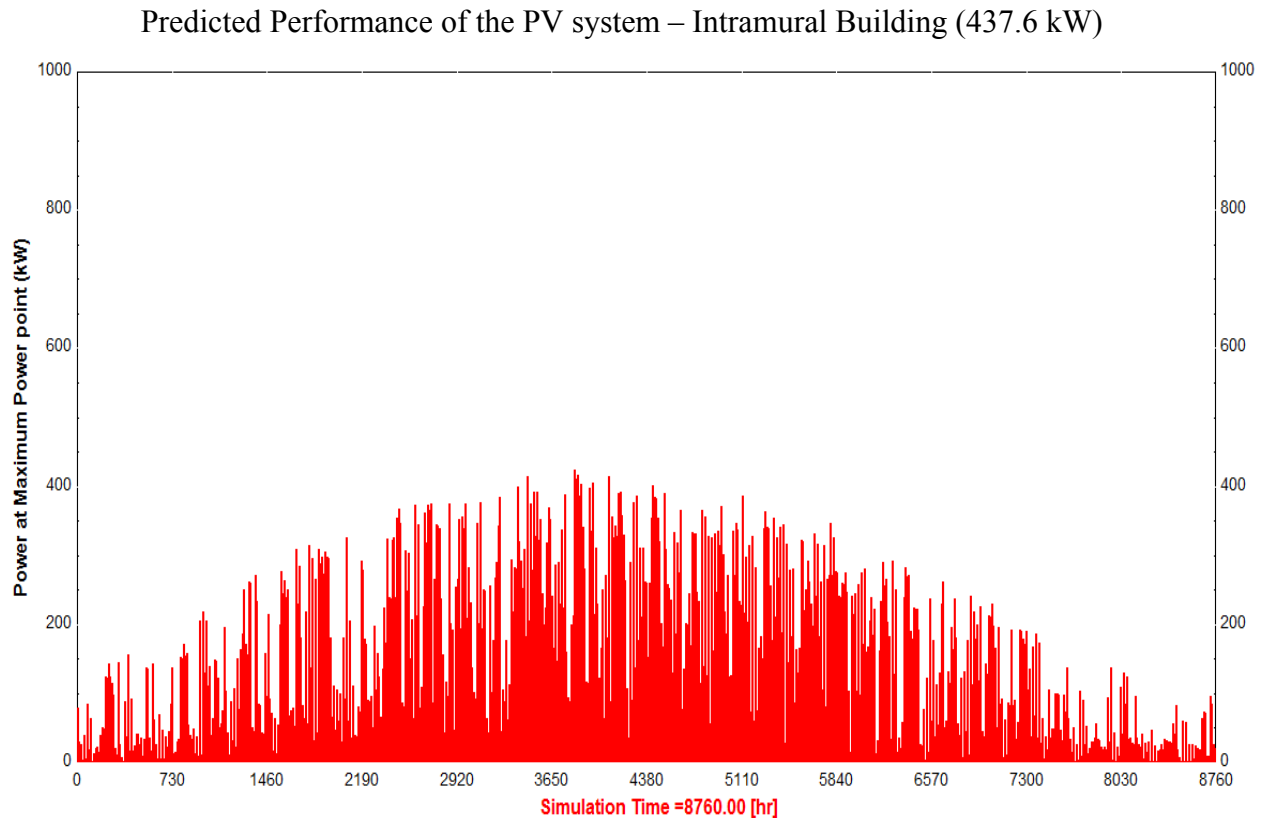
Fig 14.3 Power Output of the PVsystem for a typical year

The performance of the PV system for a typical year in State College has been predicted. As expected the PV system reaches close to its rated capacity in the summer months hitting a maximum of 424 kW on June 8th. The months of June and July had capacity factors of 16.9% and 15.8% respectively. During the winter months the output dropped considerably with capacity factors as low as 2.8% and 1.7% for the months of November and December respectively.

Predicted Performance of the PV system – Intramural Building (437.6kW)
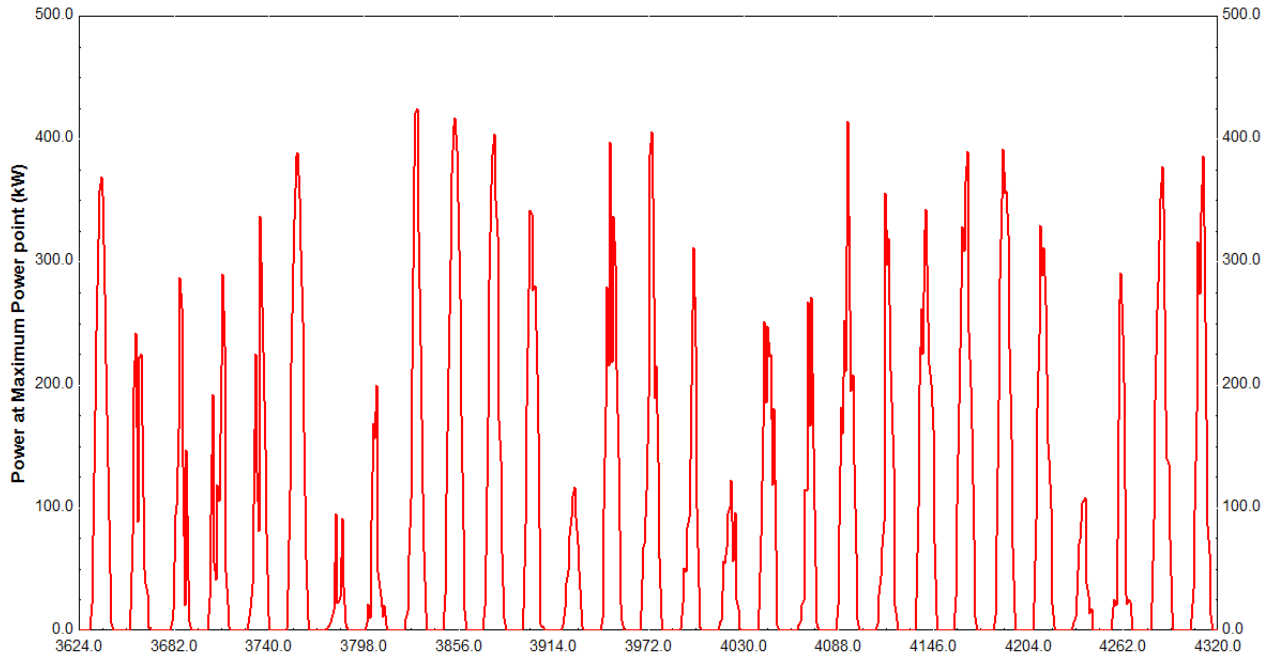

