Performance Evaluation of a DC Direct-Coupled PV System in comparison with a Typical Grid-connected AC System for a Commercial Building

A Thesis Presented

by

Utkarshaa Varshney

to

The Graduate School

in Partial Fulfillment of the

Requirements

for the Degree of

Master of Science

in

Materials Science & Engineering

Stony Brook University

December 2016

Stony Brook University

The Graduate School

Utkarshaa Varshney

We, the thesis committee for the above candidate for the

Master of Science degree, hereby recommend

acceptance of this thesis.

Dr. Alessandra Colli
Scientist, Brookhaven National Laboratory
Adjunct Professor, Stony Brook University

T. Venkatesh
Associate Professor, Graduate Program Director

Dr. Balaji Raghothamachar
Assistant Professor, Department of Materials Science & Engineering

This thesis is accepted by the Graduate School

Charles Taber

Dean of *the Graduate* School

Abstract of the Thesis

Performance Evaluation of a DC Direct-Coupled PV System in comparison with a Typical Grid-connected AC System for a Commercial Building

by

Utkarshaa Varshney

Master of Science

in

Materials Science & Engineering

Stony Brook University

2016

With exponential hike in greenhouse gas emissions and depletion of fossil fuels, advancing renewable energy technology is the best available answer to global demands of clean and green energy. Solar Photovoltaic technology, although implemented worldwide, has a large further scope of improvement to create a fully accepted solar-powered society. One such concept can be a DC based photovoltaic system, which enables the use of DC power directly from solar panels without incorporating inverters.

This thesis is based on a system-level PV project, which evaluates a newly installed DC direct-coupled system which uses DC power for office LED lighting, in comparison with existing conventional DC-AC photovoltaic systems. The main objective is to verify the efficiency of both the PV system setups for defining an optimal solution for energy performance and value proposition in order to propose this configuration for a larger market application and electric utility acceptance, in general.

The system is studied by analyzing real-time data for a period of six months, measured for the various components that constitute the system and further compared on performance and economical grounds.

At the end, it concludes with AC overall being a better and cheaper solution at present. Although, with slight modifications in the current scenario, DC can prove to be a better option in certain specific applications.

Table of Contents

6 References 49

List of Figures

List of Tables

Acknowledgments

It is difficult to overstate my indebtedness towards my supervisor, Dr. Alessandra Colli. This couldn't have been possible without her regular motivation and consistent efforts. She helped me in every sphere of my research. Throughout my thesis-writing period, she provided inspiration, sound advice and great mentoring along with some brilliant ideas. I will always be thankful to her for being an extremely wonderful advisor. I am also thankful to NYSERDA for being the supporting Organisation of this project (Project # 46941)

I would like to express gratitude to Dr. T. Venkatesh and my entire department for always being kind and helping towards me. Without his support, I wouldn't have completed my degree and thesis in due time. Also, I am extremely happy to pay my heartfelt regards to Dr. Balaji Raghothamachar for accepting my invitation to be the reader of my thesis.

On a personal note, I wish to thank my best friend, Ankur Sharma and my friends who are family, Surbhi Agarwal, Sagar Bhardwaj and Piyush Varshney for thoroughly being there for me by extending their emotional support and strength, inspite of being so far. I would also pay thankful regards to my extended family, Varsha Venkat, Sanjana Satish, Niveditha Ramasubramanian, Ashish Kulkarni, Harish Venkat, Vijay Teja, Deepika Peringanji and Medha Bhardwaj for all the love, comraderie and care they provided.

Lastly, I would like to thank my family, especially my parents Mr. Pawan and Mrs. Nisha Varshney and brother Mr. Prakhar, for believing in my abilities and standing beside me, through thick and thin, all across this journey.

1 Introduction

1.1 Background

1.1.1 Global Energy Crisis

Last couple of decades have witnessed "Energy" as the most discussed topic in laboratories, conferences and industries all across the world. Due to rapid industrialization, urbanization, rise in living standards, ever-growing depletion rate of fossil fuels along with their enormous consequences, formulated energy as the biggest global concern. US EIA (Energy Information Administration) statistics 2016 predicts a hike in global energy demand by 48% in 28 years (Fig.1) from 2012-2040. [1] In addition, anthropogenic emissions of carbon dioxide (CO_2) as a consequence of combustion of fossil fuels are expected to increase by 51% in 2040 than in 2012. [1] Although, data shows major growth only in the demands and emissions by developing non-OECD (Organisation for Economic Co-operation and Development) nations due to their strong economic growth and high population, overall results are compelling researchers, scientists and industrialists to ponder, in general.

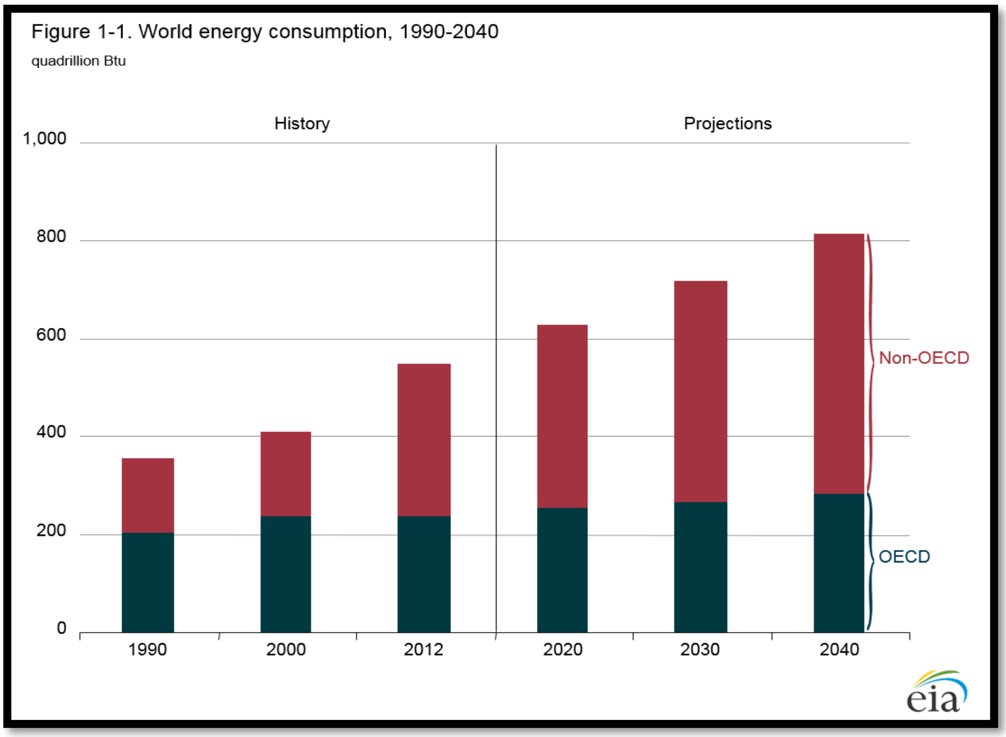

Figure.1. World Energy Demand, 1990-2040, EIA International Energy Outlook 2016

Although there can be a few answers to this energy crisis, like manufacturing of more efficient energy storage (and conversion) systems and increasing awareness to reduce wastage, the only perfect solution will be a direct increase in energy supply as demand increases. On a contrary, with the rise in demands, supply couldn't keep pace due to facility siting difficulties, resource depletion of oil and gas together with environmental constraints. [2] Similar to the demand side, financial factors proved to be the root cause of insufficient supply.

1.1.2 Rise of Renewable/Alternative Energy

"Renewable Energy" emerged as the best possible solution to the two-fold problem of limited fossil fuels and their adverse consequences on the environment. Renewable energy sources such as sun, water, wind and biomass are replenished by nature at a rate higher than their consumption, making them nearly infinite in quantity and eco-friendly at the same time. An issue with the advent of renewable energy was the development of technology to harness them in order to make it inexpensive and accessible. Fortunately, research in this field has evidently grown at a phenomenal rate to increase their usage. International Renewable Energy Agency (IRENA) published a report in 2015 that clearly demonstrates global exponential hike in the installed capacity by renewable energy sources worldwide [3] (Fig.2.) in last one and a half decade.

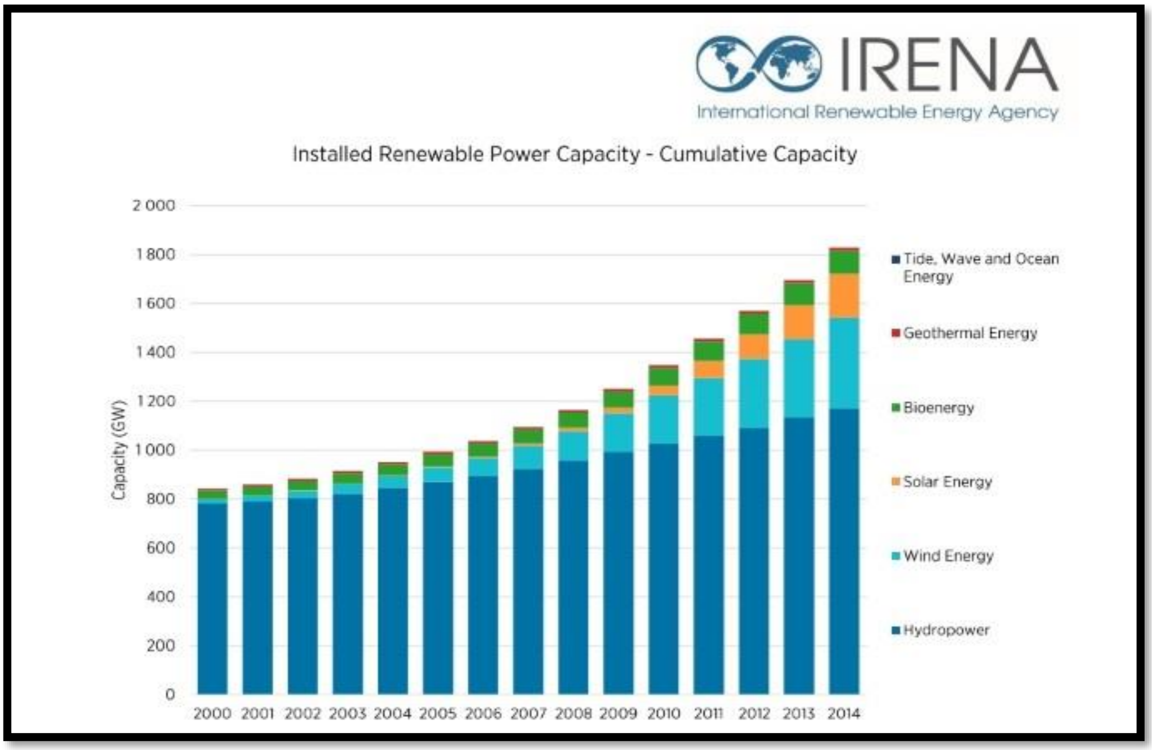

Figure.2. Global Installed Renewable Power Capacity (GW): 2000-2014

1.1.3 Barriers to Renewable Energy

Although there is an evident growth in renewable energy development, there are factors that restricted it in one or all parts of the World [4-6]:

- Geographic factors - Location is the most important factor affecting the growth of a particular renewable energy. A place with a high rainfall cannot be exploited for solar power, likewise mountains and uneven terrain is not feasible for wind farms.
- Government Policies – Countries where the government has supported it, renewables have grown exceptionally well. Renewable Portfolio Standards (RPS), Feed–In Tariffs, Financial incentives such as grants, loans, rebates and tax credits, are a few live examples.
- Economic factors – Finances still exist to be the biggest obstacle in renewable power generation to outsmart fossil fuels. Beginning with issues like development of the technology to harness a natural resource for energy generation to involving huge initial cost of the renewable energy system installations, money has proved to be an issue all across.
- Lack of Information – Even in today's age of technology, customers have insufficient information to make informed choices. In general, electric utilities provide little or no information about their greenhouse gas emissions and carbon footprints. And renewable energy technologies are relatively new, so most people know very little about them.

1.2 Literature Survey and Thesis Overview

With the background knowledge of global energy crisis and renewable energy, an intensive literature review of previous research and results on methods to efficiently harness solar energy, categories of PV systems, advancements and growth in PV industry, government policies encouraging PV, grid integration and an overview on DC systems versus AC systems is provided.

1.2.1 Solar Energy and Methods of harnessing

The Sun provides the Earth with as much energy every hour as human civilization uses every year. It is an ultimate source of energy, which directly/indirectly power all other energies (wind, water, biomass). Probably no other energy supply could conceivably be as plentiful as 120,000 terawatts that the Sun provides ceaselessly and unbidden [7].

In its natural form, Solar radiation is absorbed by Earth's land surface, water bodies and the atmosphere. When hot air containing evaporated water from the oceans rises up, water vapor condenses into clouds, creates rainfall and complete the water cycle. By photosynthesis, green plants convert solar energy into chemically stored energy, which produces food, wood and the biomass from which fossil fuels are derived.

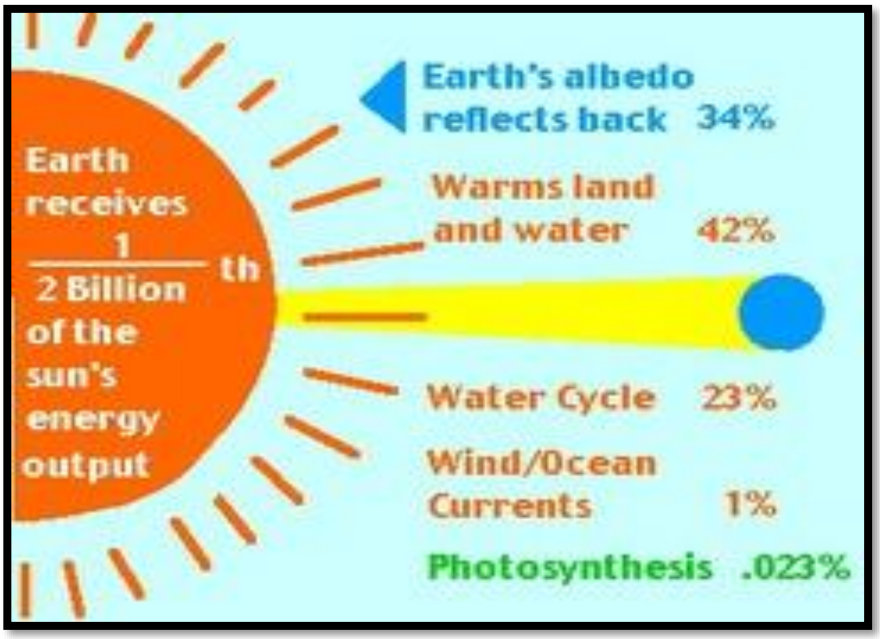

Figure 3. Sun as an ultimate source of energy for life on Earth and its contribution to various lifecycle processes

With advancements in science and technology, harnessing solar power in new anthropogenic forms came into existence. Solar power generation is one of the most sustainable ways available to generate energy as it does not create air pollution or greenhouse gas emissions of any kind during its operation. Till date, there are multiple methods how solar energy can be harnessed; some of the crucial ones are listed as follows:

- Solar Photovoltaics: Photovoltaic (PV) technology is the most popular solar harvesting technique in the market. The technology receives its name from the physical process it employs for direct conversion of light (photons) to electricity (voltage) called the photovoltaic effect that occurs naturally in some semiconductor materials. PV cells (also known as solar cells) convert sunlight into electricity. When incident photons strike and ionize the semiconductor material, it causes outer shell electrons to break free their atomic bonds and due to a semiconductor structure, the electrons are forced in one direction creating a flow of electric current. [8-9] Many solar cells are connected electrically to form a solar panel that can produce electricity in the range of a few hundred watts. Multiple panels together form solar arrays and large-scale PV arrays (referred to as solar farms) can generate commercial electric power in the range of megawatts. PV systems these days can power everything from small calculators and road signs to residential and large commercial businesses to space satellites and electrical grids.

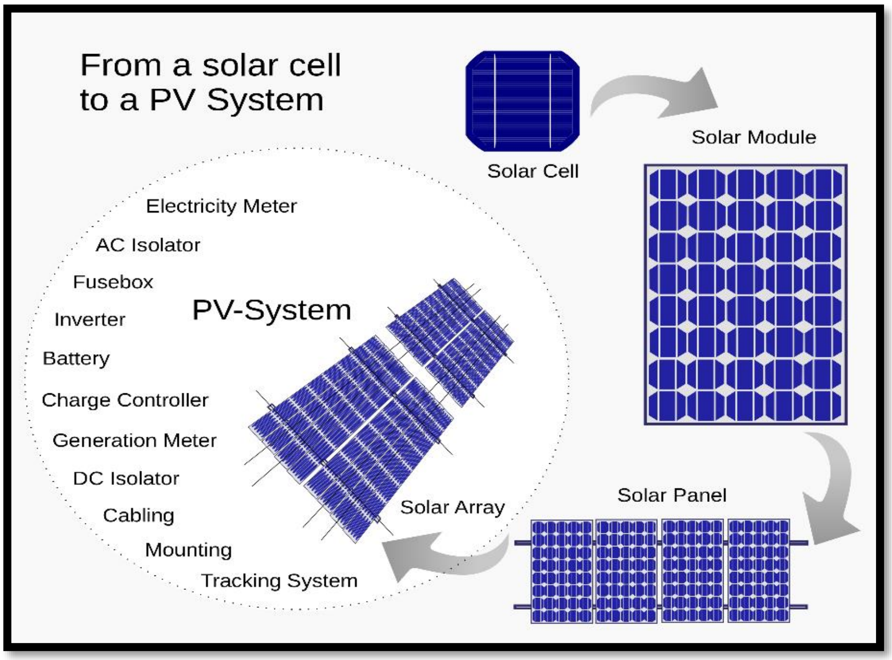

Figure 4. Semiconductor materials like Silicon are used to make solar cells which further creates a solar panel/module. Multiple modules make an array and a large solar array makes a photovoltaic system.

