INVESTIGATION OF FACTORS AFFECTING SOLAR PHOTOVOLTAIC POWER GENERATION IN SRI LANKAN CONTEXT.

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Degree of Master of Science

Department of Mechanical Engineering

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree
Master of Science/ Master of Engineering in Mechanical Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Dr. Asanka Rodrigo: ……………………. Date: ……………………

ACKNOWLEDGEMENTS

First and foremost, I have to thank my research supervisors, Dr.Asanka Rodrigo, Senior Lecture, Department of Electrical Engineering. Without his assistance, guidance and dedicated involvement in every step throughout the process, this report would have never been accomplished. I would like to thank you very much for your support and understanding over these past two years. Besides my advisor, I would like to thank you our Msc/PG Diploma course coordinator Dr. (Mrs.) M.M.I.D. Manthilake for her guidance and support to success this thesis work on time.

I would like to thank all the academic staff and nonacademic staffs who were engaged in the Master of Science in Building Services Engineering program in 2016/2017, Faculty of Engineering, University of Moratuwa

My sincere thanks also go to Eng. Nalin Wijekoon Managing Director and Eng.P. Somarathne, Director (MEP), of Design Consortium Limited, Colombo 08 for accepting the request to follow this course and encouragement during period of study.

Nobody has been more important to me in the pursuit of this project than the members of my family. I would like to thank my parents; whose love and guidance are with me in whatever I pursue. They are the ultimate role models. Most importantly, I wish to thank my loving and supportive wife, Prasadi, and my adorable baby Kenudi, Ahaswin, who provide unending inspiration.

ABSTRACT

Due to the fossil fuel prices and depleting storage capacity, as well as growing concerns about global climate change, the use of renewable energy (RE) on a national scale has become essential for any country in the world. Within the Portfolio of Renewable Energy, Solar energy generation become a most popular in small, medium and large-Scale installation.

Presently, In Sri Lanka there are many solar PV installation program has announced to encourage both individual and nation scale consumers. Under the Ministry of Power “Soorya Bala Sangramaya” or Battle for Solar Energy was launched in 2016 to increase small scale solar PV installation capacity up to 1000MW in 2025. The ultimate target of Sri Lankan government is to set 100% renewable energy in 2050 as per report published in 2017 under Asian Development Bank, and United Nations Development Program. Accordingly, in 2050, Sri Lanka total PV installation capacity is expected to increase up to 16,000MW.

The aim of this study is to look into the role of solar energy in building electrification and evaluate the key factors affecting for solar PV generation and study their energy optimization and efficiency improving method. This will help general publics who are wish to install solar PV plant or already installed in their premises to acknowledge and improve their solar power energy generation units without expanding their current system or planned solar power plant. Moreover, this will not only help domestic level solar PV plant installer but also industrial or utility scale plant.

The research's findings provide valuable and useful knowledge for policy makers, solar PV consumers and utilities as Solar PV become most important part of Sri Lanka Energy generation Mix in present and future.

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LIST OF ABBREVIATIONS

PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
CEB	Ceylon Electricity Board
LECO	Lanka Electricity Company
NREL	National Renewable Energy Laboratory
IEA	International Energy Agency
UNDP	United National Development Program
ADB	Asian Development Bank
ANOVA	Analysis of Variance
SPSS	Statistical Package for the Social Sciences
GW	Gigawatt
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance
REN	Renewable Now (Renewables Global Status Report)
HFO	Heavy Fuel Oil
NCRE	Non-Conventional Renewable Energy
STC	Standard Test Condition
AGM	Absorbent Glass Mat
MPPT	Maximum Power Point Tracking
PUCSL	Public Utility Commission of Sri Lanka
SEA	Sustainable Energy Authority
ROI	Return of Investment

CHAPTER 01

INTRODUCTION

This chapter introduce the research conducted on "Assessment of Solar Photovoltaic Plant Passive Energy Optimization Techniques" and background of solar PV energy generation. First, global context of energy usage and importance of solar PV energy is described followed by the national context. In national context will explain the requirements of more renewable energy source for Sri Lanka energy generation mix, especially use of Solar PV energy plant from domestic level to utility scale. After that, problem statement, objectives and research methodology used for the research work is explained in detail.

1.0 Global Energy Status

The increasing of need for energy by human society and due to the depletion of fossil fuel storage and growing concerns about global climate change, the use of renewable energy (RE) on a national scale has become a requirement for every country on the planet.

Most of them always accepted that the energy we make use of each day is not unlimited, still we take it for granted. Coal, petroleum, electrical power, even water has inadequate availability. Crude oil and natural gas becoming being extinct and have already become high initial cost without unexpected situations. Prices of Petroleum products have been rapidly increasing for the past years, due to the rising energy demand in electricity, transportation and the escalating shortage of energy resources. The solar energy considered as the one of most popular sources of renewable energy used for building electrifications, due to its nature of availability, scalability and initial investment compare to Wind and other renewable energy sources.

People tend to use green energy sources or alternative power sources in their building or national scale, if there are advantages over others. This may be in cost, environmentally safe, convenient to install and maintenance.

Solar PV energy has grown rapidly in recent years as a result of both technical advancements in solar energy production equipment that have resulted in cost reductions and government policies that encourage the creation and use of renewable energy. Though small-scale photovoltaic (PV) cells were used in early solar technologies for special requirements such as space shuttles and military equipment, large-scale PV systems and solar concentrated power (CSP) systems that feed into electricity grids are now commonplace.

Several studies have looked at different aspects of solar energy and optimization technologies. This thesis examines solar PV power generation and improves its performance by conducting an overall analysis of established literature, as well as journalist and other publications [12].

1.1 Importance of Solar PV Energy to Sri Lanka

According to the joint Asia Development Bank and UNDP report “100% Electricity Generation through Renewable Energy by 2050, Assessment of Sri Lanka’s Power Sector”. Sri Lanka is one of the Climate Vulnerable Forum's 43 countries that have pledged to make their electricity supply 100 percent renewable as soon as possible, preferably by 2050. This is an ambitious target for a country where per capita electricity demand is projected to rise dramatically in the coming years.

“Based on the report, by 2050, the country's installed generation capacity needs will increase from the present 3,700 megawatts (MW) to about 34,000 MW. With this, 15,000 MW are going to be solar energy and about 16,000 MW are going to be wind power. Balance capacity is probably going to be met by hydro and biomass-based power plants. The evaluation indicates that the replacement of imported fuel with renewable energy until the year 2050 provides direct financial benefits and can reduce Sri Lanka's fuel import bill by about $18 billion cumulatively. The report also identifies the necessity for structural changes within the retail electricity tariffs of Sri Lanka to ensure financial sustainability of its operations” [2].

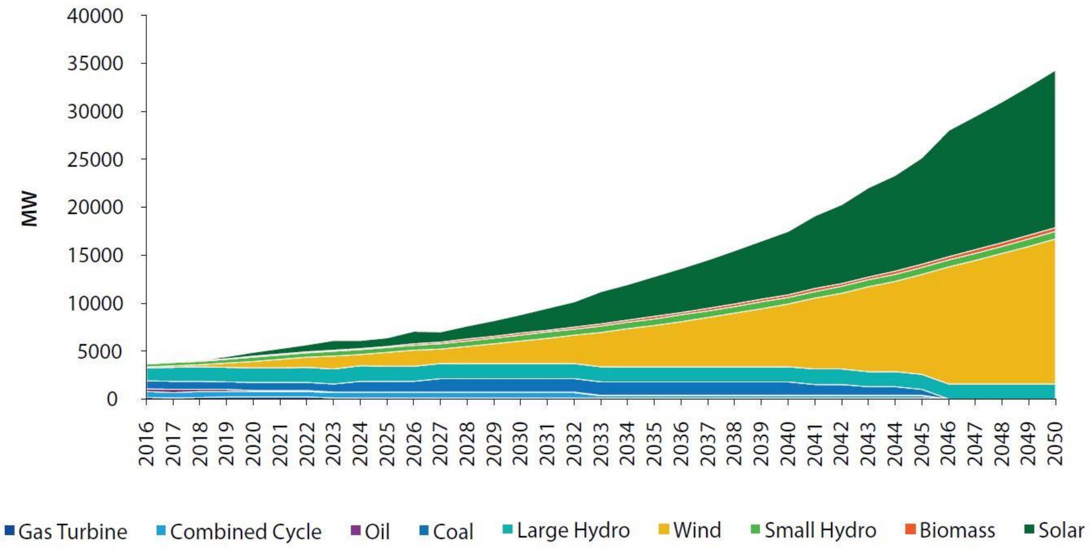


Figure 1.1: Expected Energy Mix from 2016 to 2050 in Sri Lanka

(Source: ADB/UNDP report 2017)

"The generation balance between wind and solar energy has been calculated to the point that solar energy will contribute 30% of total demand by 2050, while wind energy will contribute 50%. The assumption is that a major portion of domestic and commercial energy use will be powered by solar PV energy through an accelerated implementation of roof-top solar infrastructure" [10]. Trend of more solar power plant installation in future will lead discussing energy efficiencies of these power plant in all possible ways where one of major aim of this thesis.

1.2 Problem Statement

Energy is a key parameter for all human being in the world. Presently, all system required some source of energy to provide the expected output, especially in transportation and building electrification. Renewable energy is energy that comes from natural resources such as sunlight, wind, rain, and geothermal heat where it is very essential due to depletion and limited availability of non-renewable energy sources.

Theoretically, solar energy can provide excess energy far more than required by present global requirements. Due to evolving technology and decrement of initial cost of Solar PV system, people tend to become self-generated consumers than past where it gives less trouble on maintenance due to non-availability of moving parts. As per Solar Energy agency report each year solar installation increased by 20-30% globally to optimum use of non-renewable energy sources for sustainable future.

Presently, Ministry of Power in Sri Lanka also encourages building owners, retail consumers to install onsite solar PV system where it targets for 100% renewable energy electrification in 2050 as per ADB/UNDP report published in 2017.

The main important factors that are directly affected by improving the performance and efficiency of solar PV systems are reviewed in this article. As a result, omnipresent factors like irradiation, shading, dust or soiling, and cell operating temperature are all present. They are identified as most influenced for performance and efficiency of PV system. Issue of Irradiance and shading are mostly discussed and analyzed by many researches where already innovated equipment such as solar tracking devices and optimizers to mitigate or overcome the impact of such factors.

1.3 Objectives

As per literature review and other reading materials, it has identified that there is no any permanent or proven benchmark provided for all over the world to overcome or minimize the effect of Dust/Soiling and temperature influence for solar system performance and their system efficiency.

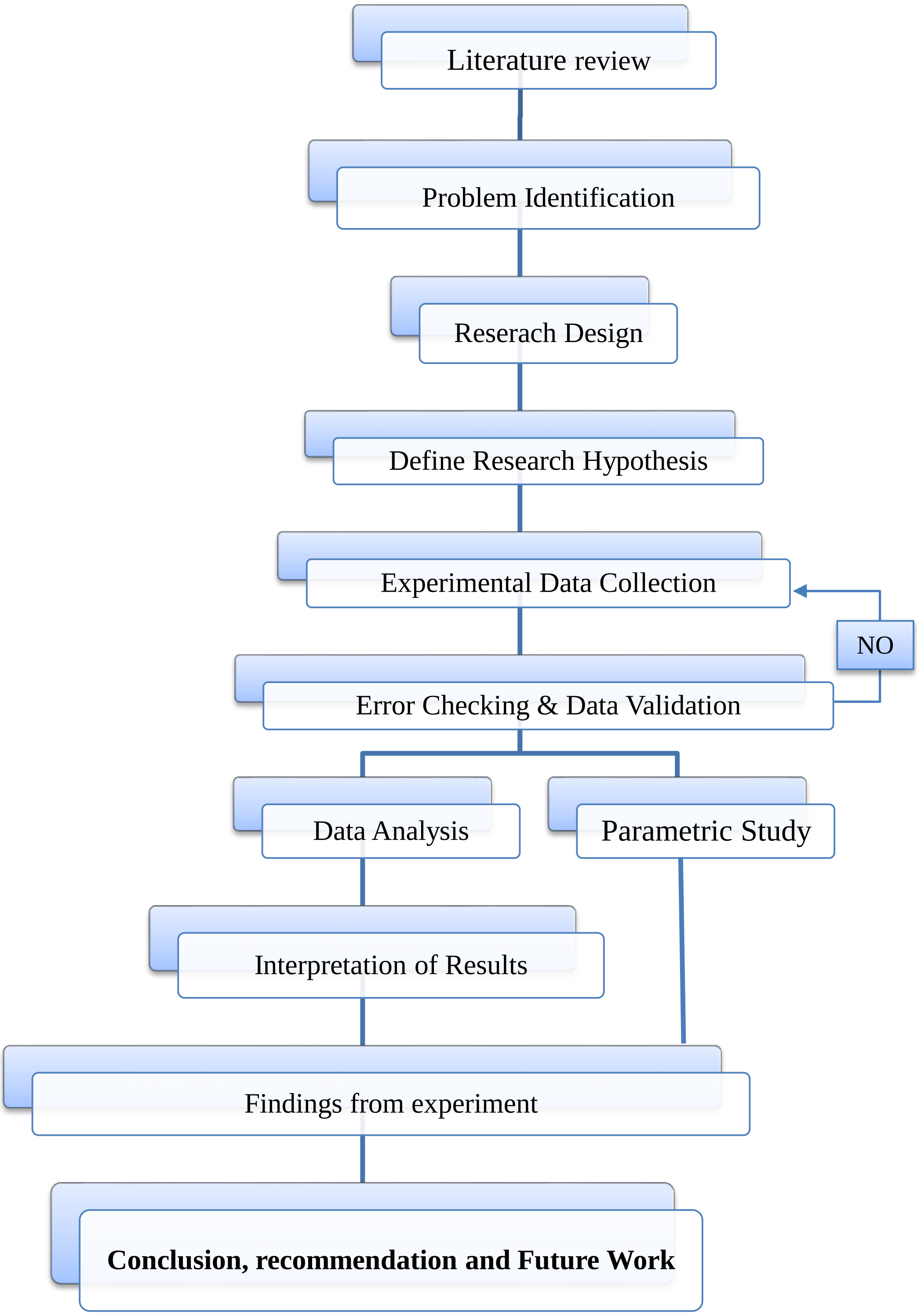
It is proposed to carry out a field test and analysis to study the influence of Dust/Soiling effect, temperature and irradiance level excluding shading. Moreover, it will study the interaction effects of these three factors individually and altogether against output power of Solar panel prior to provide benchmark for solar PV consumers to minimize the effect of dust and temperature effect while optimizing solar PV system output. Small improvement in one solar panel will gain considerable amounts of energy saving in medium, large and extra-large Solar system with same infrastructure facility and investment. This may provide additional advantage for future (GW) scale solar PV installation which is supposed to implement in Sri Lanka and other tropical region country.

1. Study and analysis of the effect of irradiance on performance solar PV panel.
2. Study and analysis of the effect of dust/soiling on performance solar PV panel.
3. Study and analysis of the effect of temperature on performance solar PV panel.
4. Provide theoretical data with analysis for interactions of irradiance, temperature and dust/soiling for Solar PV system energy generation.
5. Provide limitation and assumptions of solar PV study.
6. Proposing future works and further analysis to identified more details on major factors affecting solar PV generations.

1.4 Methodology

- Literature review on similar research area
- Study the main parameters effects for Solar panel output Power and finally overall system efficiency
- Identify main parameters to be checked and analysis in field
- Setup a field test to measure different parameters in same environmental condition
- Collect all data and Tabulated properly based on Irradiance Level, Panel temperature and amount of dust level Vs Power output
- Data aggregated with Low and High Value of Solar PV power output
- Data Analysis using Three-way Factorial Analysis of Variance (ANOVA) Design by SPSS (Statistical Package for the Social Sciences)
- Statistically calculate the main effects and their interaction effects of Irradiance, Panel Temperature and dust level for Solar Power energy Output
- Recording Results of experiment.
- Determine Maximum effects for Solar Panel output Power with different influencing factors, Irradiance, Temperature and Dust level
- Providing Conclusion for experiment
- Final Recommendation and Future Work

1.5 Workflow Chart



CHAPTER 02

LITERATURE REVIEW

In this chapter include review of literature related to principle, history of Solar PV electricity and PV system installation. Furthermore, it is discussing the previous research conducted to find out factors affecting solar PV system efficiency and their performance. The reviewed literature is divided into a few main important topics for the discussion of solar PV potential, Solar PV building electrification and their energy optimization techniques.

2.1 Principle of Solar Photovoltaic Electricity

“A solar module or panel generates electricity power by using the photovoltaic effect, which was exposed in 1839 when Edmond Becquerel, a French physicist, observed that certain conductive materials formed an electric current when exposed to sun light Two surfaces of a semiconducting material are combined to produce photovoltaic effect. One (01) layer of semi conducting material has to have a depleted numbers of electron. The layers of material absorb the photons, when it exposed to sunlight. This stimulates the electrons, causing more or less of them to ‘jump’ from one layer to other, generating an electrical current through electrical charge” [1].

Silicon, which is cut into very thin wafers, is the most common semiconducting material used to make solar cells. Any of these silicon wafers are then contaminated by being ‘doped,' resulting in an electron imbalance in the wafers. After that, the wafers are arranged to form a solar cell. The electrical current is carried by conductive metal strips connected to the cells. A photon from the sun will do one of three things when it hits the solar cell. It can either be absorbed by the cell, passed straight through it, or reflected off of it. An electrical current is produced when a photon is absorbed by the silicon.

Solar PV cells will generate most of their electricity from direct light from sun. However, they may generate electricity on cloudy days and some solar panels can even generate very small amounts of electricity on bright moonlit nights.

2.2 Solar Photovoltaic System Configurations

Solar Photovoltaic power systems are generally categorized according their component configurations, their functional and operational requirements, and how the equipment is connected to other power sources and electrical loads.

Due to variations in solar irradiance, energy produced by PV solar systems does not always meet the energy demand of end users. As a result, additional energy solutions such as energy storage systems (batteries) or renewable energy sources would be needed. PV system installation in both residential and industrial settings has been done in a variety of ways. The best device form for each location is determined by a combination of geographical, economic, and technical factors. When it comes to solar PV power generation systems, there are three different configurations to choose from:

- Off-Grid (Stand-alone systems)
- Grid-tie (Most common type used by installers in Sri Lanka)
- Grid interactive (also known as Grid-tie with power backup)

2.3 Potential of Global Solar Energy Generation

The amount of solar power incident at a location is a critical factor in solar PV energy generation technology. Irradiance is the quantity of solar power incident per unit area per unit time (measured in kWh/m2 per day or kWh/m2 per year) and is the most appropriate criterion for assessing the solar resource at a given location.

Radiation data is provided as Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) to meet the needs of various types of solar PV applications. Different components of radiation are illustrated on following illustration (Figure 04).

The earth's atmosphere absorbs and scatters some of the radiation waves that penetrate it. A straight line from the sun produces direct beam radiation. Clouds, molecules, and aerosols disperse diffuse radiation away from the direct beam. Global or cumulative radiation is the amount of direct beam, diffuse, and ground and surroundings reflected radiation arriving at the surface.

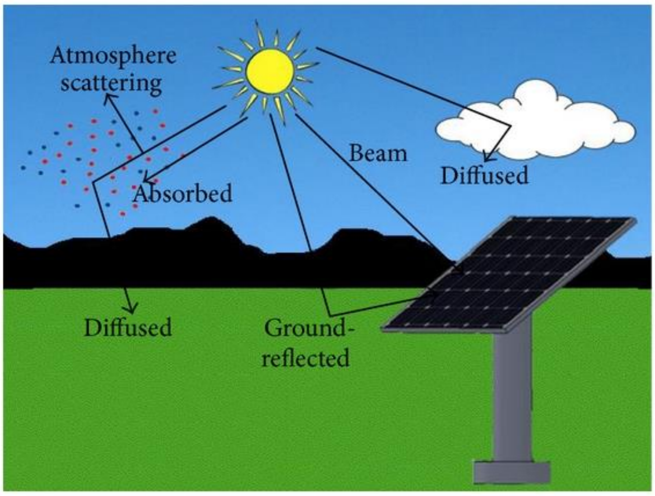


Figure 2.1: Components in Global Solar Radiation (Source: reserachgate.net)

The cumulative sum of solar power incident on a horizontal level is known as global horizontal irradiance (GHI). The amount of radiation incident on a surface that is normally held perpendicular (normal) to the direct solar beam is known as direct normal irradiance (DNI). DHI (diffuse horizontal irradiance) is a portion of the radiation that reaches a level due to scattering of sunlight within the atmosphere and reaches the level from all directions of the sky. The following expression connects these three quantities.

$GHI = DNIcosZ + DHI,$ where Z is the sun zenith angle.

For solar photovoltaic (PV) applications, GHI is the most important parameter, while DNI is the most important parameter for Concentrating Photovoltaic (CPV) plants. Because of differences in geographical location and local climate changes, the amount of GHI and DNI varies.

