Performance Study of Photovoltaic Modules Considering Natural Dust Impact on High Altitude

By

Habibur Rahman
16221027
Md Johair Haque
16221053
Zahidul Haque Showrov
16321156
Khondoker Farhana Enam
18221036

A thesis submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
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Declaration:

It is hereby declared that

1. The thesis submitted is our own original work while completing degree at BRAC University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

Student's Full Name & Signature:

Habibur Rahman 16221027	**Md Johair Haque** 16221053
Zahidul Haque Showrov 16321156	**Khondoker Farhana Enam** 18221036

Approval:

The thesis/project titled "Performance Study of Photovoltaic Modules Considering Natural Dust Impact on High Altitude" submitted by

1. Habibur Rahman (16221027)
2. Md Johair Haque (16221053)
3. Zahidul Haque Showrov (16321156)
4. Khondoker Farhana Enam (18221036)

of Fall 2020 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical & Electronic Engineering on January 13, 2021.

Examining Committee:

Supervisor:
(Member)

____
Dr. Md. Mosaddequr Rahman
Professor, Department of Electrical and Electronic Engineering
Brac University

Program Coordinator:
(Member)

____
Dr. A.S. Nazmul Huda
Assistant Professor, Department of Electrical and Electronic Engineering
Brac University

Departmental Head:
(Chair)

____
Dr. Md. Mosaddequr Rahman
Professor, Department of Electrical and Electronic Engineering
Brac University

Abstract:

In this present era, solar modules have become a popular energy conducting element. Thus, Dhaka city is not behind in this sector as it can be seen in every building's rooftop containing PV modules. However, Dhaka city is so polluted and therefore it can be seen that PV modules become dusty quickly. It is a major concern in the Middle east and there is energy loss for this reason. The purpose of this study is to compare the output between two PV modules, where one is a dusty module and another is a clean module. Moreover, in this study how dust particles affect the module at different altitudes is another concern. Here the dust particles on the modules store heat from the sun and this affects the output, also affects the short circuit current when dust particles make shadows in the module. Two modules were checked properly in indoor conditions before conducting the outdoor experiment to know the condition of those and to get the PV graph. After that outdoor experiment was conducted on a regular basis to get the continuous data and finally the comparison graph shows the results and effects, how dust affects the module's power output. Empirical method was used to calculate the solar irradiance and finally, solar incident energy was calculated from that.

Keywords: PV module; Dust; Temperature; Irradiance; Short Circuit Current; IV characteristics.

Dedication:

We dedicated to almighty Allah. Thank you for the guidance, strength, power of the mind, protection, skills & healthy life. All of those we offer to our Almighty.

However, this study is wholeheartedly dedicated to our parents Who brought us into the world, who have been our source of inspiration and gave us continuous mental strength when we thought of giving up. Who continuously provide their financial, moral & emotional support.

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Besides my supervisor, we are also thankful to Mohaimenul Islam sir for his continuous support from the start till the end of our thesis. His tremendous leadership helped us to complete our thesis timely. Without his support and motivation, we could not even imagine completing the thesis.

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Chapter 1:

1.1 Introduction

In today's era of globalization, every work done has a hidden outcome of itself. However, one of the toughest challenges faced by today's world is the change in the climate. The generation of electricity is one of the largest sources of CO2 emission. The combustion of fossil fuels such as coal is the primary source of these air emissions. As a result, the production of electricity is one of the main causes of industrial pollution which is not only causing threats to the environment but also affecting the amount of limited traditional energy sources like coal, petrol, and diesel, etc. To solve these problems researchers are searching for some alternative energy sources, called renewable energy sources, For example, solar and wind. Renewable sources are natural sources that can be used repeatedly and do not run out because it is naturally replaced There are different forms of RE such as solar, wind, biofuel, geothermal and tides. Most of the electrical power generated around the world is mainly derived from non-renewable energy sources, especially fossil fuels. However, these resources are non-perishable and would be depleted at some time in the future. Therefore, researchers think alternative sources of energy, which are renewable and environmentally friendly, are required. Though the world was much dependent on fossil fuel sources for energy in the past, this dependency is changing towards solar renewable energy nowadays. However, solar energy is a promising clean energy source of the future. Solar energy has many advantages, for example, it is long-lasting, can be used almost anywhere, and provides cost-effective solutions to energy problems.