Fig 14.5 Power Output of the PVsystem for the month of June

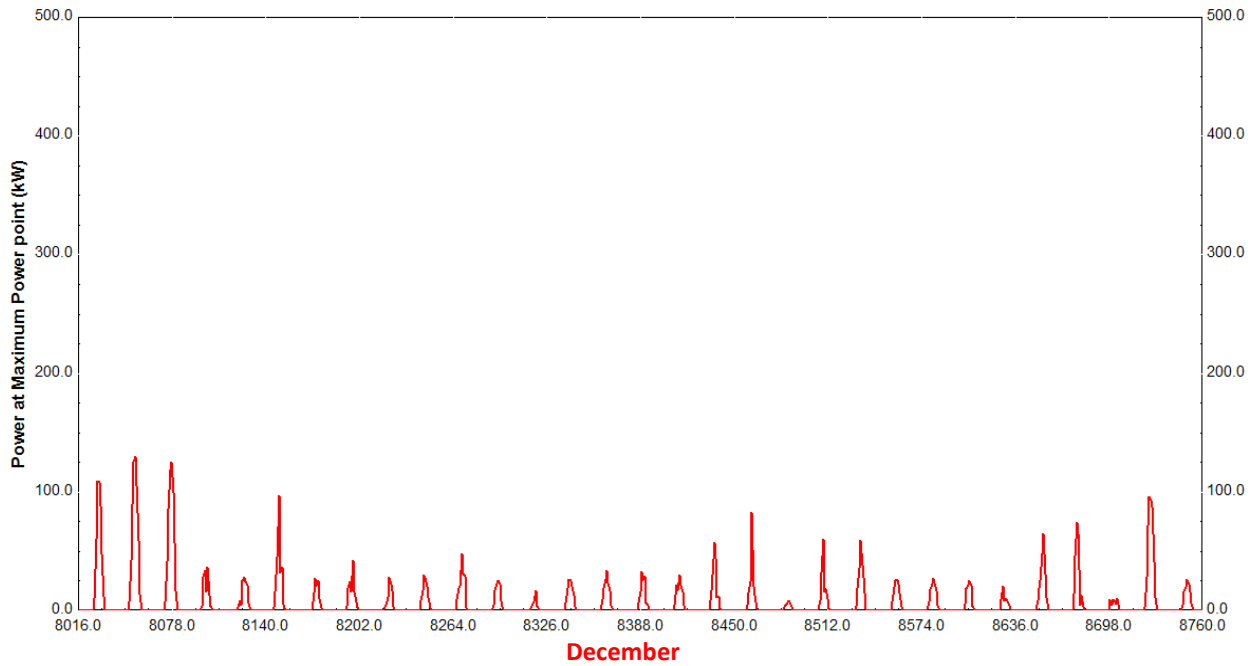Predicted Performance of the PV system – Intramural Building (437.6kW)

Fig 14.4 Power Output of the PVsystem for the month of December

The power output for a typical day of each month has been calculated. The 15th day of each month is assumed to be a good representative of the month and hence been selected as the typical day. Some of the months have been omitted to avoid clustering of the plot.
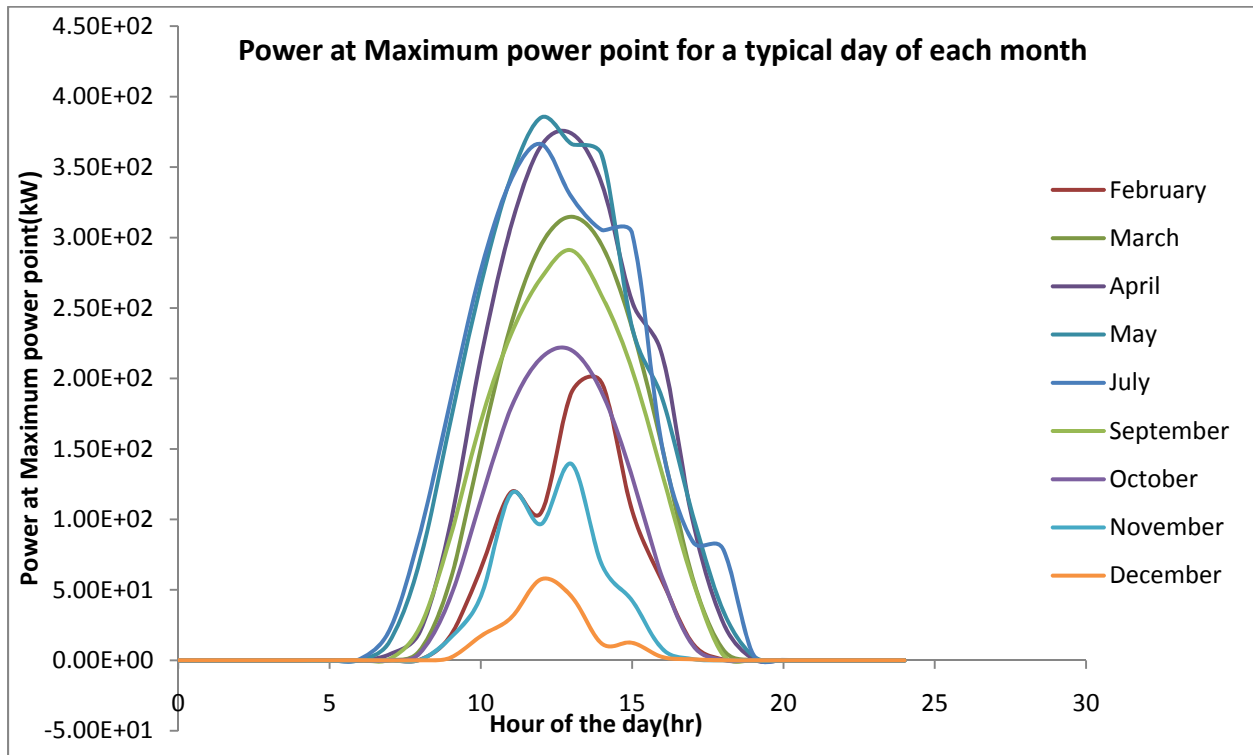
Fig 14.7 Power at maximum power point for a typical day of each month

14.2.2 Capacity Factor:

The capacity factor for the PV system was calculated to be 9.7% much lower than the 13.5% which is the case for most PV systems in the northeastern region of the U.S [65]. Due to this considerable discrepancy in the value of capacity factor, its usage was not recommended for the subsequent financial analysis.

Table 14.1 Capacity factors for a typical year

Month	Capacity Factor
January	0.026
February	0.053
March	0.087
April	0.134
May	0.153
June	0.169
July	0.158
August	0.147
September	0.100

October	0.065
November	0.028
December	0.017

14.2.3 Solar Fraction:

Solar Fraction is the ratio of amount of energy provided by the solar PV system to the total energy consumed by the building. In this section we have used the energy consumption data of the Rec Hall as the hourly consumption data is not available for the Intramural Building. The PV system designed for Rec Hall has a rated capacity of 267kW. In July 2009 a total of 79905.6 kWh was consumed by the Rec Hall building. The average power consumed was 107.40kW with the minimum and maximum being 50kW and 156kW respectively. The output of the PV system designed for Rec Hall is compared to the energy consumption of the Rec Hall as shown below. The energy produced by the PV system for a typical July month is 32719.33kWh. The fraction of the building's electricity demand that can be met by the PV system for the month of July is 40.9%.
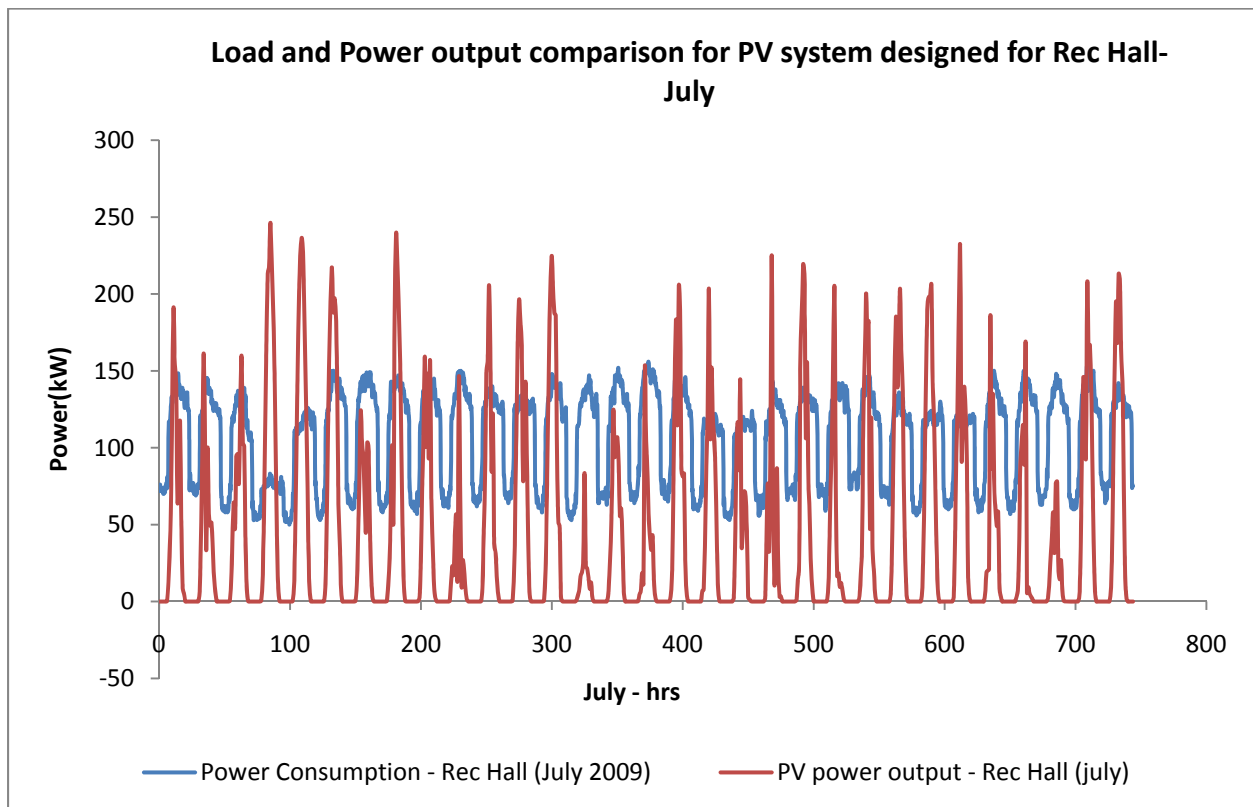