- Solar Thermal: Solar thermal energy is a technology which converts sunlight to thermal energy (or heat) using solar collectors. Solar thermal electric energy generation concentrates the light from the sun to create heat which is used to run a heat engine that turns on a generator to produce electricity. The working fluid that is heated by the concentrated sunlight can be a liquid or a gas. Working fluids include water, oil, salts, air, nitrogen and helium for various engine types including steam engines, gas turbines, Stirling engines etc. [10] Solar collectors are generally categorised into low, medium and high temperature collectors. Other applications of solar thermal energy are solar cooling, ventilation, drying, cooking and distillation.
- Passive Solar Energy: Passive solar heating is one of several design approaches collectively called passive solar design. When combined properly, these strategies can contribute to the heating, cooling and daylighting of nearly any building. [11] Taking advantage of the local climate, passive solar design uses a building's directional orientation, window placement and glazing, shading, thermal insulation and thermal mass to efficiently manage solar heat inputs in a house/building. [12]
- Artificial photosynthesis: The process of artificial photosynthesis seeks to replicate the natural phenomenon to make fuel from solar energy, but scaled up to meet the energy demands of a modern technologically driven society. While plants accomplish their tasks using chlorophyll to capture the required sunlight, proteins, and enzymes that are then converted to energy, the challenge of artificial photosynthesis is in trying to oxidize water to oxygen to jump start the physical process that produces the desired chemical reaction. Research has been concentrated on developing a catalyst to accomplish this goal and the past decade has witnessed some promising developments in this domain due to advancements in nanotechnology. [13] Among a few successful projects, scientists at Caltech created a device with an efficiency of 10% to convert

sunlight into fuel and researchers at Lawrence Berkeley National Laboratory created a system but with the efficiency of only 3%. Most impressive results came from Monash University, Australia with an energy-efficiency of 22.4%. [14]

1.2.2 Modern PV: Growth and Categories

Photovoltaic industry has been one of the most dynamic industries in the World. The advancement it has witnessed in past couple of decades is quite unbelievable. Once driven by financial incentives in developed nations, PV has started to progress in developing countries, as an answer to a crucial need of electricity. While in developed countries, PV comes in direct competition with existing plants from incumbent utilities; in emerging countries, PV already helps to satisfy a growing need for energy in general and electricity in particular. [15] With an impressive growth of about 50 GW last year, PV industry now proudly boasts a global installed capacity of 227 GW [16] and a forecast of 756 GW in less than a decade by 2025. [17]

Among a few critical drivers, this tremendous market growth is the result of reduction in the cost of solar panels by approximately 227 times in last 40 years [18] (Fig.5) On a global front, China still remains the world's biggest market, heading towards 15.3 GW, well ahead of the EU and the U.S. with more than 7 GW each. The IEA PVPS describes India, with 2 GW, as "the rising star in the PV sector" and the annual PV contribution to electricity demand had passed the 1% mark, with Italy at the top of the list at around 8%, followed by Greece at 7.4% and Germany at 7.1%. The overall global PV contribution amounts to around 1.3% of the world's electricity demand [16]

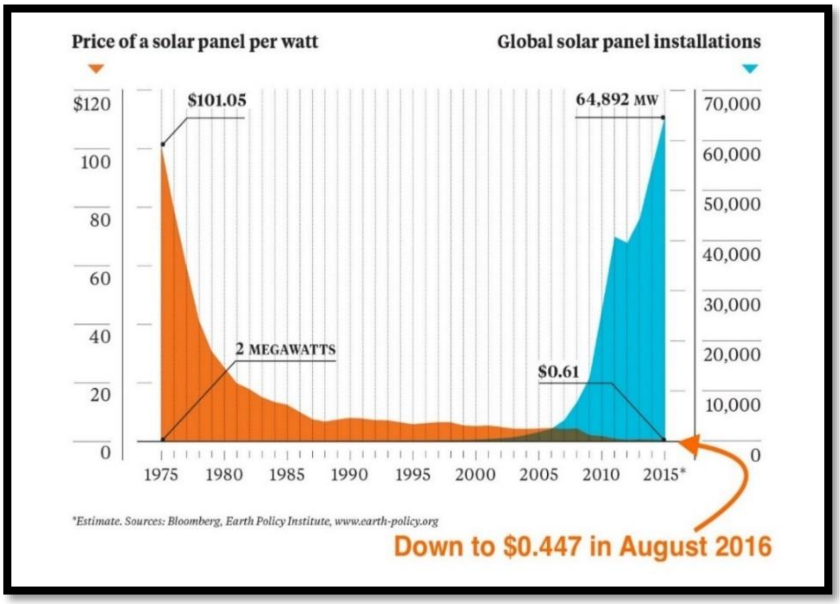

Figure 5. As price of solar panels dropped drastically, solar installation rates increased exponentially

Categories of PV systems:

1. Grid Connected(Tied) or utility interactive PV systems- This kind of photovoltaic system is designed to operate in parallel with the electric utility grid.

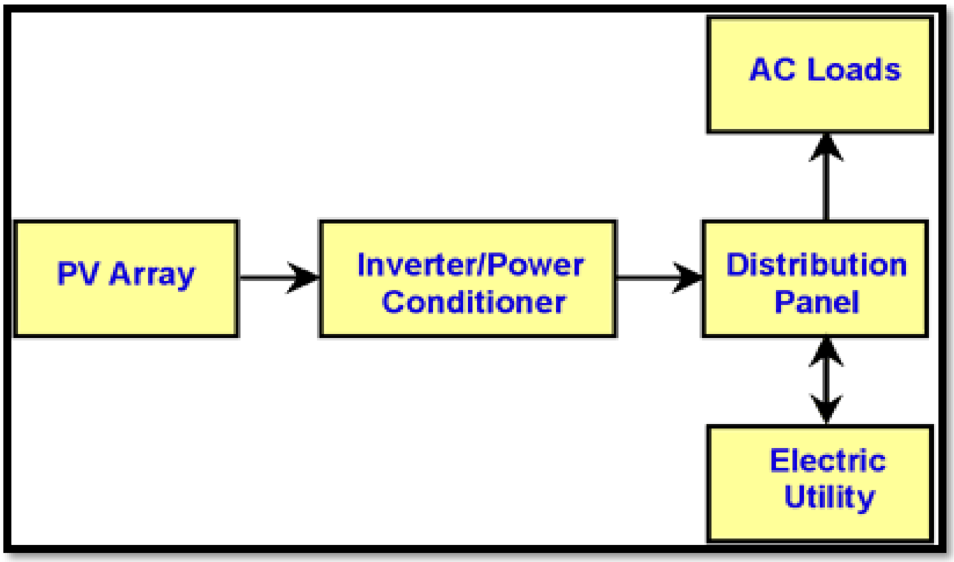

Figure 6. Block diagram of a grid-connected PV system

The primary component of such a system is an inverter or power conditioning unit(PCU) which converts DC power produced by the PV array into grid- required AC power consistent with the voltage and power quality requirements of the utility grid. Since the inverter produces electricity in sync with the grid, inverters in these systems are often referred to as "synchronous" inverters [19] On sunny days, when the array generates more energy than required, it automatically flows to the grid. In the nights and during the periods when electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility.

2. Stand-Alone PV systems- A simple stand-alone PV system is designed such that it produces power in daytime when the sun is shining to charge batteries to be used at night when the sun is unavailable. Such a PV system usually employs rechargeable batteries to store the electrical energy supplied by the PV array. Stand- alone systems are ideal for remote and rural areas and at places where other power sources are either impractical or are unavailable. Many companies now offer portable solar kits that allow you to generate your own reliable and free solar electricity anywhere you go, even in hard to reach locations.

    - The simplest kind of stand-alone PV system is a ***DC direct-coupled system***, where the DC output of a PV module or array is directly connected to a DC load. Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled systems. In special cases, an electronic DC-DC converter, called a maximum power point tracker (MPPT) is used between the array and load to help better utilize the available array maximum power output. [20] System installed for this project also employs an MPPT and is discussed in second chapter in detail.

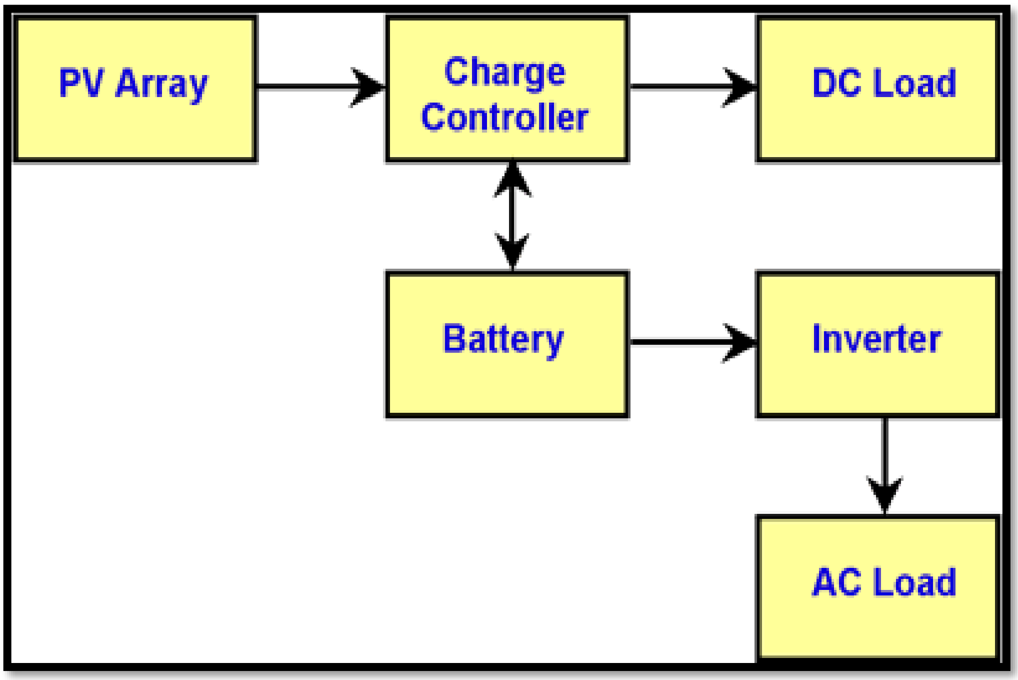

Figure 7. Block diagram of a stand-alone PV system with battery backup to power DC and AC loads [20]

1.3 Thesis Overview & Insights

Electricity prices in NY averages to 18 cents per kilowatt hour (kWh), being the third highest in the nation and almost 50% more than the country average of 12.68 cents per kilowatt hour for residential purposes. [21] Inspite of being one of the highest hydropower generating states, New York has been suffering with high electricity rates for a long time and still continues to do so. On top of these prices, Electric power prices in New York City, Long Island and the Hudson Valley are more than the rest of the state, especially during mid-afternoons due to transmission constraints on moving power into the New York City area.

The transmission line issues are attributed to New York State's electrical grid congestion problem. U.S. Department of Energy, in its first report in 2006, designated eastern New York as one of only two areas in the country as Critical Congestion areas in its most severe designation. [22] One reason of this congestion is the ever-increasing demand of electricity, to be delivered by one or a group of transmission lines, often exceeding the capacity of the transmission facility. A solution to relieve grid congestion can be solar PV integration with the national grid, it can help New Yorkers by enhancing system reliability, flexibility and efficiency which in turn will lead to reduction in operating cost of the system. [22]

For successful integration of photovoltaic systems with the grid, the first step is to improve the solar capacity. New York, inspite of being the third most populous state in United States, stands seventh (638 MW) in terms of solar installed capacity [23]. Since the state has a strong solar potential, recent investments and favourable government policies are trying to lift it to a brighter future. The New York Public Service Commission (PSC) recently announced a 10-year $1 billion commitment to develop a self-sustaining solar market in New York State that will lead to 3,000MW of PV installations across New York State by 2022. PSC's Reforming the Energy Vision (REV) Initiative aims to shape regulatory changes to promote energy efficiency and increased use of renewable energy state-wide. Other state policies to promote solar investments include a feed-in tariff through Long Island Power Authority (LIPA) and net metering. [24]

An issue of concern with the integration of PV systems with utility grid is the conversion of DC to AC power before transmission. The output of a PV system is direct current (DC) and since almost all the prevailing power systems in the World are based on alternating current (AC), energy system infrastructures that wish to incorporate solar photovoltaics, must first convert the produced DC power to AC. This adds complexity and in turn reduces efficiency of the system due to additional power conversion units. Furthermore, a large number of DC consuming appliances such as computers, desktops and televisions are being used in our residential/commercial buildings. The power supplied to these devices must then be further converted, from AC to DC adding further losses to the system. [25]

Utilization of DC power for commercial and residential loads is not entirely a new concept. Earlier, authors have compared AC versus DC power for distribution within a building [26]. The main idea behind was that DC may allow a lesser number of power conversion steps in the system. The author concludes that DC is not feasible because of losses occurring in AC-DC conversion for each house. However, DC proved to be superior if local DC generation is present. Researchers compare of AC and DC distribution systems starting from the grid [25] by varying efficiencies of power electronic converters and voltage levels of the system. They also showed that at very high efficiencies of DC/DC converters and at higher voltage of DC distribution, it becomes favourable. There is another comparison of AC and DC for low and medium voltage distribution systems. [27] In the end, this paper concludes that DC systems can perform better if the losses in semiconductor devices are reduced by half. Some authors [28] discussed feasibility of a DC system for commercial facilities by assuming that the components of DC system are available in the market with the conclusion that 325V is most suitable voltage for distribution within the facility, both technically and economically.

Following the historical trends, grid integration of DC coupled PV can be an advantageous option [29] as it can provide:

- More Flexibility- Use of DC power directly gives more flexibility to install and scale up renewable and hybrid renewable energy systems.
- Efficient Power Transfer- After generation, the high voltage DC transmission implies lower current in the connecting wires which improves the power transfer efficiency.
- Lower Costs - DC power eliminates the use of a separate inverter for each energy source. Also, due to reduced electrical current in the wires, the cost of transmission wiring is reduced.

Although the advantages of using DC are multiple, there have been issues associated with its adoption, a few common ones are as follows:

- It's quite late for the developed countries as it will be too expensive to change the already established AC standards to DC. However, adoption of DC micro grid can be an answer for developing nations where grid standards are still in the stage of improvement.
- DC is very difficult to step up and transmitting DC power at low voltage is expensive and difficult.
- The frequency of DC Power is 0 Hz. So, using it directly can cause extreme consequences, if not properly managed.

In the current project, we propose a DC system for the sole purpose of powering an office with LED lights. With detailed analysis of the system, we hope to conclude that DC can be a practically feasible option for small- scale applications. The focus is on a recently installed DC- direct coupled PV system to power a Suffolk County (New York) office building at Yaphank, NY which runs on DC power directly from the panels, avoiding the use of inverters for converting DC to AC. A novel approach for the purpose of improving the efficiency of existing systems where instead of using multiple converters to convert DC to AC and further AC to DC, a system that will solely be based on DC is proposed, eliminating the need of two sets of converters for each DC load. The main objective is to evaluate if DC systems are better potential candidates than the conventionally installed ac systems, both in performance and economics for small projects.

Figure 8. PV system installed for the project, on the roof of one of the Suffolk County buildings powering LED based lighting system located in Yaphank, NY

The project is accomplished under the umbrella of Brookhaven National Laboratory (BNL). For comparison, a conventional DC- AC solar photovoltaic system is also installed on the same building and is under consideration. A conventional AC powered lighting system is also being monitored for evaluation. For better results, we studied the system thoroughly and documented six months of data (April 18, 2016- Oct 18, 2016) to analyse total energy savings and value propositions available from DC system compared to a conventional DC-AC solar energy system with a concept that might reduce the cost involved and make it simpler to operate and analyse. The DC system is compared with AC system both in terms of performance (in reference to Performance Ratio, efficiency and Fill Factor) and economics (in context of Levelized Cost of Electricity (LCOE)) in order to present a concrete conclusion.