1.2 Background

A photovoltaic (PV) system consists of one or more solar panels coupled with an inverter and other electrical and mechanical equipment to produce electricity using energy from the Sun. Some factors decide solar efficiency. Such as solar radiation availability, tilt angle, activity temperature, aging, moisture, wind velocities and their deposition of direction & dust. However, because of cracks in the glass, broken glass and corroded inter-cell tracks, the life-span of the PV system is reduced to around 25 years. Therefore, a degradation in the performance of a solar PV panel is not required during its life span. The dust accumulation on the panel is a significant reason why solar panels are less effective. However, this problem can vary according to location, climate, seasonal changes and so on. Few worldwide researches on the efficiency of solar modules has been conducted.

The focus of renewable energy technologies is on meeting current trends in established and developing nations concern about energy security, the environment and global protection, climate change. During the late 1970s, the oil crisis occurred. This problem has pushed scientists and policy makers around the world to find new ways to make more successful and productive use of solar energy. [1] Solar energy is the leading sector for investment, accounting for 55 percent of the total new non-hydro renewable energy investment. The major share of investments within the solar sector is for PV technologies, resulting in a cumulative global PV installed capacity of 177 GW [2]

Researchers brought the development in the PV devices after conducting many researches. PV devices have been classified into three generations according to the materials and technologies used in the fabrication. Those are given bellow-

1. crystalline silicon PV cells
2. organic and polymer materials
3. dye-sensitized PV cells

4. quantum dots
5. hot carriers
6. carbon nanotubes [3–7].

Other studies regarding PV technologies consider the engineering applications of PV systems. For example-

1. solar water heaters
2. solar air heater/dryers
3. solar desalination
4. solar home lighting
5. concentrated PV
6. Building Integrated Photovoltaic (BIPV).

However, a wide range of related studies can be found concerning the feasibility and Life Cycle Assessment of PV systems [8–14]. The main essence of all these research projects is to examine the factors that affect the performance of PV devices and consequently look for potential improvements. Moreover, many research works have been done to compare the performance of PV devices within different operating conditions [15–19]

One of the most essential and crucial factors is the impact of dust accumulation on the performance of PV panels, on which many studies have been published.

Starting from the year 1990 and until the end of the year 2016, 73 studies were found to be directly related to analyzing the impact of dust accumulation on the performance of PV panels. As a result, those studies have been classified into two categories. Those are-

1. review articles [20–30]
2. original research articles [1] which contain practical case studies.

Regarding the review articles, it has been found that each study has approached the corresponding research subject from a distinct viewpoint. Mani and Pillai, 2010 [20] achieved an appraisal on the status of research in that specific area. Mekhilef et al., 2012 [21] reviewed the technical parameters of PV modules that are mostly affected by the accumulation of dust. Darwish et al., 2013 [22] reviewed the effect of some environmental variables on the performance of PV modules. Sarver et al., 2013 [23] presented a comprehensive overview of soiling problems, primarily those associated with dust and combined dust–moisture conditions. Ghazi et al., 2014 [24] assessed the patterns of dust distribution and accumulation in distinct parts of the world. Kazem et al., 2014 [25] achieved a review of the geographical and meteorological characteristics in Iraq to clarify dust causes, types, specifications, and the corresponding impact on PV panels. Sayyah et al., 2014 [26] conducted a review that comprised some of the major studies reported on energy-yield losses in different PV plants in several regions of the world. Darwish et al., 2015 [27] presented a review concerning the effects of different types of pollutants on the performance of PV devices, taking into consideration indoor and outdoor experimentations. Costa et al., 2016 [28] presented a literature review update concerning the dust and soiling issues related to solar energy systems during the time period from 2012 to 2015. Maghami et al., 2016 [29] reviewed the factors that affect the optimum yield generation of PV panels, where the authors divided the shading into two types caused by dust and soiling: soft shading and hard shading. Zaihidee et al., 2016 [30] reviewed and summarized the impacts of dust on the efficiency of PV panels and the factors that affect the dust deposition on their surfaces.

For original research case studies, can be divided into two groups: [1]

1. **Electrical performance studies:** (Pulipaka and Kumar, 2018; Fountoukis et al., 2018) reviewed that the accumulation of dust on the surface of photovoltaic cells causes a significant degradation in the efficiency of electrical generating capacity. The rate of dust accumulation on the surface of the photovoltaic cell depends on several factors, including the concentration of airborne suspended particles, the tilt angle of the cell, the dust particles' size distribution in the air, and the weather conditions of humidity, wind speed and so on (Chesnutt et al., 2017).