Fig 14.8 Rec Hall Energy consumption and PV system output comparison for July

In December 2009 a total of 70055.04 kWh was consumed by the Rec Hall. The average power consumed was 94.16kW with the minimum and maximum being 46kW and 173kW respectively. The PV system's energy production for a typical December month is 3423.59 kWh. The fraction of the building's electricity demand met by the PV system for the month of December was a meager 4.89%.
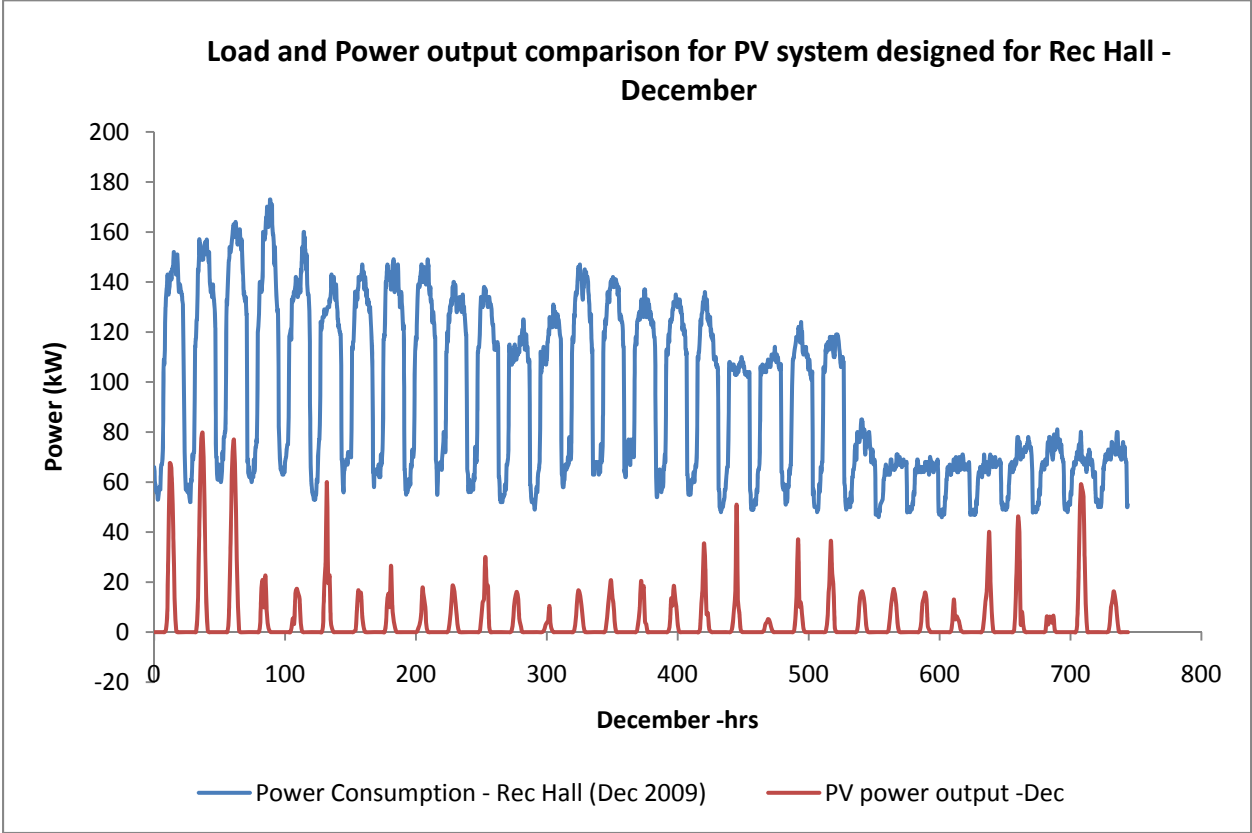

Fig 14.9 Rec Hall Energy consumption and PV system output comparison for December

15. Economic Analysis

An economic analysis was performed using Solar Advisor Model (SAM) based on input variables such as: system specifications, project location, financing, installation and operating costs, applicable tax credits and incentives.

The economic outcome of the project includes net present value (NPV), levelized cost of energy (LCOE) nominal, payback period (PBP) and a sensitivity analysis.

The analysis was performed over the life time of the project for payback period, net present value and levelized cost of energy

15.1 Solar Advisor Model (SAM) Input Parameters

- Climate & Location- **Typical Meteorological Year (**TMY20 data is used to calculate the weather conditions

- PV system specifications. This takes into consideration
  - Tilt angle
  - Azimuth angle
  - Array tracking mode
  - DC to AC derate factor (calculated based on PV module rating, inverter rating, DC wiring, AC wiring, mismatch and system availability.
  - System Degradation

- Installed cost per capacity
  - PV module cost
  - Inverter and inverter replacement cost
  - BOS cost
  - Installation cost

- Operating and maintenance cost as a function of capacity

- Utility electricity price

- SREC price

- Revenue Source
  - Sale of SRECs
  - Sale of electricity

- Financing
  - Loan term
  - Loan rate
  - Debt fraction

- o Inflation rate
- o Real discount rate

15.2 Summary of major assumptions

- Total installed cost per capacity = 7.2 $/W$_{dc}$ [66]

- Break down of installed cost [67]
  - o 60 % PV module cost
  - o 20% inverter cost
  - o 15% BOS cost
  - o 5% installation cost

- Operation and maintenance cost 25

- Electricity utility rate = 0.09 $/KWh [71]

- Solar Renewable Energy Certificate (SREC) price = 0.30$ KWh [70]

- 30 year project life time
  - o 3% inflation rate [69]
  - o 6% real discount rate [68]

- 10 year debt term
  - o 7.0 % loan rate
  - o 55% debt ratio

- Penn state has a tax exempt status and therefore, taxes or tax based incentives are not reflected in the economic analysis [OPP]