Table 01: DNI and GHI Range of different region of the World in yearly

Region	GHI Range (kWh/m^2)	DNI Range (kWh/m^2)
Africa	1600 – more than 2700	900-3200
Middle East and North Africa	1700 – more than 2700	1100-2800
Latin America and Caribbean	1000 – more than 2700	800-3800
North America	1000 – more than 2700	700-3100
Europe	Less than 700-2100	500-2300
South and Central Asia	1400-2400	1100-2500
East Asia	1000-2300	500-2600
South East Asia and Pacific	900-2600	900-3200

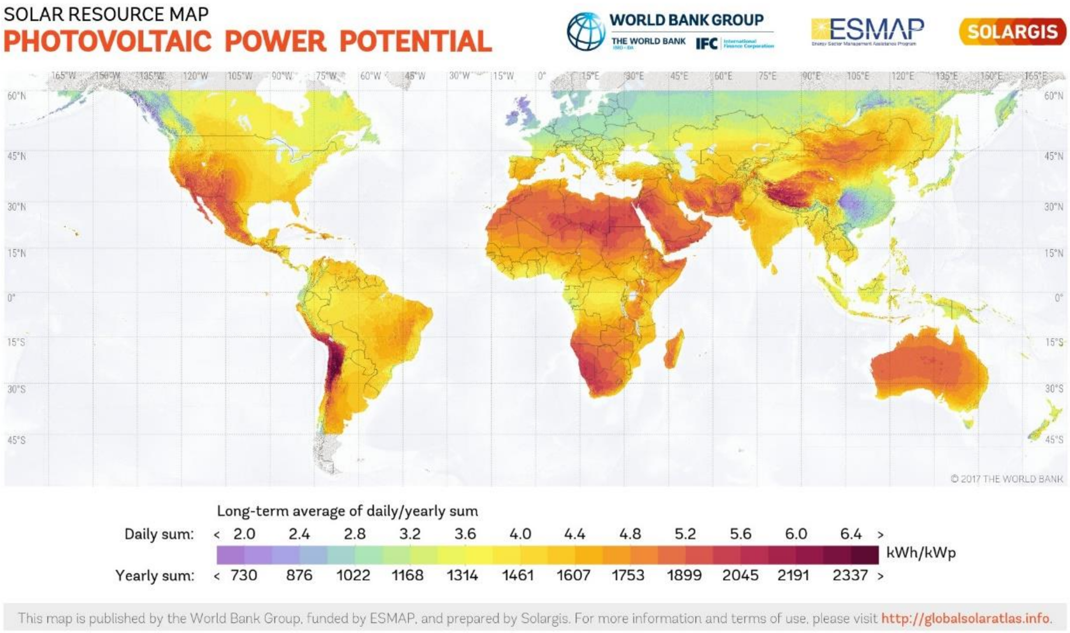


Figure 2.2: Global Solar PV Potential Map (Source: *globalsolaratlas.info/*)

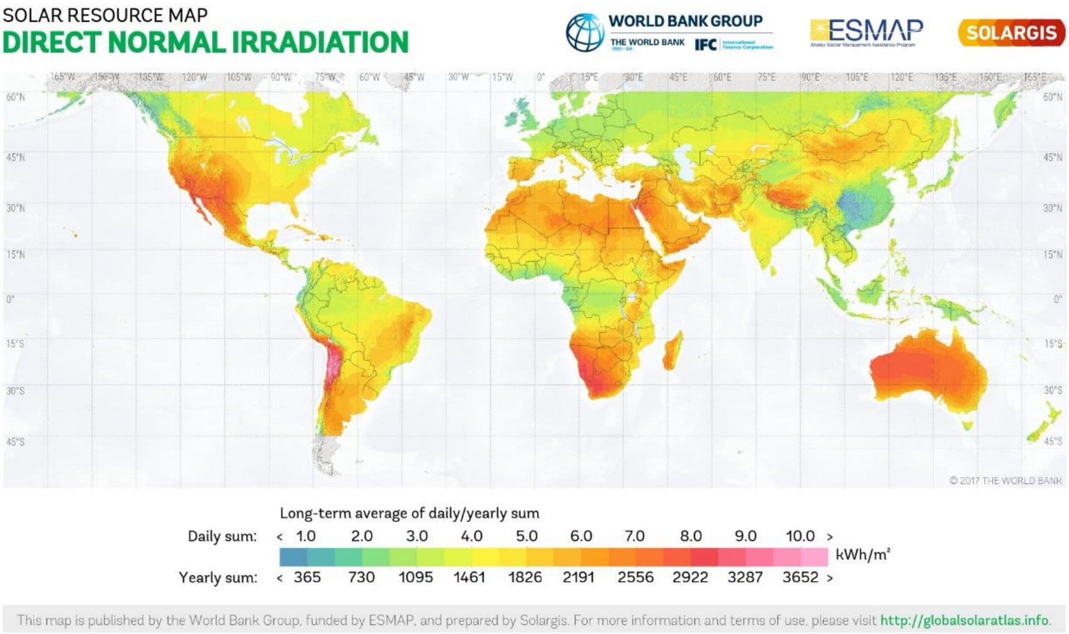


Figure 2.3: Global Direct Normal Irradiation (Source: *globalsolaratlas.info/*)

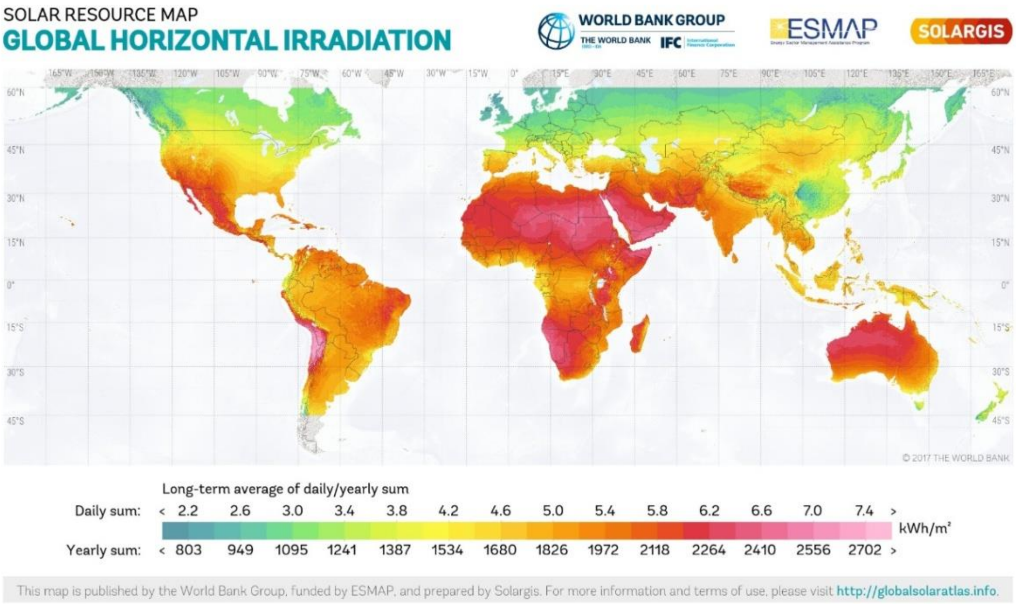


Figure 2.4: Global Direct Horizontal Irradiation (Source: *globalsolaratlas.info/*)

By considering irradiance level, dust/soiling and temperature parameters, Minimum Annual technical potential of solar energy is estimated as 37,492 Mtoea which is approximately 436million GWH/year [8].

2.4 Present Solar Energy status and resources

“Solar energy markets have regained traction since the early 2000s, and have recently experienced remarkable growth. From almost no power in the early 1990s to more than 75GW by the end of 2016, solar-based electricity generation systems had been built all over the world. This equates to more than 31,000 solar panels being installed every hour. By the end of the year, global solar PV capacity had reached at least 303 GW”. [3].

The growing competitiveness of solar PV manufacturers and their new technologies, as well as increasing electricity demand and increased awareness of solar PV's potential as countries tried to reduce pollution and CO2 emissions, both contributed to the market's rise [10].

Solar PV is now widely regarded as a cost-competitive source of electricity generation and energy access to all peoples on the planet in many developing markets [11]. Nonetheless, in most nations, the power of ministers or energy regulators is still largely influenced by government incentives or legislation.

“For the fourth time in conservative years, the Asian region outperformed all other markets, accounting for roughly two-thirds of global additions in 2016. China, the United States, India, Japan, and the United Kingdom were the top five solar PV energy producers in 2016, accounting for around 85% of new installations. Germany, the Republic of Korea, Australia, and the Philippines and chille rounded out the top ten countries for additions” [3].

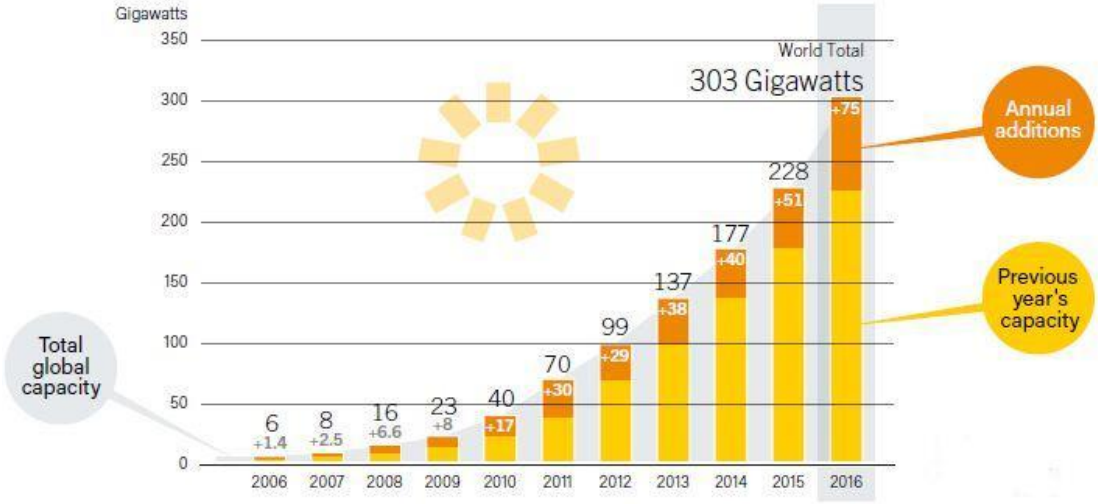


Figure 2.5: Solar PV Global Capacity and Annual Additions, 2006-2016 (Source – REN21 Report 2017)

"China added 34.5 GW in 2016, an increase of 126 percent over 2015, bringing its total solar PV capacity to 77.4 GW, far exceeding that of any other nation. Facing a downward revision to China's 2020 target due to a slowdown in the growth of electricity demand, the record increase occurred" [3].

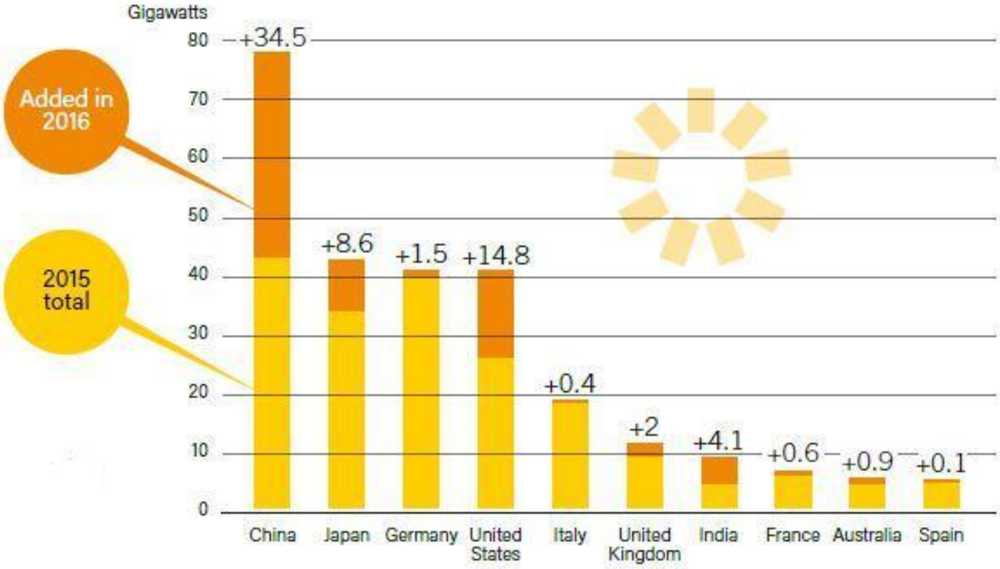


Figure 2.6: Additions of Solar PV Capacity for top 10 countries, 2016 (Source – REN21 Report 2017)

"Since the end of 2012, China's rapid expansion of solar PV capacity has caused power grid congestion and interconnection delays. Curtailment became a major issue in 2015, and problems worsened in 2016 due to insufficient transmission. In 2016, China set minimum guaranteed usage hours (purchase requirements) for solar (and wind) power plants in affected areas, and continued to construct many ultra-high-voltage power transmission lines to link north-western provinces with coastal areas, in order to address curtailment challenges. Despite these obstacles, solar PV generated 66.2 TWh of electricity last year (up 69 percent from 2015), which is equal to 1% of China's annual power generation needs" [3].

Solar Energy potential of India and their market is very important to evaluate local context in terms of solar energy generations, efficiencies and evolving technology. India is a tropical country in South Asia with plenty of sunlight and long days. In a year of normal weather, there are approximately 301 bright sunshine days. In theory, India receives 5000 trillion kWh of solar power per year (approximately 600 TW) across its entire land area. Daily solar energy incident over India averages between 4 and 7 kWh/m2. The number of hours of sunshine in a year varies by geographical area, ranging from 2,300 to 3,200. This demand is much greater than India's current total energy consumption [9].

"In the Asian zone, the Republic of Korea followed India, adding 0.9 GW to rank seventh in additions and end 2016 with 4.4 GW. Both the Philippines and Thailand agreed to increase their national goals by approximately 0.8 GW (total of 0.9 GW) and more than 0.7 GW (total of 2.15 GW), respectively" [3].

2.5 Present status of Electricity Generation in Sri Lanka

Several energy sources, including imported fossil fuels and indigenous non-fossil fuels, are currently used to meet Sri Lanka's electricity energy demands. The majority of the country's energy needs are met by biomass, an indigenous fuel source, and imported fossil fuels, mostly petroleum and coal. The rest comes from domestic sources like big hydro and renewable energy sources like wind, small hydro, solar, and wind.

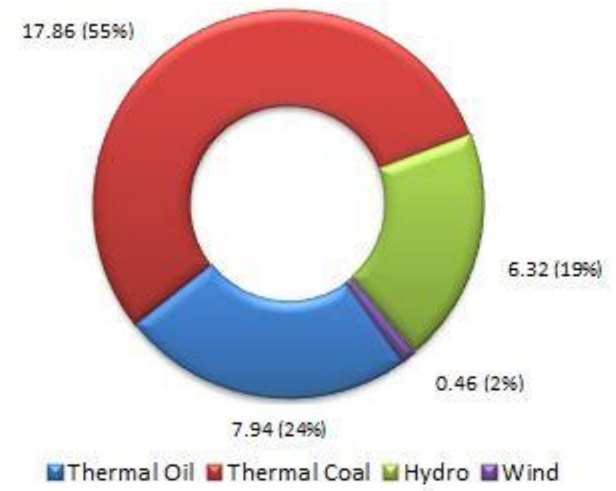


Figure 2.7: Sri Lanka Energy Generation Mix in May 2018 (Source – energy.gov.lk)

In 2016, Sri Lanka's annual electricity demand was around 12,000 GWh, and installed power plant capacity was around 4018 MW, according to the Purchasing Power Group (PPP). There are 1726 MW of hydro power, 1215 MW of thermal power, and 176 MW of other renewables in this installed capacity [11].

Thermal power plants use coal, heavy fuel oil (HFO), and diesel to produce electricity. The low cost option for power generation is hydropower. The second cheapest option for electricity generation is coal. Electricity generation increased by 8.1% from 13,090 GWh in 2015 to 14,148GWh in 2016 reflecting the dry weather conditions and additional demand for consumers. Thermal power generation increased by 13.6 percent to 5,047 GWh as a result. Since 2014, the Norechchole coal power plant has supplied 900MW of electricity to Sri Lanka.

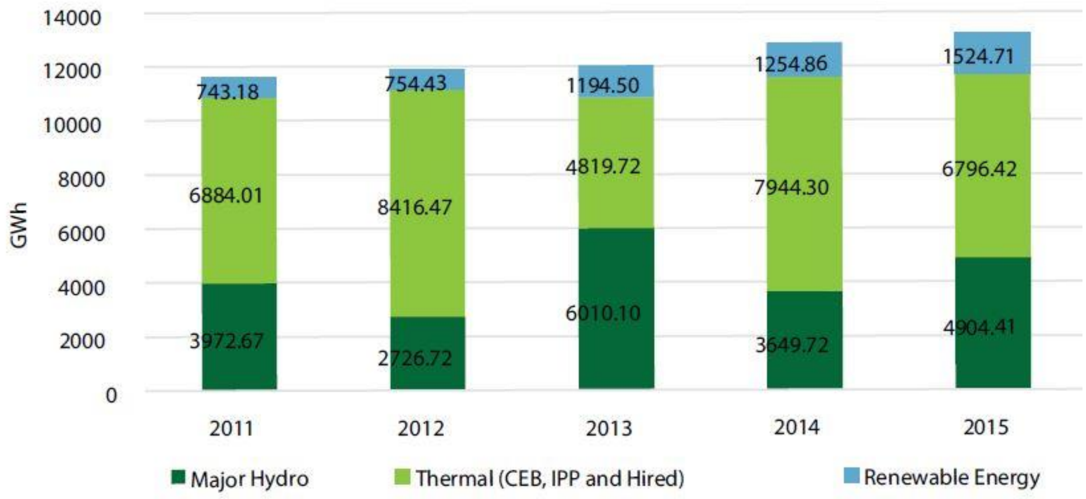


Figure 2.8: Sri Lanka Electricity Generation 2011 -2015 (Source: energy.gov.lk)

As seen in Figure 2.8, in recent years, Sri Lanka has been primarily reliant on fossil fuels for electricity generation. According to Sri Lanka's National Energy Policy and Strategies (NEPS), in 2014, the country achieved its goal of producing at least 10% of its electricity from renewable sources.

Table 02: Energy cost of generation as follows (Actual 2017 – Source CEB)

Source	Unit Cost (Rs/kWh)
CEB – Hydro	2.56
CEB – Thermal	25.73
CEB – Coal	9.03
IPP – Thermal	26.77
Renewable Energy	17.45
Generation Average	***14.41***

2.5.1 Present Status of Non-Conventional Renewable Energy (NCRE) Sector in Sri Lanka

Today, all countries around the world are concerned about energy security and long-term development, and the role of renewable energy sources in this has become increasingly important. As a result, renewable energy is emerging as the energy supply alternative for the twenty-first century. Sri Lanka, a small island off the coast of India, has also embraced renewable energy as a source of electricity, setting a number of precedents in the process.

Sri Lanka launched a National Energy Policy in 2006, emphasizing the importance of fostering energy efficiency and conservation, with the primary goal of encouraging indigenous energy resources. Small hydro plants, solar power, wind power, and biomass projects are examples of NCRE (Non-Conventional Renewable Energy) sources. The government set a target of using non-conventional renewable energy to produce a minimum of 10% of the grid's electricity by 2015, which it met successfully.

NCRE power production has been steadily increasing since 1996, with a total capacity of 557.6MW added until 2017. The installed capacity of NCRE Energy sources has grown at a compound annual growth rate of 10% over the last seven years, highlighting the importance of NCRE in generating electricity.

Table 03: Total NCRE Project and Their Capacity up to July 2017 (Source: CEB.lk)

Project Type	**No. of Projects**	**Capacity (MW)**
Wind Power	15	128.850
Solar Power	8	51.360
Mini Hydro Power	181	353.744
Biomass – Agricultural and Industrial Waste Power	4	13.080
Biomass – Dendro Power	5	11.020
Total - Commissioned	213	**557.654**

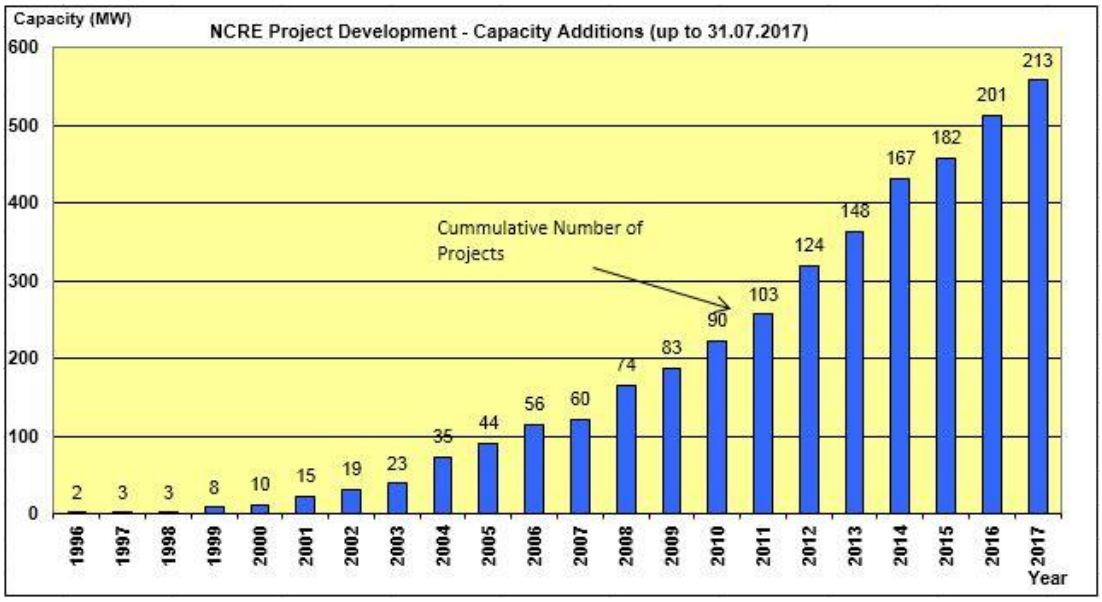


Figure 2.9: NCRE Project Development Progress (1996 – 2017)

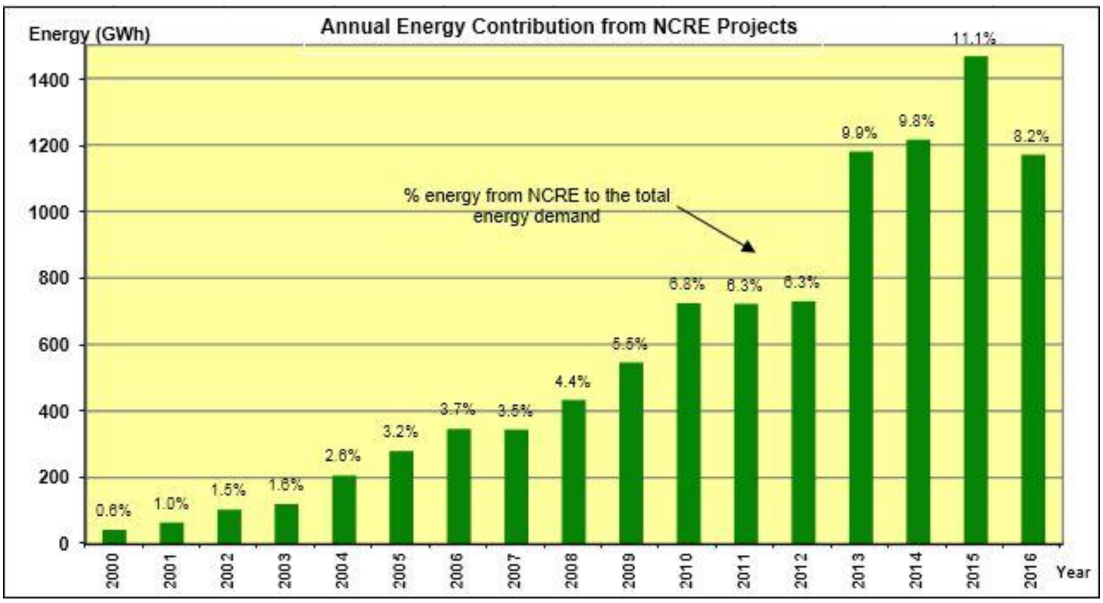


Figure 2.10: NCRE Annual Energy Contribution (2000 to 2016)

Table 04: NCRE total installation Capacity from 2009 to 2017

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017
Cap (MW)	188	222	257	320	363	431	457	512	558

Table 05: NRCE Energy Generation in GWH from 2009 to 2016

Year	2009	2010	2011	2012	2013	2014	2015	2016
Energy (GWh)	546	727	722	730	1178	1215	1466	1170

Sri Lanka's government has prioritized the construction of renewable energy projects as part of a strategy to diversify the electricity sector from high-cost thermal power generation to low-cost operation power plants. As a result, necessary incentives and funding were given for the production of renewable energy resources (Mini Hydro, Biomass, and Wind, Solar etc...).