   However, most of the studies surveyed covered electrical performance aspects and parameters, represented in measuring several parameters of dusty/polluted PV modules in comparison to clean PV modules,[1] such as

   a) the short circuit currents

   b) the maximum current

   c) the open circuit voltage

   d) the maximum voltage

   e) the output powers

   f) the energy output

   The other weather parameters are-

   a) solar radiation

   b) air humidity

   c) wind speed

   d) air temperature

   e) and PV panel surface temperature. [1]

2. Optical performance studies: Only a few studies were found regarding this aspect, where the optical transmittance of dusty/polluted PV panels were measured and presented according to the dust density on their surfaces [31]. Moreover, some of these studies demonstrated the transmittance results in correlation to other parameters, such as different tilt angles of PV modules [28], the number of days of exposure of PV panels to the outdoor dust/polluted environment [32], and the dust deposition density [33]. Numerical simulation and other theoretical analysis tools were rarely utilized [34].

In addition, not all of the studies were found to have measured the same exact parameters, instead, several variations were found to be demonstrated in the results. For example-

1. Some studies demonstrated the typical graphic results of the I-V characteristics of a PV panel
2. Other studies presented the electrical performance parameters in terms of a P-V curve [35,36**]**.
3. Other studies presented the electrical performance parameters in terms of a P-V curve [35,36].
4. Some studies were found to be interested in examining the composition of the accumulated dust on the accumulated dust on the corresponding PV panels, as well as the distribution and particle size of the corresponding PV panels.
5. In some studies, the investigation conducted for the distribution and particle size of the dust/pollutants, and their correlation to the solar irradiance, efficiency, and fill factor [37,38,39].

The surveyed studies exhibited the utilization of different testing equipment without referring to any calibration procedures that took place before the experiments. A large variety of testing equipment found in that sense, ranging from simple resistor circuits [40], I-V source meter devices [41], to even precise large-scale PV analyzers [42].

1.3 Aims and Objective

This investigates the change in performance on the basis of dust accumulation. The experiment shows the difference how much power clean module can provide and how much a dusty module can provide in different times in a day.

1.4 Scope of the Work

The focus of the study was to get the knowledge of power loss in PV modules due to dust. To make it easy, also an indoor experiment was taken. Indoor experiment was helpful because we controlled the temperature by using fan and also by switching the lights. IV graph was taken easily from the indoor experiment and it showed the condition of the both modules. So that easily we can compare the output of these two modules.

1.5 Thesis Organization:

The book is structured as follows. **Chapter 1** is about a general introduction followed by the background and the objectives of the thesis. **Chapter 2** provides the theoretical background of the study. **Chapter 3** describes the necessary experimental setup. The results and analyses have been discussed in **Chapter 4**. Finally, conclusion and future work suggestions are provided in **Chapter 5**.

Chapter 2: Theoretical background

2.1 Theory behind Solar Photovoltaic

The sun is one of the sources of renewable energy. And it is the main source of energy for solar photovoltaic. The photovoltaic cell is a semiconductor device that converts directly the sunlight into electric power. It is known that any element that converts sunlight into electricity is called Photo Voltaic device or PV device.

Generally, the term photovoltaic effect refers to the generation of a potential difference at the junction of two different materials in response to visible or other electromagnetic radiation. Thus, the broad study area of solar energy conversion into electrical energy is denoted as photovoltaic.

2.2 Solar energy

It is established that through an energy conversion mechanism, PV cells transform sunlight into electricity. Photons (light energy) fall on the cells of most PV cells, resulting in exciting electrons in the atoms of a semiconductors. The principal element of solar PV systems is silicon. The generation of electrical voltage and current results in the energizing of electrons. As PV systems are used cleanly and safely, PV systems have gained a great deal of attention today. By producing electricity in an efficient, clean and quiet way that can minimize future electricity costs and reduce reliance on grid power, me owners get an incentive for these systems. The lifespan of PV cells, however is very large. As we know for instance, that SA, the first PV system built in 1954, still works today. The output voltage, current and power of the PV device differ as the solar irradiation functions vary. Solar thermal collectors and a set of flow pipes linked to heating water or buildings are used to absorb heat. Solar thermal active systems are capturing solar radiation to the surrounding heat air. [42]

2.3 Parameter used:

Significant parameters related to the degradation of solar PV efficiency. For example, solar irradiation, electric current production, were calculated in the present study. The key instruments used in the analysis were a current sensor and a temperature sensor that were attached to a data logger.

2.4 Environmental impact & effect of dust on the performance of PV system:

Internal and external elements, such as structural characteristics, aging, radiation, shading, temperature, wind, pollution and cleanliness, significantly affect the efficiency of PV systems. Any type of climate change induces changes in solar radiation and ambient temperature, thereby causing changes in the efficiency of solar PV generation. [42]

Dust is plays important role for the solar PV panel performance. However, the tilt angle of the solar cell panels greatly influences the amount of dust collected on the surface of the panels. If the dust deposition mass increases, the module's power output, performance and effectiveness decreases. However, for this smaller size of dust the performance decreases. Those smaller dust particles block further radiation on the surface of the PV module.