15.3 Model Limitations

- PV array shading doesn't affect the system output
- Fixed SREC price through the life of the project
- Revenue generated through sale of SRECs is calculated annually

Costs	Base Case	Reduced Costs Case
Total Installed Cost per Capacity ($/W)	7.2	5.2
Module Cost ($)	1,761,510	1,265,310
Inverter Cost ($)	587,170	421770
BOS Cost ($)	440,378	316,327
Install Cost ($)	146,793	105,442
Contingency Cost ($)	29,358.50	21088.5
Present Value of O and M ($)	148,734	106,845

Table 15.1 Comparing Base Case and Reduced Costs Case, IM Building

Annual Energy (kWh)	457,587.80	457,587.80	kWh
LCOE(nom)	39.58	20.96	¢/kWh
LCOE(real)	29.58	15.67	¢/kWh
Net Present Value	(-1,186,944.88)	(-394612.56)	$
Payback	18.56	13.04	years
Capacity Factor (%)	12.6%	12.6%	

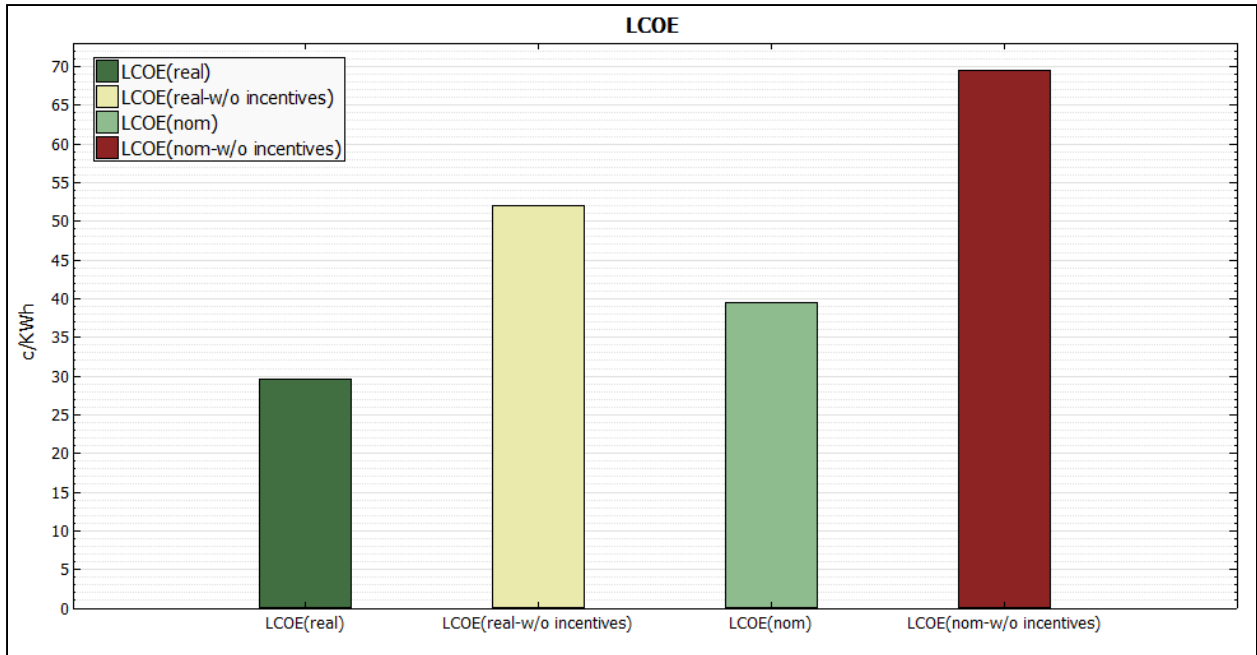Table 15.2 Output parameters for IM building

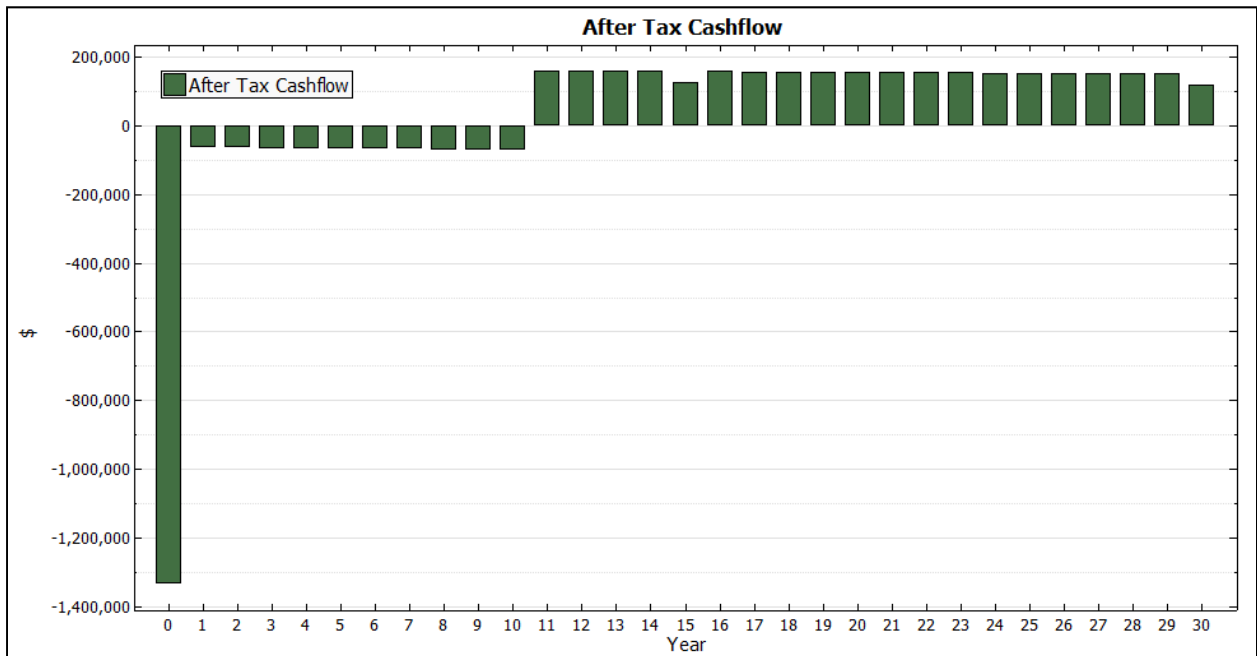Figure: Levelized Cost of Energy for IM Building (base case)   *w/o incentive ignores the SREC price

Figure 15.2 After Tax Cash flow, IM Building (base case)