1.4 References

1. U.S. Energy Information Administration (EIA), International Energy Outlook 2016 (Washington, DC: May 11, 2016), https://www.eia.gov/forecasts/ieo/world.cfm
2. U.S Environmental Protection Agency, EPA's Position on the Energy Crisis, https://www.epa.gov/aboutepa/epas-position-energy-crisis
3. International Renewable Energy Agency (IRENA), Renewable Energy Capacity Statistics 2015
4. I. Malika, G. Siyalb, A. Abdullaha, A. Alamc, K. Zamanb, P. Kyophilavongd, M. Shahbaze, S. Balochb, T. Shamsb, "Turn on the lights: Macroeconomic factors affecting renewable energy in Pakistan", Renewable and Sustainable Energy Reviews, Volume 38, October 2014, Pages 277–284
5. Z. Esin, "A Feasibility Study on Renewable Energy Generation", http://ese.wustl.edu/ContentFiles/Research/UndergraduateResearch/CompletedProjects/WebPages/sp10/ZeynepEsin/Factors%20Affecting%20Renewable%20Energy%20Development.html
6. Powerful Solutions: Seven Ways to Switch America to Renewable Electricity, UCS, "Barriers to Renewable Energy Technologies", 1999
7. Oliver Morton, Solar energy: A new day dawning? Silicon Valley sunrise, Nature 443, 19-22 (7 September 2006) | doi:10.1038/443019a
8. Solar Photovoltaic Technology Basics, NREL
9. Photovoltaic (Solar Electric) Solar energy industries association
10. Solar Thermal vs. Photovoltaic, Solar Thermal Energy: An Industry Report, http://www.solar-thermal.com/solar_vs_pv.html
11. J. Fosdick, Passive Solar Heating, Whole Building Design guide, US Department of Energy
12. Solar Energy in New York, Large and Small Systems for Heat and Power: NY state Department of Environmental Conservation, http://www.dec.ny.gov/energy/43231.html
13. Photosynthesis Education, Artificial Photosynthesis, http://photosynthesiseducation.com/artificial-photosynthesis/
14. T. Maverick, Artificial Photosynthesis to Power the Future, Wall Street Daily-Feb 10, 2016, http://www.wallstreetdaily.com/2016/02/10/artificial-photosynthesis-energy/
15. 2015 Snapshot of Global Photovolatic Markets, Report IEA PVPS T1-29:2016, International Energy Agency
16. EDGAR MEZA, IEA PVPS: Installed PV capacity at 227 GW worldwide PV magazine: Photovoltaic markets and technology
17. Solar Photovoltaic (PV) Market, Update 2016 - Global Market Size, Market Share, Average Price, Regulations and Key Country Analysis to 2025, June 2016
18. Earth Policy Institute, http://www.earthpolicy.org/

19. Photovoltaic Systems: All About Grid-Connected PV Systems, http://www.motherearthnews.com/renewable-energy/solar-power/photovoltaic-systems-grid-connected-ze0z1202zhir
20. Types of PV systems, Solar Electricity Basics: Florida Solar Energy Centre, http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/types_of_pv.htm
21. Electric Power Monthly, Average Price of Electricity to Ultimate Customers by End-Use Sector, July 2016, US EIA
22. AC Transmission Upgrades, 08/27/15; New York State Department of public service
23. Top 10 Solar States, SEIA
24. New York State Solar Policy, SEIA
25. M. Starke, L. Tolbert, B. Ozpineci, "AC vs. DC Distribution: A Loss Comparison", 978-1-4244-1904-3/08/$25.00 ©2008IEEE
26. D. Hammerstrom, "AC versus dc distribution systems --Did we get it right?" Power Engineering Society General Meeting, pp.1–5, June 2007
27. D. Nilsson, A. Sannino, "Efficiency analysis of low- and medium voltage dc distribution systems," Power Engineering Society General Meeting, vol. 2, pp. 2315 – 2321, June 2004
28. A. Sannino, G.Postiglione, M. H. J.Bollen, "Feasibility of a dc network for commercial facilities," IEEE Transactions on Industry Applications, vol. 39, no. 5, pp. 1499 – 1507, Sept.-Oct. 2003
29. RE bus DC microgrid, RE bus alliance, http://rebuspower.com/owners.shtml

2 Installed System: At a glance

2.1 Components that constitute the System

The PV plant setup is divided into 3 portions: the two strings on the left are DC- direct coupled and are composed of 7 panels each; the portion on the right is a typical AC grid connected photovoltaic installation that has 38 panels, divided into three strings, one with 10 modules and two with 14 modules each.

2.1.1 DC Powered Lighting System

- Solar Modules: The photovoltaic system incorporates polycrystalline Silicon modules by Trina Solar with a power rating of 235W and a maximum efficiency of 14.4%. Module dimensions and specifications at Standard Test Conditions STC (air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C) are shown below. [1]

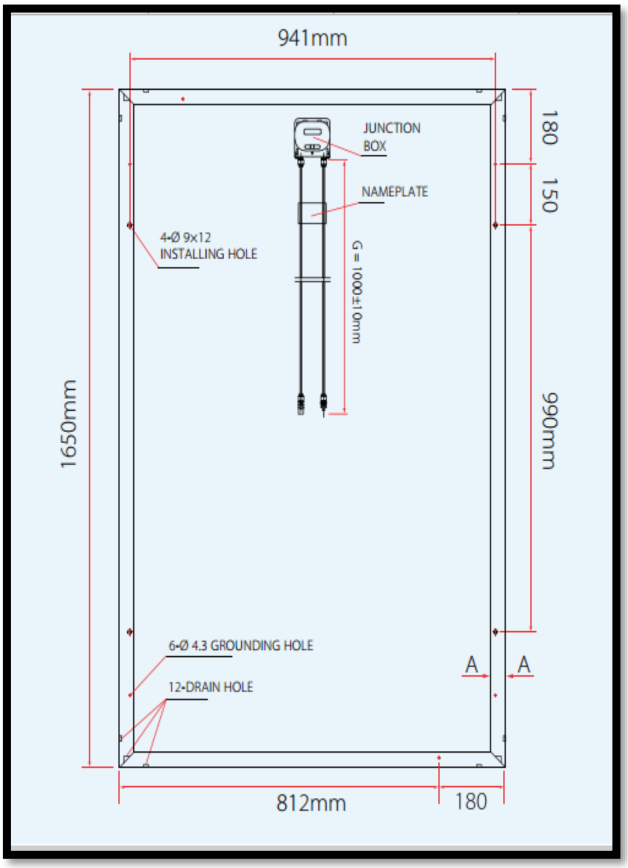

Figure 1. Dimensions of Polycrystalline modules incorporated in the system [1]

Electrical Parameters	**Values**
Peak Power	235 W
Open Circuit Voltage	37.2 V
Short Circuit Current	8.55 A
Max. Efficiency	14.4%

Table 1. Specifications of Polycrystalline Silicon modules at STC [1]

- Maximum Power Point Tracker (MPPT) Controllers: MPPT is an integral part of the DC side of the system. The output of panels is fed into MPPT controller in order to regulate the power before feeding it to the light load.

  It is an electronic DC to DC converter which optimizes the match between the solar array (PV panels) and the load by reducing a higher voltage DC output from solar panels down to a lower voltage to meet the load requirements. MPPT works through a maximum power point algorithm that continuously adjusts the operating voltage of the array to find the maximum power point. As the voltage change, input power is measured and compared to the amount of input power noted at the previous operating voltage. The unit will continue adjusting the operating voltage to stay on the maximum power point. This is an important component as maximum power point varies throughout the day due to array temperature, shading, and sunlight intensity. Table 2 elaborates the specifications* of the equipment as follows:

Electrical Parameters	**Values**
Output Voltage	24.5 VDC
Maximum Continuous Output Current	63 ADC
Maximum Continuous Output Power	1600 W
Efficiency	97.5% peak at approx. 60% load
Quiescent Power	0.7 W

Table 2. Specifications of Maximum Power Point Tracking Controllers installed in the system*

- Power Server Module (PSM): PSM serves as a heart of DC direct coupled lighting system. It accepts DC power from MPPT (and AC from the grid, when panels are insufficient to meet the demands) and convert it to lighting-ready 24-volt DC in the most efficient possible way. The PSM takes input from sensors and most efficiently allocate energy towards lighting. It has 16 channels, each rated for 100 watts at 24 volts in order to provide power and control for up to 32 lighting fixtures. * Total voltage and current produced by the 2 strings of the PV arrays are dedicated for powering the intended DC loads.

- Inverter: In order to continue providing light to the office and avoid power outage on rainy (and not so sunny) days, DC side also employs inverters that allow to supply energy from the grid whenever solar arrays are not self-sufficient to do so. These inverters take AC power from the grid and feed into maximum power point tracking controllers which pushes them to power server module and operate the lights.

  For the present project, single-phase string inverter is installed to get the most efficient energy harvesting and transformer less operation with efficiency as high as 97% [2]. Being on the walls outside the building, it is designed as a completely sealed unit to withstand the harshest environmental conditions. One of the key benefits it possess is a dual input section to process two independent input strings. The voltage and current providing excess power from the PV array serve the DC LED lighting system that is exported to the electric grid, at the input and output of the dedicated inverter.

- DC drivers: DC drivers are a crucial part of the project, especially as in this equipment; we intend to see the possibility to make the proposed system better than the existing AC systems with efficiencies as high as 96%. Input of the dc driver is 24V DC which it steps up to 36 V DC reducing the current up to 1.11 A.

Electrical Parameters	**Values**
Input Power	170-305 V AC single phase; 13.5 A max.; 50/60 Hz
Output Per Channel	24 VDC ± 3%, 95 W maximum current limited to 3.96 A continuous, Rated impulse current: 80 A for 0.2 msec
Efficiency	94% max.

Table 3. Specifications of Power Server Module*

2.1.2 AC Powered Lighting System

- Panels: The AC powered lighting system constitutes similar kind of solar panels as the DC side, only with a different arrangement. AC side constitutes a total of 38 modules, distributed into three strings, one with 10 panels and the other two with 14 panels each. They are polycrystalline Silicon modules by Trina Solar with a power rating of 235W and a maximum efficiency of 14.4%. Module dimensions and specifications at Standard

Test Conditions STC (air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C) are demonstrated and mentioned in fig. 1 and table 1 respectively.

- Inverters: For AC photovoltaic systems, DC-AC inverter is the most important component and so the conversion efficiency is predominant to the economics and operation of the total PV system. Extremely high efficiency, not only in the nominal power range but also under a part-load condition is a requirement for PV inverters in grid-connected as well as in stand-alone systems. [3] For grid-connected systems, since the inverter produces electricity in sync with the grid, inverters in these systems are often referred to as 'synchronous' inverters. On sunny days, when the array generates more energy than required, it automatically flows to the grid. In the nights and during the periods when electrical loads are greater than the PV system output, the balance of power required by the loads is received from the utility grid.

  For this project, Sunny Boy inverter (by SMA) is used to serve the purpose. [4] Maximum power production is derived by wide input voltage and operating temperature ranges. Multiple inbuilt MPPTs mitigate the effect of shade and allow the installation at challenging sites. The AC voltage, current and power leaving the inverter is being directed to the electric network.

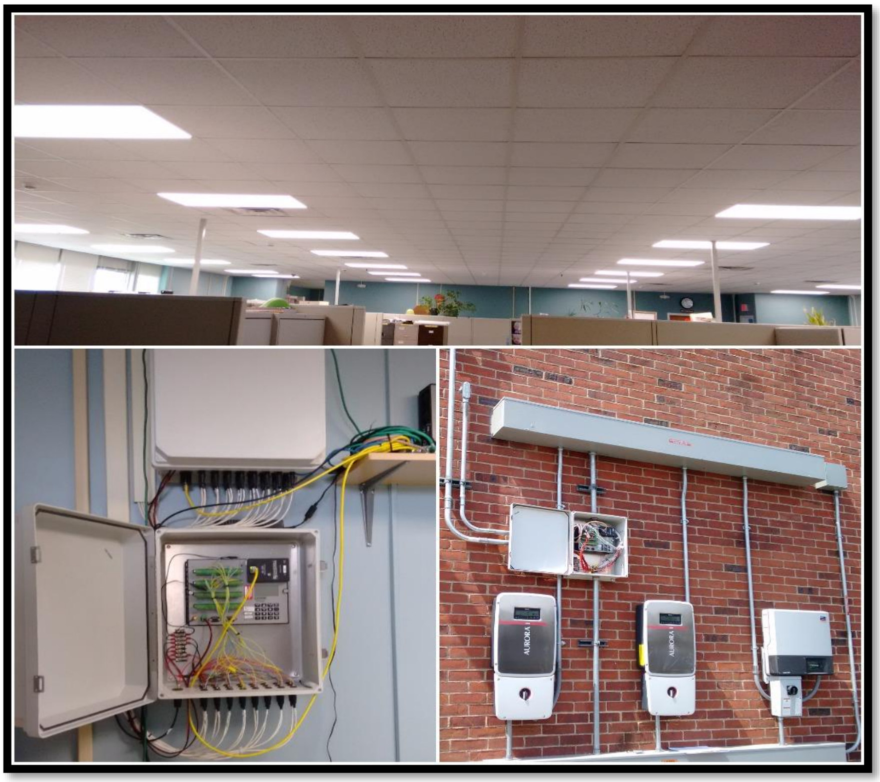

Figure 2. LED lights in the office [top], installed set of data loggers [down-left]; Inverters, temperature and power sensors outside the building [top-right]

- AC Drivers: AC drivers serve the purpose of constant current dimming and belong to Start Lighting. Table 4 mentions the general specifications of AC drivers installed in the system.

Electrical Parameters	**Values**
Input voltage rating	100Vac ~277Vac
Input current	<0.25A(rms)/230Vac
Maximum Output Load	46 W
Operating temperature	-20ºC ~ 50ºC

Table 4 Start AC Driver specifications *

2.1.3 Data Acquisition System

- Data loggers: The data loggers incorporated in the system are from Campbell Scientific [5]. There are a total of 3 data loggers namely a CR1000 and two CR3000 collecting all the meteorological and electric variables to be measured on a continuous basis. They are connected to a local computer to store data and allow BNL to check it remotely for in time detection of malfunctions.

Figure 3. CR 1000 (left) and CR3000 (right) from Campbell Scientific

- Irradiance Sensor: Kipp & Zonen SP Lite 2 silicon pyranometer serves as an irradiance sensor for the system [6]. It is located at the site to detect the irradiance on the modules, at an inclination of 22.5 degrees from the horizontal plane and facing south. It can be used under all weather conditions to measure solar energy received from the entire hemisphere (with a field of view of 180°) to give a voltage output that is proportional to the incoming radiation.

Figure 4. SP Lite2 irradiance sensor for irradiance detection

- <u>Temperature sensor:</u> The temperature sensors, both for the ambient air and PV modules are from Omega, respectively. A fast response copper tip RTD sensor 100 Ohm, class A DIN, with platinum element, and a surface-mount Thermistor sensor. There is one location for ambient temperature measurement sensor and 3 locations for PV module temperature measurement sensors in the system.

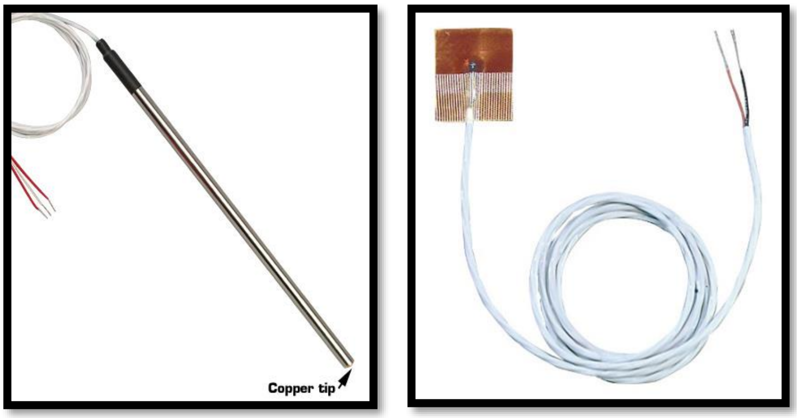

Figure 5. Fast response copper tip RTD sensor 100 Ohm, class A DIN, with platinum element for ambient temperature (left) and surface-mount Thermistor sensor for PV module temperature (right)

- <u>Electric sensor:</u> A total of 66 electric sensors (33 for voltage and 33 for current) are installed for voltage and current measurements throughout the system. In addition, two power sensors are installed at the output of AC inverter and at the feeding point of the AC light group.

- <u>Power supplies and cables:</u> Power supplies rating 12 V and 24 V are employed for providing power to sensors and data loggers. Cables, connectors and fuses are also used wherever required.

2.1.4 Lighting Arrangement

- LED lights: The Light Emitting Diode(LED) lights installed in the office are in general, fed directly by the DC system when 24 V DC power output from PSM reaches the DC panel controller, whose output has two cables going to each panel. At times when the sunlight is not sufficient, AC power from the grid enters PSM and accomplishes the lighting purpose by AC panel controller.