Red dust, ash, sand, calcium carbonate, silica, etc. may be found in the various pollutant depositions. The presence of air pollution can significantly deteriorate the energy yield of PV panels; even after a short duration of the panels' outdoor exposure (e.g., 2 months) without cleaning, it may cause a decrement of 6.5 percent in energy pro duction approximately (Sarver et al. 2013) [43]. The deposition of dust on the top of the PV panel is very high in desert areas. The decrease in solar efficiency is around 40 percent due to dust on the PV panel. In this sense, different methods of cleaning are adopted for different PV system.

Recently (Kumar and Chaurasia 2014) [44] The analysis under this category of the environmental effects is the most frequent and problematic one as compared to others. Thus, this is faced on a regular basis throughout the year, unlike other conditions. Pollution basically, in respect to PV panel, is the accumulation of dust particles on the PV module surface.

Most recently (2014, Kumar and Chourasia) [44] the analysis under this category of environmental impacts is the most common and troublesome one compared to others the studies. Therefore, this is experienced on a daily basis during the year. In terms of PV panels, the accumulation of dust particles on the surface of the PV module can be noted as pollution. In accordance with the vicinity in which the panel was held, these particles may consist of sand, ash etc. (Adinoyi and Said 2013) [45]. in the experiment carried out under this group contains analysis of the decrease in solar irradiation due to dust accumulation of dust on the solar PV system is seen in the GBU hostel itself. The effect of deposited dust particles on PV modules was investigated experimentally by researchers (Rajput and Sudhakar 2013) [46] However, they provided a concept for electrical performance. The parameters such as radiation availability, successful operating strategies, design and sizing of these systems were the targeted factors of this analysis. It has been concluded that the efficiency of solar PV modules is significantly reduced by dust. A performance analysis on the environmental effects on PV modules was also carried out by the researchers (Darwish 2013) [47]. The study concluded that the average daily energy loss caused by dust accumulated on the surface of the PV module over a year is about 4.4 percent. Regular energy losses can be greater than 20 percent over long stretches without rain.

Depending on several environmental conditions, dust particles vary in phase, type, chemical and physical properties. In addition to wind speed, air, humidity and temperature play an important role in defining isolated dust and how it can settle in the PV cell. [42]

Figure 2. 1 Clean and Dusty Module

2.5 Temperature effect on solar module & Cleanness:

Sun is the main source of energy for solar cells. A solar cell works at daytime when solar light incidence on the PV module. The performance of a solar cell increases at the higher light intensity and vice versa.

The dust particles on a solar PV minimize the availability of transmission area. As a result, cells are unable to receive sufficiently incident photons [48]. Due to dust accumulation on solar cells, scientists face a significant challenge. Various studies have focused on this and shown that more than 50 percent of solar PV output decreases within a span of one month due to uncleaned panels [49][50].The previous study also indicates that in spring and summer, the effect of dust on PV output will be greater than in autumn and winter.[51] Google, the leading IT organization, examined the impact of dust on flat and tilted panels of a 1.6 MW solar project at its headquarters in California[52] After 15 months of installation, they concluded saying that flat panels are more likely to be affected than tilted panels [53] .So, it is a proven fact that cleanliness and temperature affect the performance of a solar PV module to a great extent. The clean and cool panel insures higher efficiency. So, it is necessary to keep the solar panel clean to get the highest performance.

Temperature is one of the important factors which controls the performance and efficiency of solar modules. Imperfect temperature reduces the solar module's efficiency. Jiang and Lu (2015) conducted an experimental analysis of dust deposition on the photovoltaic modules surface. The researchers stated that the energy output can be increased by 0.947–0.971 through increasing temperature gradient near the module surface [54]. However, in other research (Jiang and Lu 2015) the effect of thermophoresis under different temperatures has been investigated. It was found out that for the temperature below 40 °C, the deposition rate of solar module decreases [55]. Therefore, in Kaldellis and Kapsali (2011), the authors have mentioned additional important factors which have impact on the power output of the PV modules. They stated that-

1. The monthly reduction in the energy production of building integrated photovoltaic systems could be about 1-10 percent due to overheating
2. However, the reduction range is 1 to 5 percent for the non-optimal incidence angle.
3. Another factor that reduces energy production by 5 percent is ageing.
4. Lastly, reduction for snow and partial shading can be also crucial but it is dependent on the location [56][57]