15.4 Sensitivity Analysis

A sensitivity analysis was performed to indicate the degree to which the economics of the project were affected given varying costs and discount rates.
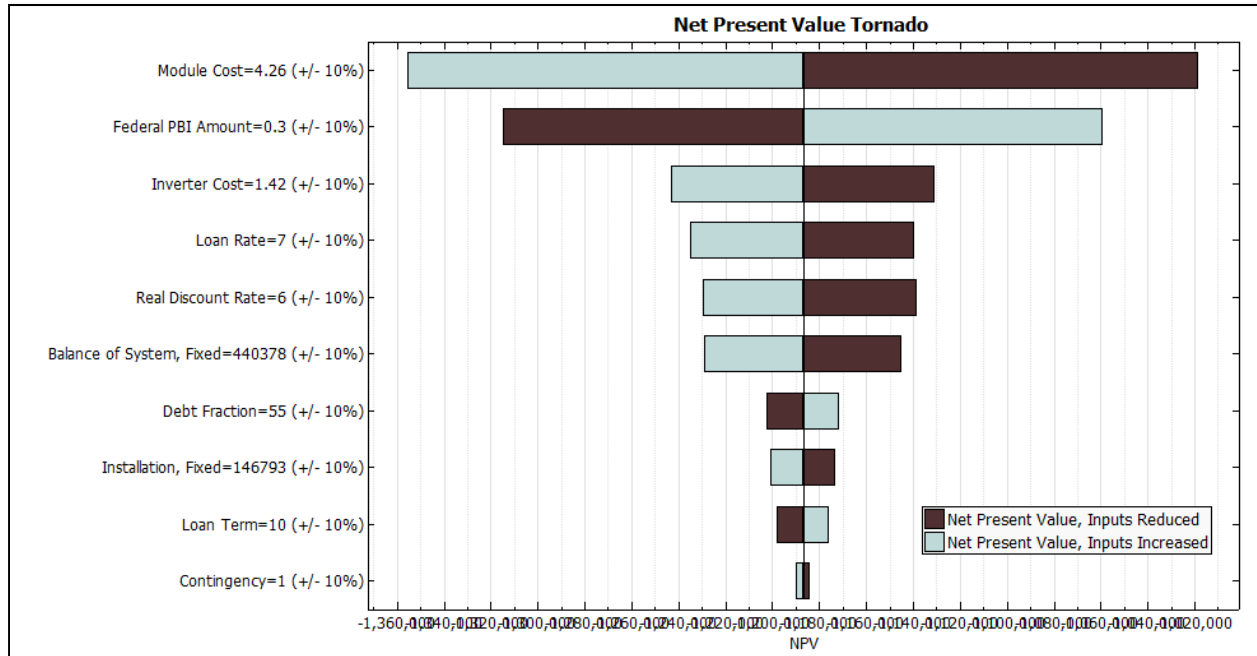

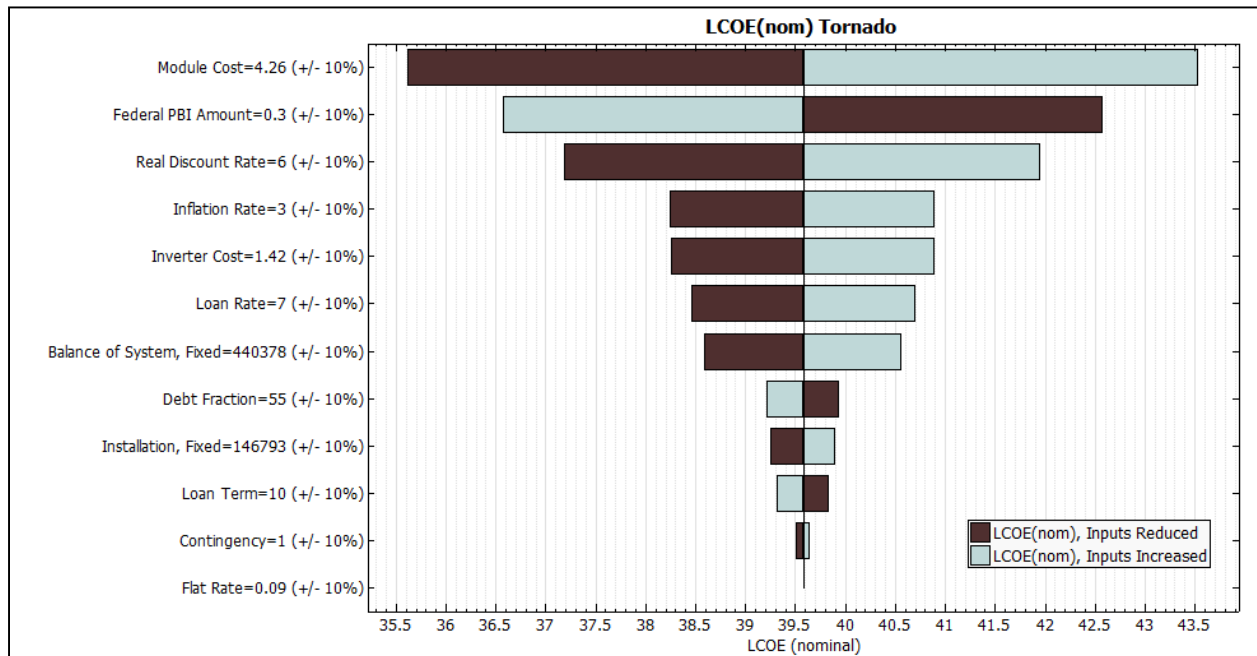Figure 15.3 Sensitivity Analysis on NPV, IM Building (base case)

Figure 15.4 Sensitivity Analysis on LCOE, IM Building (base case)

16. Emission Analysis

16.1 Life Cycle CO_2 Emission Analysis

A full CO_2-balance within the life-cycle of a PV-system requires examination of the CO_2 sinks and sources at the location and under the conditions of production, during transport, installation and operation, as well as the site of recycling [72].

In most cases the use of renewable energies such as PV reduces the specific carbon dioxide emissions of a country considerably. To find out the exact amount of reduction, a detailed carbon dioxide balance of the entire life-cycle of PV-power plants, including production, transport installation, operation, dismantling, was set up [73].

Table16.1 Simplified life cycle material and energy usage to produce one m^2 of CdTe module on the basis of 9% conversion efficiency [73]

Life Cycle Stage	Input materials, parts, and energy	Amount
Materials Production	Cell Materials (CdTe, CdS, $CdCl_2$, other)	0.065 kg
	Encapsulation (glass, EVA, other)	21.8 kg
Module Manufacturing	Chemicals (acids, cleaning agents)	0.85 kg
	Consumables (safety/maintenance hardware)	0.22 kg
	Water	300 kg
	Electricity (processing)	52.6 kWh
	Electricity (overhead)	4.9 kWh
	Electricity (office use)	1.1 kWh
	Office Supplies	$ 0.37
Transportation	Distillate Fuel Oil	0.15 L

Fthenakis et al (2005) investigated the life cycle impact metrics with software "Simapro". Commercial databases (e.g., Franklin, U.S. Input-Output, Ecoinvent and ETH-ESU) were used to calculate emissions and energy consumptions that were not provided by suppliers. The life cycle energy demand is determined from the Life Cycle Inventory (LCI) in Table10.4.1 along with the materials and energy databases in Simapro. The life cycle energy from each stage is converted from thermal, electrical, and feedstock energy to primary energy according to the conversion efficiencies described in those materials and energy databases, and then aggregated across stages into the one number. The materials production stage (cell materials, encapsulations) accounts for 35%, the module manufacturing stage (electricity, consumables, chemicals, and office supplies) 64%, and the transportation stage 1% of the life cycle primary energy demand respectively. The electricity demand during the CdTe film deposition accounts for the greatest primary energy use (84%) during the module manufacturing stage, while encapsulation materials including glass and EVA (Ethyl Vinyl Acetate), dominate the energy requirement (94%) during the materials production stage [73].