2.5.2 Overview of Solar Energy in Sri Lanka

Sri Lanka receives a substantial solar energy resources exist throughout much of the year in adequate quantities for many applications of Sri Lanka has been described as a region with a high potential for harnessing solar energy because it is located near to the equator and thus does not exhibit significant seasonal variation. Passive solar heating/cooling, solar water heating, solar power, and desalination are all examples of this. Many solar energy applications are currently in use in Sri Lanka to meet remote energy needs in most of the country's non-electrified areas. There is a great deal of room to expand the use of this renewable energy source. Solar photovoltaic technology is currently cost-effective for meeting remote energy needs and providing a distributed source of electricity without requiring extensive grid infrastructure or causing grid disruption [12].

According to the solar resource map which is published by the World Bank Group, funded by ESMAP, and prepared by Solargis, Global Horizontal Solar Irradiation of levels of Sri Lanka is between 4.5 -5.8 kWh/m^2 (daily) for most of area and irradiation levels are around 4.4kWh/m^2/day over the country's central mountains. “The annual results for Sri Lanka, which range from 4.5 to 6.0 kWh/m^2/day, are steady with, and slightly higher than earlier studies using recorders of sunshine, which gave results of 4.2 to 5.6 kWh/m^2/day” [4].

“The variability in global horizontal solar resources is relatively small across most of the cities and rural area of the Sri Lanka, regardless of the impact of terrain characteristics on cloud formation. The resource generally varies spatially at most 20% to 30% during any given season. The utmost resources are in the northern and southern regions, and the lowest resources are in the interior hill country” [11].

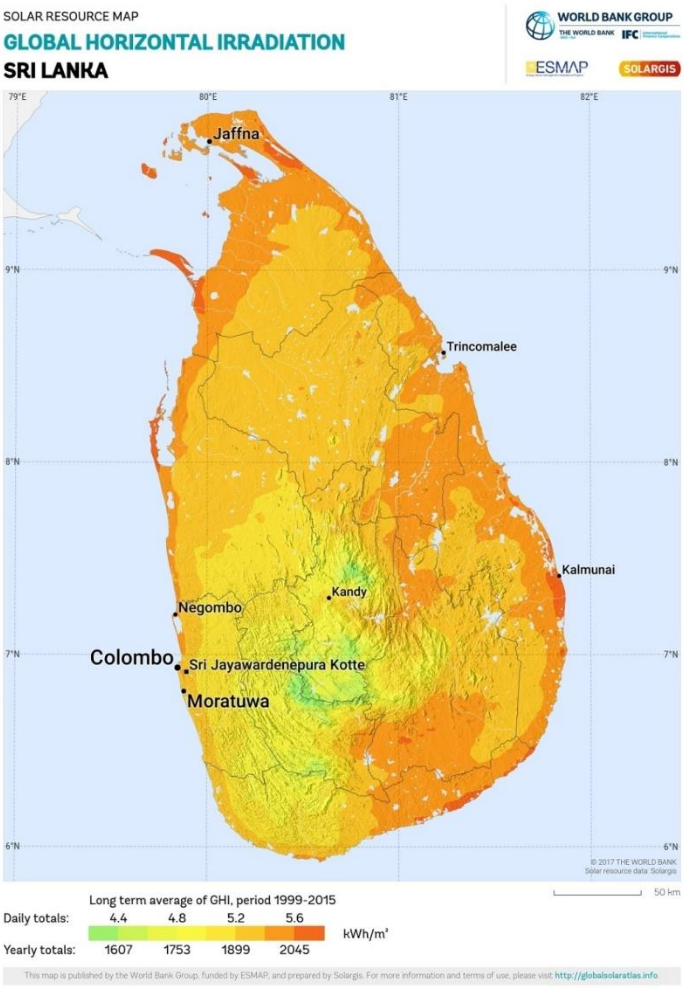


Figure 2.11: GHI Map in Sri Lanka (Source: *globalsolaratlas.inf/*)

Based on figure 2.11, about 2000 kWh/m^2 of irradiance per year has been received by Sri Lanka. As a result, the potential for harnessing solar energy is enormous. Further, Solar Map published by World Bank group funded by ESMAP, most part of the country has PV Electricity potential about 3.8 – 4.6 kWh/kWp/day which means 1kWp Solar PV system generate 1387 – 1680 kWh per annum.

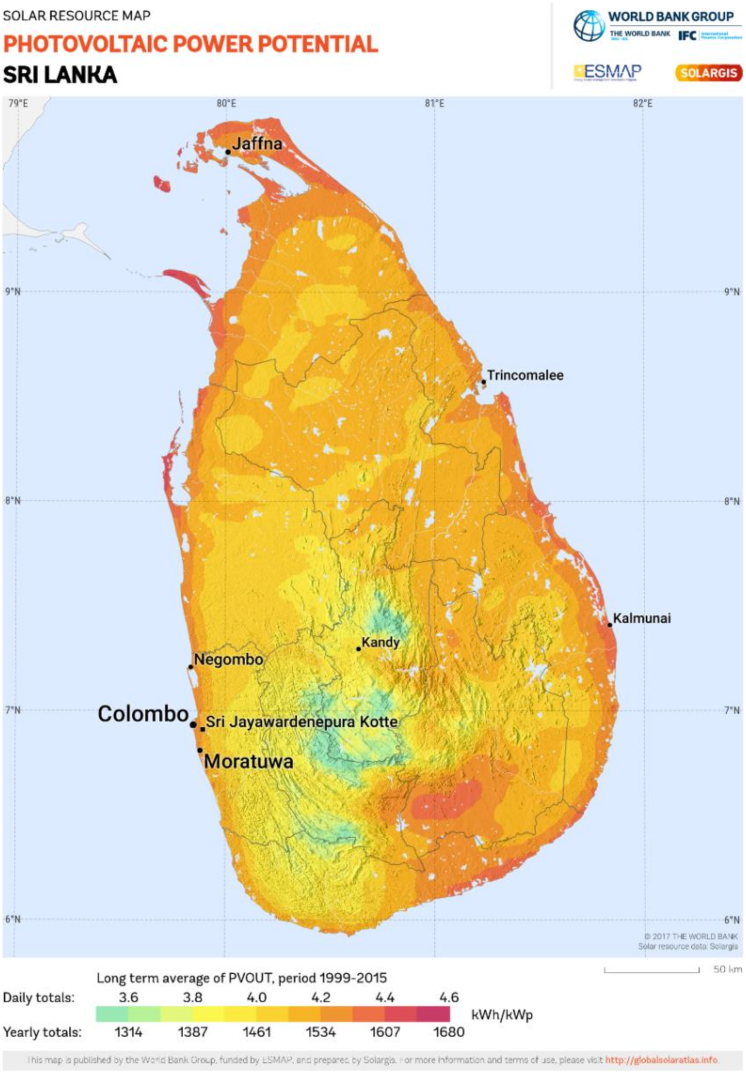


Figure 2.12: Solar PV Potential Map in Sri Lanka (Source: *globalsolaratlas.inf/*)

2.5.3 Present Solar Installation in Sri Lanka

For Sri Lanka's future energy needs, solar energy could be the best option. It is one of the best options for achieving the ambitious goal of increasing NCRE share to 100% by 2050 from the current 10% [4].

Following tables indicated major Solar PV capacity Installed and planned by Ceylon Electricity Board (CEB) at present.

Table 06: Solar PV Installed Capacity forecast by CEB

Year	Solar PV installed Capacity in national Grid (MW)
Solar PV Upto 2017 July	51.36
2018/2019 –Ongoing	90x1MW Solar Plant all over the country
2019 – feasibility Studied done	100MW
Total PV Capacity in End of 2019	241.36 MW

Apart from utility scale Solar PV power plant, Government of Sri Lanka is encouraged all other individual consumers to installed roof top solar power plant cater for their energy demand and excess can export to the country national grid. The major Project under this scheme was launched in 2016 named as “Soorya Bala Sangramaya” or Battle for Solar Energy Program. The project's goal is to add 200 megawatts of solar PV capacity to the national grid by 2020, 1000 megawatts by 2025, and minimize carbon dioxide emissions from thermal power plants (coal, diesel, and HFO) by 150,000 metric tons per year after 2020.

Electricity customers will be able to produce and use electricity in their homes using a solar PV system under this scheme. In the event that they produce more power than they need, it has the option of selling it to the national grid or storing it for future use. The consumer can choose a preferred choice based on their electricity consumption requirements introduced by Public Utility Commission together with Ceylon Electricity Board and Lanka Electricity Company. These are categorized as Net Accounting, Net Metering, and Micro Solar Power Producer. Each category gives distinct advantages to end customers as per their PV installed capacity and investment. Solar PV installation in small scale in a country will effectively aware general public regarding greenery environment and reduce use of conventional energy source in daytime.

2.6 Technical Overview of Solar PV system Components

The major part of a solar PV power generation system is the solar panels, inverter, AC/DC cables and protection equipments. There are various types of solar panels available in the market with different construction and efficacies. Solar panels, also known as photovoltaic (PV) solar modules, generate electricity power from the sun. If the sun provides more energy, the solar panels can produce additional power. Individual solar cells are used to make the majority of solar modules (panels), which are attached in a 60 or 72 cell configuration in industrial solar panels. Since a typical solar cell produces around 0.6V (dc), connecting in series within the PV panel results in a higher functional voltage. Solar panels with 60 cells are commonly wired in three strings of 20 with bi-pass diodes.

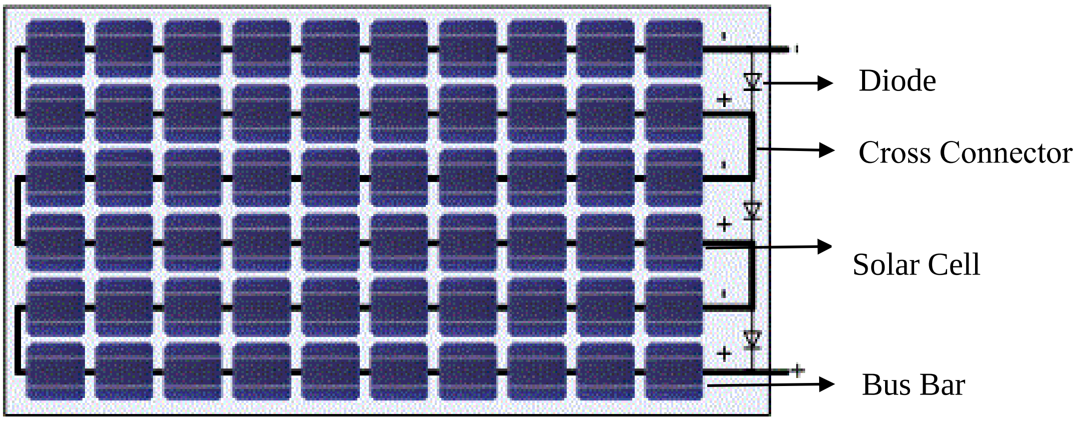


Figure: 2.13 Solar cell connection of a typical solar module (Panel)

The majority available solar panels rated 200Wp or above as 24V solar PV panels, with bigger solar panels are 30/36V panels. A solar PV array is made up of solar panels that have been connected together. As multiple panels are connected together, they can generate a higher current or operate at a higher voltage up to 1000Vdc. As solar panels are connected in sequence, the voltage of the array is increased. In a stand-alone system, it will typically be 12V, 24V, or 48V, while in a grid-tied system, it will be several hundred volts.

A solar PV array can produce more power while retaining the same voltage as individual panels when solar modules are connected in parallel.

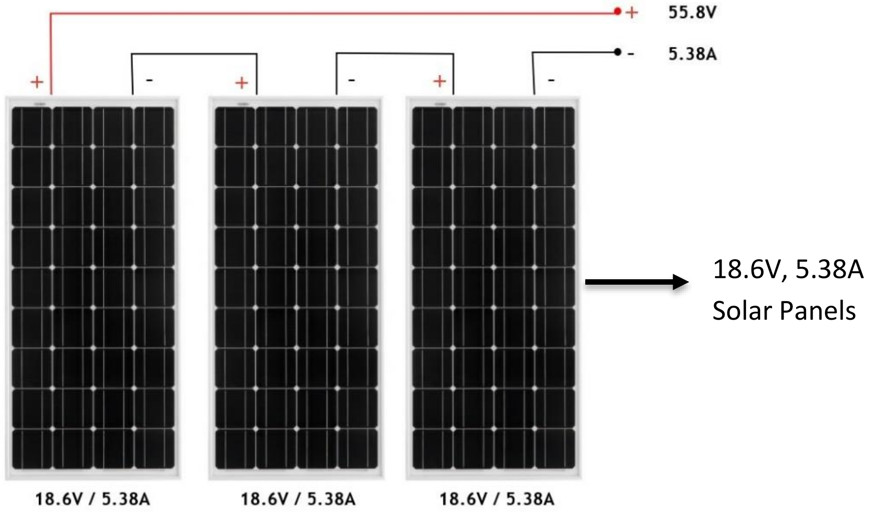


Figure 2.14: Series Connection of Solar Panels

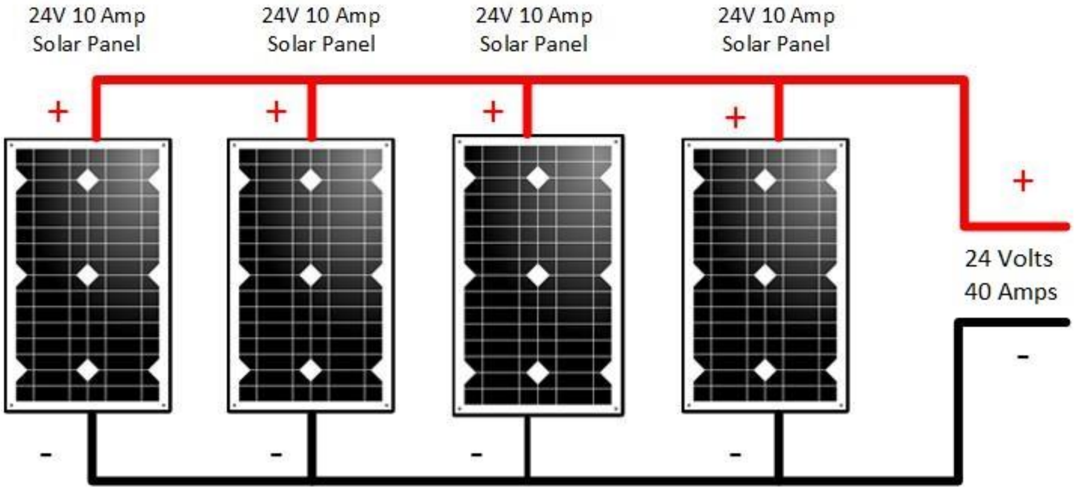


Figure 2.15: Connecting Solar Panels in Parallel

2.6.1 Type of Solar Panels and efficiencies

Every Solar PV module is made from a single silicon crystal. Individual cells are made by filtering, melting, and crystallizing silicon into ingots, which are then cut into thin wafers. Monocrystalline PV modules are usually black or iridescent blue in colour.

Monocrystalline devices have a high efficiency of 15-20% due to the fact that they are made of premium silicon, making them cost efficient in the long run. By 2020, their efficiency is projected to rise to 23%, with a further increase to 25% in the future [13]. Monocrystalline solar panels have two significant flaws: a high initial cost and a high degree of fragility. The Czochralski process, which results in substantial silicon waste, is used to produce monocrystalline silicon.

Polycrystalline or Multi-crystalline

Solar cells consisting of multi-layered silicon crystals are used in polycrystalline or multi-crystalline plates. Polycrystalline solar cells do not have the same uniform appearance as monocrystalline solar cells. The manufacturing process is cost-effective, simple, and reduces silicon waste when compared to mono-crystalline panels. Polycrystalline panels have a higher temperature co-efficient than single crystal panels, meaning that panel power output will decrease as cell temperature rises; however, these variations are small in practice.

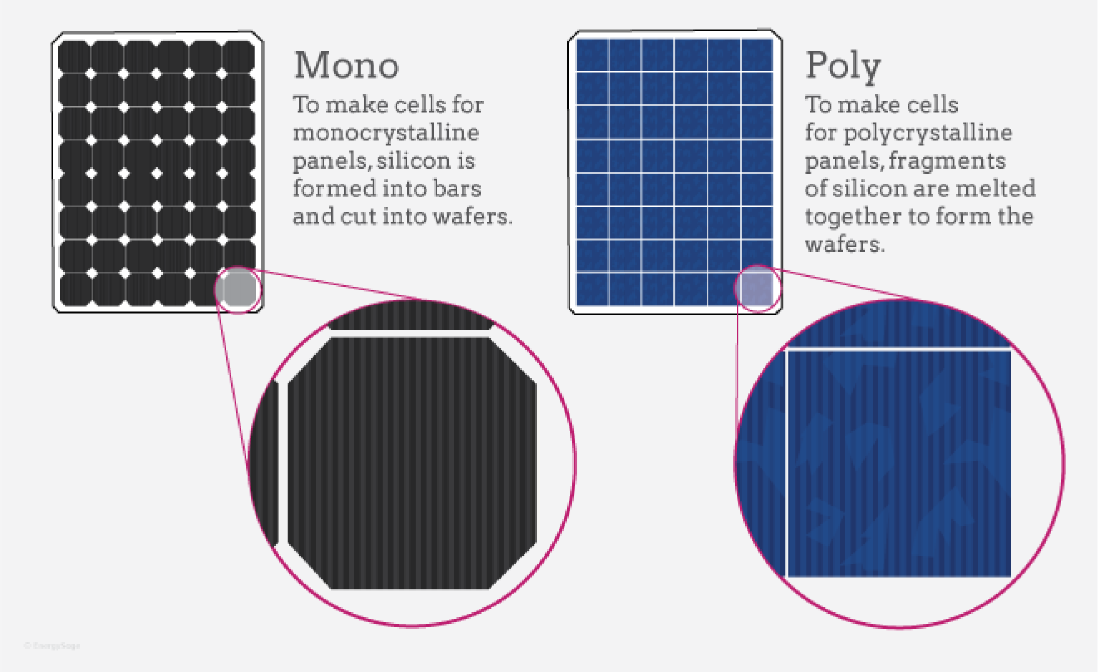


Figure 2.16: Mono-Crystalline and Poly-Crystalline Panel Construction

Thin Films Solar Panels

“Amorphous solar panels are another name for thin film solar panels. Thin-film solar panels are created by depositing thin layers of semiconductor material onto various surfaces, including glass. Thin film solar cells are easier to produce, more stable, simpler, and lighter in weight than traditional silicon solar cells. With the exception of molding or slicing crystalline silicon, the silicon used in amorphous panels has no crystalline structure. As a result, the four major types of thin films are amorphous silicon, copper, indium, gallium, selenide (CIGS), cadmium telluride (CdTe), and organic photovoltaic cells (OPC)” [17].

On paper, thin film solar panels are the least effective, converting only 6–8% of usable sunlight into electricity. Unlike other solar panel technologies, this type of solar panel performs well even in partially shaded conditions. Although it's ideal to avoid shading wherever and wherever possible, even if a portion of the array is in the shade, thin film panels can still operate at a high level of performance.

Figure 2.17: Different Type Solar Cells Construction Appearance

Thin-film PVs, also known as 3rd generation PVs, are a growing class of solar PV modules that use technologies that have the potential to surpass current performance and efficiency limits based on various materials. DSSC (dye-sensitized solar cell), organic photovoltaic (OPV), quantum dot (QD) PV, and perovskite PV are all members of this 3rd generation thin film solar PV family.

A perovskite solar cell is a type of solar cell that uses a perovskite structured compound as the light-harvesting active layer, most commonly a hybrid organic-inorganic lead or tin halide-based material. Perovskite products, such as methylammonium lead halides, are inexpensive and straightforward to create.

2.6.2 Solar PV inverters

Solar PV inverters are used to convert a variable DC (direct current) voltage from photovoltaic arrays into AC (alternating current) which are used to power appliances and utility grids. The inverter converts DC power produced by solar panels into AC power via an inversion phase. This inversion is accomplished with the aid of solid-state devices such as Insulated Gate Bipolar Transistors (IGBTs). When these devices are connected in a standard H-Bridge configuration, the DC power is oscillated, resulting in AC power. Between the units, a step up transformer is used. At this stage, the AC power output is obtained, which can either be consumed locally or fed into the grid. Inverters without transformers are now available, and they have higher efficiencies than inverters with transformers.

In every solar inverter, there is a microcontroller chip that can be programmed to execute various complex algorithms precisely. Via the Maximum Power Point Tracking (MPPT) algorithm, the controller maximizes the power output from the solar photovoltaic panels.

There are different types of Solar inverter available in the market, however Grid-Tie inverts are most popular in many countries of the world due to higher cost and less lifetime of standalone and off-grid system.

Aside from grid-tied central inverters, the micro inverter is a more recent development. Micro-inverters, which can be attached to individual solar modules and provide a high voltage alternating current, are available in the industry. Micro inverters are also included with some manufacturers' products. Solar panels with built-in micro-inverters are usually reserved for grid-tied systems [17].