2.6 Geographical impact for the accumulation of dust:

Different journals have stated the reduction of performance due to accumulation of dust on solar modules differently. In a journal it has been stated that in In Athens, the density of dust was 1 g/m^2 in 2 weeks, and the power output of the photovoltaic modules will be reduced by about 6.5% of the normal power outputs [58]. Indonesia, two weeks of dust accumulation had reduced photovoltaic power generation by 10.8%. [59]. Another journal stated that in Belgium, dust accumulation caused 3% to 4% of constant power loss after 5 weeks [60]. Likewise, In Saudi Arabia, after placing the photovoltaic modules at an angle of 26° for 45 days, the transmittance was reduced by 20% [61]. Tanesab et al conducted a study on the effect of dust on the performance of a PV module that has been exposed for almost two decades (18 years) without cleaning in Perth Australia, their results showing degradation of 8–12 %. [62]. Therefore, In Kathmandu, in 5-month time, the density of dust on photovoltaic modules was 9.6711 g/m^2 and the output power was reduced by 29.76% [62] [63], In many cases, it has been stated that soil & dirt are responsible for 15% monthly reduction in the output which is the highest value among all other parameters. So, the impact of dust accumulation is need to understand to reduce the impact of dust accumulation and enhance the performance of solar modules.

2.7 Seasonal change effect on dust accumulation:

An experiment done in the coastal zone of Antofagasta; northern Chile shows that the change of dust accumulation depends on seasonal changes. In this experiment amorphous/microcrystalline silicon tandem thin films and mono crystalline silicon solar cells were used. The global tilted solar irradiation reached mean values of 8.5 kW h/m^2 day in summer and 6 kW h/m^2 day in winter demonstrating the high radiation available there. In this paper researchers analyzed how the performance ratio is influenced by the dust accumulation and the ambient temperature associated to this place. The result they found out that the difference of energy yield between the technologies became larger for summer and smaller for winter. Therefore, that the performance ratio decreased due to the dust accumulation between −0.04%/day up to −0.13%/day for positive ambient temperature gradient, and between

−0.13%/day up to −0.18%/day for negative ambient temperature gradient. [62] However, other statistics can be including about rainfall. Deran Black, a 70-day experiment with no rainfall shows the density of dust was 6.0986 g/m, which causes the reduction of power output by 21.47%. [64]

Furthermore, in an experiment in Bangalore, India shows that the seasonal change also effects the efficiency of solar modules. In summer, the SPV modules attain maximum efficiency (η_{max}) at T_{mod} of 45 °C, but in winter, it is at 55 °C. In summer, for temperature T_{mod} > 45 °C, module efficiency (η) reduces by 0.08% per degree rise in temperature. In monsoon, for temperature T_{mod} > 35 °C, efficiency (η) reduces by 0.04% per degree rise in temperature. In post-monsoon period, for temperature T_{mod} > 38 °C, efficiency η reduces by 0.06% per degree rise temperature. However, in winters, the modules attain maximum efficiency η_{max} at temperature T_{mod} of 55 °C, without much drop-in efficiency. This is mainly because of intermittent natural cooling that takes places at the surface of the modules, due to cool breeze and lower ambient temperatures. [65]

2.8 Solar modules, cells and array:

A bulk silicon PV module consists of multiple individual solar cells connected, nearly always in series, to increase the power and voltage above that from a single solar cell. The voltage of a PV module is usually chosen to be compatible with a 12V battery [66]. A standard module has a series of 60 or 72 cells. In order to function, the 72-cell modules can be field-wired to act either as one 24 V module with all 72 cells in series or as 12 V modules with two parallel strings with 36 series cells each. Therefore, several modules can be wired in series to increase voltage and to increase current in parallel, to generate high power. Deciding how many modules should be connected in series and how many in parallel to deliver whatever energy is required is an essential element in PV device design. his type of module combinations is referred to as an array. [67]

2.9 Basic of a solar cell:

It is possible to consider the cell as the current generator. the reason behind this is solar cell is simply p-n junction which can directly converts the energy of light into electrical energy. This phenomenon occurs by photovoltaic effect to convert the light into electrical energy. The overwhelming majority of solar cells are fabricated from silicon with increasing efficiency and lowering cost as the materials range from non-crystalline to polycrystalline to crystalline silicon forms. The recombination and dark loss are represented by the diodes. There are series resistances due to junction resistance and metallic contacts in a practical solar cell. However, there is shunt loss on the surface of the junction. Finally, attention is given to the effect of temperature and solar irradiance. A behavioral model is therefore created to simulate a solar cell's performance under various operating conditions.