According to Fthekins et al calculations, the final number that they found with Simapro software is 1200 MJ/m^2 =333 kWh/m^2. This is the amount of energy needed to produce $1m^2$ of CdTe

module. These calculations are based on a 9% efficiency, 1800 kWh/ m^2/yr of solar irradiation, and 30 years lifetime.
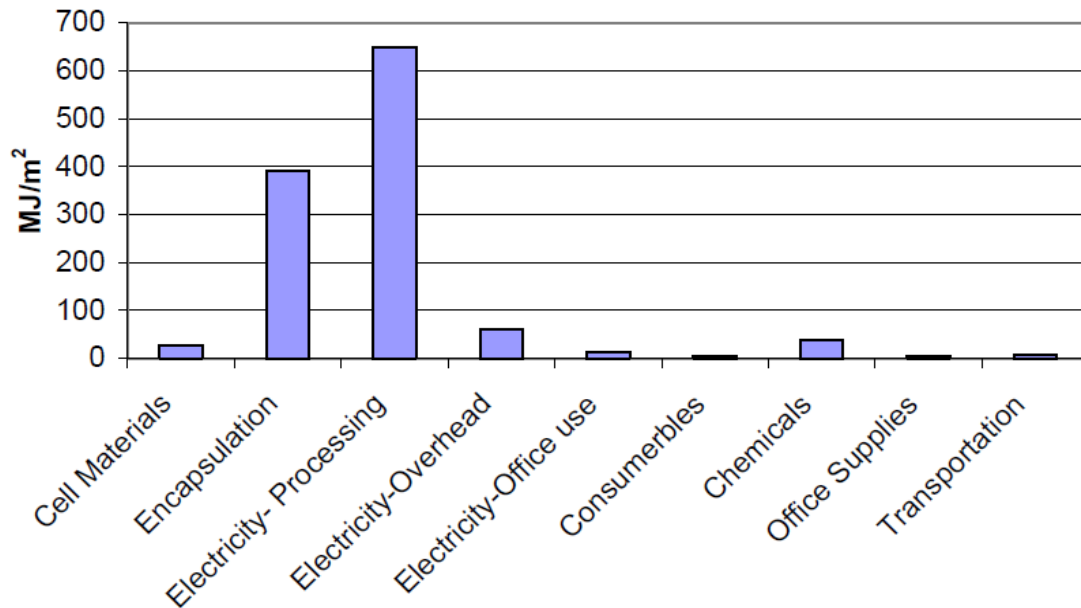

Figure16.1 Breakdown of life cycle energy demand during the materials production, manufacturing, and transportation stages of the CdTe life cycle [73].

The energy payback time is defined as the time period for a PV system to generate the same amount of energy used to produce the PV system. After this calculation our system energy payback time is found to be 2.35 years.

Fthenakis et al estimate 18 g CO_2-eq/kWh for the CdTe life cycle stages investigated is a significant improvement compared with crystalline Si modules which currently dominate rooftop applications [73]. We consider this number for our system CO_2 emission calculations.PV module power output degrades over time. Several mechanisms contribute to the degradation, and degree of degradation varies between module technologies. Also, the rate of the degradation changes over time. We assumed two percent degradation per year and used this assumption for emission calculations [74, 75] .

Table16.2 Life cycle emission analysis for selected building

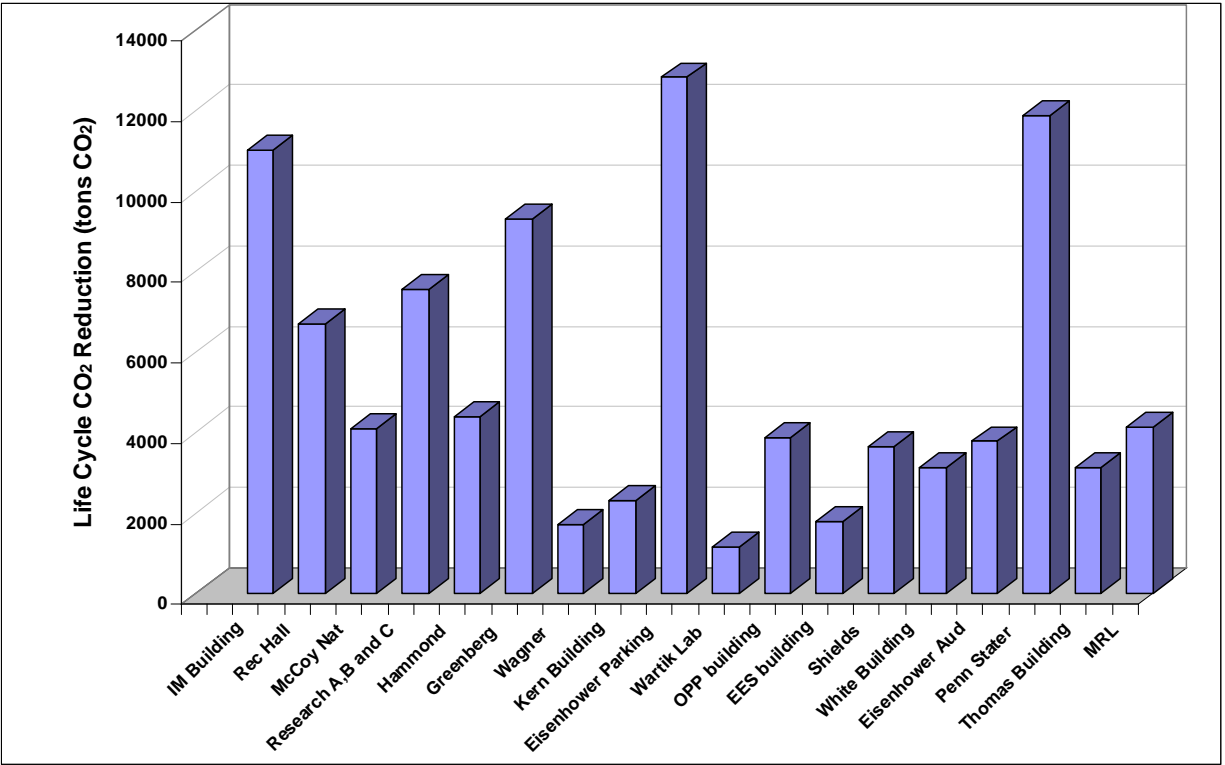| Buildings Names	CO_2 Emission During Production (tons CO_2)	CO_2 Emission Reduction During Operation (tons CO_2)	Net Life Cycle CO_2 Emission Reduction (tons CO_2)
IM Building	1273.48	12282.03	**11008.55**
Rec Hall	775.47	7479.57	**6704.10**
McCoy Nat	472.51	4557.22	**4084.72**
Research A,B and C	875.79	8446.87	**7571.08**
Hammond	510.21	4920.53	**4410.32**
Greenberg	1076.54	10383.75	**9307.21**
Wagner	197.75	1907.36	**1709.61**
Kern Building	266.14	2568.12	**2301.98**
Eisenhower Parking	1483.06	14302.92	**12819.87**
Wartik Lab	132.75	1280.66	**1147.91**
OPP building	447.56	4316.54	**3868.97**
EES building	209.14	2016.35	**1807.21**
Shields	422.32	4073.57	**3651.25**
White Building	361.36	3485.47	**3124.11**
Eisenhower Auditorium	437.81	4223.44	**3785.63**
Penn Stater	1373.10	13242.52	**11869.41**
Thomas Building	362.47	3495.02	**3132.56**
MRL	478.07	4613.99	**4135.92**