  The specifications of both the controllers are as follows:

Electrical Parameters	**DC Controller**	**AC controller**
Size	603*1213 mm	603*1213 mm
Wattage	46 W	46 W
Input Voltage	24 V DC	100 – 277 V AC
T_a	-25°C to 40°C	-25°C to 40°C

Table 5 Specifications of LED light controllers*

- Light Fixture Measurements: The luminous flux density is measured on a non-continuous basis. The illuminance on the work-plane is measured through a LED specific light meter from Extech (model LT 45 (Fig. 6)). Additionally, in order to account the possible decay of LED spectrum in time, a spectrometer (Ocean Optics USB2000) is used to measure the spectrum of light, already owned by Brookhaven National Laboratory.

Figure 6. Extech LT 45 light meter for LED lights (left), Ocean Optics USB2000 Spectrometer (right)

2.2 Monitoring Approach and Measured Variables

For effective monitoring of the system, the approach chosen taken is to install research-grade instruments to measure solar irradiance, together with current and voltage at various positions in the system, starting from the output of panels to the final input of the LED lights, including inputs and outputs of each intermediary equipment. The electricity delivered to and absorbed from the grid is also monitored for comparison purposes. All the data is collected by an automated data collection system. The database resides on a locally installed computer, which is also connected for remote access from BNL.

Fig. 7 shows the system architecture with all the measurement points indicated.

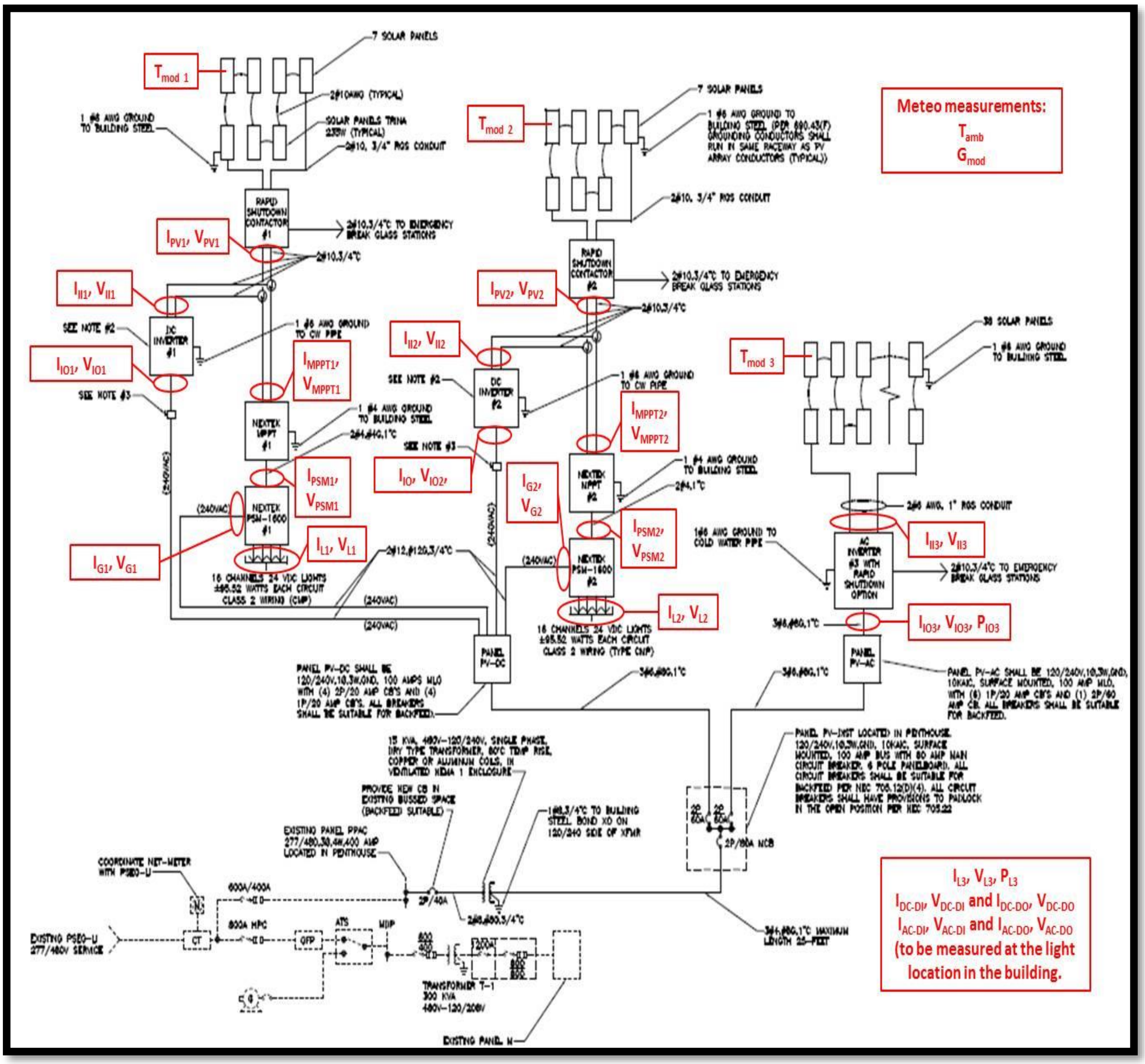

Figure 7. Reading points for meteorological and electrical variables

Data Acquisition System (DAS) comprises of a group of components that together convert analog signals into digital values for processing the data. [7] The data acquisition system proposed for this project is capable of sampling, measuring and storing data twice per minute (every 30 sec). The twice per minute data is further averaged over 15 minute intervals as appropriate for long-term storage and simpler for data analysis and calculations. Fig. 8 shows the system layout schematics.

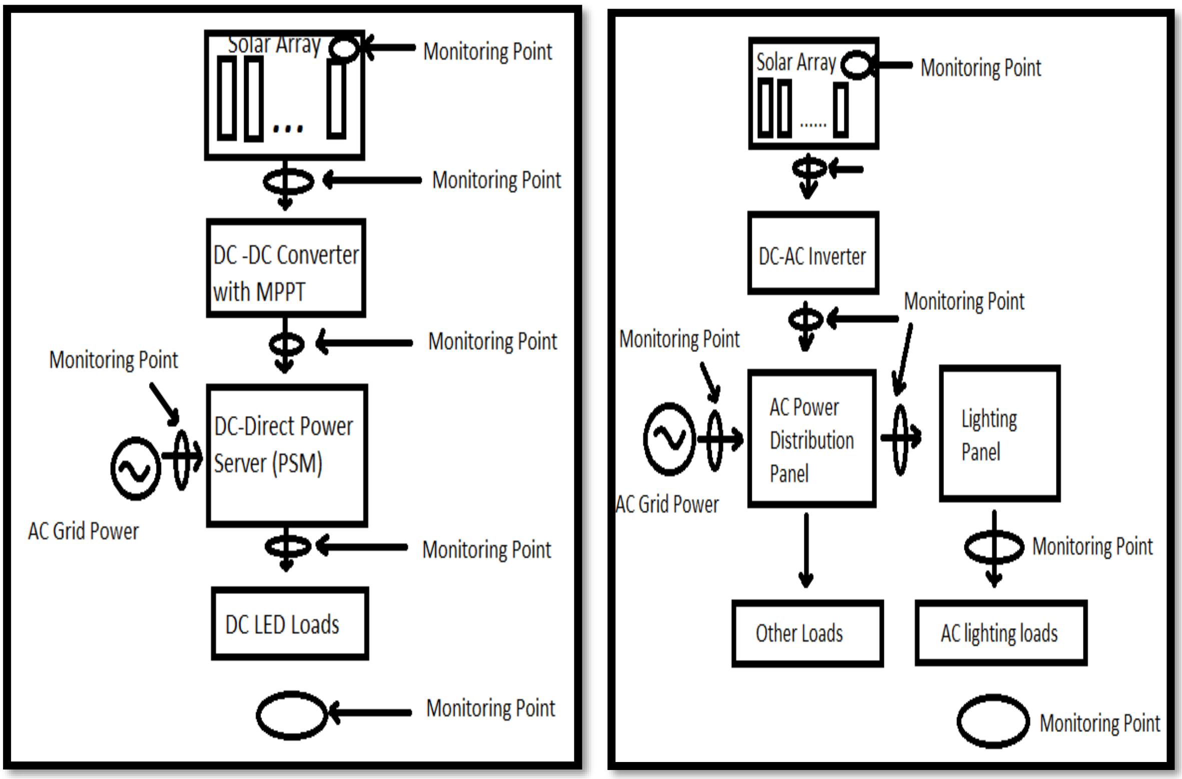

Figure 8. System Layout Schematics, DC-Direct Coupled System (left), DC-AC Conventional System (Right)

**Note:* For confidential reasons on research grounds, the names and details of manufacturers cannot be revealed.

2.3 References

1. TSM-PC05, TSM-PA05; Trina Solar Datasheet- June 2012, US
2. Aurora Uno General Specification, Power One- A member of ABB group
3. Antonio Luque and Steven Hegedus, *Handbook of Photovoltaic Science and Engineering*
4. Solar Inverters – SMA America, http://www.sma-america.com/products/solarinverters.html
5. Dataloggers and Data Acquisition Systems- Campbell Scientific, https://www.campbellsci.com/dataloggers
6. SP Lite2 Pyranometer- Kip and Zonen since 1830, http://www.kippzonen.com/Product/9/SP-Lite2-Pyranometer#.V_xQTfkrLIU
7. Wikipedia – Data Acquisition, https://en.wikipedia.org/wiki/Data_acquisition

3 Economic Analysis

With increase in global concerns regarding environmental damage by coal and other fossil fuels, renewable energy came as a solution and its adoption has matured with time and technical advancements, yet there are multiple barriers towards its absolute consumption, restricting the exploitation to its full potential. Cost effectiveness of new technologies is one of the most crucial factors with almost all renewable energy technologies (RETs), which however heaped miles in the past few decades but still has a long way to go.

3.1 Solar PV Cost Analysis

Solar photovoltaic (PV) technology is one of the fastest growing RETs in the world [1, 2] with predicted capacity of 756.1 GW by 2025 from 0.26 GW in 2000 [3, 4]. However, the market growth is tremendous, attributed to technological innovations and industrial advancements, economics still persists as the biggest hindrance in the vision of a complete solar powered society [5]. Despite of multiple tax incentives and rebates, solar power still hasn't become a successful contributor towards World energy production (only 0.6% of total U.S generation is by solar [6]).

In general discussions, the tipping point in photovoltaic technology can be achieved with grid parity [7-9], considering the electricity rates from the grid are increasing, along with decreasing prices of PV. Grid parity occurs when the cost of electricity from a renewable energy source is equal or lesser than the purchasing price of electricity from utility grid. Although, about 102 countries already have achieved grid parity [10] the hurdles of expensive balance of system, installation prices and indirect costs still persists in most of the developing and underdeveloped nations, where it still suffers the dismissal for being too hard on the pocket.

The financial stability of alternative energy projects can be evaluated using multiple methods, the most common for PV are as follows:

- Price per peak watt ($\$/W_p$)

$$\$/W_p = \frac{Capital\ Costs\ (in\ \$)}{Peak\ Power\ Output\ (in\ W)}$$

- Levelized Cost of Electricity (LCOE, \$/kWh)

$$\text{LCOE (\$/kWh)} = \frac{Total\ Lifetime\ Costs\ (\ in\ \$)}{Lifetime\ Electricity\ Generation\ (in\ kWh)}$$

- ✓ Note: A useful existed correspondence for standard assumptions is that $\$1/W_p$ is equivalent to \$0.06 /kWh.

Among the two, the LCOE is more often considered an important metric to assess the cost competitiveness of electricity generating technologies, especially solar PV [11-13]. Since it takes into consideration the total operating costs in the lifetime of a system, LCOE enables comparison between significantly different technologies, but it can also be used to compare the variations in cost of energy within the same technology. It helps in recognizing the options related to employing different components or system design, which can be further explored and evaluated to see what impact they have on LCOE, in order to check the areas where cost-saving research would be valuable.

LCOE is a crucial metric than dollar per peak watt as for same \$/W value of a PV plant, it can significantly vary, depending upon factors like regular maintenance costs, capacity factor (varies with location, solar irradiance values and weather conditions), lifetime and interest rates. Since LCOE is a result affected by a lot of factors, a number of assumptions are made before calculating the LCOE. The authenticity of these assumptions, in turn, affects the correctness of the output value.

3.2 Drivers of Levelized Cost of Electricity (LCOE)

Since the LCOE depends upon a lot of factors, making suitable assumptions for concerned parameters is a crucial step to achieve numbers that can be trusted both by performance and finance. [14-16]

A few important parameters that should be taken into consideration are as follows:

- Capacity Factor- Capacity factor is defined as the ratio of the actual electricity generation per year (kWh/year) by the system divided by the electricity (kWh) that would have been generated if the system meets nameplate capacity throughout its lifetime (i.e. rated peak power). It varies in a wide range with location, solar irradiance and weather conditions (i.e. for the same place, it differs with months and seasonal weather conditions). For example, the capacity factors in California is in the range of 33% [17], while in Massachusetts it is 13-15% [18], making the LCOE of solar electricity in California much lesser than the East coast States in the US.

- Solar Insolation- This is a dominant factor which makes the LCOE of comparing projects differ majorly due to different locations and facing varied seasons. Annual solar irradiance is predominant for calculation of annual energy generation by a plant. As an example, a plant with same nameplate capacity, orientation and tilt angle will have lower LCOE in California (4.9 kWh/m^2/day in LA, CA) than in New York (3.8 kWh/m^2/day in Albany, NY) [19] due to lesser area-related costs and providing high-value energy.

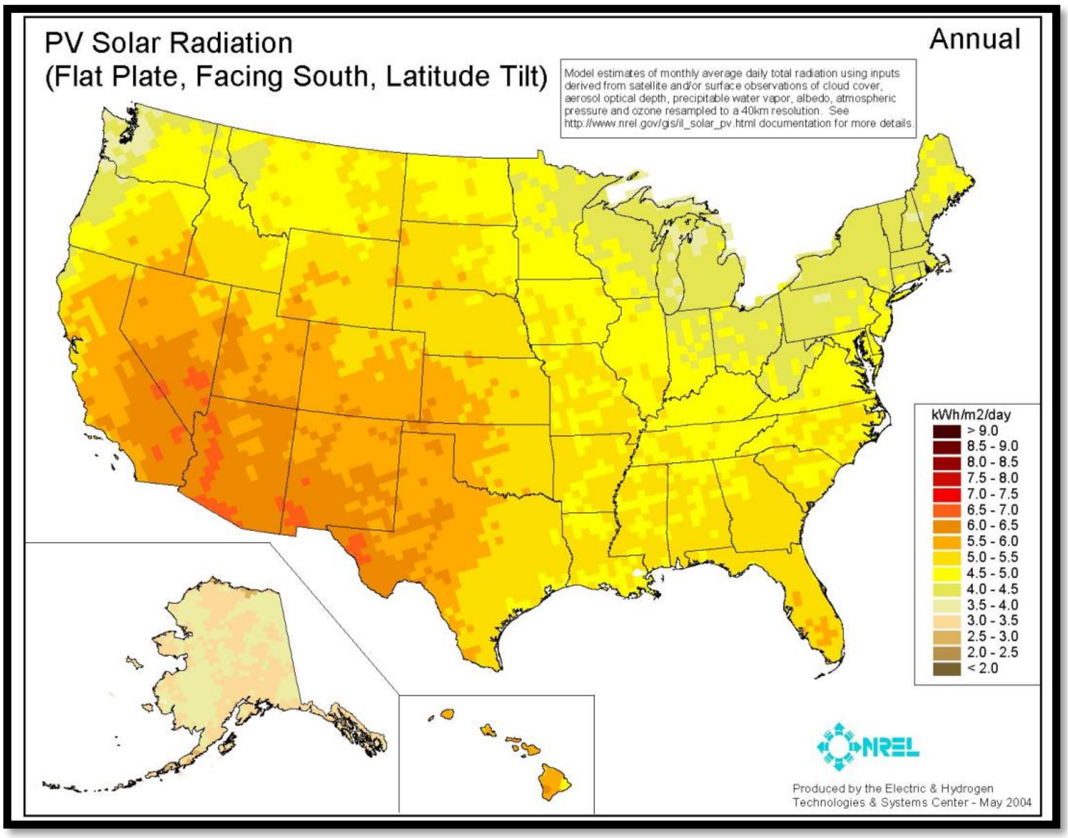

Figure 1 Variation in solar radiation by state, NREL, May 2004

- Capital Cost- There are a few standard values for the capital cost per nameplate ($/kWh) for utility scale systems [20] which are in the range of megawatts and higher. For small scale projects, the capital cost can be calculated by adding the cost of all the involved components, including initial component costs, labor, installation, indirect and owner costs. Capital costs vary significantly with the location of the plant due to the different labor wages in different areas, designing cost and energy productivity differences by region.

- Operation and Maintenance Costs (O&M)- Since the fuel cost is zero for PV plants, this quantity doesn't vary significantly with plant's electricity generation and are classified as 'fixed' costs, while costs to sustain generation are termed as 'variable'.