Power optimizers are also popular in many parts of the world especially for roof top solar PV installation to improve power output. If one of solar panels in your system is underperforming, a Micro Inverter or a Power Optimizer device will ensure that system still produces a substantial amount of power. If one panel fails, the others will continue to produce electricity, if it has a Micro Inverter or Power Optimizer Inverter installed in the system.

Figure 2.18: Installation of Micro Inverters on a roof

2.6.3 Solar Cables

Solar cables for cabling the solar modules and connecting to the AC/DC inverter in all photovoltaic systems. These solar DC cables shall be weather, abrasion and UV-resistant, halogen free, double insulated, cross-linked type for permanent outdoor use. Where normal DC cables are PVC insulated with 5-6 years lifetime and solar cables are produced for 25yeras lifetime with maximum 10% decrease of efficiency.

Figure 2.19: DC Solar Cable (Source:polycab Cabling)

2.7 Factors Affecting Solar PV system output Efficiency

Many losses limit the performance of photovoltaic power generation systems, some of which are controllable and some of which are uncontrollable. Following factors identified as major concerns for drop down the solar PV Module output and their efficiencies.

1. **Irradiance**
2. **Temperature**
3. **Dust or soiling**
4. Shading (not discussed in analysis)

Above factors affecting for efficiency of Solar Module output and ultimately Solar PV plant output.

Based on these facts, it is very essential to discuss these factors in depth to identify the best way of optimizing solar PV output

Irradiance

Irradiance is a measurement of the amount of solar energy (sunlight) that falls on a specific surface. The higher the irradiance level on a solar cell, the more energy it will produce more energy. In actual condition solar irradiance will varies throughout the day. The angle of the sun, hazy weather, passing clouds, and air pollution can change irradiance levels. However, the total energy received from the sun by the system remains relatively constant for one year (year to year). Typically, energy received from the sun only varies between 5-10% of the average in a year. In a typical solar panel, rated power output is mentioned in STC (Standard test condition) of 1000 W/m^2 irradiance and 25 °C temperature.

“The maximum absorption of solar radiation occurs when the panel surface is perpendicular to the direct sun’s rays ($\theta=0$). The higher direct irradiance on a surface perpendicular to the solar radiation causes the increased energy yield. At daytime with high direct radiation, solar tracking can achieved energy gains over horizontal orientation in the order of 50% in summer and up to 300% in winter” [19]. Presently, most of high energy efficiency solar power plant will have tracking system to gain highest performance over years.

Temperature

When solar PV modules are exposed to high temperatures, they generate less power than when they are in a cooler environment. On a day with a cool breeze and a hazy light, solar PV systems will also generate more energy than when the sun is burning and the temperature is higher. The temperature of a solar panel's working surface is a critical factor in the photovoltaic conversion process. It is widely accepted that as the working temperature of a PV module rises, so does its performance. The temperature of the cells is a critical factor that reduces the module's efficiency and power output. “Increases in cell temperature reduce the band gap of a semi-conductor while affecting semiconductor material properties. The increasing temperature cause decrease in the band gap of a semiconductor can be seen increasing the energy of the electrons in the material” [16].

Solar Panel Power ratings are mentioned in Standard Test Condition (STC), they're tested against a 1,000 W/m2 light source at 25°C (77°F). The solar panel will produce more energy at a lower temperature, although it will generate less at a higher temperature.

Solar cells are heated when solar panels are exposed to sunlight, mostly because infrared radiation is absorbed by them. Since solar modules are dark in color, they can generate a lot of heat. A solar panel can easily reach 80–90°C (160–175°F) in a hot climate. Manufacturers of solar panels offer data in the form of a temperature coefficient of power rating, which illustrates the effects of temperature on their panels. Per 1°C rise in cell temperature, it's calculated as a percentage of total power loss.

This value is typically in the range of 0.5 percent, which means for every 1°C rise in temperature, the mounted solar array loses 0.5 percent of its power capacity, and for every 1°C reduction in temperature, the solar array's power production improves by 0.5 percent.

Table-07 shows the effect on efficiency for a 200W (STC condition) solar panel at various temperatures, assuming a temperature coefficient of 0.5 percent:

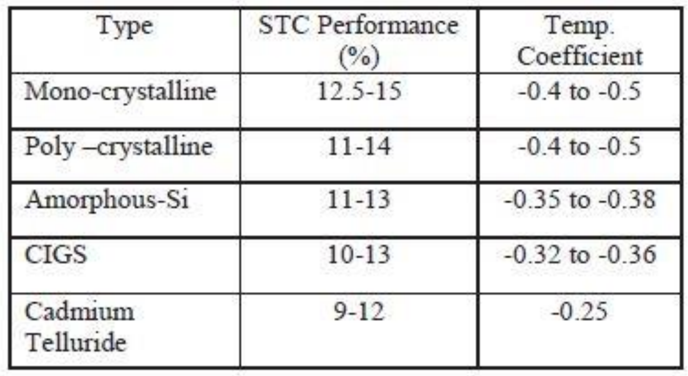
Table 07: Solar Panel Power Output Variation with Module Temperature

Temperature	5°C	15°C	25°C	35°C	45°C	55°C
Output of a 200W panel	220W	210W	200W	190W	180W	170W
% of Gain or Loss	10%	5%	0	-5%	-10%	-15%

The ambient temperature in Sri Lanka, India, and other tropical countries is well above 25 degrees Celsius, and solar panel temperature is an important consideration when designing a solar PV device.

Table 08 shows the STC (Standard Test Condition) efficiency and Temperature Co-efficient of different types of solar modules.

Table 08: Different Types solar module efficiency and their Temperature coefficient [17]



Type	STC Performance (%)	Temp. Coefficient
Mono-crystalline	12.5-15	-0.4 to -0.5
Poly –crystalline	11-14	-0.4 to -0.5
Amorphous-Si	11-13	-0.35 to -0.38
CIGS	10-13	-0.32 to -0.36
Cadmium Telluride	9-12	-0.25

“It is investigated the temperature effect on polycrystalline PV modules with the temperature range of 61°C to 75°C and irradiance range of 780 W/m^2 to 1250 W/m^2 respectively. This investigation shows that in this situation the PV modules lost at least of 35% efficiency, and 18% of the output power compared with the standard testing conditions” [5].

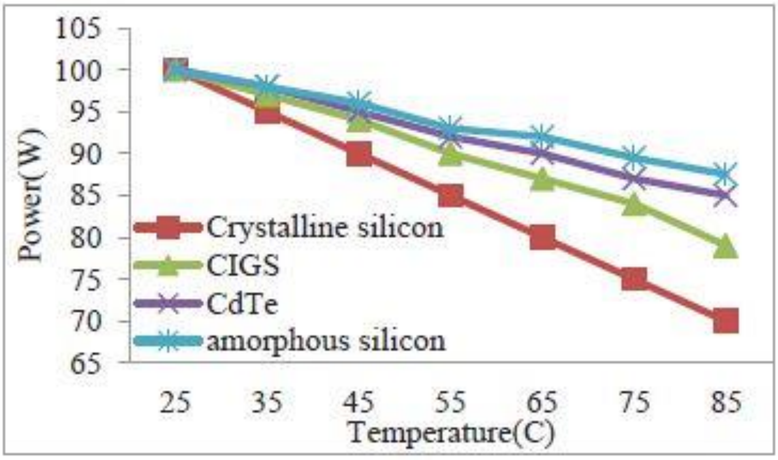


Figure 2.20: Effect of Temperature Co-efficient on different Solar Modules [17]

“It has analyzed the results of a long-term performance of two different types of solar PV module with 80W Polycrystalline and 75W Monocrystalline panel based on actual data measured over a period of six years in the Gobi Desert of Mongolia. This study observed that the high output has been achieved due to the operating condition in an extreme low ambient temperature and the PV module degradation rate indicated is only -1.5 %/yr after six years of exposure test. In summary, this study exhibited that a PV module with a high temperature coefficient, such as crystalline silicon, is useful for use in the Gobi Desert area” [18].

“It has analyzed the “effect of temperature on the I-V characteristics of a Polycrystalline solar cell” and found that current parameters of each experimented module increase with increasing temperature while voltage parameters decrease. As per analysis about 9.8% and 12% decrement in Voc and Vpp, respectively has been observed. This shows temperature has a crucial impact on solar module voltage parameters rather than current parameters” [17].

Figure 25 and 26 show that the variation of the voltage and current parameters with PV panel temperature.

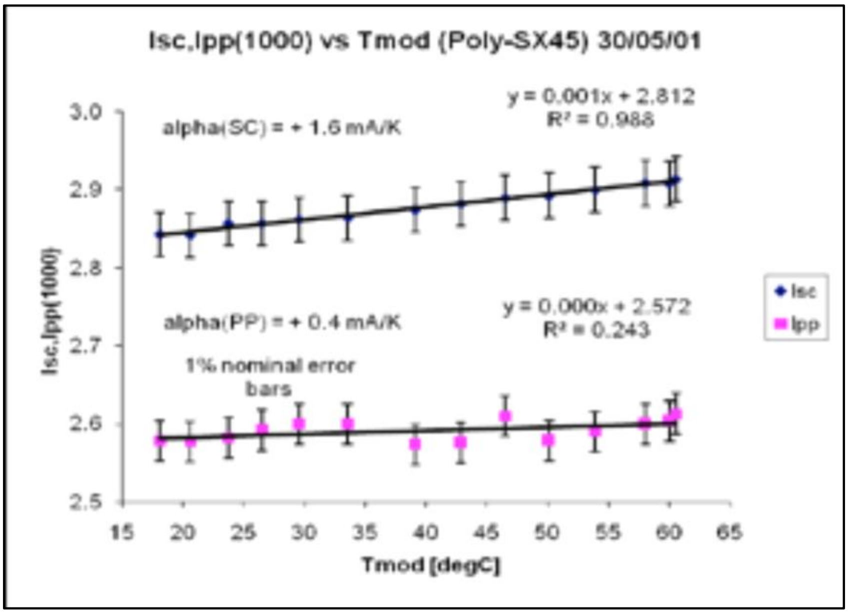


Figure 2.21: Isc and peak current graphs Vs module temperature of Modules [18]

Since changing weather conditions influence a PV panel's current and voltage performance, it's critical to characterize the system's response to these factors so that the PV panel's associated equipment can be designed accordingly.

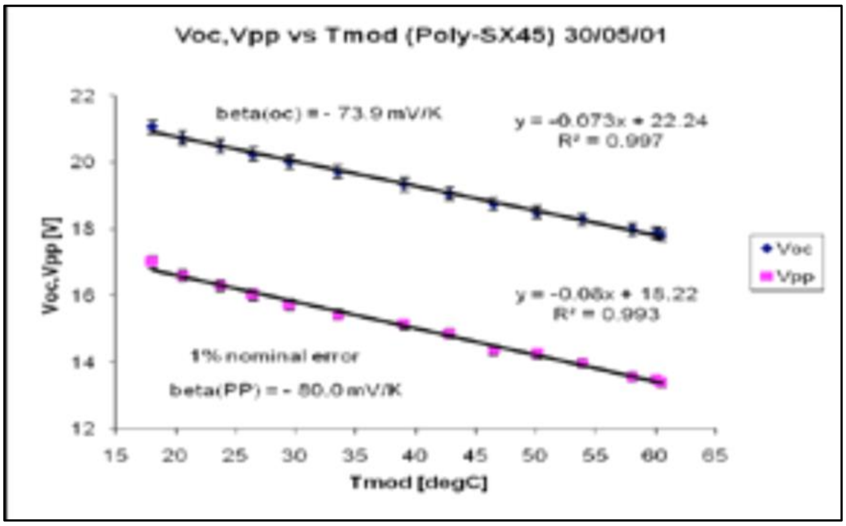


Figure 2.22: Open Circuit and peak voltage Vs module temperature of Modules [17]

According to their findings, the maximum output power density for polycrystalline silicon decreased by 17% as module temperature increased from 15 to 60 degrees Celsius, with the band gap of the solar cell calculated to be 1.09eV. This is a significant amount of energy wasted, ranging from small rooftop solar panels to large-scale MW-scale projects.

Soiling or Dust

This is referring dirt, dust and other debris settling on the surface of the solar modules. This blocks sunlight from reaching the solar cells and reduces solar system performance.

Over the last decade, no local studies have been found in the impact of dust on the degradation of the solar cell's efficiency. However as per research carry out by Sulaiman S. A, University Technology Petronas, Malaysia (2011), exhibit that, dust has significant effect on the performance of the solar PV panel. As per analysis, it is shown that peak power generated can be reduced up to 18% because of dust. However, they have done this analysis based on artificial materials such as Mud, Talcum, plastic in lab environment. Further, their calculation is based on lower irradiance levels. Accordingly, their final values may change or varied in actual environmental condition.

The studied of "factors affecting the PV based Power Generation" and found that, dust or soiling effect can block the sun's rays from reaching the solar cell, solar panels have a significant impact on PV production [19].

It looked into the impact of dirt accumulation on PV panel results. "This experiment was carried out using a clean solar panel with talcum, dust, sand, water droplets, and moss for light irradiances of 310 W/m2 and 250 W/m2, respectively. According to the findings, the solar panel's power production was decreased by between 9% and 31% due to the presence of talcum, between 60% and 70% due to dust, between 70% and 80% due to sand, and between 77 and 83 percent due to sand. Table 09 displays the production levels of various load cases for 310 W/m2 light radiation" [25].

Table 09: The output power for various loads was determined by light radiation of 310W/m² [18]

Testing Loads	Power (W)				
	Clean	Talcum	Dust	Sand	Moss
Short Circuit	0	0	0	0	0
12V Bulb 21/5 W	3.45	2.37 (-31 %)	1.02 (-70%)	0.68 (-80%)	0.66 (-81%)
12V Bulb 10W	8.68	6.65 (-11%)	2.37 (-73%)	1.87 (-78%)	1.44 (-83%)
12 V Festoon Bulb 10W	8.89	7.41 (-17%)	2.83 (-68%)	2.20 (-75%)	1.68 (-81%)
12V Motor 18W	8.15	7.38 (-9%)	3.09 (-62%)	2.37 (-71%)	1.81 (- 78%)
12 V Bulb 8W	3.16	3.01 (-5%)	2.75 (-13%)	3.12 (-1%)	2.65 (-16%)
No Load	0	0	0	0	0

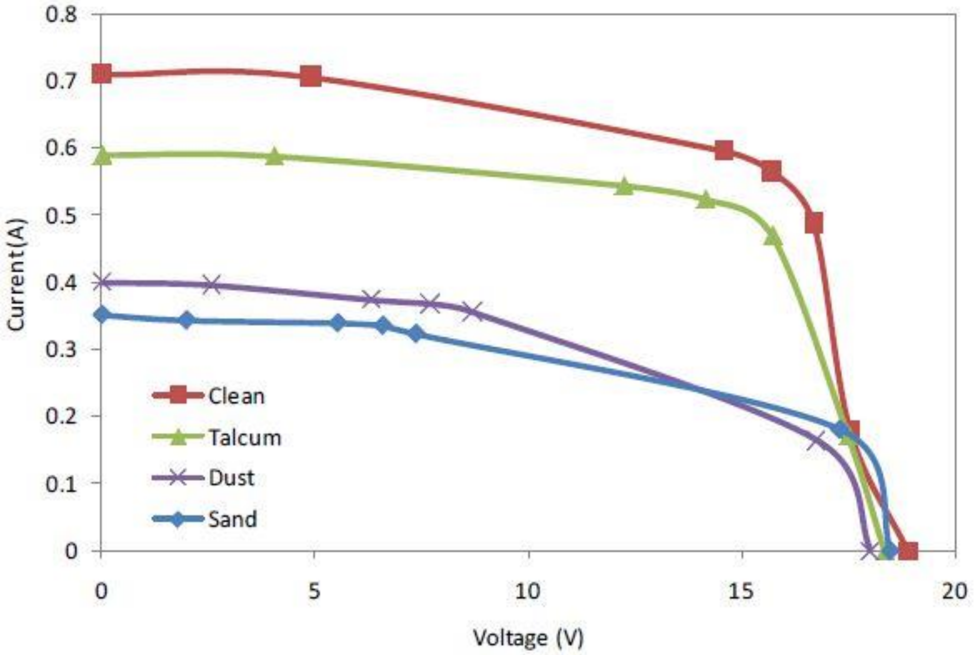


Figure 2.23: I-V Features at radiation Intensity of 310W/m² [18]

Figure 2.23 depicts a radiation level of 310W/m2, the I-V properties are shown. The overall power was 8.9 W for a light irradiance of 310 W/m2 when a clean solar panel was used, but this was significantly reduced in the presence of talcum, sand, and moss, as well as dust. This suggests that routine cleaning is needed to ensure full energy harvesting from solar PV technology.

Shading

The efficiency of a solar PV energy system will be significantly impacted by shading on solar modules. Even a small amount of shading has a significant effect on the amount of energy that a solar system can produce. As a result, it's important that the solar PV array is kept as shade-free as possible.

Although it is impossible to achieve completely shade-free space, reducing shade to the bare minimum by carefully studying the site environment is critical and the responsibility of Solar Engineers and Consultants.

As shown in figure 2.13, Solar panels contain several solar cells, approximately 0.6 volts are produced by each silicon cell. The figure in the example panel has 60 cells connected in series, producing 36 volts of output. They are arranged in three groups of twenty in a linked sequence. By-pass diodes have been mounted in each group, bypassing the group of cells. If one or more cells in a group are shaded, the entire group of 20 cells is essentially turned off.

Soft and hard shading sources are the two styles of shading sources. The sun rays falling on the PV module is diffused by a shadow spread caused by taller objects such as a chimney, vent, etc. from afar, contributing to soft source shading. The light cannot enter the cells because of hard sources.

“Tree leaves, bird droppings, snow, and thick dust or other impurities on the module's surface cause hard source shading. If the solar cell is fully shaded, it will absorb rather than generate energy, and will serve as a load” [19]. Further, shaded panel may affect for entire solar array, to overcome this issue power optimizers attached to each panel are used by panel manufacture.

CHAPTER 03

DATA COLLECTION and ANALYSIS

This chapter explain the data collection procedures, equipment which were used and apply during experiment period. Further, it describes how the intended research data were collected for analysis including environmental conditions. The chapter covers; details of location where experimental setup installed, instruments and accessories used during data collection with their technical details. Finally, it describes, how collected data were aggregated and analysis with IBM SPSS software package.

3.1 Data Collection

Location: The analysis was conducted after data recorded from solar measuring models installed in Averihena Road, Colombo 05 (6°53'4.01"N - 79°52'46.81"E). where exact location is shown as per Figure 3.1.

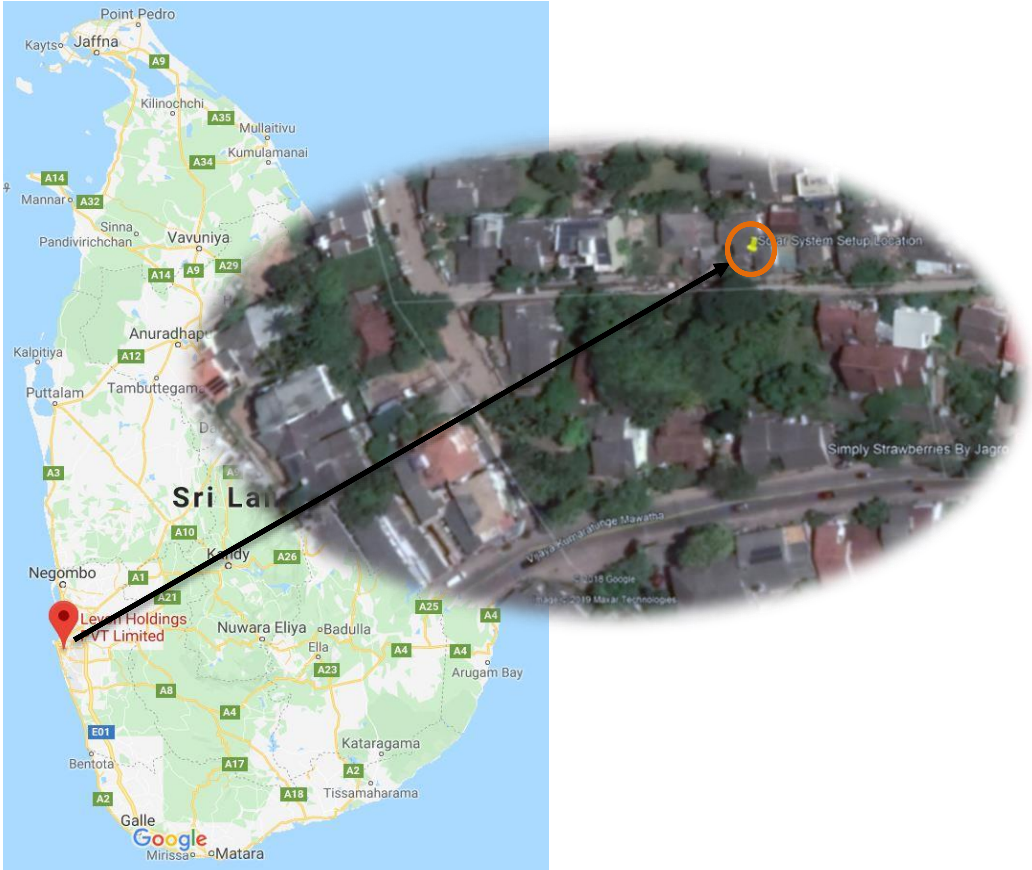


Figure 3.1 Location of Experimental Setup Installation and Data Collection

3.1.1 Experimental Setup.

Total analysis data were collected using three off-Grid independent solar power generation system. One prototype consists of 150Wp Solar Module (3), Off-Grid Charging Controller with logger, DC Battery (1), DC Load (2) and Inverter as per Figure 3.2;

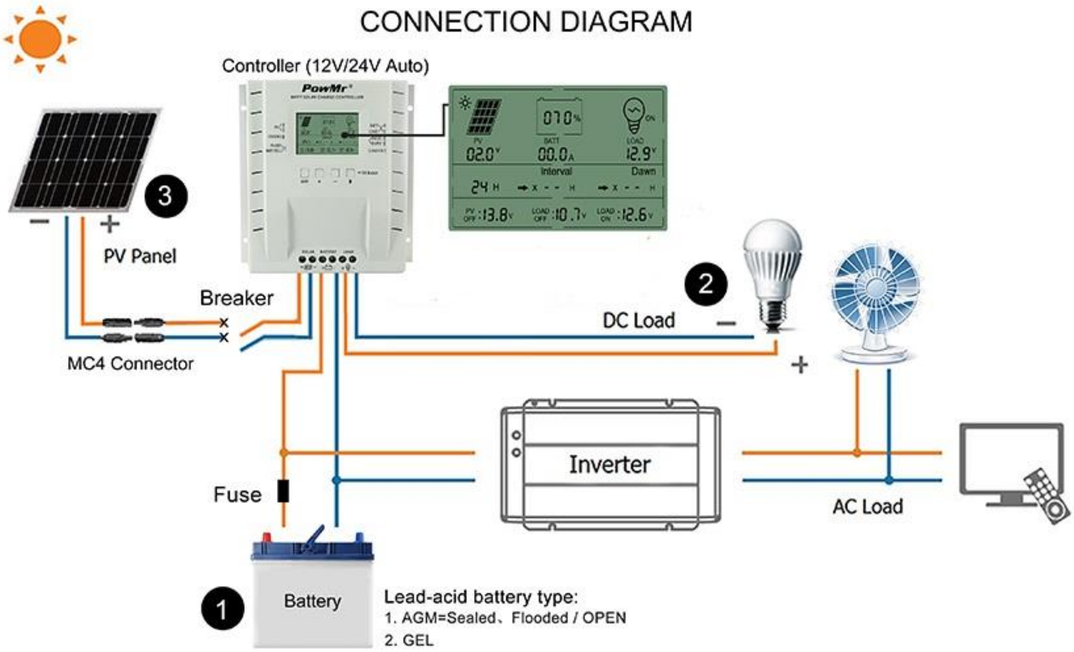


Figure 3.2 Solar System experimental Setup Diagram

A proposed prototype was consisting of above main equipment and accessories to collect and measuring following data;

Experiment Setup 01 – Measuring Solar Panel output power with **high dust** amount than ambient condition solar Module.