Figure16.2 Life cycle CO_2 emission reduction analysis for selected buildings
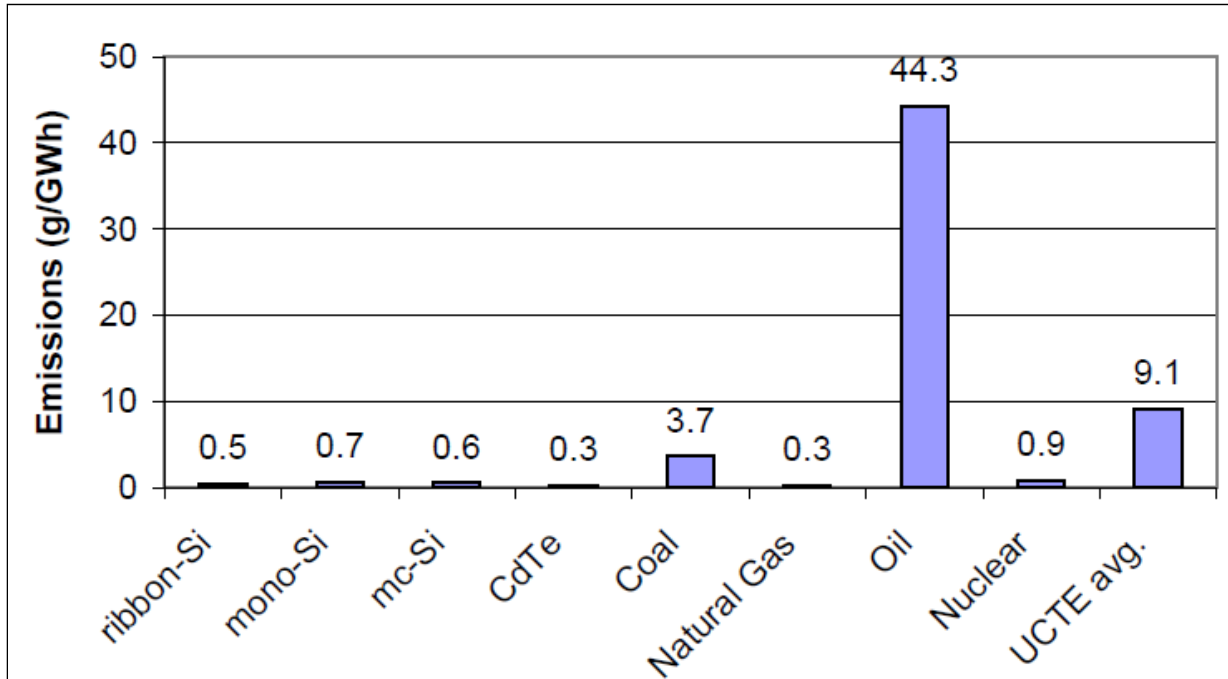
16.2 Cadmium Emission Analysis:

Figure16.3 Life cycle atmospheric Cd emissions of the four PV modules, coal, natural gas, oil, nuclear and average electricity-production [76].

It can be seen from the figure above that the CdTe PV cell, when it replaces coal-burning for electricity generation, will prevent Cd emissions in addition to preventing large quantities of CO_2, SO_2, NO_x, and particulate emissions. The direct Cd emissions during the life-cycle of CdTe PV modules are much smaller than those from generating the electricity used in producing these same modules [76].

Thus, when CdTe displaces coal, it displaces 3.4 g of Cd emissions per GWh produced, and likewise, for heavy-oil, it displaces 44.0 g Cd/GWh. According to these numbers when we compare our PV system Cd emission versus coal power plant, we can easily see how CdTe PV cells produce little amount of Cd emission.
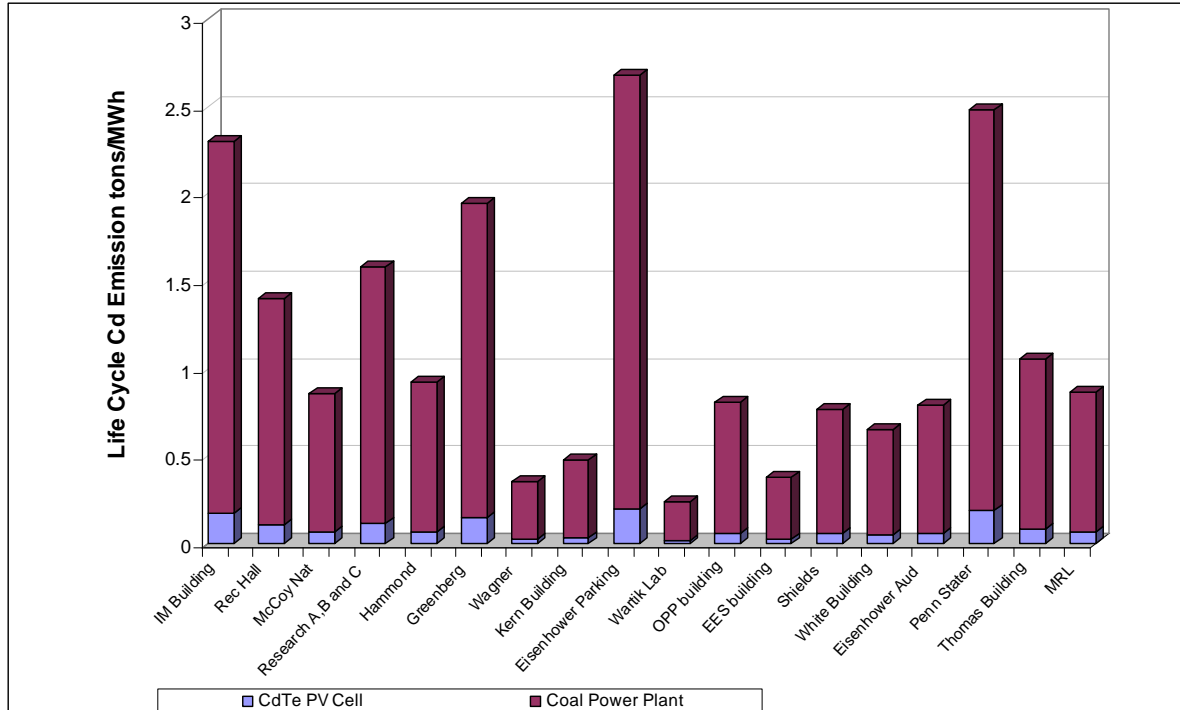
Figure16.4 Comparison of CdTe PV cell life Cycle Cd Emission and Coal Power Plant Life Cycle Cd Emission

CdTe PV systems require less energy input in their production than other commercial PV systems, and less energy translates to lower emission of heavy metals (including Cd), as well as SO_2, NO_x, and CO_2 in the CdTe cycle than in the cycles of the other commercial PV technologies. In any case, emissions from any type of PV system are expected to be lower than those from conventional energy systems because PV does not require fuel to operate [76, 77]. PV technologies provide the benefits of significantly curbing air emissions harmful to human and ecological health.

Although the EPBT of CdTe PV is much lower than that of the other PV systems, its electrical conversion efficiency was the lowest in the group. Life cycle emission analysis considering both production and operational mode of the PV system revealed a net reduction in carbon dioxide emissions.

Our system EPBT time was 2.35 years. Highest life cycle CO2 emission reduction was calculated to be 11,869.41, 11,008.55, and 9,307.21 tons of CO_2 for Penn Stater, IM building, and Greenberg Ice Pavilion, respectively.

17. Conclusions

Our study revealed that the University Park campus has a total solar PV total potential of at least 3.56 MW. There is a potential for solar PV to provide upto 3939.57MWh annually which is equal to 3939 S-RECs. This is equivalent to around 4.7% of the green power that Penn State purchases and 0.94% of the current total electricity demand. Pennsylvania's Alternate Energy Portfolio Standards require all EDCs (electric distribution companies) and EGSs (electric generation suppliers) to provide 0.5% of their power through solar PV by the year 2020. Penn State though not an EDC or EGS has the potential to meet this standard should it make a voluntary commitment (assuming the electricity demand remains the same). However for 3.56MW of solar PV to be installed we need at least 18 buildings from Tier I and Tier II categories. Our site survey has revealed that the Rec Hall and the Intramural Building are the best candidates for immediate implementation. With a combined capacity of 704kW they produce upto 779 MWh annually.

The TRNSYS simulation showed the capacity factor of a PV system in State College to be 9.7% which is significantly less than the 13.5% for most PV systems in the northeastern region of the U.S. Hence the need to improve the TRNSYS model so that it is in agreement with the literature. The TRNSYS model can be further improved by utilizing State College weather data which is currently not available in the TMY 2 data sets but will be made available through the TMY 3 data sets.