3.3 U.S Department of Energy's Sun Shot Initiative

Sun Shot initiative is a mission launched by United States Department of Energy in February 2011, which aims to reduce the total installation cost of solar power systems to $0.06 per kilowatt-hour (kWh) by 2020 for attaining grid parity across the country. Today, SunShot is about 70% of its way toward achieving the program's goal, with only halfway into the program's ten-year timeline. Since Sun Shot's launch in 2011, the average price per kWh of a utility-scale photovoltaic (PV) project (Prices may vary significantly with state) has dropped from about $0.21 to $0.11 [20]

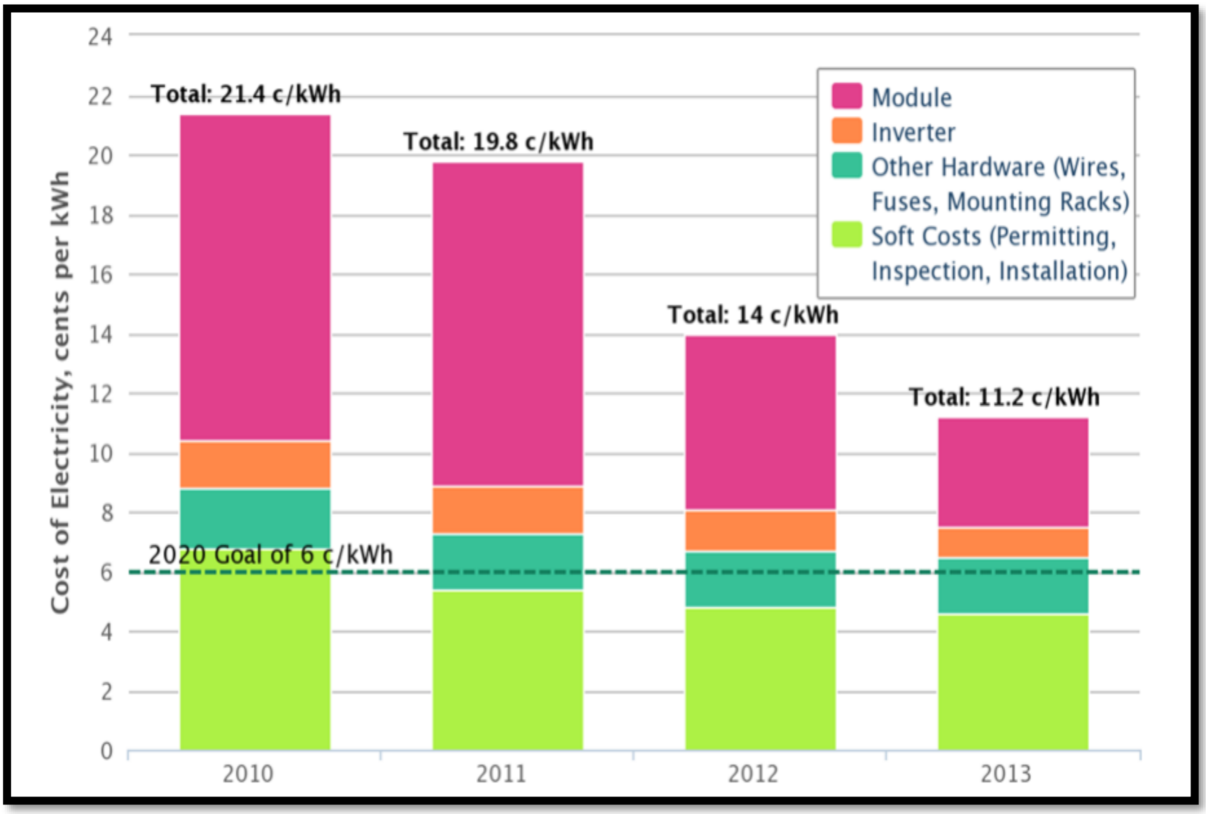

Figure 2 DOE Sun Shot Progress: The falling prices of Utility Scale Photovoltaic projects
Source: Office of Energy Efficiency and Renewable Energy, DOE

The mission supports technological advancements and innovative efforts by private companies, universities and national laboratories to drive down the cost of solar electricity to meet the sun shot target by reducing solar technology cost, PV grid integration cost and accelerating solar deployment nationwide.

In order to achieve the goals, there are five major areas it has been based and focused upon:

1. Photovoltaics (PV)
2. Concentrating solar power (CSP)

3. Soft costs (or balance of systems costs)
4. Systems integration
5. Technology to market.

Technology/Market	Benchmark 2010 Price	Reference 2020 Price	SunShot 2020 Price
Utility-Scale PV ($/W$_{DC}$)	4.00	2.51	1.00
Commercial Rooftop PV ($/W$_{DC}$)	5.00	3.36	1.25
Residential Rooftop PV ($/W$_{DC}$)	6.00	3.78	1.50
CSP ($/W$_{AC}$)	7.20[a]	6.64[a]	3.60[b]

[a] CSP system with 6 hours of thermal storage
[b] CSP system with 14 hours of thermal storage

Figure 3 Benchmarked 2010 Solar Prices and Projected 2020 Solar Energy Prices (2010 $/W)
Source: SunShot Vision study, p.4

3.4 Financial Analysis of the Project

The installed photovoltaic system is divided into two sections, AC and DC sides and for the purpose of comparison, the economic analysis of the two is separately performed.

<u>AC Side of the system</u>

- Nameplate Capacity = 38 panels * Power rating of one module
  = 38 * 235 W = 8.93 kW
- Component Costs:
  1. PV Modules = $220 [21]
  2. AC Inverter = $2789 [22]
  3. AC LED drivers plus fixtures = $3220 [22]
  4. Total Capital Costs = (38* $220) + 2789 + 3220 = $14,370

- Capacity Factor = 15.7% or 0.157 [23]
- Electricity generation = Nameplate Capacity* Capacity factor* Hours in a year
  = 8.93 kW * 0.157 * 365 *24 hours = 12,281.6 kWh

- Fixed Operation &Maintenance Cost = $11.7/kW-year [22]
- Variable Operation and Maintenance Cost = $0.0/ kW
- Total O&M = (Nameplate capacity * Fixed O&M) + (Electricity generation/1000* variable O&M)

  = 8.93 kW * $11.7/kW-year

  = $ 104.5/year
- Capital Cost repayment = 6%
- Annual return to investors factor (fraction of O&M + amortized cap) = 9%
- Rate of Interest per year = 0.09(Annual O&M + Annual Capital Cost)

  = 0.09 (104.5+ 1120.9)

  = $ 110.3/ year
- Lifetime = 25 years
- Salvage Value = $0/year
- Factor to annualize capital (A/P, 6%, 25 years) = $[0.06\ (1+0.06)^{25}] / [(1+0.06)^{25} – 1]$

  = 0.078
- Annual Capital Cost = 0.078* Capital Cost

  = $ 1120.9/year
- Levelized Cost of Electricity (LCOE):

  = [(Annual Capital Cost-Salvage value) + Total O&M + Rate of interest per year]/ Electricity generation

  = [$(1120.9-0) + (104.5) + (110.3)]/ 12,281.6 kWh

  = $ 0.11/kWh
- Fraction of LCOE due to capital cost:

  = Annual Capital Cost/ (Annual Capital Cost + Total O&M + Rate of interest per year)

  = [1120.9/ (1120.9 +104.5+ 110.3)] *100

  = 83.9%

<u>DC System (Taking both the DC systems and so the numbers are doubled)</u>

- Nameplate Capacity = 14 panels * Power rating of one module

  = 14*235 W = 3.3 kW

- Component Costs-
  1. PV Modules = $220 [21]
  2. Maximum Power Point Tracker(MPPT) Controller = $1040 [22]
  3. Power Server Module(PSM) = $2987 [22]
  4. DC Inverter = $1281[22]
  5. DC LED drivers plus fixtures = $2660 [22]

6. Total Capital Costs = (14*220) + (2*1040) +(2*2987) + (2*1281) + 2660 = $ 16,356

- Electricity generation = Nameplate Capacity* Capacity factor* Hours in a year
  = 3.3 kW * 0.157 * 365 *24 hours = 4538.6 kWh
- Capacity Factor = 15.7% or 0.157 [23]
- Fixed Operation & Maintenance Cost = $11.7/kW-year [22]
- Variable Operation & Maintenance Cost = $0.0/ kW
- Total O&M = (Nameplate capacity * Fixed O&M) + (Electricity generation/1000* variable O&M)
  = 3.3 kW * $11.7/kW-year
  = $ 38.61/year
- Capital Cost repayment = 6%
- Annual return to investors factor (fraction of O&M + amortized cap) = 9%
- Rate of Interest per year = 0.09(Annual O&M + Annual Capital Cost)
  = 0.09 (38.61+ 1276)
  = $ 118/ year
- Lifetime = 25 years
- Salvage Value = $0/year
- Factor to annualize capital (A/P, 6%, 25 years) = 0.078
- Annual Capital Cost = 0.078* Capital Cost
  = $ 1276/year
- Levelized Cost of Electricity (LCOE):
  = [(Annual Capital Cost-Salvage value) + Total O&M + Rate of interest per year]/ Electricity generation
  = [$(1276) + (38.61) + (118)]/ 4538.6 kWh
  = $ 0.31/kWh

- Fraction of LCOE due to capital cost:
  = Annual Capital Cost/ (Annual Capital Cost + Total O&M + Rate of interest per year)
  = [1276/ (1276+38.61+ 118)] *100
  = 89.1%

	AC Side	**DC Side**
Inputs		
Nameplate Capacity	8.93 kW	3.3 kW
Capacity Factor	0.157	0.157
Capital Cost	$14,370	$ 16,356
Fixed O&M cost	$11.7/kW-year	$11.7/kW-year
Variable O&M cost	$0	$0
Electricity generated in a year	**12,281.6 kWh**	4538.6 kWh
Total O&M cost	$ 104.5/year	$ 38.61/year
Capital cot repayment	0.06	0.06
Annual Return to Investors factor (fraction of OM+ amortized capital)	0.09	0.09
Lifetime	25 years	25 years
Salvage Value	$0	$0
Factor to annualize capital (A/P, 6%, 25 years)	0.078	0.078
Results		
Annual Capital Cost	$ 1121/year	$ 1276/year
Annual Salvage Value	$0/year	$0/year
Annual Total O&M	$ 104.5/year	$ 38.61/year
Rate of Interest per year	$ 110.3/ year	$ 118/ year
Electricity generation in a year	12,281.6 kWh	4538.6 kWh
Levelized Cost of Electricity	$ 0.11/kWh	$ 0.31/kWh
Fraction of LCOE due to capital cost	83.9%	89.1%

Table 6: LCOE results for the two sides of the system

3.5 References

1. Renewable Energy Policy Network for the 21st century (REN21). Renewables 2010 global status report. Paris; 2010. p. 1–80
2. J. Kirkegaard, T. Hanemann, L. Weischer, M. Miller. Toward a sunny future? Global integration in the solar PV Industry, World Resources Institute (WRI) Working Paper Series; May 2010. p. 1–66
3. P. Mints, the 12-step solar program: towards an incentive-less future. Navigant Consulting on Electo IQ. http://www.electroiq.com [accessed 19.01.2011]
4. J Hill. Global Installed Solar PV Capacity Will Surpass 756 GW by 2025, Global Data, clean technical
5. M. Kordy, M. Badr, K. Abed, M. Ibrahim, Economical evaluation of electricity generation considering externalities, Elsevier Volume 25, Issue 2, February 2002, Pages 317–328
6. What is U.S. electricity generation by energy source? US Energy Information Administration, April 1, 2016
7. P. Denholm, R. Margolis, S. Ong, B. Roberts, Break-even cost for residential photovoltaics in the United States: key drivers and sensitivities. National Renewable Energy Laboratory (NREL) technical report; 2009. p. 1–33
8. C. Breyer, A. Gerlach, J. Müller, H. Behacker, A. Milner. Grid-parity analysis for EU and US regions and market segments—dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio. Proceedings of 24th European photovoltaic solar energy conference. 2009. P 4492–500
9. S. Hegedus, A. Luque. Achievements and challenges of solar electricity from photovoltaics. In: Luque A, Hegedus S, editors. Handbook of photovoltaic science and engineering. 2nd ed. John Wiley and Sons Ltd.; 2011. p. 1–38
10. S. Wenham, Solar 2013 conference, Melbourne, Applied Materials
11. P. Singh, S. Singh. Realistic generation cost of solar photovoltaic electricity. Renewable Energy 2010; 35:563–9
12. T. Cheyney. Chipping away at levelized costs: SunPods, Sunsonix seek lower solar LCOE in field and fabs, PV-tech.org. <http://international.pv-tech.org/chip shots blog/chipping away at levelized costs sunpods sunsonix seek lower solar lcoe175> [accessed 1.07.2010]
13. S. Darling, F You, T. Veselka, A. Velosa. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 2011: 7 p (Advance article)
14. S. Darling, F. You, T. Veselka and A. Velosa, Assumptions and the levelized cost of energy for photovoltaics, DOI: 10.1039/C0EE00698J (Analysis) Energy Environ. Sci., 2011, 4, 3133-3139- Royal Society of Chemistry
15. S. Reichelstein, M. Yorston, the prospects for cost competitive solar PV power, Energy Policy Volume 55, April 2013, Pages 117–127, Elsevier
16. M. Cambell, the drivers of Levelized cost of electricity for Utility-scale Photovoltaics, 2008-Sunpower

17. P. Danko, Big Solar in US West Is Kicking Ass, March 10, 2015, Breaking Energy
18. Capacity factor – Wikipedia, https://en.wikipedia.org/wiki/Capacity_factor
19. 30-Year Average of Monthly Solar Radiation, 1961-1990, Weather Bureau Army Navy (WBAN) Identification Numbers- NREL
20. Office of Energy Efficiency and Renewable Energy, US DOE, Sun Shot Initiative Mission, http://energy.gov/eere/sunshot/sunshot-initiative-mission
21. Solar Systems USA, http://www.solarsystems-usa.net/solarpanels/trinasolar/tsm-235pc05/#.WCfdYbIrLIW
22. These prices are collected from the officials of office of the county and the installing staff
23. Clean Energy Action Project- Long Island Solar Farm- Silicon Photovoltaic- Solar Power- Case Studies

4 Data Analysis

During the course of the considered project, the analysis of collected data is performed in two parts:

1. From the beginning of the system operation to August 23, 2016 included.
2. From August 24, 2016 to October 18, 2016 included.

The division point is given by the replacement of the initially installed Maximum Power Point Tracker (MPPT) controllers for a more efficient overall performance.

After complete installation of the system, the data loggers began collecting data on April 18, 2016 at various measurement locations throughout the system architecture. The data is measured and stored at a rate of twice per minute (every 30 sec). This data is further averaged over an interval of 15 minutes, as appropriate for long-term storage and simplicity of calculations. The complete data set follows a timeline of six months, from April 18- Oct 18, 2016 along with the change of MPPTs on Aug 24, 2016. Although the collection of data was on a continuous basis, there are a couple of short intervals when data acquisition system showed inconsistency due to recording issues on the local computer (hardware problems and network firewall update). Fortunately, these short periods of no data, neither impacted the system performance nor the conclusions that it infers.

Fig. 1 shows the irradiance values throughout the course of analysis. The reduction in the values after August is an expected trend due to the advent of cooler weather conditions in New York. The values of less than 400 W/m^2 can be associated with cloudy or bad weather days.

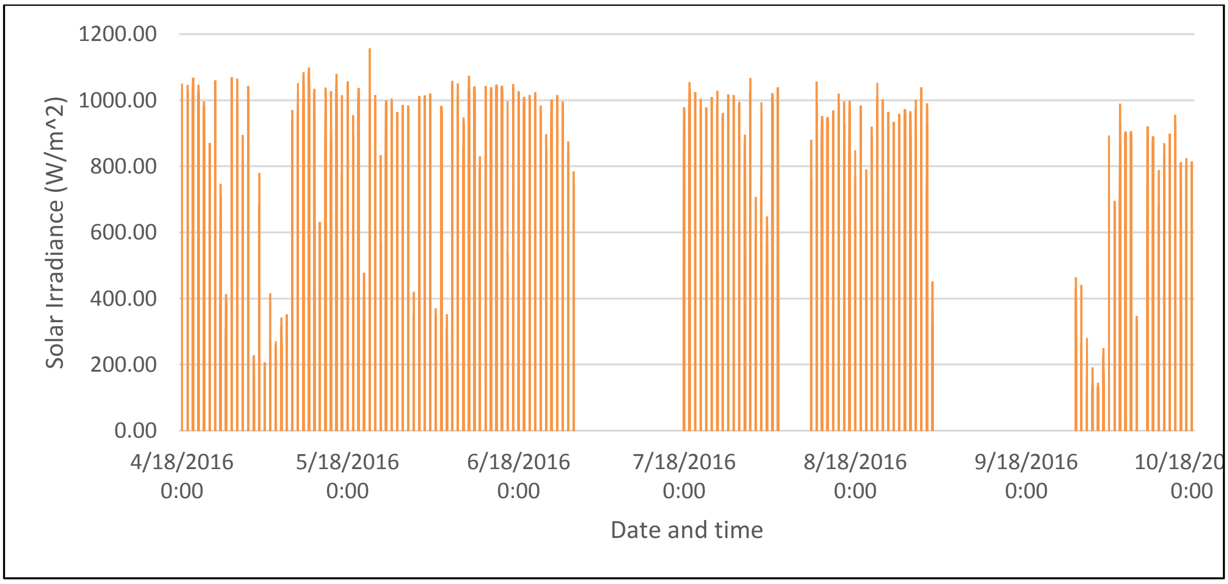

Figure 1 Solar irradiance variation with seasons for considered time interval

Note: The data loggers are measuring the system twenty-four hours but for studying the system, only the day-time values corresponding to the irradiance equal or above 100 W/m^2 are taken into consideration.