Experiment Setup 02 – Measuring solar panel output power with ambient condition. It does not contain any additional cooling effects or added dust level

Experiment Setup 03 – Measuring Solar Panel Output power with controllable temperature and dust level. This sample is cooled using artificial airflow and periodic water splashing (Every 10min interval)

Above prototype were assembled with DC cables, Switch Gear (MCB) and 16A Double pole switch which is shown in figure 3.3 as follows. All solar modules were faced to North-South with 5° tilt angle.

Figure 3.3: Actual Prototype Setup

3.1.2 Experiment Setup Hardware

Throughout the world many research work [10]-[12] were completed with limited environmental condition with control environments. Some of research carried out with very low irradiation level, 310W/m^2 to study the influence of dust accumulation with artificial dust including talcum powder, moss [20]. However, by considering actual environmental condition as much as possible will provide better and accurate results. This will help to decide optimum efficiency level and then reduce initial investment for upcoming solar power generation plant, especially for roof mounted Building solar PV System. Accordingly, all data was collected in actual environmental condition with data logging and taking down with minimal human error. All three identical solar experimental setup was connected to 150Wp Solar panel via 32A Epever MPPT Solar charging controller, 26Ah AGM Lead-Acid Sealed battery. 7W DC LED bulb directly connected to solar controller while whole system connected to 1000Wp Off-Grid Inverter for connected AC Load where it will help for fast discharging of batteries with similar charging rate as per shown in Figure 3.4.

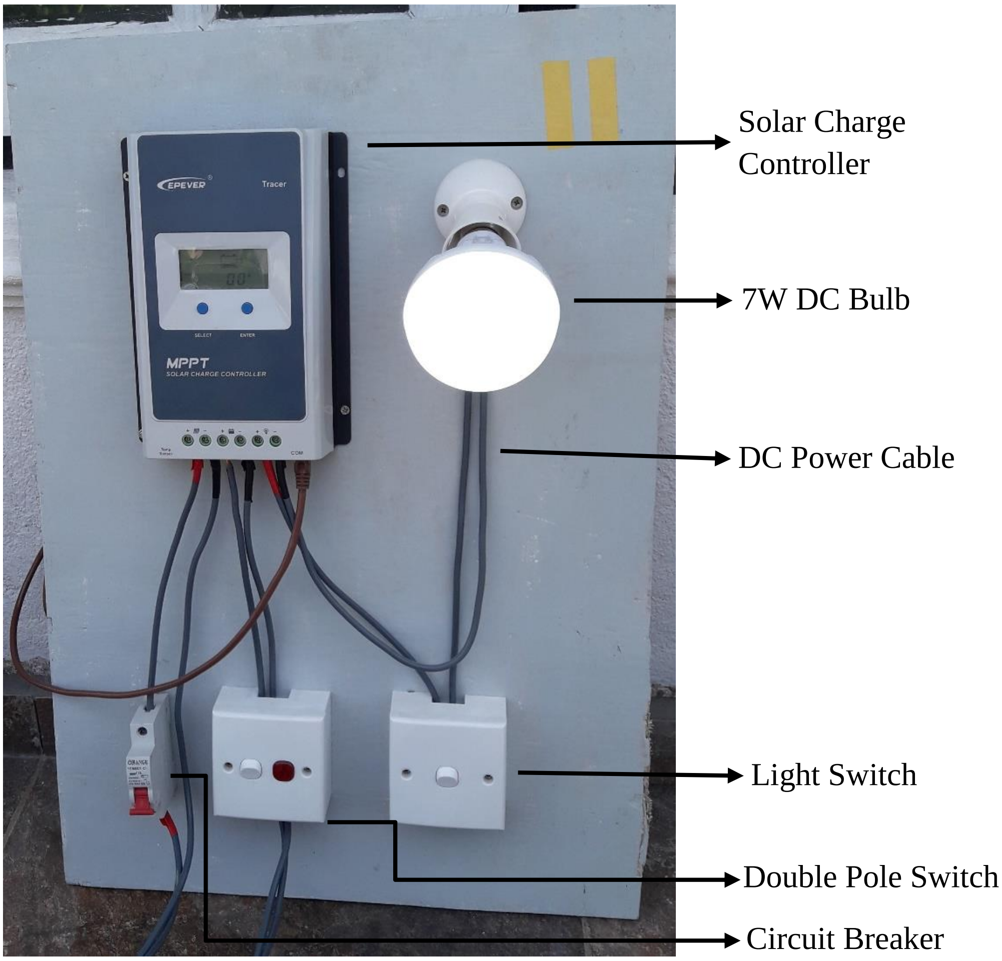


Figure 3.4: Solar System Setup Wiring Diagram

Epever 30A MPPT Solar Charge Controller

During experiments, It was installed 3Nor of 30A MPPT Charger Controller (Model-Epever 3210AN**)**, to measure Solar Panel output data (I, V and W) and load output data for comparison purpose and further analysis. All data were collected using inbuilt LCD display and remotely through data logging facility of Solar charge controller.

Table 10: Technical Parameters of Epever 3210AN Solar Charging controller

Rated Current for Charge/Discharge	30Amp
Range of Battery Voltage	8-32V
Max Open Circuit Voltage for PV	92V @25°C
Max Input Power for PV	780W/24V and 390W/12V
Self-Consumption	≤12mA
Temp Compensation co-efficient	-3mV/ °C/2V for Lead Acid battery
Working Temperature	-20°C ~ +70°C

- **Excide 26Ah/12V AGM Lead-Acid battery**

NXT-26/12 AGM batteries were used to store the sun energy through solar panel while collecting solar power generation data. For continuous discharging all three batteries were connected parallel to Pure Sine Wave 1000Wp inverter and AC load.

Table 11: Technical Parameters of Excide AGM Lead-Acid Battery

Battery Voltage	12V
Battery Capacity	26Ah, 1.75V/Cell @20hr
Internal resistance	10 m-Ohm
Max Discharge Current	390A

- **Digital Thermostat and Logger**

Two MASTECH MS6514 Dual Channel is installed to measure the all three solar panel back temperature using Type K temperature sensor.

Table 12: Technical Parameters of MASTECH Digital Thermostat

Measurement Range	Type K: -200 °C to +1372 °C
Resolution	0.1 °C
No of Channel	Two
Accuracy	K,J,E,T ±(0.2%+ 0.5°C)
Data Logging	1000 Groups
Other Function	Ambient temperature compensation

- **Digital Data logging Solar Irradiance Meter**

One TES-1333R pyranometer is located at the middle of experimental setup incline with solar module tilt angle. This measures the in-plane global irradiance in the range of 400-1100 nm.

Table 13: Technical Parameters of MASTECH Digital Thermostat

Range	0-2000 W/m²
Resolution	1 W/m²
Spectral Response	400-1100 nm
Accuracy	± 10 W/m² and ±0.38 W/m²/°C after 25°C
Angular Accuracy	Cosine correction <5% for angle <60°
Sampling Time	0.4S

- **Fluke 62MAX+ Dual Laser Infrared Thermometer**

High Accuracy Fluke 62Max+ Laser infrared thermometer was used to measure Solar Panel surface temperature and accuracy of back panel temperature measured by type K Temperature sensor.

Table 14: Technical Parameters of Fluke Infrared Thermometer

Measurement Range	-30 °C to +650 °C
Display Resolution	0.1 °C
Optical Resolution	12:1
Accuracy	±1°C or ±1.0% of Reading, whichever is greater
Spectral Response	8 to 14 Microns

- **Type-K Temperature Sensor**

Rugged Type-K washer thermocouple with flexible lead used for Solar Panel back surface temperature measurement. One thermocouple installed Center of each Solar panel back and connected to MS6514 digital meter for reading the measurement.

Table 15: Technical Parameters of Surface mounted Temperature Sensor

Temperature Range	-50 °C to +400 °C
Type and Material	Type-K, M6, Material -Brass
Accuracy	Class 1 (±1.5°C Between -40 °C to 375°C)

- **Solar Module**

150Wp Poly crystalline, 36 Cell Solar Modules (Model- Yingli SZYL-P150-18) were used during the experiment period. All three modules were installed in same orientation and tilt angle. Data was collected during sunny days with less cloud coverage and non-availability of shading effects on panels.

Table 16: Technical Parameters of 150Wp Yingli Solar Module (SZYL-P150-18)

Power Output*	150Wp
Power Output Tolerance	0-5W
Module Efficiency	15.2%
Voltage @Pmax	18.1V
Open Circuit Voltage	21.5V
Temp. Coefficient @Pmax	0.42% per °C

*All above Data were mentioned at STC (Standard Test Condition)

3.2 Data Collection Procedure

All data were collected between 11.00AM to 3.00PM with sunny weather condition on 12th and 21St April 2019, 01st and 05th May 2019. Outdoor weather condition of Colombo 05 area of same time period is shown in table 17.

Table 17: Environmental conditions of Experiments Data Collection period in Colombo 05 *(source - https://www.worldweatheronline.com)*

Date	Outdoor Temperature (Max/Average)	Relative humidity	Wind Speed (kM/hr)
12th April 2019	34°C / 26°C	67%	12-16
21st April 2019	33°C / 26°C	75%	9-12
01st May 2019	34°C / 29°C	80%	18-22
05th May 2019	33°C / 26°C	65%	15-18

Proposed Experimental setup was consisting of above main equipments and accessories to collect and measuring following data;

Experiment Setup 01 – Measuring Solar Panel output power with **high dust** amount than ambient condition solar Module. Initially 0.25kg/m^2 of dust were evenly distributed on solar panel. However, with amount of wind condition and direction, initial amount of dust could not be exactly distribute without disturbing data collection process.

Experiment Setup 02 – Measuring solar panel output power with ambient condition. It does not contain any additional cooling effects or added dust level

Experiment Setup 03 – Measuring Solar Panel Output power with controllable temperature and dust level. This solar module is cooled using artificial airflow fan with 1340RPM and controlled water splashing on solar modules (Every 5min interval) at rate of 1.5l/min as shown in Figure 3.6.

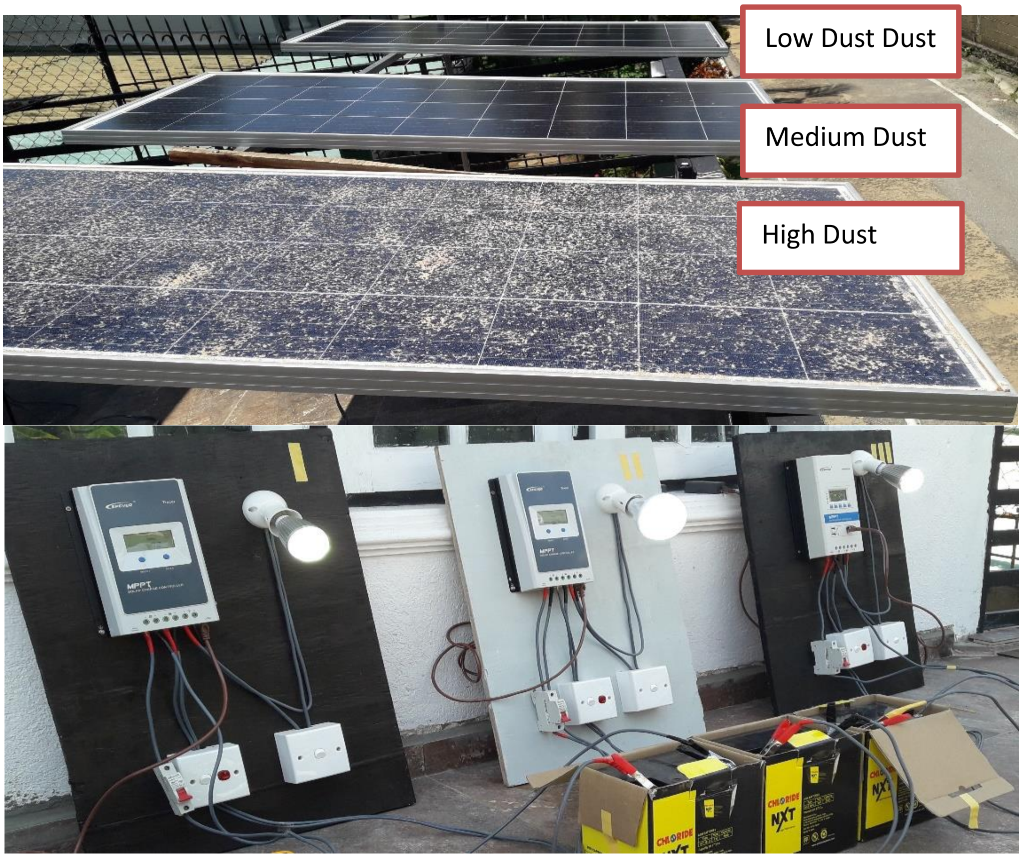


Figure 3.5: Photographs of Experimental Setup

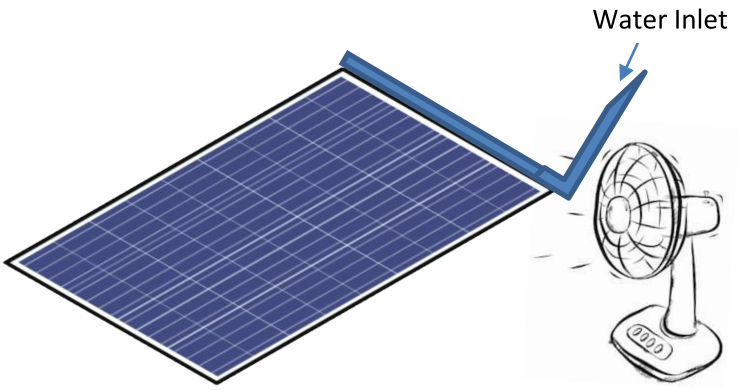


Figure 3.6: Cooling Method of Solar Modules

3.3 Data Analysis

All collected data were sorted ascending order based on solar irradiance level and a graph was plotted against irradiance level Vs Solar Panel Power output of each setup using Microsoft Excel which was in shown in Figure 3.7 to 3.10;

Observations of Readings;

Maximum Output power recorded in Setup 03 which is 136.08W @891W/m^2 irradiance level.

Lowest Output power recorded in Setup 01 which was 30.4W @237W/m^2 solar irradiance Level.

Based on this graph; Solar panel power output is always increase with increase of irradiance level. However, the increase level was different on each experiment setup.

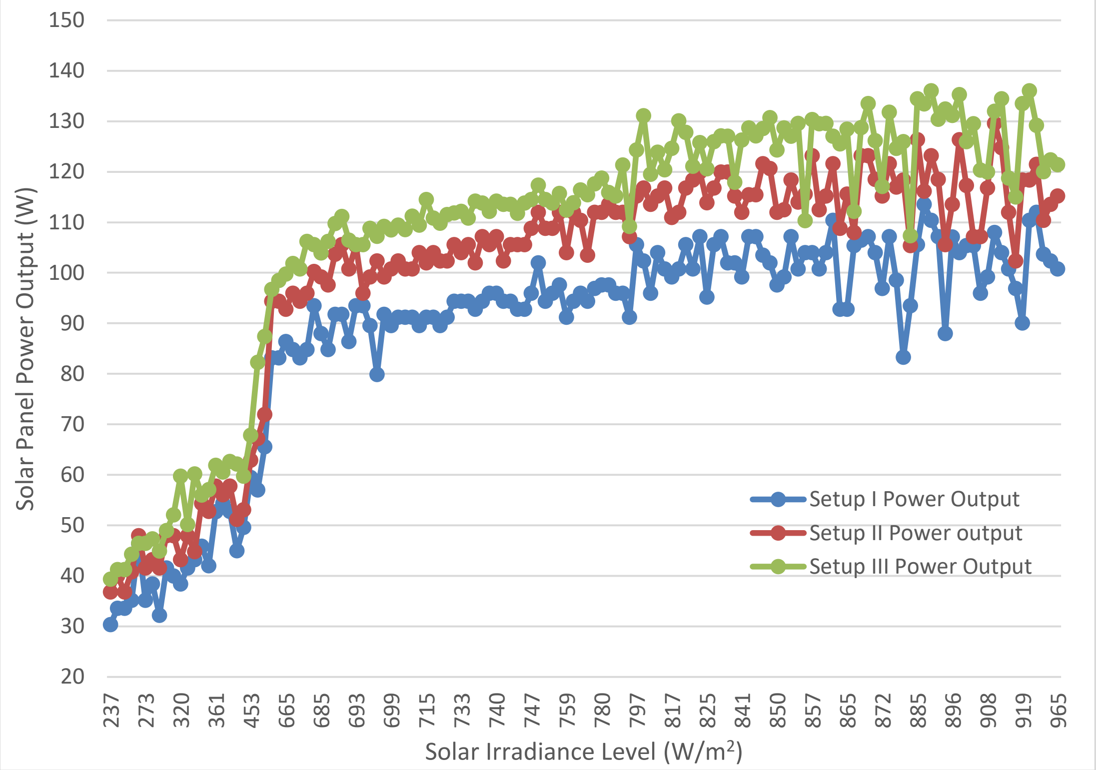


Figure 3.7: Irradiance Level Vs Solar Power Output of all experiment Set-Up

As per analysis from above graph it is clearly showing that solar panel output is increased with irradiation level in between tested irradiance level of 237-965 W/m^2. Power increment is highest on experiment setup III which was kept under control of panel temperature and dust level as low as possible. Lowest output readings shown by experiment setup I which was kept uncontrollable with high dust level.