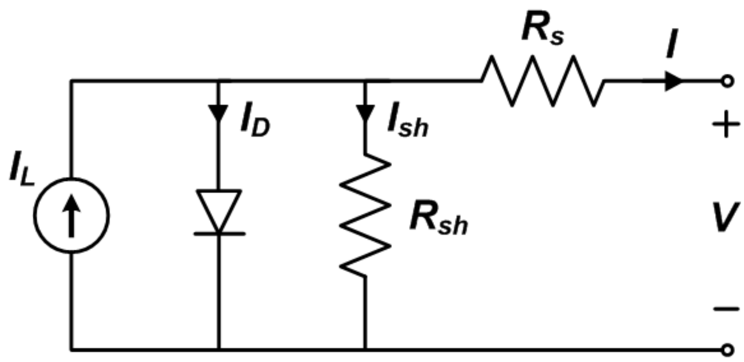

Figure 2. 2 Equivalent Electrical Circuit of a Practical Solar Cell

Under the light, solar cell produces a photocurrent which is fed to the load after the losses occur. The load voltage and load current can be calculated using the following formula:

Load Current,

$$I = I_L - I_D - I_{sh} \quad (1)$$

This equation is taken from a paper named “Effect of accumulated dust on the performance of solar PV module”.[68]

2.10 Solar Irradiance

The sun powered irradiance is the yield of light energy from the whole plate of the Sun, estimated at the Earth. The sun oriented phantom irradiance is a proportion of the splendor of the whole Sun at a frequency of light. It is also called short-wave radiation. Sun based radiation comes in numerous structures, for example, visible light, radio waves, heat (infrared), x-rays, and ultraviolet rays. Ordinarily, at the point of computing sun-based energy, it was picked to discover the measure of irradiance from the direct daylight that is seen by the PV boards and to do so Empirical method was used and for this some parameters were required like azimuth angle, solar altitude, latitude, declination angle and observer location. A brief portrayal pretty much every one of these highlights and their individual figures characterizing the equivalent are shown in this segment.[70]

2.11 Describing Different Angles and Equations:

2.11.1 Solar Altitude

Solar altitude alludes to the angle of the sun which is relative to the Earth's horizon. It is measured in degrees. Solar altitude value varies based on the time of day, the month, the year and the latitude on Earth. Solar altitude (α) is shown in figure below,

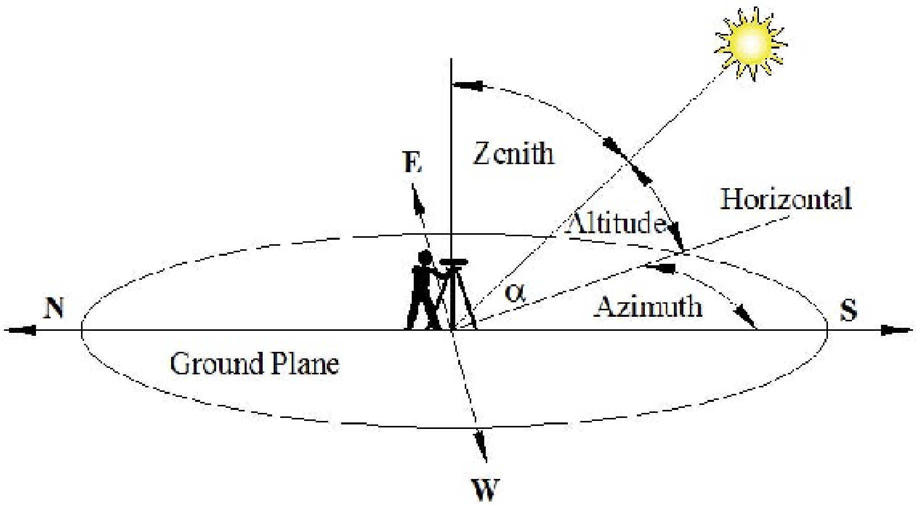

Figure 2. 3 Solar altitude(α)

Solar Altitude Equation: $\alpha = \sin^{-1}(\sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega)$

2.11.2 Zenith Angle

Zenith angle is the angle between the Zenith and the center of the sun's disc. The solar elevation angle is the altitude of the Sun, the angle between the center of the Sun's disc and the horizon. As these two angles are integral of each other, the cosine of either one of them equals the sine of the other. Zenith Angle is shown in Figure 2.3 where, is known as Zenith Angle.

The equation of Zenith angle is given below,

$$\theta = 90^o - \alpha$$

2.11.3 Declination Angle

The declination angle (δ), varies seasonally due to the rotation of the Earth around the sun and tilt of the Earth on its axis of rotation. The Earth is tilted by 23.45° and the declination angle varies plus or minus of this amount. Only at the spring and fall equinoxes is the declination angle becomes 0°.

The Equation of declination angle is given below,

$$\delta = 23.45°\sin\left[\frac{360(n-80)}{365}\right]$$

2.11.4 Latitude Angle

Latitude is a geographic coordinate that specifies the north–south position of a point on the Earth's surface. Latitude is an angle (defined below) which ranges from 0° at the Equator to 90° (North or South) at the poles.