4.1 Analysis with originally installed MPPTs

1. PV Array: With a total of 52 polycrystalline Si modules, the complete system is rated at 12.2 kW. Non-uniform distribution of panels between DC and AC sides of the system, make it slightly difficult to examine. The DC side constitutes 14 modules with a power output of 3.3 kW, whereas AC side employs 38 panels, making a total capacity of 8.93kW. For accurate comparison, the panel efficiencies of DC and AC sides are separately calculated.

   The efficiency of solar panels is measured as their ability to convert sunlight into usable and human consumable form of energy. It is calculated as follows:

$$\eta_{PV} = \frac{Pmax}{A * G}$$

   where P_{max} is maximum electrical power output of the panel, A is the total module area including the frame (which is 62.32 m^2 for AC side and 22.96 m^2 for DC side) and G is the solar irradiance on the plane of array. The maximum efficiency of the employed solar panels, reported by the datasheet is 14.4%. The variation in efficiencies for the AC and DC portions of the system are shown in fig. 2 and are averaged as follows:

   - AC Side – 12.53 %
   - DC Side – 11.68 %

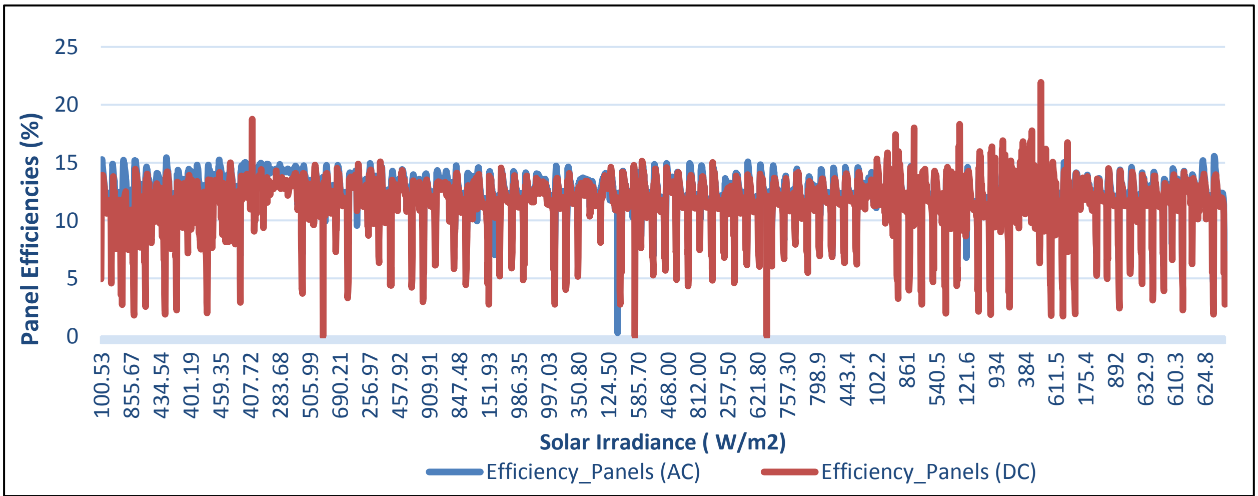

Figure 2 Variations in the panel efficiencies of different portions of installed PV system

The performance of photovoltaic array is also examined by evaluating its performance ratio(PR) which considers the overall effect of losses (due to module temperature, irradiance, component efficiencies and faults) on the power output of the array. It is calculated as follows:

$$PR = \frac{Yf}{Yr}$$

where, Y_f is the final yield expressed as the energy production in kWh divided by the peak power in kW and Y_r = H/G, where respectively H is the in-plane insolation (in kWh/m²), and G is the irradiance at STC (1 kW/m²).

The average PR values calculated (considering daytime) are as follows:

- PV DC side- 0.815
- PV AC side- 0.830

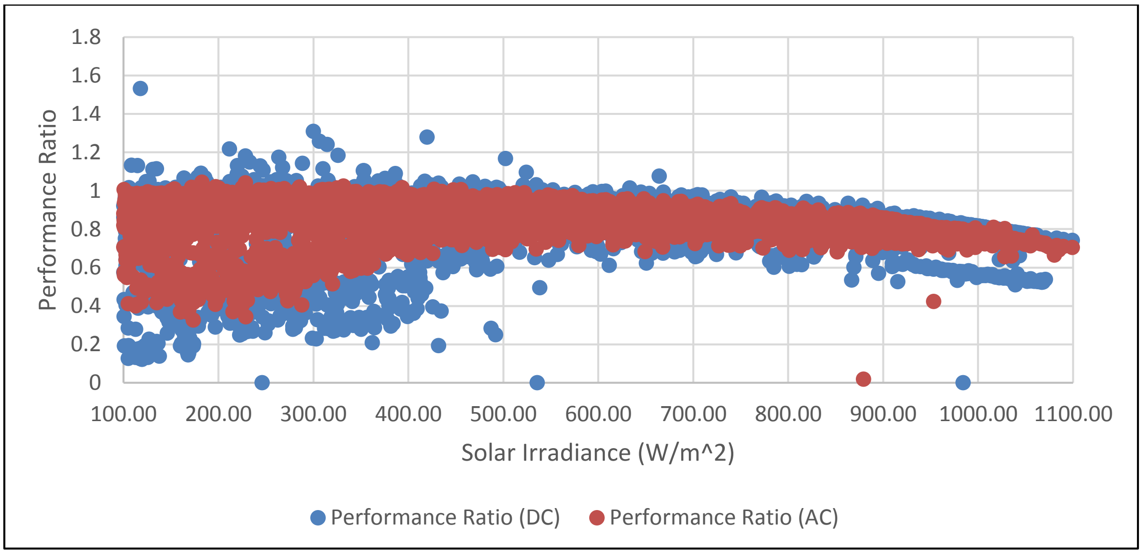

Figure 3 Variations in the Performance ratio of AC and DC sides of the installed PV system

2. AC-Side Inverter: The performance of an AC photovoltaic system depends majorly on the working of inverter that is incorporated to convert the DC produced by the solar array to AC for further use. The efficiency of inverter is calculated as follows:

$$\eta_{INV} = \frac{Pout}{Pin}$$

where P_{out} and P_{in} are output and input power of and to the inverter respectively. The AC side inverter works with an average efficiency of 94.5%, when only daytime values are considered (in the timeframe of 9:00 am – 4:00 pm) and is almost consistent in performance. (Fig.4) This time frame has been chosen in order to evaluate the period of steady performance, avoiding the non-linearity present at the beginning and end of the day due to low irradiance values.

- Power outputs of the two separate AC blocks consisting 10 and 28 (two strings with 14 panels each) modules, respectively marks the input to the inverter as shown in fig.5 The graph shows an expected linear rise in PV array output with increasing irradiance along with the highest power output of second block almost thrice that of the first block, clearly attributing to the number of modules which are nearly three times in the second as compared to first.

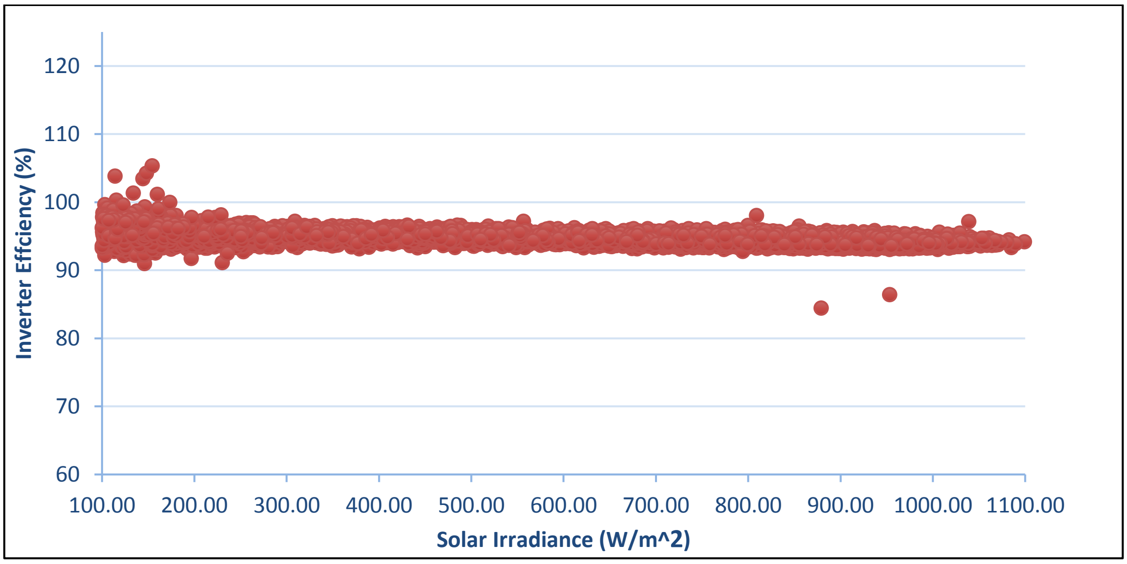

Figure 4 Stability in inverter efficiency, considering values above 100 W/m^2 in operation

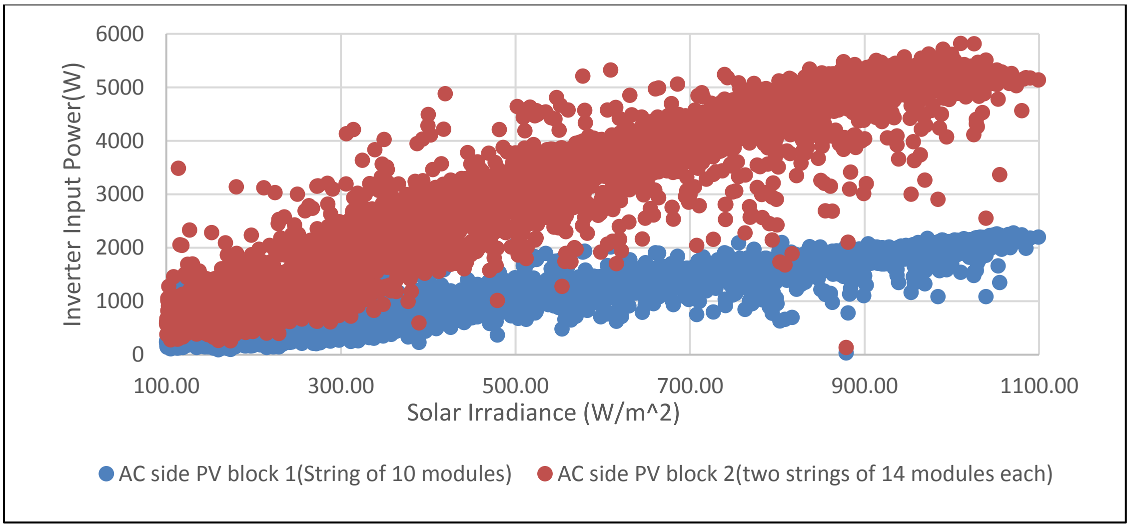

Figure 5. 15-minute average power versus irradiance for two AC PV blocks at inverter input

3. Maximum Power Point Tracker (MPPT) controllers: The MPPT efficiency is measured as the ratio of actual power to the maximum available power of the array. It can be calculated as follows:

$$\eta_{MPPT} = \frac{P}{Pmax}$$

- The average MPPT efficiency, installed at the DC side of the system is 85.6%. (in the timeframe of 9:00 am – 4:00 pm) Since the two DC systems are exactly similar in nature, the analysis is performed taking only one into consideration, with an assumption of the second working in similar way. The detailed examination of MPPT performance shows that they are much less efficient than their reported datasheet values, aiming at 97.5% (peak at approximately 60% load). This was the sole motivation to test them again and replace them if possible to ensure better performance of the DC side.

4. Power Server Module: The PSM efficiency is the ratio of output power to the input power at PSM. It can be calculated as follows:

$$\eta_{PSM} = \frac{Pout}{Pin}$$

- The DC-side average PSM efficiency is 91.4% (for daytime values, in the timeframe of 9:00 am – 4:00 pm).

5. LED Light Drivers: Three drivers on the AC side and three drivers on the DC side are monitored as samples to define the efficiency of those adopted in the design. The efficiency is calculated as the ratio of output power to the input power as:

$$\eta_{D} = \frac{Pout}{Pin}$$

- AC LED drivers: The average efficiencies of the three AC LED drivers are 93.95%, 94.67% and 95.388% respectively. The average overall efficiency is 94.67%. Fig.6 shows the efficiency of AC drivers.

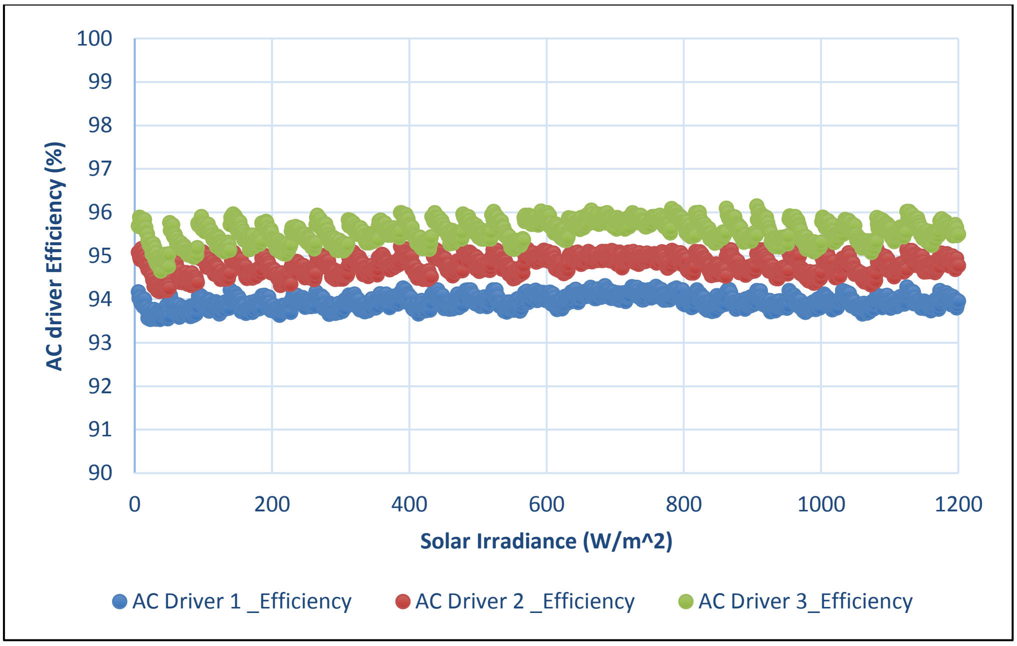

Figure. 6 AC driver efficiencies versus irradiance

- DC LED drivers: The average efficiency of the three DC LED drivers is 95.53%, 94.79% and 93.81%. The average overall efficiency is 94.7%. Fig.7 shows the efficiency of DC drivers.

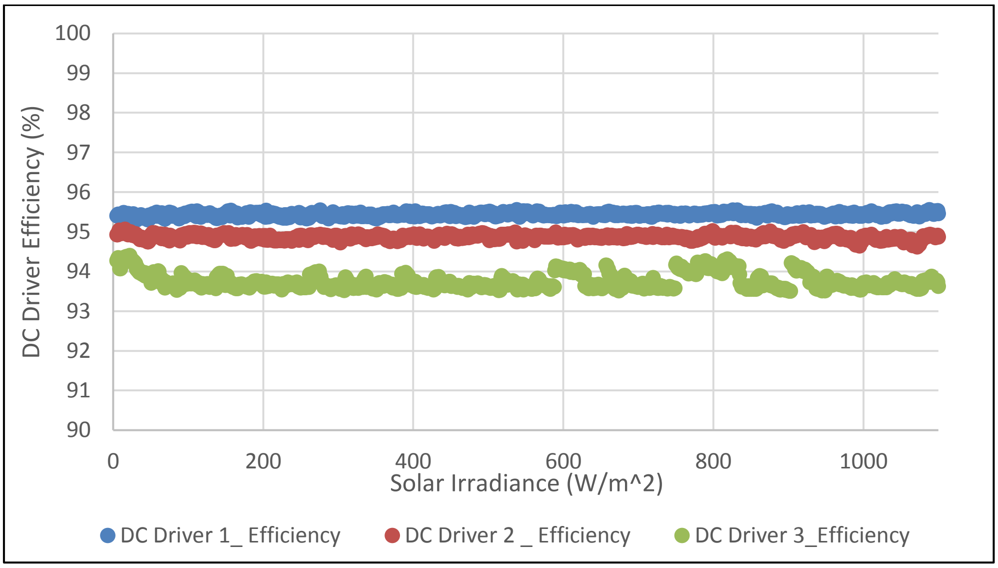

Figure 7 DC driver efficiencies versus irradiance

4.2 Analysis following the change of MPPTs on August 24, 2016

While examining the initially installed system, performance of MPPT controllers turned out to be lower than expected. In order to improve the system efficiency, the MPPTs on the DC sides have been replaced. The possible variations that could have occurred as a consequence of this replacement are studied and reported as follows.