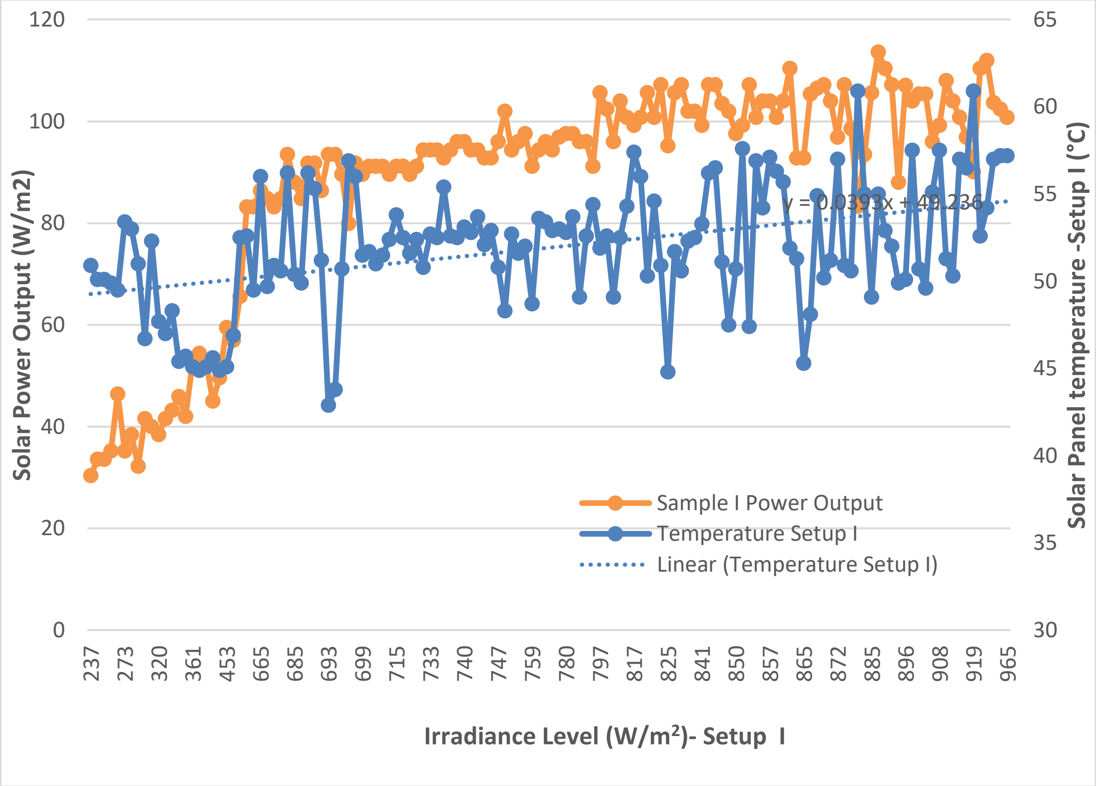


Figure 3.8: Solar Panel Temperature Vs Solar Power Output Setup I

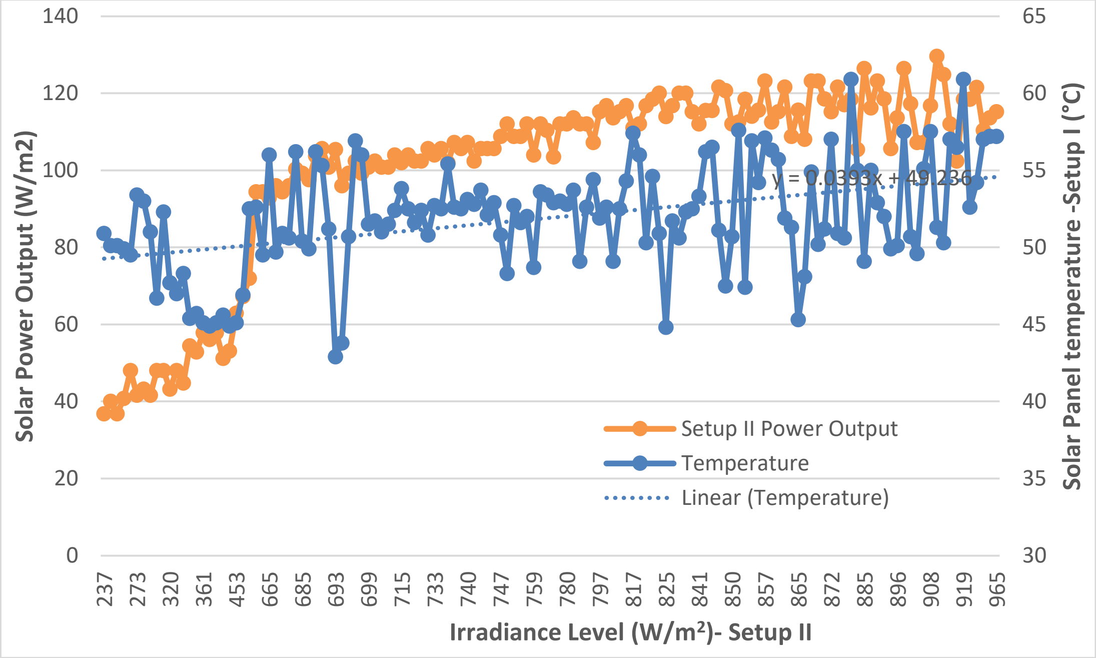


Figure 3.9: Solar Panel Temperature Vs Solar Power Output Setup II

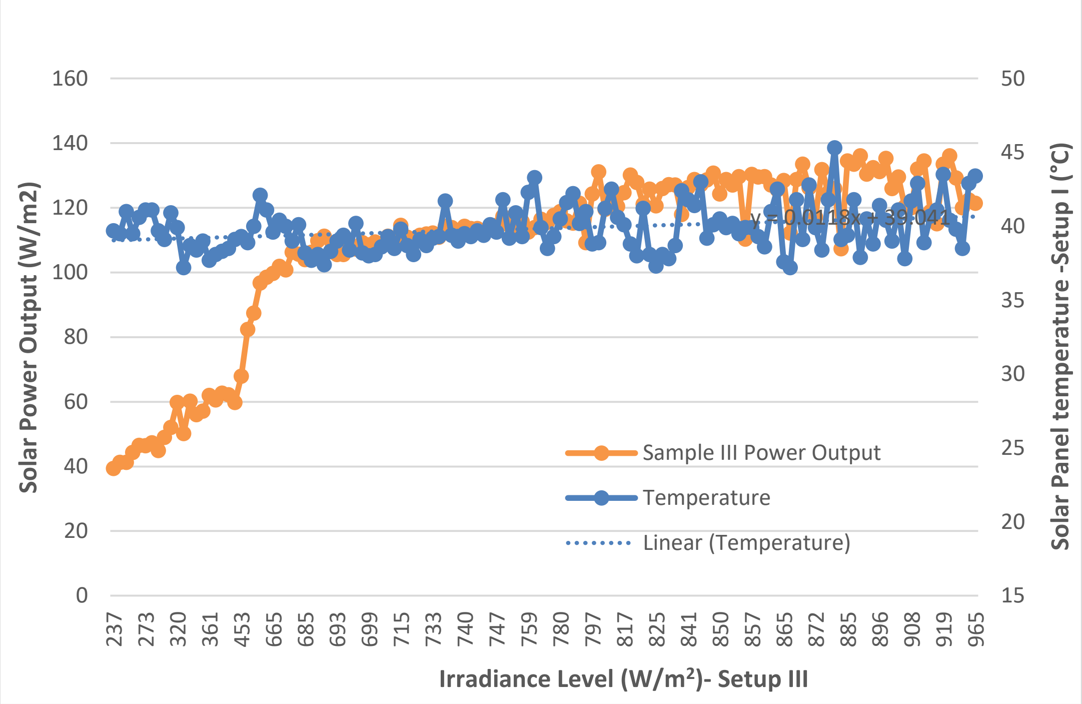


Figure 3.10: Panel Temperature Vs Power Output and Irradiance Level of Setup III

Each experimental setup panel temperature and power output with respect to irradiance level was plotted as per Figure 3.8, 3.9 and 3.9.

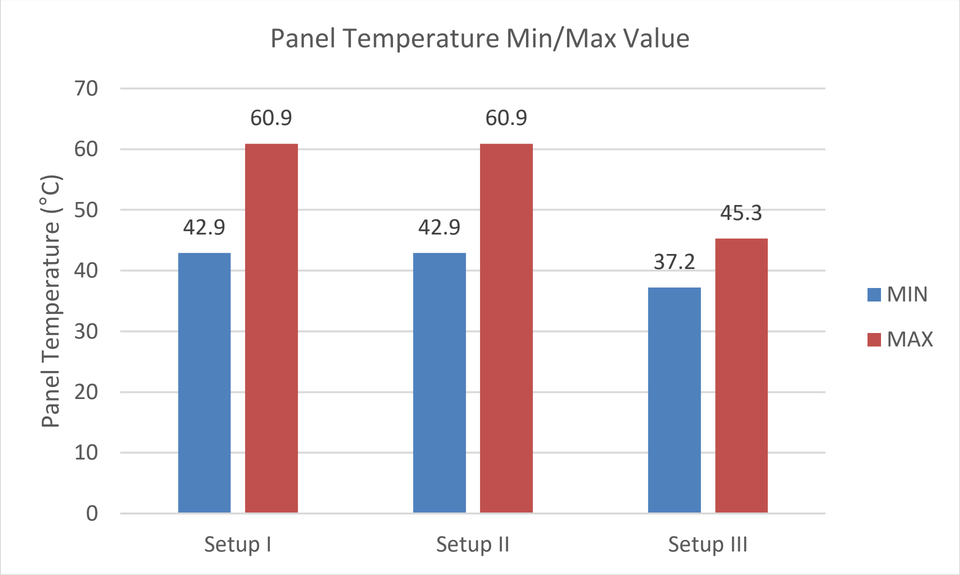


Figure 3.11: Min/Max Solar Panel Temperature of Experiment Setups

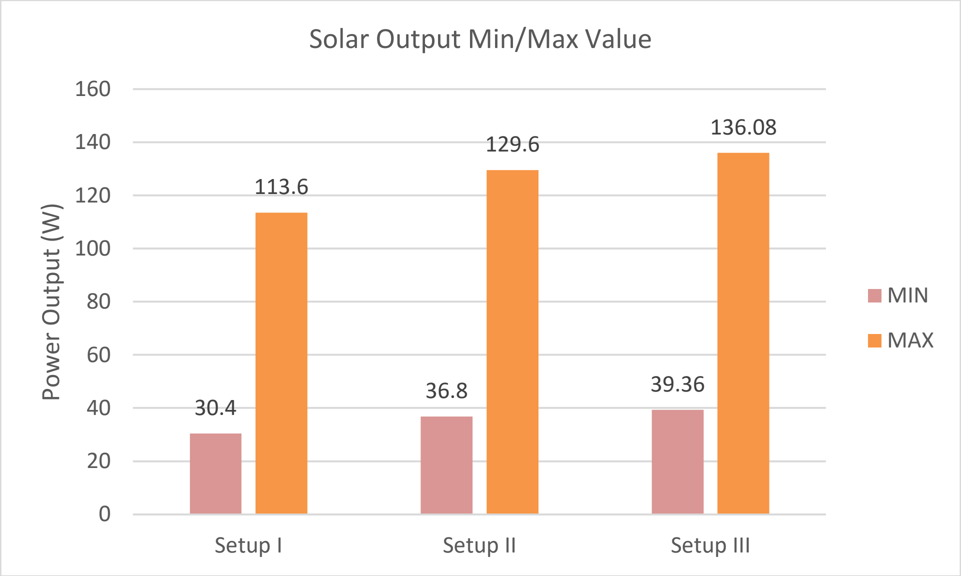


Figure 3.12: Solar Panel Min/Max Power Output of each Setup

Table 18: Min/Max Solar Panel Power Output in Percentage compare to Setup III

Setup No		**Power Output (W)**			**Temperature of Panel (°C)**			**Irradiation (W/m^2)**
		I	II	III	I	II	III	All Setup
III	MAX	110.4	123.2	**136.08**	52.9	52.9	37.9	891
		-18.87%	-9.47%	0%	0	0	-15	
	MIN	30.4	36.8	**39.36**	50.9	50.9	39.7	237
		-22.76%	-6.50%	0%	0	0	-11.2	
II	MAX	108	**129.6**	132.02	51.3	51.3	42.9	909
		-18.19%	-1.83%	0.00%	0	0	-8.4	
	MIN	33.6	**36.8**	41.25	50.1	50.1	41	250
		-18.55%	-10.79%	0.00%	0	0	-9.1	
I	MAX	**113.6**	116.2	133.45	55	55	41.8	890
		-14.87%	-12.93%	0.00%	0	0	-13.2	
	MIN	**30.4**	36.8	39.36	50.9	50.9	39.7	237
		-22.76%	-6.50%	0.00%	0	0	-11.2	
Average		-19.34%	-8.00%	0.00%				

By considering maximum /minimum power output level of each experimental setup as per tabulated in table 18, it can observe that solar module exposed to natural environment conditions (Setup II) and module with added dust (Setup I) have considerable decreased in power level from Low to high irradiation level from average reduction from 8% to 19.34%. However, it is showing higher reduction in power level in setup I in low level of irradiation.

3.4 Statistical Analytic Techniques

In terms of the analysis part, the statistic method was used to preliminary treatment of data. The Three-Way Factorial Design ANOVA (Analysis of Variance) method was selected as a method to calculate the analysis for statistic. The term "analysis of variance" refers to a technique that uses variances to determine if the dependent variable's "means" are different. This approach determines whether the groups are all part of one larger population or separate populations with different characteristics by comparing the variance between group means to the variance within groups.

Three-way factorial design ANOVA is the techniques that used theories to decide the outcomes, such as the null hypothesis (H0), which is the assumption being tested in the analysis. The H0 is a declaration that "no impact" or "no transition" exists. When checking a H0, the potential outcomes are "reject" or "fail to reject." Rejecting H0 implies that there is sufficient evidence in the data and the test to dismiss the null hypothesis. The data is said to be statistically important when H0 is rejected. Failure to refute the null hypothesis indicates that the data and test do not provide sufficient evidence to reject the null hypothesis.

To execute a Factorial Design ANOVA, it should have at least one independent Variable (IV) with two or more levels, as well as a continuous response variable. Data from approximately normally distributed populations with equal variances between define factor levels are required for factorial ANOVA. These violations may be corrected by transformations of the original dataset. There are equations involved in Factorial Design ANOVA and showing in Table 19.

Table 19: Three Way ANOVA Statistics Formula Table

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F Statistics
Factor A	SS_A	(a-1)	$MS_A = \frac{SS_A}{(\mathrm{a} - 1)}$	$\frac{MS_A}{\mathrm{MSE}}$
Factor B	SS_B	(b-1)	$MS_B = \frac{SS_B}{(\mathrm{b} - 1)}$	$\frac{MS_B}{\mathrm{MSE}}$
Factor C	SS_C	(c-1)	$MS_C = \frac{SS_C}{(c - 1)}$	$\frac{MS_C}{\mathrm{MSE}}$
AB Interaction	SS_{AB}	(a-1)(b-1)	$MS_{AB} = \frac{SS_{AB}}{(a - 1)(b - 1)}$	$\frac{MS_{AB}}{\mathrm{MSE}}$
AC Interaction	SS_{AC}	(a-1) (c-1)	$MS_{AC} = \frac{SS_{AC}}{(a - 1)(c - 1)}$	$\frac{MS_{AC}}{\mathrm{MSE}}$
BC Interaction	SS_{BC}	(b-1) (c-1)	$MS_{BC} = \frac{SS_{BC}}{(b - 1)(c - 1)}$	$\frac{MS_{BC}}{\mathrm{MSE}}$
ABC Interaction	SS_{ABC}	(a-1)(b-1)(c-1)	$MS_{ABC} = \frac{SS_{ABC}}{(a - b)(b - 1)(c - 1)}$	$\frac{MS_{ABC}}{\mathrm{MSE}}$
Error	SS_E	N-abc	$MS_E = \frac{SS_E}{(\mathrm{N} - \mathrm{abc})}$	
Total	SS_T	N-1		

Where;

A, B and C	- Independent Variables
a	- Number of Levels of Independent Variables A
b	- Number of Levels of Independent Variables B
c	- Number of Levels of Independent Variables C
N	- Total Number of Observations in all cells

$$SS_{total} = \sum X^2 - \frac{(\sum X)2}{N} \tag{1}$$

$$SS_A = \sum \frac{\sum(for\ each\ row\ )^2}{n\ for\ each\ row} - \frac{(\sum X)^2}{N} \tag{2}$$

$$SS_C = \sum \frac{\sum(for\ each\ column\ )^2}{n\ for\ each\ column} - \frac{(\sum X)^2}{N} \tag{3}$$

$$SS_{between} = \frac{(\sum X_1)^2}{n_1} + \cdots \frac{(\sum X_{ac})^2}{n_{ac}} - \frac{(\sum X)^2}{N} \tag{4}$$

$$SS_{AC} = SS_B - SS_A - SS_C \tag{5}$$

$$SS_B = SS_{total} - SS_{between} \tag{6}$$

According to the experiment setup, independent variables (IV) divided to two levels to analysis the main and interaction effect through statistical calculation;

Table 20: Defining Independent Variables Levels for Analysis

Dependent Variable	**Independent Variables**	**Levels**	
Solar Power Output (W)	A- Irradiation Level (W/m^2)	Low	High
	B- Solar Panel Temperature (°C)	Low	High
	C- Dust Level on Panel Surface	Low	High

Assumptions made in 2x2x2 Factorial Design ANOVA

1. Normality of Sampling Distribution of Means; the distribution of sample means in normally distributed
2. Independence of Error
3. Absence of Outliers; Outlying readings eliminated from the readings
4. Homogeneity of Variance; Population variance in different levels of each independent variables are equal.

Define Objective of Three-Way Factorial Design ANOVA

[1]. To examine the influence of Irradiance Level on Solar Panel Power Output
[2]. To examine the influence of PV module Temperature on Panel Power Output
[3]. To examine the influence of dust level on Solar Panel Power Output
[4]. To examine the influence of interaction between irradiance level and solar panel temperature on solar panel output power
[5]. To examine the influence of interaction between irradiance level and dust level on solar panel output power
[6]. To examine the influence of interaction between dust level and solar panel temperature on solar panel output power
[7]. To examine the influence of interaction between irradiance level, PV module temperature and amount of dust level on solar panel power output

Define hypothesis for this Analysis

Effect of factor A; Irradiation Amount

H_0: There is no difference between the means of solar panel power output for the two levels of irradiation amount.

H_1: There is a difference between the means of solar panel power output for the two levels of irradiation amount.

Factor B Effect; Panel Temperature

H_0: There is no difference among the “means” of PV module power output for the two levels of panel temperature.

H_1: There is a difference between the means of solar panel power output for the two levels of panel temperature.

Factor C effect; Dust amount

H_0: There is no difference between the means of solar panel power output for the two levels of dust amount.

H_1: There is a difference between the means of solar PV module power output for the two levels of dust amount.

Interaction between Factor A and B

H_0: There is no significant influence of interaction between irradiation amount and panel temperature on Solar Panel power output

H_1: There is a significant influence of interaction between irradiation amount and panel temperature on Solar Panel power output

Interaction Effect of Factor A and Factor C

H_0: There is no significant influence of interaction between irradiation levels and dust amount on Solar Panel power output

H_1: There is a significant influence of interaction between irradiance level and amount of dust levels on Solar Panel power output

Interaction Effect of Factor B and Factor C

H_0: There is no significant influence of interaction between Panel temperature and dust amount on Solar Panel power output

H_1: There is a significant influence of interaction between Panel temperature and dust amount on Solar Panel power output

Interaction Effect of Factor A, B and C

H_0: There is no significant influence of interaction among Irradiation Levels, Panel temperature and dust amount on Solar Panel power output

H_1: There is a significant influence of interaction between Irradiance Levels, Panel temperature and dust amount on Solar Panel power output

Method of Statistical Calculation and Decision Making

The null hypothesis H_0 will be rejected (not all means are equal), if $þ < α$

The null hypothesis H_0 will not be rejected (there is no difference between means), if $þ \geq α$. Where α is the significance level which is used as 0.05 for analysis purpose.

Above three-way factorial design ANOVA calculation was performed by using IBM SPSS Version 24. The "Statistical Package for the Social Sciences" (SPSS) is a flexible and responsive program created to undertake a range of statistical measures for calculating, analyzing, and presenting data; IBM SPSS software package is commonly used in the social and behavioral science analysis. It was developed by Norman H. Nie and C. Hadlai Hull in the year 1968. After SPSS was acquired by IBM in 2009, it's officially recognized as IBM SPSS Statistics. The core program of this software package is called SPSS Base and several features are available for the range of statistical, data entry or reporting capabilities [24]. SPSS comprises all basic statistical tests and multivariate analyses such as;

- t-tests;
- ANOVA;
- Regression;
- Correlations and other association measures;
- Nonparametric tests;
- Factor analysis;

Define Values for SPSS V24 Analysis

All three independent variables have divided into two levels based on their values to maintain the homogeneity of variance and it was shown in Table 21.

Table 21: SPSS Independent Variable Level

IV name	Irradiation Level (Ir)	Panel Temperature (T)	Dust Level
"Low" =1	$Ir \leq 760$ W/m^2	$T \leq 50$℃	Setup III (Control)
"High"=2	$Ir > 760$ W/m^2	$T > 50$℃	Setup I (Dust Added)

CHAPTER 04

RESULTS AND DISCUSSION

In this chapter the results of the research analysis are presented and discuss with reference to the aim of the experiment. Statistically calculated results will further be explained in this section which was obtained by three-way factorial ANOVA Design manipulated from IBM SPSS Version 24. Finally, it will discuss whether irradiation Levels, Panel temperature and Dust level and their interaction effect has significant influence for Solar Panel power output and their efficiency based on factorial ANOVA design.

4.1 Verification of three-Way factorial ANOVA Assumptions

The assumption of random sampling implies that all cases in the population have an equivalent chance of being selected into the sample. The randomly sampled data assumption has been satisfied in this analysis where all eight (08) groups' data selected from total 450 readings through SPSS "Random Sample of Cases". Based on reading of the Bartholow et al. (2002), violating the assumption of random sampling will lead to the non-accuracy of the p-value derived from a non-random sample.

The normally distributed data assumption also needs to be tested for each of the groups associated with all the mean comparisons. So, the three main effect hypotheses each have two means associated with them, consequently, all six of those distributions need to be evaluated for normality. Moreover, the hypothesis of interaction effect has twenty different "mean value" associated with it, consequently, all twenty of those distributions need to be evaluated for normality. However, it is unnecessary and counterproductive to test distributions for normality with a statistical test, when only someone is interested in evaluating the assumption of normality. ANOVA is relatively robust to deviations from normality. Therefore, it is recommendable to evaluate the absolute values of skew and kurtosis. If they are less than |2.0| and |9.0| respectively, then running a regular ANOVA on those data will be accepted (Schmider, Ziegler, Danay, Beyer, and Bühner, 2010). Based on calculation through SPSS V24, absolute value of Skewness and kurtosis were summarize in table 22.

Table 22: Summary of Skewness and Kurtosis Value of all combination of IV’s

Dependent Variable: Solar Panel Power Output		
Calculated Configuration	**|Skewness|**	**|Kurtosis|**
Low Irradiation	0.100	1.720
High Irradiation	0.414	0.124
Low Temperature	0.026	1.591
High Temperature	1.954	3.716
Low Dust	0.919	0.426
High Dust	0.689	1.006
Low Irradiance x Low Dust	0.282	1.789
Low Irradiance x High Dust	0.220	1.727
High Irradiance x Low Dust	0.039	1.607
High Irradiance x High Dust	0.958	2.170
Low Irradiance x Low Temperature	1.218	0.736
Low Irradiance x High Temperature	1.779	1.874
High Irradiance x Low Temperature	0.596	0.861
High Irradiance x High Temperature	1.263	1.965
Low Temperature x Low Dust	0.152	1.927
Low Temperature x High Dust	0.193	1.661
High Temperature x Low Dust	0.107	1.451
High Temperature x High Dust	1.560	1.157
Low Irradiance x Low Temperature x Low Dust	1.526	2.774
Low Irradiance x Low Temperature x High Dust	1.298	0.341
Low Irradiance x High Temperature x Low Dust	1.072	1.816
Low Irradiance x High Temperature x High Dust	0.863	0.966
High Irradiance x Low Temperature x Low Dust	0.562	0.363
High Irradiance x Low Temperature x High Dust	0.537	0.207
High Irradiance x High Temperature x Low Dust	0.817	0.549
High Irradiance x High Temperature x High Dust	**2.177**	4.090

According to the summary table of Skewness and Kurtosis of three-way interaction for high Irradiance, high temperature and high dust level is slightly exceed the absolute value of defined skewness value and neglected due to nature of output value and kurtosis is also within required limits.

The assumption of homogeneity of variance is that the variance within each of the population is equal and it was tested for this analysis. Based on the results manipulated within the SPSS table entitled “Levene’s Test of Equality of Error Variances”, the assumption of homogeneity of variance has been violated, F (7, 152) = 16.16, p < .001. However, in this case, as the sample sizes (N=20 for each group) were equal, the p-values estimated from the ANOVA will be robust and accurate [20].