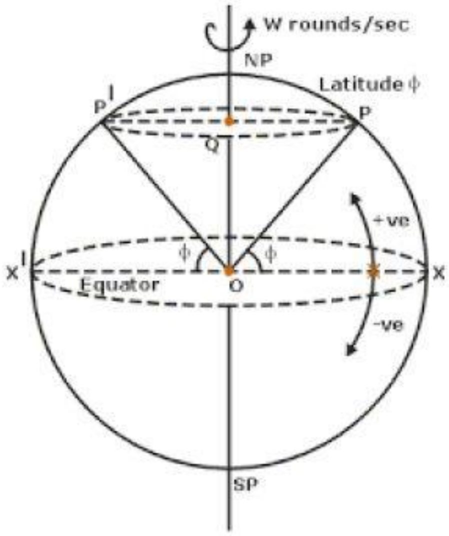

Figure 2. 4 Latitude angle

2.11.5 Sunrise Angle

Sunrise angle can be considered as the angle when the sun is positioned exactly on the horizon at dawn. Generally, sunrise angle (ω_S) is calculated in degrees.

The equation is given below,

$$\omega_s = \cos^{-1}(-\tan\delta * \tan\phi)$$

2.11.6 Hour Angle

The solar hour angle is an expression of time, expressed in angular measurement, usually degrees, from solar noon. At noon the hour angle is 0 degree. The time before solar noon is represented as negative degrees, and the local time after solar noon represented as positive degrees.

The Equation expressing hour angle is given below,

$$\omega = -\omega_s + \left(\left(2 * \frac{\omega_s}{t}\right) * (T - S_r)\right)$$

Here, T is particular time of a day.t is total day hour available is sun rise time of the day.

2.11.7 Sunrise and Sunset Time

We need to calculate the sun rise and sun set time of a particular day in order to find out total hours of sunlight available on that particular day. we got the value of total day hour, *t* of a day by subtracting sunrise time from sunset. The equation is given below,

We also got Sunset time similarly.

Sunrise equation:

$$S_r = 12 - \left(\frac{1}{15}\right) * \left(\cos^{-1}(-\tan\delta * \tan\phi)\right)$$

Sunset equation:

$$S_r = 12 + \left(\frac{1}{15}\right) * \left(\cos^{-1}(-\tan\delta * \tan\phi)\right)$$

Finally, by subtracting these two values we found the value of total day hours available.

$$t = S_s - S_r$$

2.11.8 Solar Irradiance

Solar irradiance was calculated by the equation given below.

$$I = I_0 * cos\delta * cos\theta$$

In this experiment, both modules were fixed. Since both modules were fixed, declination angle δ will vary depending on season and zenith angle θ will vary depending on time. The value of I_0 is 1367W/m^2 which is solar irradiance in space.

2.11.9 Cumulative Incident Energy

Cumulative Incident energy which is considered as total of all intensity values calculated over a given time period. It can easily calculate total energy generation for certain time period such as for a day, for a month or even for a year. Considering a particular day was calculated using numerical integration of Intensity for a given time period like total number of hours available from dawn to dusk. In terms of months all days were summed like sunny day, rainy day, cloudy day to get monthly incident energy.

$$E = \int_{Sunrise}^{Sunset} I * dt$$

Chapter 3: Experimental Setup and Methodology

Experimental setup is a must in order to perform the experiment in both indoor and outdoor condition. Firstly, both clean and dusty modules which were used for our experiment were cleaned and put in a black box. It was done to make both the modules reach its idle condition and so that both modules give us same short circuit current result. Indoor experiment was performed to get the exact knowledge of the PV module's IV characteristics. This process was not possible in outdoor condition as there are many parameters such as temperature, irradiation, rain etc. For performing the indoor experiment, a big black wooden box was made for different illumination with 8 incandescent light bulbs. By using this method light and temperature can be controlled. For measuring the outdoor data like short circuit current and modules temperature a data logger device was made which can measure current, temperature and store them in real time. After that all the data of different days were shorted for using different purposes. Finally, from the shorted data different calculation and graphical representation were performed. The whole indoor and outdoor experimental process and its setup is written in this chapter.

3.1 Setup for IV characteristics of PV module

For getting the IV characteristics of PV module a big black wooden box was made for different illumination with 8 incandescent light bulbs of 200 watts shown in Figure 3.1 and Figure 3.2. By controlling the bulb light on the module surface were controlled. Besides a temperature sensor was used for noticing and controlling the temperature of the module. A rheostat was used to vary the load of the modules. Data of IV was taken from both of the modules when the temperature range was between (21- 27) ℃. Temperature was controlled by using a high-speed fan. Figure 3.3 shows the schematic part of the indoor setup where an ammeter was connected in series and voltmeter was connected in parallel with the module.