1. PV Array: Upon calculation, the variation in photovoltaic panel efficiencies for the AC and DC portions of the system are shown in fig. 8 and the average numbers are as follows:

- AC Side – 13.12 %
- DC Side – 10.46 %

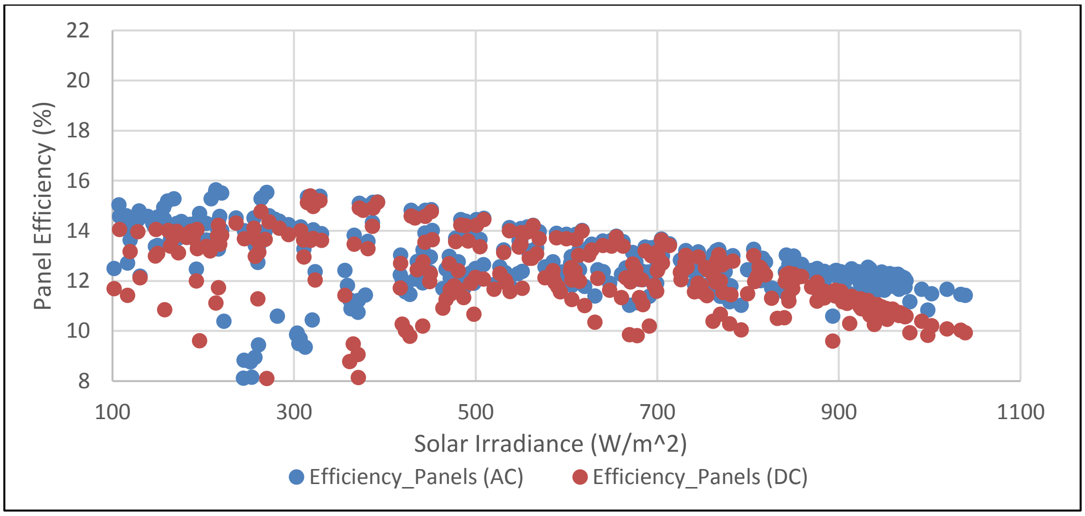

Figure 8 Variations in the panel efficiencies of different portions of installed PV system

Average PR values for various portions of the system are as follows:

- AC Side- 0.822
- DC Side- 0.71

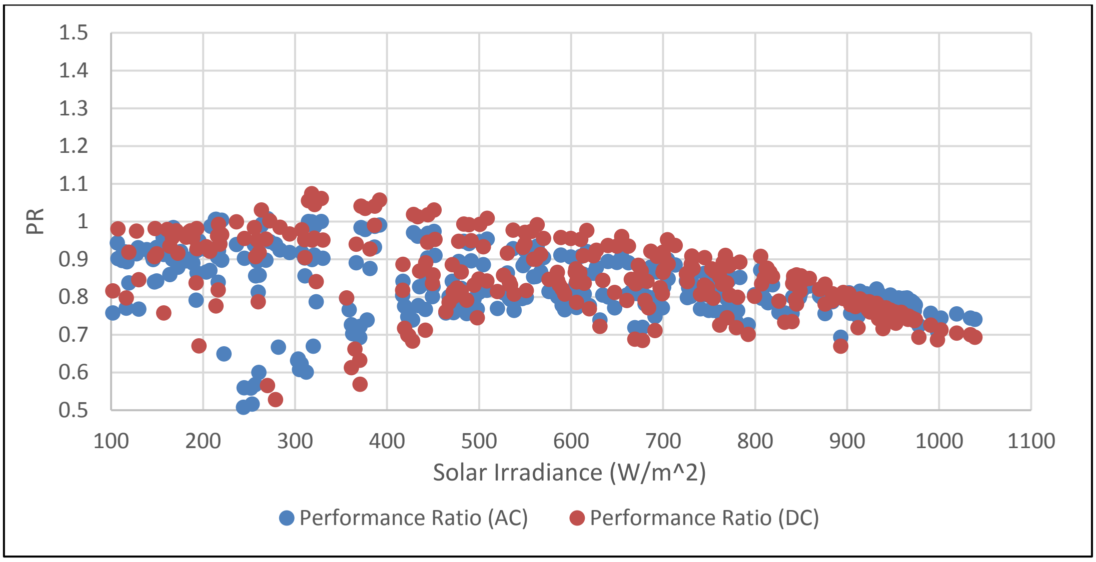

Figure 9 Variations in the PR values of different portions of installed PV system

2. <u>AC-Side Inverter:</u> The AC side inverter works with an average efficiency of 91.7%, when considered only daytime values (in the timeframe of 9:00 am – 4:00 pm) and results are almost constant throughout. Fig. 10 depicts a couple of spikes which can be due to the system harmonics or fluctuations, once in a while.

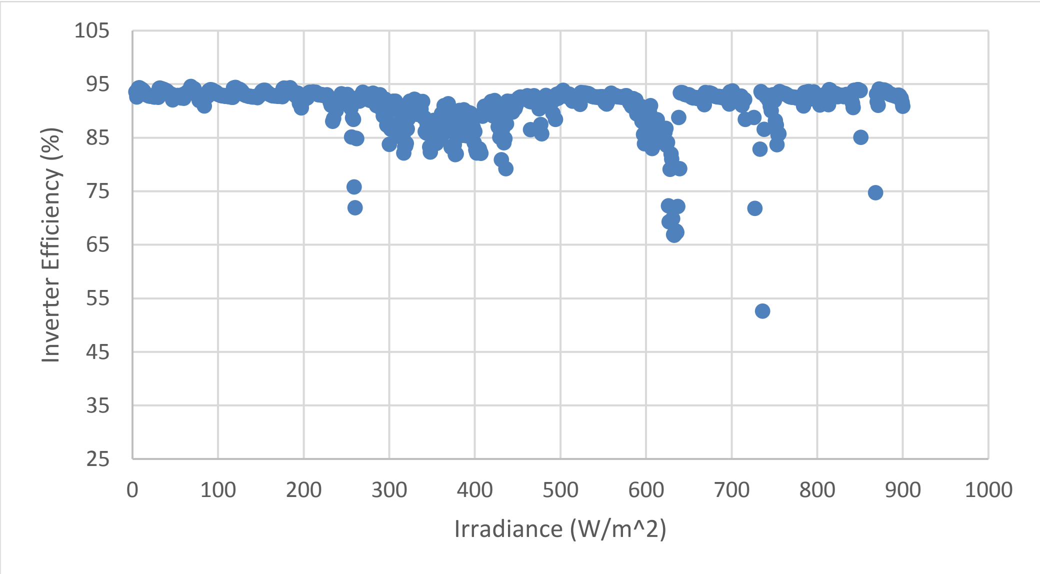

Figure 10 Inverter efficiency versus irradiance, considering daytime values between 9 am-4pm

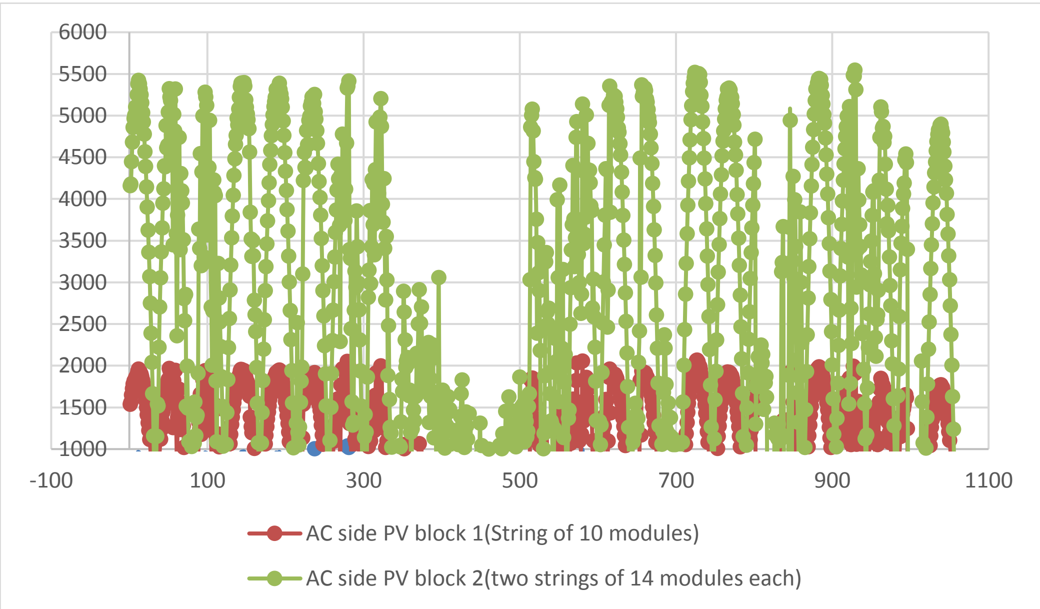

Figure.11 15-minute average power at inverter input versus irradiance for two AC PV blocks

3. <u>Maximum Power Point Tracker (MPPT) controllers</u>: The major focus after the replacement lies on the performance of new MPPTs and how they affect the overall DC

side performance. The average calculated efficiency of the new MPPT is 90.7%, in the timeframe of 9:00 am – 4:00 pm.

- There are a few instances where the PV DC system didn't respond as expected. The reason behind being the instant shut down of maximum power point trackers due to the tripping of arc fault protection circuit breakers. The actual cause is still unclear and we are focused to explore the issue, which might be from the input side (array and MPPT) or can be an internal fault within the circuit breakers.

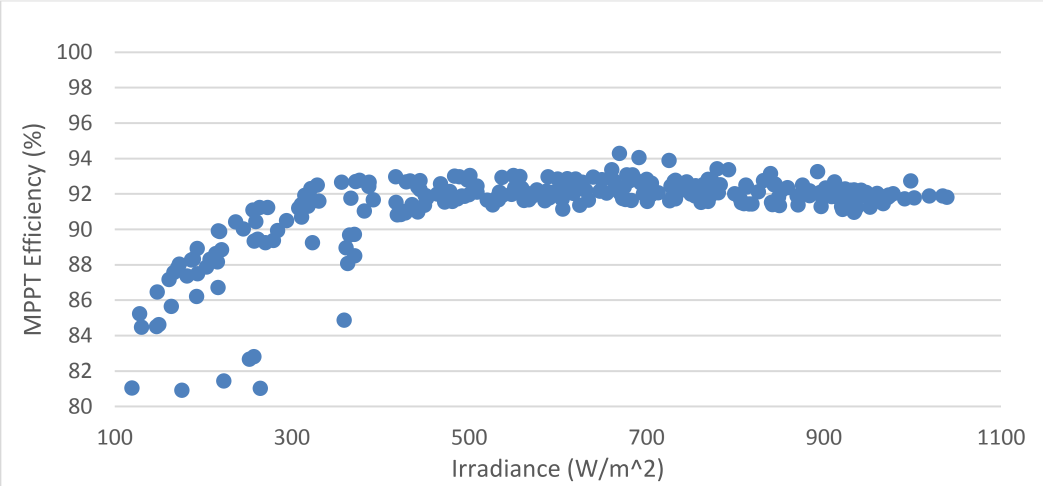

Figure 12 MPPT efficiency versus solar Irradiance

4. <u>Power Server Module</u>: The DC-side average PSM efficiency after the change of maximum power point trackers is 93.15% (in consideration of the feasible values from 9:00 am – 4:00 pm), which is about a percent greater than the case earlier.

   While analysing the data, there was a time when the PSM was fed only by the AC power from the grid in consequence of the turning off of the PV electricity by the intervention of the arc fault protection. During this period the PSM worked with an efficiency of 89.8%.

   - Concerning the output of PV array, the sensors sometimes have shown an offset error at lower levels of irradiance. While calculating the efficiencies and studying the performance of system components, they are taken into consideration, although they are generally negligible since they are in range of uncertainty of the sensors.

5. <u>LED Light Drivers</u>: The monitoring plan for the system foresees to collect data from only three sample AC drivers and three sample DC drivers, as input and output current and voltage.

- AC LED drivers: The average efficiencies of the three AC LED drivers is 94.00%, 94.72% and 95.42% respectively. The average efficiency for the three of them is 94.7%.

- DC LED drivers: The average efficiency of the three DC LED drivers is 95.64%, 94.79% and 94.06%. The average efficiency for the three of them is 94.83%.

4.3 Measurement and Analysis of LED lights

As its true for all electrical systems, evaluation of the load component is as important as the source. For currently installed photovoltaic system, the load is 84 LED light fixtures, that are fitted in the office building and are partially fed by AC (28) and DC (28 by PSM-1 and 28 by PSM-2) sides of the system. After complete data analysis of the system under consideration, focus shifted to the measurements of LED lights and the conclusions that can be drawn.

<u>Measurement of LED light Intensities</u>

Since the sole motive of this system is to power the lights for continuous uninterrupted office lighting, the lights are always switched in office hours and so this measurement of lights is irrespective of the weather and season in which they are performed.

For measuring the intensities of LED lights that are fed by the system, a frustum of cone is made with the narrower part closed at the bottom to incorporate the sensors (especially designed for LEDs) and wider part kept open in order to allow the light to fall on the sensors to take the measurements. The reason to measure light intensity using a frustum is to prevent any other light (from the sun outside the window, other overhead lights and individual table lamps) entering inside it while the measurement of one particular LED is in progress.

Fig. 13 shows the frustum tool with attached sensors at the bottom.

Fig. 14 shows the light intensity levels measured on a fine day for the three cases on different locations in the office.

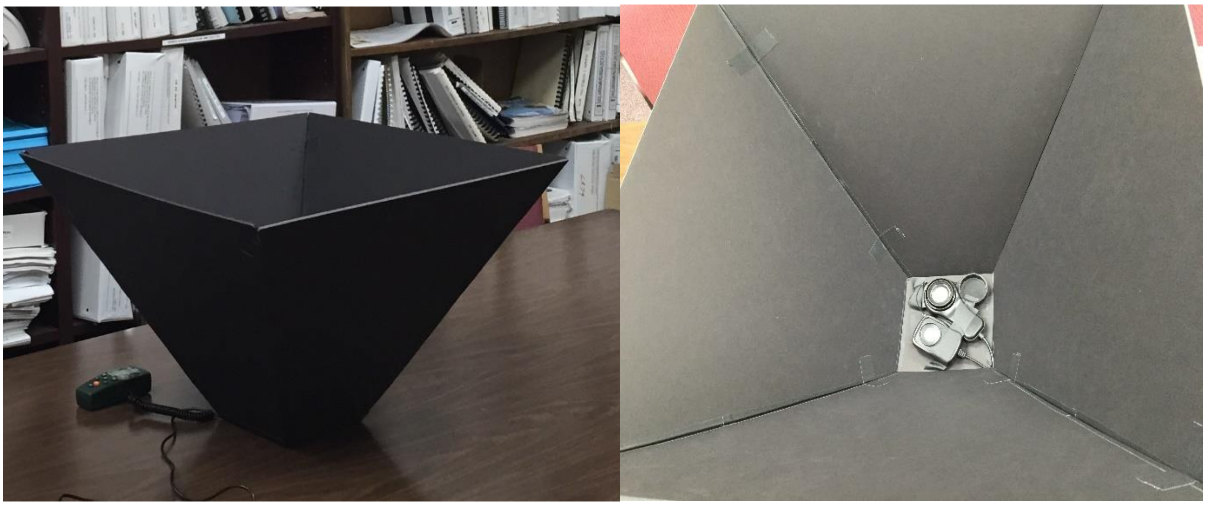

Figure 13 The frustum used for light intensity measurements (left); sensors attached at the bottom (right)

4.4 Results

- The average intensity of AC-fed LED lights is 4268.49 lumen (396.70 foot-candle) with an average power rating of 38.8 Watts.
- The intensities of the lights which are fed by two DC sides are 3724.04 lumen (346.10 foot-candle) and 3667.01 (340.80 foot-candle) respectively with power ratings of 33.85 and 33.34 Watts.