Table 23: Evaluating of Homogeneity of Variance of recorded data through SPSS

Levene's Test of Equality of Error Variances[a]			
Dependent Variable: Solar Panel Power Output (W)			
F	df1	df2	Sig.
16.161	7	152	.000
Tests the null hypothesis that the error variance of the dependent variable is equal across groups.			
a. Design: Intercept + Irradiation.Level + Panel.Temperature + Dust.Level + Irradiation.Level * Panel.Temperature + Irradiation.Level * Dust.Level + Panel.Temperature * Dust.Level + Irradiation.Level * Panel.Temperature * Dust.Level			

4.2 Interpretation of Three-Way Factorial ANOVA SPSS Results

In Figure 4.1 to 4.3, representing clustered bar chart with 95% confidence interval error bars for the four means associated with each group of the influence of independent variables to solar system power output study. The error bars shown in each different graph is representing 95% confidence intervals. Smaller error bars denote greater confidence in the mean point estimates. Based on clustered bar chart of this experiment low error bar showing for High temperature/Low Dust, High Irradiance/Low Dust and High irradiance/Low dust groups compare to other group combination.

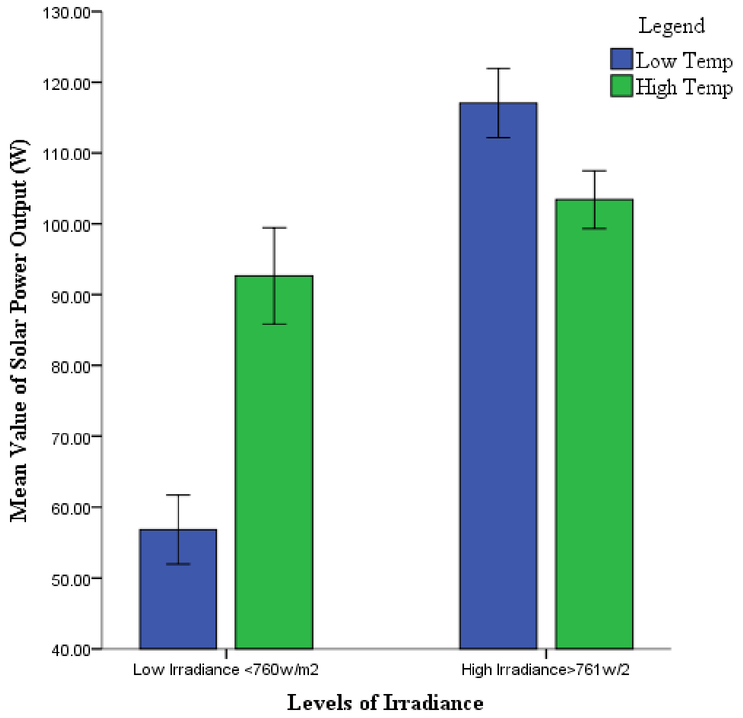


Figure 4.1: Solar Power Output Means and 95% confidence levels with Error Bars for Solar Irradiance Vs Temperature Levels

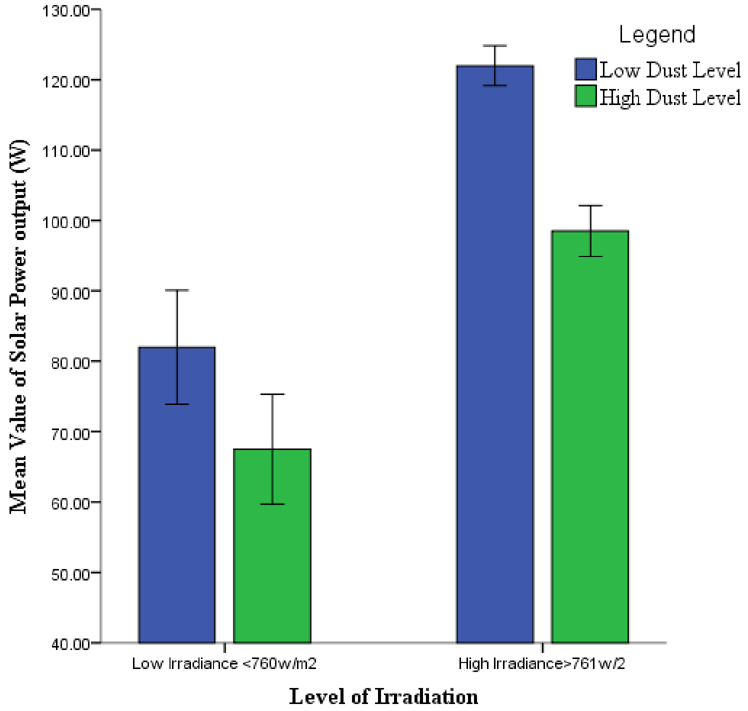


Figure 4.2: Solar Power Output Means and 95% confidence Levels with Error Bars for Solar Irradiation Vs Dust Levels

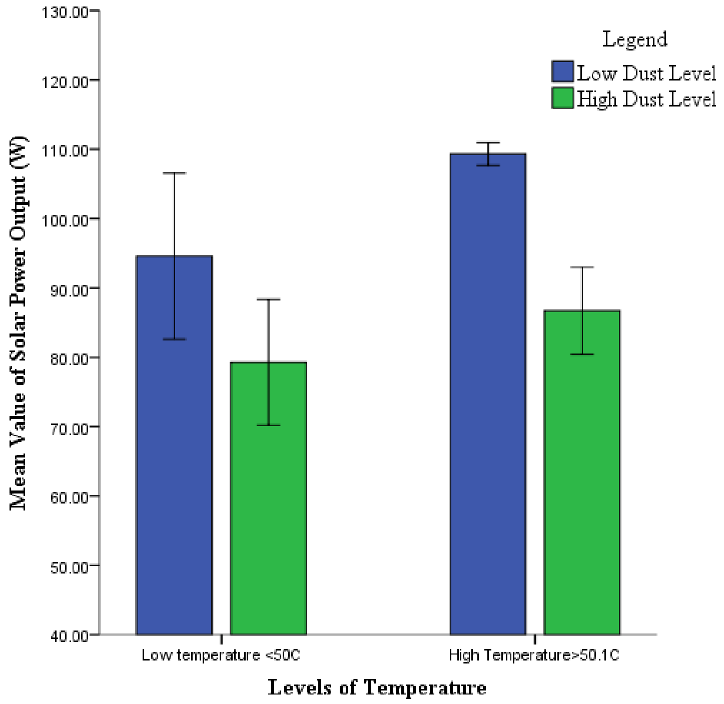


Figure 4.3: Solar Power Output Means and 95% confidence Intervals with Error Bars for Temperature Vs Dust Levels

One of the key results associated with the analysis is SPSS table entitled 'Descriptive Statistics' which includes the means and standard deviations. During the Analysis it was make sure the random sample sizes (n=20) were equal across the all groups, in order to simplify the heterogeneity of variance issue in 2x2x2 factorial between-subjects ANOVA.

As per shown in the table-24 entitled 'Descriptive Statistics', High irradiance (>760W/m^2), Low Temperature (≤50°C) and Low dust group has highest mean value with low standard deviation which implies that this combination will ensure more power out than other combination and all data sets clustered about the mean values. Lowest mean Value and highest standard deviation exhibit by Low Irradiance, Low temperature and High Dust value group with value of 54.75 and 16.86 respectively. As per results, it is showing lowest mean value for High Temperature and High dust value combination irrespective of solar irradiation level. Low value of the standard deviation of the independent variables combination is indicating that more of the data is clustered about mean value and large standard deviation showing in Low Irradiance, Low Temperature and low/high dust level groups and Low irradiance, high temperature with high dust data group is indicating that readings are more spread out. This was a clear indication of inconsistent of solar power output value in low irradiance values than the other groups.

Table 24: Descriptive Statistics for Solar Panel Power Output Disaggregated by Independent Variables (N= 160)

Dependent Variable (DV): Solar Panel Power Output (W)					
IV1	**IV2**	**IV3**	**Mean**	**Std. Deviation**	**N**
Low Irradiance (<760W/m^2)	Low temp ≤50°C	Low Dust Level	58.8455	13.59750	20
		High Dust Level	54.7500	16.86037	20
		Total	56.7978	15.26001	40
	High Temp >50°C	Low Dust Level	105.0650	2.49764	20
		High Dust Level	80.2200	24.47651	20
		Total	92.6425	21.28811	40
	Total	Low Dust Level	81.9553	25.31539	40
		High Dust Level	67.4850	24.42743	40
		Total	74.7201	25.76744	80
High Irradiance (>761W/m^2)	Low temp ≤50°C	Low Dust Level	**130.3200**	2.63295	20
		High Dust Level	103.7850	9.91980	20
		Total	117.0525	15.22685	40
	High Temp >50°C	Low Dust Level	113.6250	2.94777	20
		High Dust Level	93.1950	10.27288	20
		Total	103.4100	12.75414	40
	Total	Low Dust Level	121.9725	8.89258	40
		High Dust Level	98.4900	11.31851	40
		Total	110.2312	15.55262	80
Total	Low temp ≤50°C	Low Dust Level	94.5828	37.46133	40
		High Dust Level	79.2675	28.33641	40
		Total	86.9251	33.89055	80
	High Temp >50°C	Low Dust Level	109.3450	5.10495	40
		High Dust Level	86.7075	19.65830	40
		Total	98.0263	18.25869	80
	Total	Low Dust Level	101.9639	27.58314	80
		High Dust Level	82.9875	24.51910	80
		Total	92.4757	27.70048	160

4.2.1 Interpretation of Main effects of the Experiment Analysis

Most important information, regarding experiment is indicated in SPSS table entitled 'Tests of Between-Subjects Effects' shown in table-25. The last three columns in this table, which show the "F-values (F), significance levels (Sig.), and effect size indices", are the most significant (Partial Eta Squared). These represent the indication of above test with three main effects and their interaction effect which was ultimate goal of the experimental setup.

The findings indicate that the key impact of irradiance was statistically important, F (1, 152) = 311.83, $p < .001$, partial η2 = .672, high irradiance group had significantly higher contribution to PV panel power output (M=110.23) than provided by low irradiance level group (M=74.72). The scale of the gap in total solar panel power output can be concluded between high and low irradiance level groups is highest (Partial Eta Squared =0.672). This should not be unexpected due to amount of irradiance is the main factor which decide the Solar panel power output.

The Panel temperature main effect was statistically significant, F (1, 152) = 30.47, $p < .001$, partial η2 = .167, high module temperature group had significantly higher contribution to Solar panel power output (M=98.03) than provided by low panel temperature group (M=86.93). The scale of the gap in total solar panel power output can be concluded between high and low solar panel temperature groups is low (Partial Eta Squared =0.167). Main reason for this effect will that panel temperature is depending upon on sun irradiance levels.

Finally, the amount of dust level main effect was also statistically significant, F (1, 152) = 89.05, $p <0.001$, partial η2 = .369. High dust level group had significantly lower contribution to Solar panel power output (M=82.99) than provided by low dust level setups (M=101.96). The scale of the gap in total solar panel power output can be concluded between high and low solar panel temperature groups were moderate (Partial Eta Squared =0.369). Due to all three main effects are statically significant, all null hypothesis was reject and conclude that Solar panel power output was depend on all three independent variable factors under experiment analysis condition namely irradiance level, Panel temperature and amount of dust levels.

Table 25: Evaluating Main Effects and their interaction on Solar Panel Power Output; Table Generated through SPSS V24

Tests of Between-Subjects Effects						
Dependent Variable: Solar Panel Power Output (W)						
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	97416.261[a]	7	13916.61	86.03	.000	.798
Intercept	1368280.45	1	1368280.4	8458.85	.000	.982
Irradiance (A)	50441.60	1	50441.60	311.83	.000	.672
Temperature (B)	4929.40	1	4929.40	30.47	.000	.167
Dust Level (C)	14404.11	1	14404.11	89.05	.000	.369
A x B	24489.88	1	24489.88	151.40	.000	.499
A x C	812.21	1	812.21	5.02	.026	.032
B x C	536.15	1	536.15	3.31	**.071**	.021
A x B x C	*1802.91*	*1*	*1802.91*	*11.15*	*.001*	*.068*
Error	24587.104	152	161.757			
Total	1490283.81	160				
Corrected Total	122003.365	159				
a. R Squared = .798 (Adjusted R Squared = .789)						

4.2.2 Interpretation of Interaction effects of the Experiment Analysis

The Predicted interaction effects between irradiance Level, Solar Panel Temperature F (1,152)= 151.40, P<0.001, partial η2 = .499 and irradiance level and Amount of Dust Level F(1,152)= 5.02, P=0.026, partial η2 = .032 were statistically significant and reject the null hypothesis. However, the interaction between temperature and dust level was not statistically significant F(1,152)= 3.31, P=0.071, partial η2 = .021. But this was qualified by three way interaction among Irradiance Level, Panel Temperature and Amount of Dust Level, F(1,152)= 11.15, P=0.001, partial η2 = .068. It means that that two-way interaction between two independent variables is moderate by third independent variable.

For analyzing the effect of third variable, it was decomposing two-way interaction with isolating third variable irradiance level and panel temperature in each different analysis. As per output results shown in table 26, it can observe that two way interaction between Irradiance and Amount of Dust Level is statistically significant at low temperature condition (T≤50 °C) where; F (1, 76) = 17.529, P<0.001 with partial η2 = .187 and not statistically significant at high temperature condition (T>50 °C) where; F (1, 76) = 0.542, P=0.464 with partial η2 = .007.

As per Statistical calculation results shown table 27 for isolating irradiance level across the interaction between Panel Temperature and amount of dust level. According to analysis, the interaction between Panel temperature and dust level is only significant at Low irradiance level where; F(1, 76) = 8.014, P=0.006 with partial η2 = .095. Moreover, at high irradiance level the interaction effect between two independent variable Panel temperature and amount of dust level is not statistically significant F (1,76) = 3.395, P=0.069 with partial η2 = .043.

Behavior of Irradiance Level and Panel temperature on Solar Panel Output

As seen in Figure 4.4, along the x-axis, the primary effect of irradiance levels can be seen for both temperature levels. That is, all temperature levels in the high irradiance category produce more Solar Power than their low irradiance level counterparts. The key influence for panel temperature occurs in the low irradiance level (760W/m2) rather than the high irradiance level (>760W/m2), according to contrasts between temperature levels (Green line for Low temperature and Blue line for Low temperature).

In the high irradiance group, low temperature level had significantly higher solar output (M=117.05) than high temperature levels (M=103.41), imitating the main effect of Solar Panel temperature. Though, in the low irradiance level group, did not have higher solar panel output (M=56.80) than provided in high temperature group (M=92.64)

Table 26: Evaluating Main Effects and their interaction on Solar Panel Power Output; *Split by Temperature Levels*

Tests of Between-Subjects Effects						
Dependent Variable: Power.Output						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial η2
Low Panel Temperature (T≤50 °C)						
Corrected Model	79821.491[a]	3	26607.16	185.255	.000	.880
Intercept	604478.189	1	604478.19	4208.733	.000	.982
Irradiance	72612.698	1	72612.70	505.572	.000	.869
Dust Level	4691.138	1	4691.14	32.662	.000	.301
Irradiance x Dust Level	2517.656	1	2517.66	17.529	.000	.187
Error	10915.479	76	143.63			
Total	695215.159	80				
High Panel Temperature (T > 50 °C)						
Corrected Total	90736.971	79				
Corrected Model	12665.370[b]	3	4221.79	23.469	.000	.481
Intercept	768731.655	1	768731.66	4273.348	.000	.983
Irradiance Level	2318.781	1	2318.78	12.890	.001	.145
Dust Level	10249.128	1	10249.12	56.974	.000	.428
Irradiance * Dust Level	97.461	1	97.46	.542	.464	.007
Error	13671.624	76	179.890			
Total	795068.650	80				
Corrected Total	26336.995	79				
a. R Squared = .880 (Adjusted R Squared = .875)						
b. R Squared = .481 (Adjusted R Squared = .460)						

Table 27: Evaluating Main Effects and their interaction on Solar Panel Power Output; *Split by Irradiance Levels*

Tests of Between-Subjects Effects						
Dependent Variable: Power Output						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial η2
Low Irradiance (≤760 W/m^2)						
Corrected Model	32037.394[a]	3	10679.13	39.75	.000	.611
Intercept	446647.766	1	446647.77	1662.72	.000	.956
Dust Level	4187.763	1	4187.76	15.59	.000	.170
Panel Temp	25696.922	1	25696.92	95.66	.000	.557
Dust Level * Panel Temp	2152.709	1	2152.71	8.01	.006	.095
Error	20415.535	76	268.62			
Total	499100.695	80				
Corrected Total	52452.929	79				
High Irradiance (>760 W/m^2)						
Corrected Model	14937.267[b]	3	4979.09	90.71	.000	.782
Intercept	972074.278	1	972074.28	17709.80	.000	.996
Dust Level	11028.556	1	11028.56	200.92	.000	.726
Panel Temp	3722.356	1	3722.36	67.82	.000	.472
Dust Level * Panel Temp	186.355	1	186.35	3.39	.069	.043
Error	4171.569	76	54.89			
Total	991183.114	80				
Corrected Total	19108.836	79				
a. R Squared = .611 (Adjusted R Squared = .595)						
b. R Squared = .782 (Adjusted R Squared = .773)						

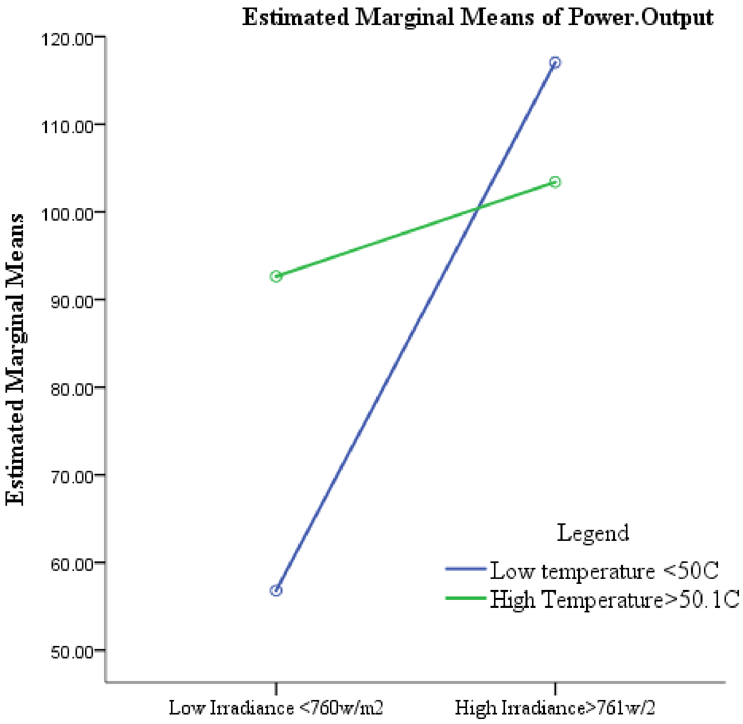


Figure 4.4: Plot of the mean "Solar Panel Power output" for each Combination of Levels of "Panel Temperature" and "Irradiance Level"

Behavior of Irradiance Level and Amount of Dust on Solar Panel Output

As per Figure 4.4, along the x-axis, the main influence of irradiance levels can be seen with both high and low dust levels. That is, in the high irradiance group, both high and low dust levels resulted in more Solar Power generation than provided in the low irradiance level group. However, comparisons between high/low dust levels (the blue line for Low dust and the green line for high dust setup) shows that the main effect of amount of dust levels appears more on solar PV output in the low irradiance level (≤760W/m^2) than high irradiance level (>760W/m^2)

In the high irradiance group, low dust group provided significantly higher solar output (M=121.97) than high dust level setup (M=98.49), reflecting the main effect of amount of dust/soiling effect on solar PV output. Nevertheless, in the low irradiance level group, dust level didn't provide higher solar panel output (M=81.96) than provided in high dust group (M=67.49)

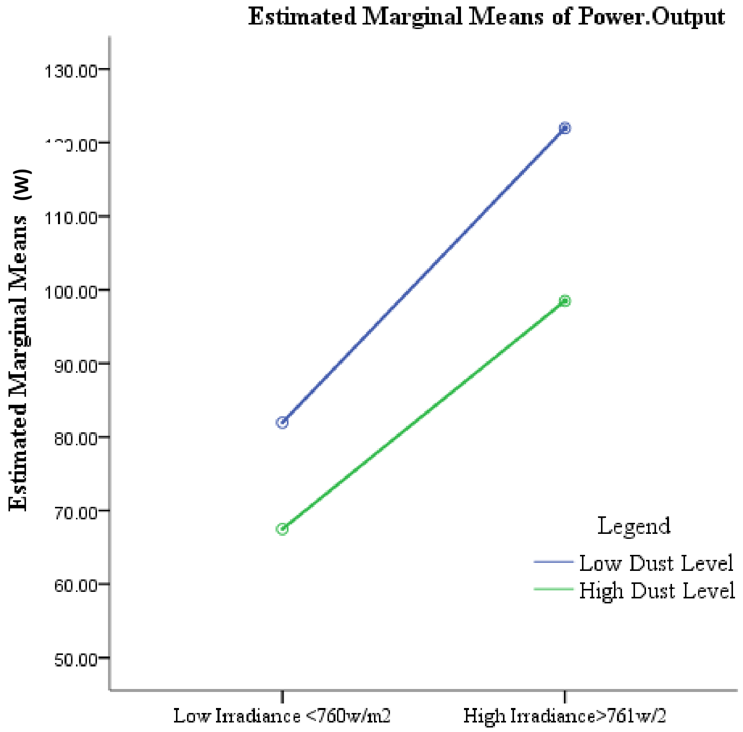


Figure 4.5: Plot of the mean “Solar Panel Power output” for each Combination of Levels of “Amount of Dust” and “Irradiance”

Behavior of Irradiance Level and Amount of Dust on Solar Panel Output

As per Figure 4.6, the main effect of panel temperature levels can be seen for both high/low dust levels along x-axis. That is, both high and low dust levels in high temperature group provided high Solar Power output than provided in the low temperature level group. However, comparisons between amount of dust level group (the blue line for Low dust and the green line for high dust setup) shows that the main effect of amount of dust levels appears more on solar PV output in both low irradiance level (≤760W/m^2) and high irradiance level (>760W/m^2)

In the high temperature group, low dust group provided significantly higher solar output (M=109.34) than high dust level setup (M=86.71. Furthermore, in the low temperature level group also provide considerable amount of Solar PV Output (M=94.58) than contributed by high dust group (M=79.27)

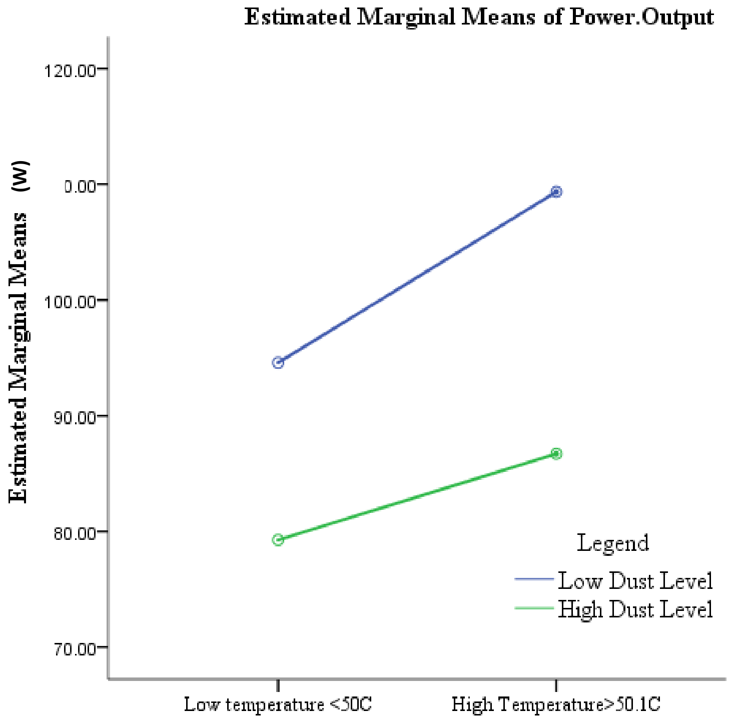


Figure 4.6: Plot of the mean "Solar Panel Power output" for each Combination of Levels of "Amount of Dust" and "Panel Temperature"

Behavior of Irradiance Level, Panel Temperature and Amount of Dust on Solar Panel Output

As per figure 4.7, the main outcome of Irradiance levels can be perceived for both temperature levels along x-axis with Low and high dust level group separately. Which indicates, both temperature levels in high irradiance group provide higher Solar Power output than their counterparts in the low irradiance level group for both dust amount group. Apart from above, comparisons between temperature levels (Green line for Low temperature and Blue line for Low temperature) shows that the main outcome for panel temperature seems in the low irradiance level with Low dust level group than high irradiance level and high dust level group.