As part of the financial analysis two economic scenarios were compared by varying the total installed cost per capacity. Both the scenarios gave a negative NPV (net present value) which means that the project is not economically feasible however the effect on payback period was noticeable which was shortened by 5 years in one case. The SREC price of 0.30$/KWh is not even close to the nominal LCOE price of 0.39$/KWh and for the overall economic calculations, the total installed cost per capacity remained at 7.2$/W.

18. Appendix A

A: Energy to produce of CdTe module for one building.

333kWh/m^2 : Energy to produce one m^2 of CdTe module.Fthenakis et al. (2005) found this number with Simapro Software.

$$A = Number\ of\ modules * Module\ area(m^2) * 333 \left(\frac{kWh}{m^2}\right)$$

B: CO_2 emission during usage of energy to produce CdTe PV module

0.941 tons CO_2 /MWh : Energy information, EIA (2009)

$$B = \frac{A}{1000} * 0.941$$

C: Life cycle CO_2 reduction during operation for 30 years

We assume that regredation is 2%

$$C = \sum_{n=1}^{30} B * (0.98)^{n-1}$$

D: CO_2 emission during operation

$$D = Power\ output * 0.018$$

18 g/kWh emission for the CdTe life cycle. Fthenakis et al. (2005) found this number with Simapro Software.

Net Life Cycle CO_2 Reduction=C-D-B

E: Cd Emission for CdTe PV cell for 30 year life time

0.3 g/GWh : Production of life cycle atmospheric Cd emission for CdTe PV cell. (Fthenakis et al. 2006)

E= Power Output(MWh) * 0.3/1000 (tons/MWh)

F: Life cycle Cd emission for coal power plant

3.7 g/GWh: Production of life cycle atmospheric Cd emission for coal power plant. (Fthenakis et al. 2006)

F= Power Output(MWh) * 3.7/1000 (tons/MWh)

Energy Payback Time (EPBT)= $(E_{mat} + E_{manuf} + E_{trans})/E_{annual}$

E_{mat} = Primary energy required to produce materials comprising CdTe PV module

E_{manuf} = Primary energy required to manufacture CdTe PV module

E_{trans} = Primary energy required to transport materials for producing and manufacturing

E_{annual} = Annual electricity generation primary energy units

19. APPENDIX B

Incident Radiation (W/m^2) for a typical month of June
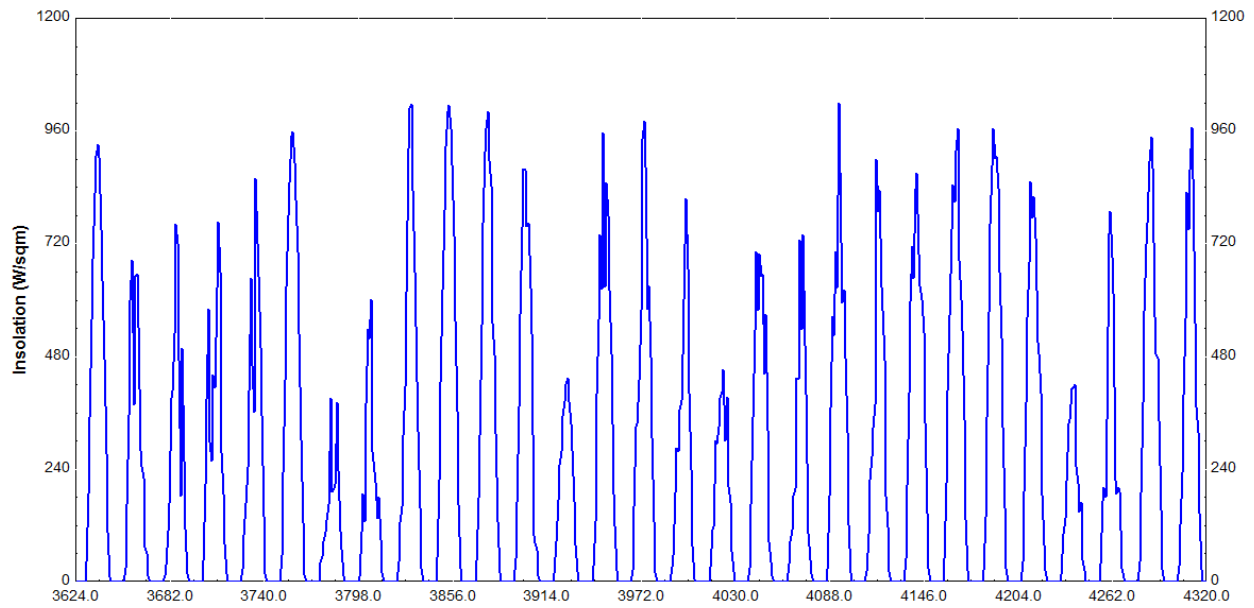

Fig 1 Incident Radiation (W/m^2) for the month of June

Incident Radiation (W/m^2) for a typical month of December
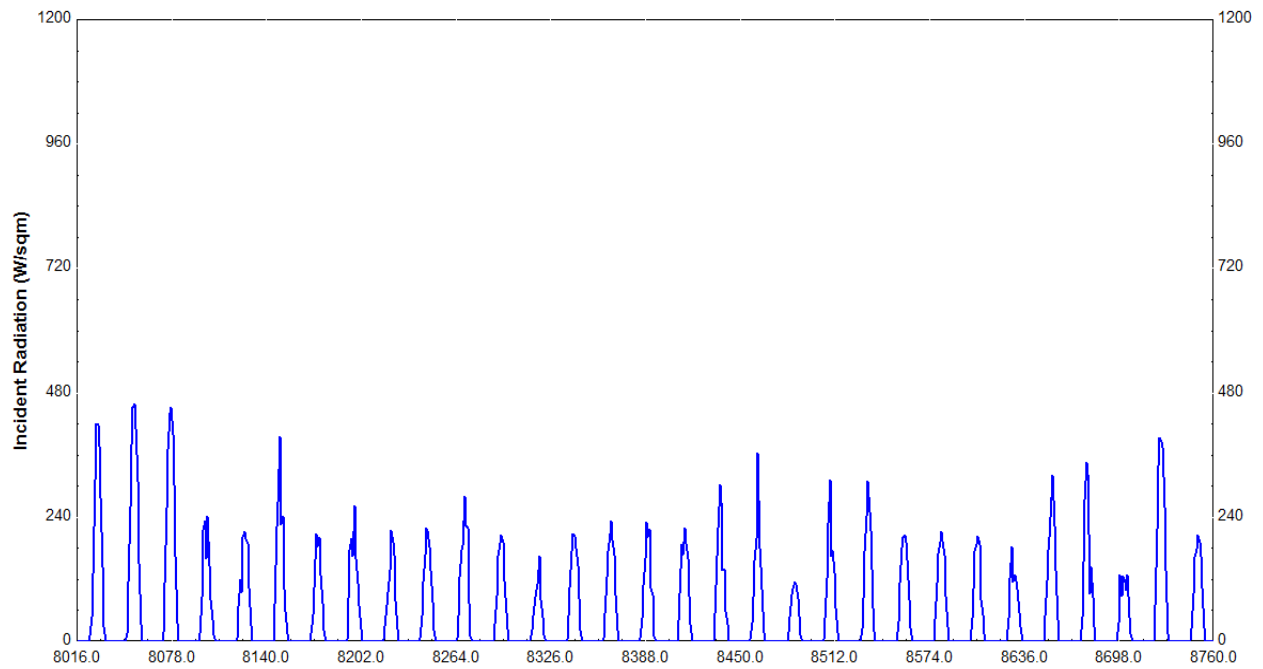

Fig 2 Incident Radiation (W/m^2) for the month of December

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