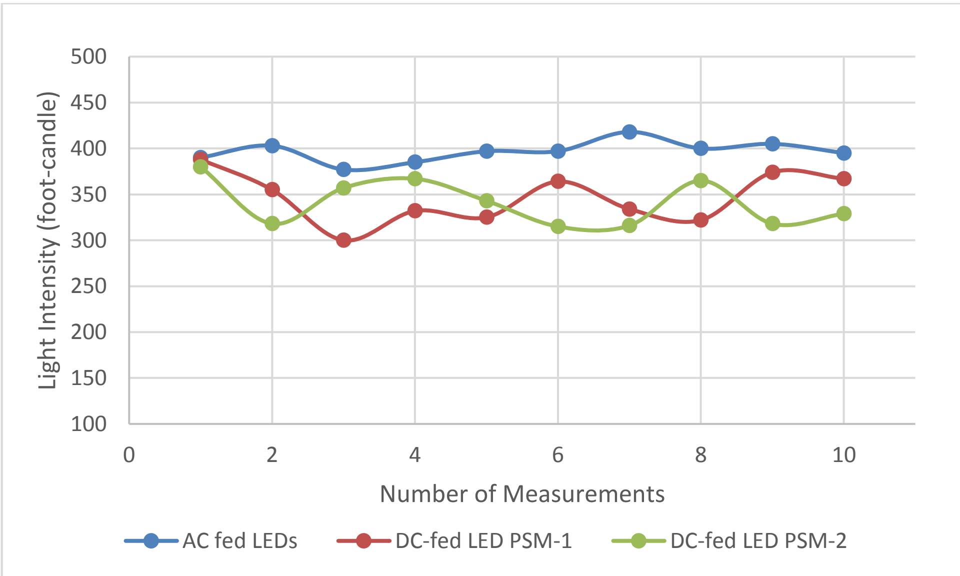

Figure 14 Intensities of LEDs fed by the AC and DC sides of the system

5 Observations and Conclusions

5.1 Objective

The main focus of this work is to analyse the current and future prospects of a DC direct-coupled photovoltaic system feeding LED office lights, in terms of performance, costs and benefits, in comparison with a conventional photovoltaic system. Among solar enthusiasts worldwide, a common topic of discussion has always been, if we could avoid the use of expensive inverters to convert DC to AC while incorporating solar PV systems for residential and industrial applications. The primary goal of the project is to check if we can feed DC produced by solar panels directly to the load, without compromising on efficiency and economics of the current systems.

This chapter will summarize the research, identify the methodology used, review the data analysis, discuss the results and propose a few future prospects.

5.2 Methodology

For true comparison, we installed a PV system, which comprises of AC and DC sides, operating with and without inverters respectively on the same roof and compare their performance with recorded real-time data. The entire setup is divided (not equally) into two parts, namely DC and AC portions, which works independently to feed the load, being DC LED lights, fitted in a Suffolk County office building at Yaphank, New York.

The DC side is a grid-integrated photovoltaic system (due to New York state's income tax credit of 25% on the cost of the system for grid connected and net metered residential solar electric and solar thermal systems) used to power the DC LED office lights during weekdays without interruptions and feed the additional energy production to the grid when the building is closed, for example during weekends and holidays. The AC side is a conventional DC-AC photovoltaic generation system connected to the utility.

After installation, data loggers started recording data for the two sides of the system and collected data is thoroughly examined by calculating performance of the components, efficiency of the system and comparison of their economic status for nearly six months (April 18, 2016- October 18, 2016) with a replacement of MPPTs in between, with an expectation of better overall performance. A small study concerning the behaviour of load, when its fed separately by the DC and AC sides is also conducted to provide results with complete evaluation of the system from source to the load.

5.3 Major Observations

In a time frame of six months, the review of the installed system mainly resulted in the following observations:

<u>Performance Analysis</u>

- On close examination, the AC solar PV array proves to be more efficient (12.53 % in contrast to DC side with an efficiency of 11.68%) by about a percent on an average. Also, the fluctuations in panel operating efficiencies, witnessed on the DC side are much higher, especially for lower levels of solar irradiance in comparison with AC side.
- The performance ratio of the system is almost equal for both the sides with AC slightly being on a higher edge. (0.82 for DC and 0.83 for AC).
- The AC inverter, being the only crucial component in operation of AC-side of the system works up to the mark with efficiencies of 94.5% and 91.7% consistently throughout the course of consideration, making AC side of the system better in performance throughout, before and after the replacement of MPPTs on the DC-coupled system side.
- The Maximum Power Point Tracker (MPPT) controllers were installed to make DC system operate at its maximum power point throughout the considered timespan of the project. Initially installed MPPTs showed an efficiency of 85.6%, lower than what was declared on the datasheet. They were then replaced on Aug 24, 2016 for better overall performance, and the analysis after their replacement shows their average efficiency increased by about 5%, reported at 90.7%. This significant rise in the MPPT performance proved to be a key in the improved DC side implementation. It must be stated that the MPPT adopted in the DC-coupled system are still in a development stage and along this project their efficiency has been highly improved. However, an important aspect of their limited performance resides in the fact that they also act as voltage adapters and they bring the voltage from the PV system level (maximum power voltage per module 29.3 V * 7 modules = 205.1 V) to the level needed to feed the PSM component (24.5 V). This large voltage step needs to be diversely handled or reduced to improve the efficiency of the MPPT component.
- A lesser known component called Power Server Module (PSM) served as the heart of DC portion of the installed PV system. This component is working with efficiencies of 91.4% and 93.2%, respectively in the period before and after August 24, 2016. For a short period of time due to the action of a too sensitive arc fault protection that closed off the PV DC input, the PSM was fed only by AC power from the utility grid, showing, in that case, an efficiency of 89.8%. This unexpected exercise proved that this component works much better when the DC input is active and, thus, it should be considered a very important component of DC direct coupled photovoltaic systems.
- LED drivers employed on both the sides of the system works very efficiently. In comparison, the DC drivers working marginally better (earlier working with 94.7% efficiency in comparison to 94.67% and 94.83% as compared to 94.7% of AC drivers) than their AC counter-parts.

Economic Analysis

- For financial comparison of the two sides that make the system, economic analysis is performed with the same assumptions of capacity factor, lifetime, salvage value and the fixed and variable operation and maintenance costs. Levelized cost of electricity (LCOE) for the two sides vary in a wide range with DC costs $0.31/kWh, capital cost constituting 89.1% of the total cost outcome in contrast with $0.11/kWh for AC, capital cost making 83.9% of the total share. The high LCOE for the DC side can be attributed to the higher expenses of its constituent components, making it a system with more number of components with lesser electricity generation.

Load Analysis

- LED light fixtures, which are fitted in the office building served as the load for the installed system. They are partially fed by AC (28 fixtures) and DC (28 fixtures by PSM-1 and 28 fixtures by PSM-2) sides of the system. The average light intensity of the AC-fed LED lights (4268.49 lumen with an average power rating of 38.8 Watts) came out to be higher than those fed by the DC-side (3667.01 with power ratings of 33.85 and 33.34 Watts). A good point to ponder after studying the behaviour of LED lights is the lights that are fed by the DC-side produce a more stable light as compared to AC-side fed lights. We could detect this instability issue directly when measuring the light intensity, as the lumen value on the light meter showed variations up to ±10 lumens around the average value. As a consequence, we can argue that the DC LED lights may offer a better comfort zone for the people working at their desk and using computers in comparison with the same LED fixtures fed by AC power. Additional studies to prove this concept could be a topic for future research.

5.4 Recommendations and Remarks

The ultimate aim of the project, which is to examine DC-direct coupled photovoltaic system in comparison with the conventional DC-AC solar energy generation systems on various grounds has been achieved. By the end of the analysis, a few outcomes align with the expectations while others contradict. On an overall basis, the AC side proved to be better in multi-fold scenarios of efficient performance and lesser involved cost of operation. The DC side although demonstrated itself as a better solution concerning healthcare and comfort prospects in longer terms.

Although this research justifies the comparison of the two probable ways photovoltaic systems can be employed, there can be a better scope for DC systems in near future with a few additional remarks:

- A point where there can be a scope of improvement in efficient performance of DC-direct coupled systems is exploring a device that combines the function of MPPT and PSM into a single component, which will in one way, reduce the total capital cost and in turn improve its performance by reducing the number of components in which the overall energy is getting lost before meeting the load requirements.

- Another crucial reason why the recent DC system came out to be much more expensive is electricity generation, which is extremely low for such a large capital investment. On similar grounds, I realize that DC-direct coupled systems could be a better solution, if they are installed for a larger load demand as installing them with a higher nameplate capacity will increase the electricity generation while not increasing the capital cost in the same ratio, which will lead to a lower LCOE.

6 References

Chapter 1

30. U.S. Energy Information Administration (EIA), International Energy Outlook 2016 (Washington, DC: May 11, 2016), https://www.eia.gov/forecasts/ieo/world.cfm
31. U.S Environmental Protection Agency, EPA's Position on the Energy Crisis, https://www.epa.gov/aboutepa/epas-position-energy-crisis
32. International Renewable Energy Agency (IRENA), Renewable Energy Capacity Statistics 2015
33. I. Malika, G. Siyalb, A. Abdullaha, A. Alamc, K. Zamanb, P. Kyophilavongd, M. Shahbaze, S. Balochb, T. Shamsb, "Turn on the lights: Macroeconomic factors affecting renewable energy in Pakistan", Renewable and Sustainable Energy Reviews, Volume 38, October 2014, Pages 277–284
34. Z. Esin, "A Feasibility Study on Renewable Energy Generation", http://ese.wustl.edu/ContentFiles/Research/UndergraduateResearch/CompletedProjects/WebPages/sp10/ZeynepEsin/Factors%20Affecting%20Renewable%20Energy%20Development.html
35. Powerful Solutions: Seven Ways to Switch America to Renewable Electricity, UCS, "Barriers to Renewable Energy Technologies", 1999
36. Oliver Morton, Solar energy: A new day dawning? Silicon Valley sunrise, Nature 443, 19-22 (7 September 2006) | doi:10.1038/443019a
37. Solar Photovoltaic Technology Basics, NREL
38. Photovoltaic (Solar Electric) Solar energy industries association
39. Solar Thermal vs. Photovoltaic, Solar Thermal Energy: An Industry Report, http://www.solar-thermal.com/solar_vs_pv.html
40. J. Fosdick, Passive Solar Heating, Whole Building Design guide, US Department of Energy
41. Solar Energy in New York, Large and Small Systems for Heat and Power: NY state Department of Environmental Conservation, http://www.dec.ny.gov/energy/43231.html
42. Photosynthesis Education, Artificial Photosynthesis, http://photosynthesiseducation.com/artificial-photosynthesis/
43. T. Maverick, Artificial Photosynthesis to Power the Future, Wall Street Daily-Feb 10, 2016, http://www.wallstreetdaily.com/2016/02/10/artificial-photosynthesis-energy/
44. 2015 Snapshot of Global Photovolatic Markets, Report IEA PVPS T1-29:2016, International Energy Agency
45. EDGAR MEZA, IEA PVPS: Installed PV capacity at 227 GW worldwide PV magazine: Photovoltaic markets and technology

46. Solar Photovoltaic (PV) Market, Update 2016 - Global Market Size, Market Share, Average Price, Regulations and Key Country Analysis to 2025, June 2016
47. Earth Policy Institute, http://www.earthpolicy.org/
48. Photovoltaic Systems: All About Grid-Connected PV Systems, http://www.motherearthnews.com/renewable-energy/solar-power/photovoltaic-systems-grid-connected-ze0z1202zhir
49. Types of PV systems, Solar Electricity Basics: Florida Solar Energy Centre, http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/types_of_pv.htm
50. Electric Power Monthly, Average Price of Electricity to Ultimate Customers by End-Use Sector, July 2016, US EIA
51. AC Transmission Upgrades, 08/27/15; New York State Department of public service
52. Top 10 Solar States, SEIA
53. New York State Solar Policy, SEIA
54. M. Starke, L. Tolbert, B. Ozpineci, "AC vs. DC Distribution: A Loss Comparison", 978-1-4244-1904-3/08/$25.00 ©2008IEEE
55. D. Hammerstrom, "AC versus dc distribution systems --Did we get it right?" Power Engineering Society General Meeting, pp.1–5, June 2007
56. D. Nilsson, A. Sannino, "Efficiency analysis of low- and medium voltage dc distribution systems," Power Engineering Society General Meeting, vol. 2, pp. 2315 – 2321, June 2004
57. A. Sannino, G.Postiglione, M. H. J.Bollen, "Feasibility of a dc network for commercial facilities," IEEE Transactions on Industry Applications, vol. 39, no. 5, pp. 1499 – 1507, Sept.-Oct. 2003
58. RE bus DC microgrid, RE bus alliance, http://rebuspower.com/owners.shtml

Chapter 2

1. TSM-PC05, TSM-PA05; Trina Solar Datasheet- June 2012, US
2. Aurora Uno General Specification, Power One- A member of ABB group
3. Antonio Luque and Steven Hegedus, *Handbook of Photovoltaic Science and Engineering*
4. Solar Inverters – SMA America, http://www.sma-america.com/products/solarinverters.html
5. Dataloggers and Data Acquisition Systems- Campbell Scientific, https://www.campbellsci.com/dataloggers
6. SP Lite2 Pyranometer- Kip and Zonen since 1830, http://www.kippzonen.com/Product/9/SP-Lite2-Pyranometer#.V_xQTfkrLIU
7. Wikipedia – Data Acquisition, https://en.wikipedia.org/wiki/Data_acquisition

Chapter 3

24. Renewable Energy Policy Network for the 21st century (REN21). Renewables 2010 global status report. Paris; 2010. p. 1–80
25. J. Kirkegaard, T. Hanemann, L. Weischer, M. Miller. Toward a sunny future? Global integration in the solar PV Industry, World Resources Institute (WRI) Working Paper Series; May 2010. p. 1–66
26. P. Mints, the 12-step solar program: towards an incentive-less future. Navigant Consulting on Electo IQ. http://www.electroiq.com [accessed 19.01.2011]
27. J Hill. Global Installed Solar PV Capacity Will Surpass 756 GW by 2025, Global Data, clean technical
28. M. Kordy, M. Badr, K. Abed, M. Ibrahim, Economical evaluation of electricity generation considering externalities, Elsevier Volume 25, Issue 2, February 2002, Pages 317–328
29. What is U.S. electricity generation by energy source? US Energy Information Administration, April 1, 2016
30. P. Denholm, R. Margolis, S. Ong, B. Roberts, Break-even cost for residential photovoltaics in the United States: key drivers and sensitivities. National Renewable Energy Laboratory (NREL) technical report; 2009. p. 1–33
31. C. Breyer, A. Gerlach, J. Müller, H. Behacker, A. Milner. Grid-parity analysis for EU and US regions and market segments—dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio. Proceedings of 24th European photovoltaic solar energy conference. 2009. P 4492–500
32. S. Hegedus, A. Luque. Achievements and challenges of solar electricity from photovoltaics. In: Luque A, Hegedus S, editors. Handbook of photovoltaic science and engineering. 2nd ed. John Wiley and Sons Ltd.; 2011. p. 1–38
33. S. Wenham, Solar 2013 conference, Melbourne, Applied Materials
34. P. Singh, S. Singh. Realistic generation cost of solar photovoltaic electricity. Renewable Energy 2010; 35:563–9
35. T. Cheyney. Chipping away at levelized costs: SunPods, Sunsonix seek lower solar LCOE in field and fabs, PV-tech.org. <http://international.pv-tech.org/chip shots blog/chipping away at levelized costs sunpods sunsonix seek lower solar lcoe175> [accessed 1.07.2010]
36. S. Darling, F You, T. Veselka, A. Velosa. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 2011: 7 p (Advance article)
37. S. Darling, F. You, T. Veselka and A. Velosa, Assumptions and the levelized cost of energy for photovoltaics, DOI: 10.1039/C0EE00698J (Analysis) Energy Environ. Sci., 2011, 4, 3133-3139- Royal Society of Chemistry
38. S. Reichelstein, M. Yorston, the prospects for cost competitive solar PV power, Energy Policy Volume 55, April 2013, Pages 117–127, Elsevier
39. M. Cambell, the drivers of Levelized cost of electricity for Utility-scale Photovoltaics, 2008-Sunpower
40. P. Danko, Big Solar in US West Is Kicking Ass, March 10, 2015, Breaking Energy
41. Capacity factor – Wikipedia, https://en.wikipedia.org/wiki/Capacity_factor

42. 30-Year Average of Monthly Solar Radiation, 1961-1990, Weather Bureau Army Navy (WBAN) Identification Numbers- NREL
43. Office of Energy Efficiency and Renewable Energy, US DOE, Sun Shot Initiative Mission, http://energy.gov/eere/sunshot/sunshot-initiative-mission
44. Solar Systems USA, http://www.solarsystems-usa.net/solarpanels/trinasolar/tsm-235pc05/#.WCfdYbIrLIW
45. These prices are collected from the officials of office of the county and the installing staff
46. Clean Energy Action Project- Long Island Solar Farm- Silicon Photovoltaic- Solar Power- Case Studies