In the high irradiance group, low temperature group (≤50°C) and low dust group provided significantly highest solar output (M=130.32) than high dust level setup (M=103.79). Reflecting, the main effect of Solar Panel temperature, Amount of Dust levels along with levels of irradiance. However, in the low irradiance level group with low dust group, did not have higher solar panel output (M=58.85) than provided in high temperature group (M=105.06).

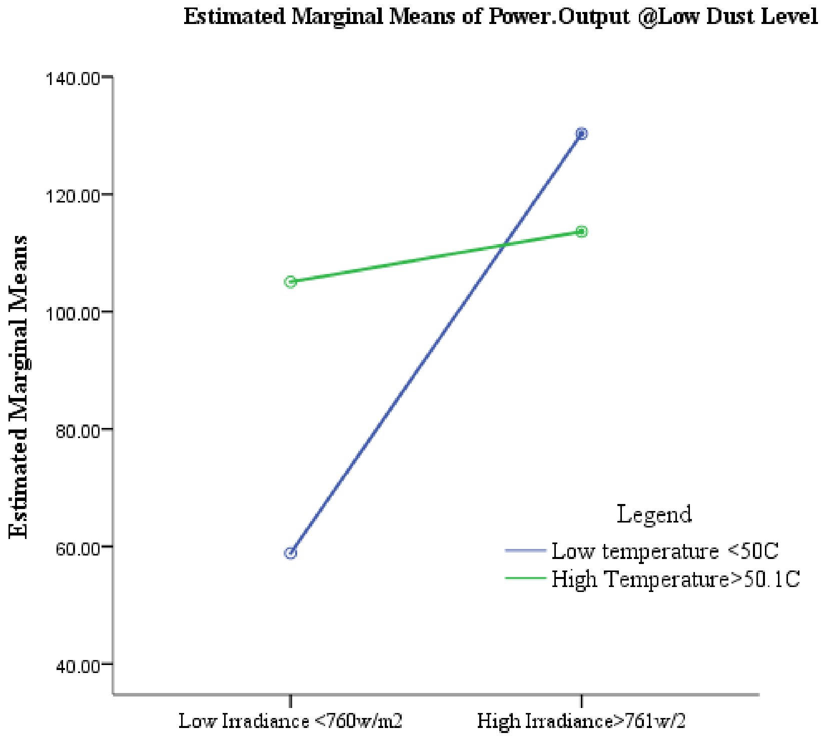


Figure 4.7: Plot of the mean "Solar Panel Power output" for each Levels of "Panel Temperature" and "Irradiance" at Low Dust Level

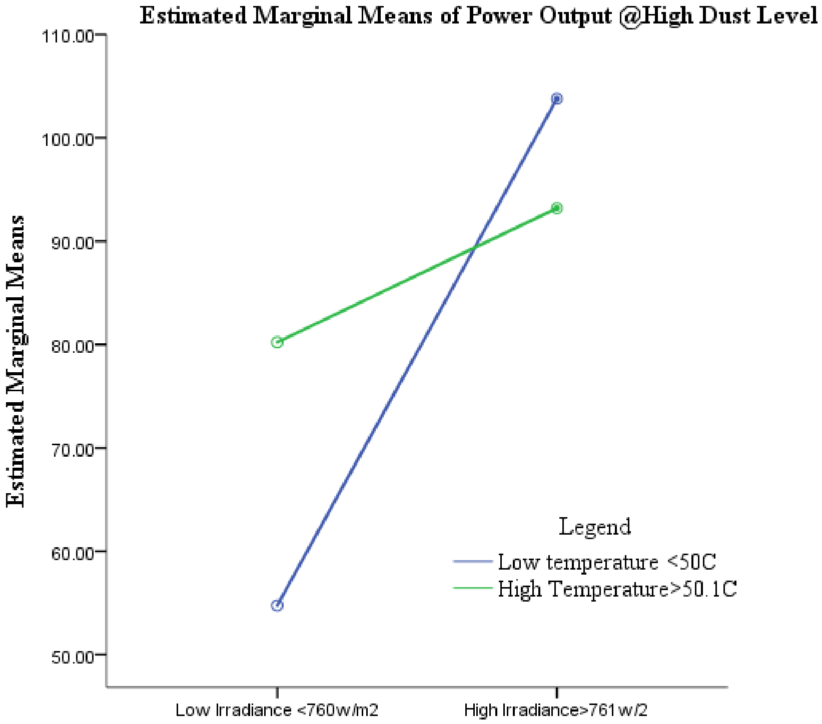


Figure 4.7: Plot of the mean “Solar Panel Power output” for each Levels of “Panel Temperature” and “Irradiance” at High Dust Level

4.3 Simple Effect Analysis of each Independent Variables

Comparisons of mean value of Solar panel power output will provide the percentage effect of dependent variable. This was calculated for each group with changing one independent variable at a time and other two independent variable was kept unchanged in each condition. Figure 4.8, showing the solar output mean for each group of different condition. All three independent variables the maximum and minimum effect size was calculated and tabulated in table no-28, 29 and 30. According to the calculation it is showing that Amount of high dust levels will effect to reduce Solar panel power output with maximum of 23.6% and minimum of 7.0% and it is tend to reduce the effect percentages with increase of irradiance levels.

The calculation of Panel temperature effect for solar panel power output also showing that it will affect to reduce output power of solar panel with increase of irradiance, amount of dust level and their interaction effects.

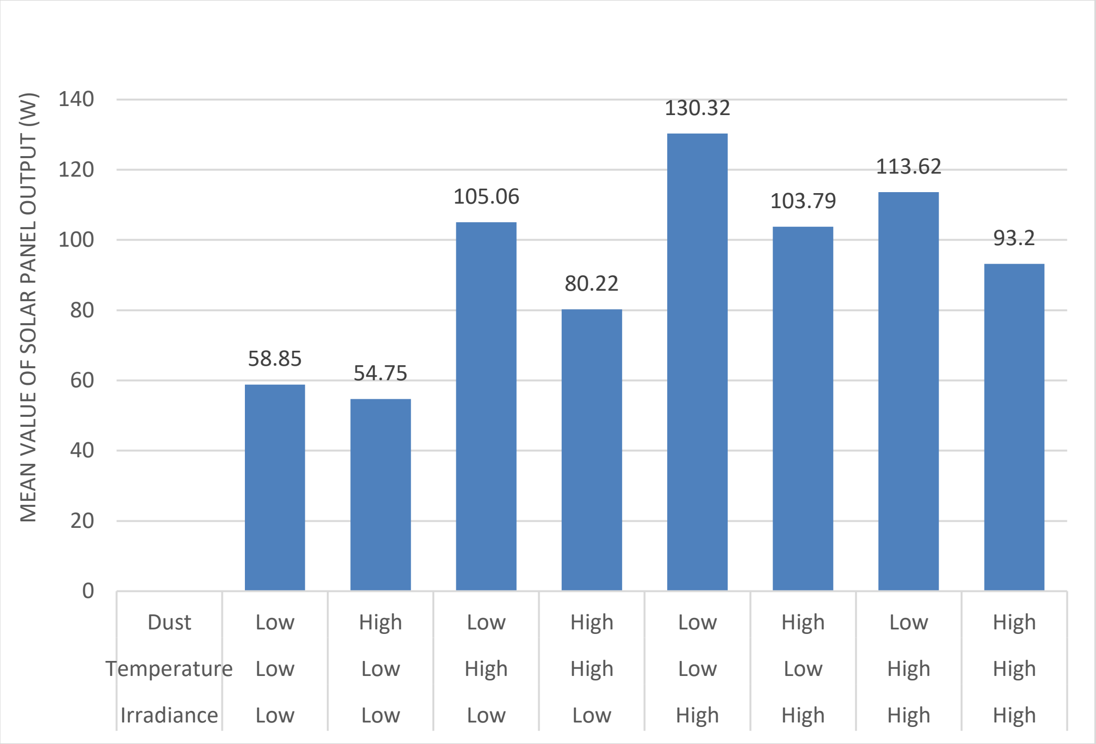


Figure 4.8: Mean Value of Solar Panel output Power Vs Independent Variables

Table 28: Quantifying Solar Panel Power output change in % based on Level of Dusts

Irradiance Level	Panel Temperature	Amount of Dust	Mean of Solar Output	%
Low	Low	Low	58.85	
Low	Low	High	54.75	-7.0%
Low	High	Low	105.06	
Low	High	High	80.22	-23.6%
High	Low	Low	130.32	
High	Low	High	103.79	-20.4%
High	High	Low	113.62	
High	High	High	93.2	-18.0%

Regarding the irradiance level effect on dependent variable of experiment work; solar panel power output also shown in table 30. Based on results its showing that high irradiance level is always contributed to achieve high solar output with different amount of percentage due to the interaction effect of amount of dust levels and Panel temperature.

Table 29: Quantifying Solar Panel Power output change in % based on Panel Temperature

Irradiance Level	Amount of Dust Level	Panel Temperature	Mean of Solar Output	%
Low	Low	Low	58.85	
Low	Low	High	105.06	78.5%
Low	High	Low	54.75	
Low	High	High	80.22	46.5%
High	Low	Low	130.32	
High	Low	High	113.62	-12.8%
High	High	Low	103.79	
High	High	High	93.2	-10.2%

Table 30: Quantifying Solar Panel Power output change in % based on Irradiance Level

Panel Temperature	Amount of Dust Level	Irradiance Level	Mean of Solar Output	%
Low	Low	Low	58.85	
Low	Low	High	130.32	121.4%
Low	High	Low	54.75	
Low	High	High	103.79	89.6%
High	Low	Low	105.06	
High	Low	High	113.62	8.1%
High	High	Low	80.22	
High	High	High	93.2	16.2%

CHAPTER 05

CONCLUSION AND FUTURE WORK

5.1 Conclusion and Key Findings

Presently, Sri Lanka is moreover depending on fossil fuel-based energy generation method due to lack of renewable and viable energy source in main energy mix generation. Accordingly, installation of renewable energy sources are encouraged by all energy policy makers and hence installation of roof mounted scattered solar PV plant to utility scale MW scale solar PV generation plants are already planned and installed throughout the country with optimum use of land area to achieve high plant performance with proper planning. Government of Sri Lanka and relevant energy authorities like Public Utility Commission (PUCSL) and Sustainable Energy Authority (SEA) are encouraging domestic level to industry level energy consumers to installed more Solar PV plant with various initiative program like “Soorya Bala Sangramaya” including more attractive benefits for investment of renewable energy sector to increase the energy share from total generation.

Latest report issued by Sustainable energy authority (SEA) of Sri Lanka “Renewable Energy Development Plan Phase 1; 2019-2025” stated that it is already planned addition of 1564MW capacity solar power before end of 2025. This total capacity included 330MW of scattered type small roof mounted solar PV installation. Furthermore, as per ADB/UNDP report published in 2017. In 2050, solar PV energy contribution will be 30% out of 34000MW total expected energy demand in Sri Lanka to achieve 100% electrification through renewable energy sources [03]. All these initiative programs and report suggest that Solar PV Generation will be a main energy sector of energy generation plan of Sri Lanka. Accordingly, Solar PV Power plant performance and efficiency will be a key measurement to achieve high energy generation during limited and productive sun hours during daytime and various other influencing factors.

Based on the experiment carried out for finding main external parameters and their interaction on solar panel power output and their efficiency, it was found that all main parameters tested were affects for solar panel power output production. Accordingly, Irradiance Level, Panel temperature and amount of dust levels were significantly reducing the panel power output maximum of 23.6% and 12.8% for high dust amount and high panel temperature respectively. This is by considering all possible combination of three independent variables of Irradiance Level, Panel temperature and Amount of Dust level. Moreover, irradiance level is the key factor of generating solar power and expected a linear relationship with output and irradiance level. However, according to the results obtained, solar panel output is increased with irradiance level and it is not a linear relationship due to affecting other two independent variable, Panel temperature and amount of dust level.

Finally, three-way factorial ANOVA design statistical analysis performed through IBM SPSS V24 shows that there was a significant three-way interaction effects between Irradiance Level, Panel temperature and amount of dust level. In theory and previous research work identified and showing that Irradiance Level will cause for Panel temperature changes and at the same time increment of irradiance Level will decrease the effect of dust level deposited on solar panel. This experiment results and relevant statistical analysis shows that such two-way interaction is moderate by either Panel temperature or irradiance level. Moreover, it can conclude that magnitude of such three-way interaction is strong in Low irradiance and Low temperature than high temperature and high irradiance level.

Based on these results, it can conclude that, more attention is required to control the solar PV power plant external passive parameters such as panel temperature and amount of dust level to achieve a higher solar energy production other than main active parameters effects for solar PV production.

5.2 Recommendation

Based on above conclusion, small scattered roof top mounted solar power plant to utility scale solar power generation plant shall consider best way of minimizing solar panel cell temperature and amount of dust level deposited on solar panels where cause of this effect in long term will result substantial degradation of energy generation and plant performance due to considerable amount of power loss. Accordingly, it is responsible of Solar design engineers, building designer and building services engineers involving of such project to introduce optimum location for receiving high irradiance level, mechanism to reduce panel temperature and amount of dust level with minimum initial investment. Moreover, small investment on this matter will increase energy generation units will lower Return of Investment (ROI) and high efficiency. This will be more effective by considering higher cumulative solar PV power plant installation where national target is achieving 100% renewable energy production in 2050.

5.3 Limitation due to Assumptions

There are limitations of experiment in actual environmental conditions due to various practical difficulties and unavoidable reasons as described below;

- Data sets were insufficient for carried out three-way Factorial ANOVA design with three levels for each independent variable due to limitation of achieving different precious environment condition including maintain low, medium and high temperature with high, medium and low irradiance level in actual condition.
- Assuming solar panel cell temperature as average value of panel back temperature, may not be corrected and actual condition will be higher than the measuring value.
- Assuming amount of dust quantity is equally distributed in solar panel surface will not be in actual environmental condition due to wind flow with different direction.
- Assuming all three experiments setups are equal will not be in actual working conditions where solar panels will have module mismatch even though it is same model and manufactured by same manufacture. All other equipment which are used for each setup may carry same non-identical nature and will have different error ratios.
- For statistical analysis of factorial ANOVA design, all group sample selected by automatic random sample via SPSS software and limited to 20 readings for

each group may reduce sample size and will reduce the accuracy of final results.

- Solar panels of each setups were installed with adequate air space where good air circulation was available and panel temperature rise was considerably lower. However, in most of roof top solar PV installation limited air gaps between roof and solar modules may experience high temperature rise than experimental setup.

5.4 Future Work

As per research outcome, there was a significant interaction effect of Irradiance Level, Panel temperature and amount of dust level for power output of solar panel. Accordingly, it shall introduce a mathematical equation to quantify this effect after creating a suitable model through modeling software as a future work for this research work. This will help general public to get an idea of how much energy can save or improve in their solar plant by maintaining suitable environmental condition and designer also can initiative any special requirement at project planning stage other than operation and maintenance of such system.

REFERENCES

[1]. Michael Boxwell, *Solar Electricity Handbook, 11th Ed*. United Kingdom: Greenstream Publishing Limited, 2017.

[2]. Manpreet Singh (KPMG India) , Sandip Keswani (KPMG India), Puneet Chitkara (KPMG India), *100% Electricity Generation through Renewable Energy By 2050, Assessment of Sri Lanka's Power Sector Published by ADB and UNDP* , 2017 ,pp. 14-36.

[3]. F. S. Janet, L. Sawin, *REN21 Renewables 2017 Global Status Report*. Paris: Frankfurt School–UNEP Collaborating Centre for Climate & Sustainable Energy, 2017, PP 63-72.

[4]. D. Renné; R. George; B. Marion; D. Heimiller; C. Gueymard, "*Solar Resource Assessment for Sri Lanka and Maldives", 2003*

[5]. F. Mehmet Eminb Meral, *"A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems,"* June 2011, Pages 2176-2184.

[6]. J. G. S. Nalani, "Assessment of Rooftop Solar Net Metering Concept: Consumer and Utility Point of View," University of Moratuwa, Moratuwa, Sri Lanka, 2015, PP 2-25.

[7]. sunpowercorp.com, "Key factors for Solar Performance," *https://us.sunpower.com/,* 2017. [Online]. Available: https://us.sunpower.com/sites/sunpower/ files/media-library/white-papers/wp-key-factors-solar-performance.pdf [Accessed: 06-Oct-2018].

[8]. Govinda R.Timilsina, Lado Kurdgelashvili, Patrick A.Narbel, "Solar energy: Markets, economics and policies," Jan. 2012, PP 1-10.

[9]. Dr. Subrat Sahu, “Solar Energy Technology Adoption: Select Literature Review and Indian Evidences,” 2017, PP 01-03.

[10]. “Sri Lanka Energy Production and Usage details,” *http://www.energy.gov.lk/*, 2018. [Online]. Available: http://www.energy.gov.lk/images/energy-balance/energy-balance-2018-lq1.pdf. [Accessed: 06-Oct-2018].

[11]. “Energy Production details and data library,” *http://www.ceb.lk/*, 2018. [Online]. Available: http://www.ceb.lk/knowledge-center. [Accessed: 06-Jun-2018].

[12]. Md. Rejwanur Rashid Mojumdar, Arif Md. Waliullah Bhuiyan, Hamza Kadir, “Design and Analysis of an Optimized Grid-tied PV System: Perspective Bangladesh,” 2011.

[13]. C. N. Adam Faiers, “Consumer attitudes towards domestic solar power systems,” September 2006, PP 1797-1807.

[14]. M. L. James Macey White, “Perovskite solar technology leader’s solar cell exceeds highest ever performing single-junction silicon solar cell,” *www.oxfordpv.com/*, 25-Jun-2018. [Online]. Available: https://www.oxfordpv.com/news/oxford-pv-sets-world-record-perovskite-solar-cell. [Accessed: 06-Sep-2018].

[15]. D. Levitan, “Is Anything Stopping a Truly Massive Build-Out of Desert Solar Power?,” Jul. 2013.

[16]. J. Nelson, *The Physics of Solar Cells*. United Kingdom: Imperial College Press, 2003.

[17]. A. K. Seng, *Handbook for Solar Photovoltaic (PV) Systems*. Singapore: EMA and BCA, 2010.

[18]. A. Adiyabat, “Evaluation of solar energy potential and PV module performance in the Gobi Desert of Mongolia,” 2006, PP-553-566.

[19]. M. Hosenuzzamana, N. A. Rahima, J.Selvaraja, M. Hasanuzzamana, “Factors Affecting the PV Based Power Generation,” University of Malaya, Kuala Lumpur, Malaysia, 2014.

[20]. Rogan, J. C., and Keselman, H. J., Ed.,” *Is the ANOVA F-test robust to variance heterogeneity when sample sizes are equal? An investigation via a coefficient of variation”*, vol. 14, no. 4. American Educational Research Journal, 1997, PP-493-498.

[21]. Manuel C. Voelkle, Phillip L. Ackerman, and Werner W. Wittmann, “Effect Sizes and F ratios < 1.0. Sense or Nonsense? Methodology,” *Methodology,* vol. 3, no. 1, pp. 35–46, Jan. 2007.

[22]. D. N. Joanes and C. A. Gill, Ed., *Comparing Measures of Sample Skewness and Kurtosis*, vol. 47, no. 1. Journal of the Royal Statistical Society, 1998, PP 183-189.

[23]. J. W. Tukey, Ed, *The Future of Data Analysis*, vol. 33, no. 1. Institute of Mathematical Statistics, 1962, PP 1-67.

[24]. Sweet, S. A., and Grace-Martin, K, *Data analysis with SPSS: a first course in applied statistics (4th ed.).* Boston: Allyn and Bacon, 2012.

[25]. Shaharin Anwar Sulaiman, Atul Kumar Singh, Mior Maarof Mior Mokhtar, Mohammed A. Bou-Rabee, “Influence of Dirt Accumulation on Performance of PV Panels,” 2014.

APPENDICES