Figure 3. 1 Indoor Experimental Setup

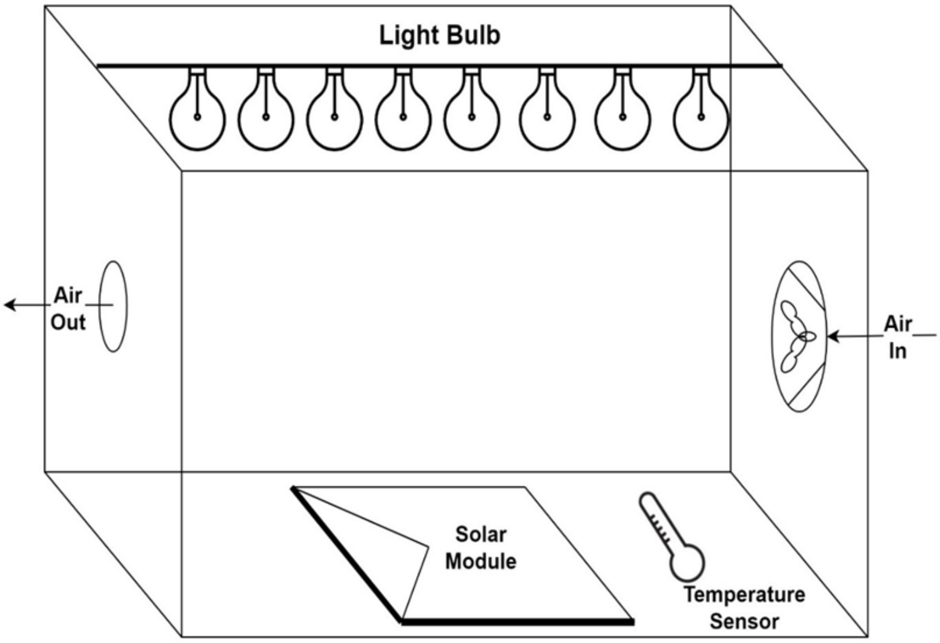

Figure 3. 2 Indoor Experimental Setup Schematic Diagram

For measuring the short circuit current Switch S2 was closed. Next, for measuring the open circuit voltage both Switch S1 and S2 were kept open. Meanwhile load was gradually increased using 100Ω rheostat to get the complete IV characteristics of the modules which is shown in Figure 3.4. Temperature was kept under control (almost25°C) with the help of a fan for getting standard temperature condition. For the measurement purpose temperature was increased to our expected level in the closed black box. When it went above our desire level, we turned on a fan shown in figure 3.2 to control the solar modules surface temperature.

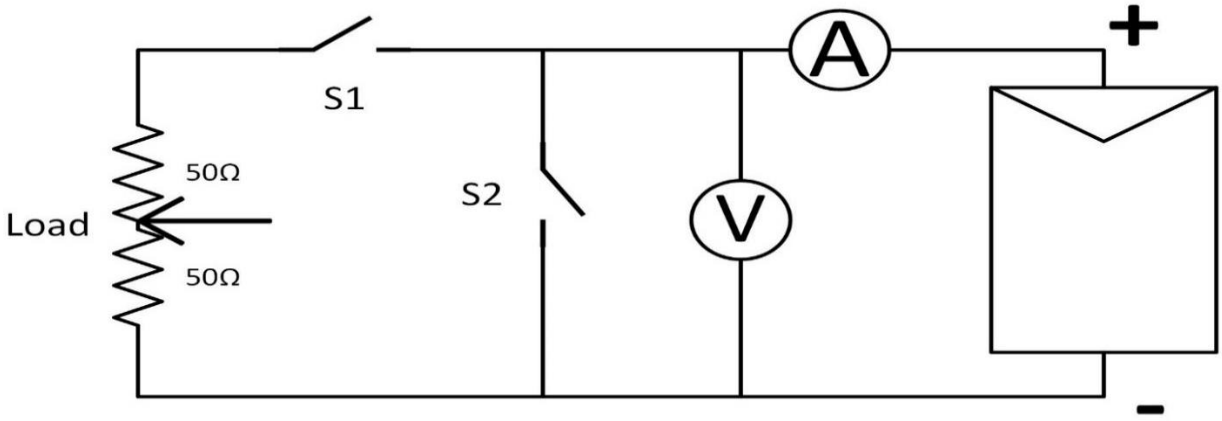

Figure 3. 3 Schematic circuit diagram of experimental setup for I-V measurement of PV module

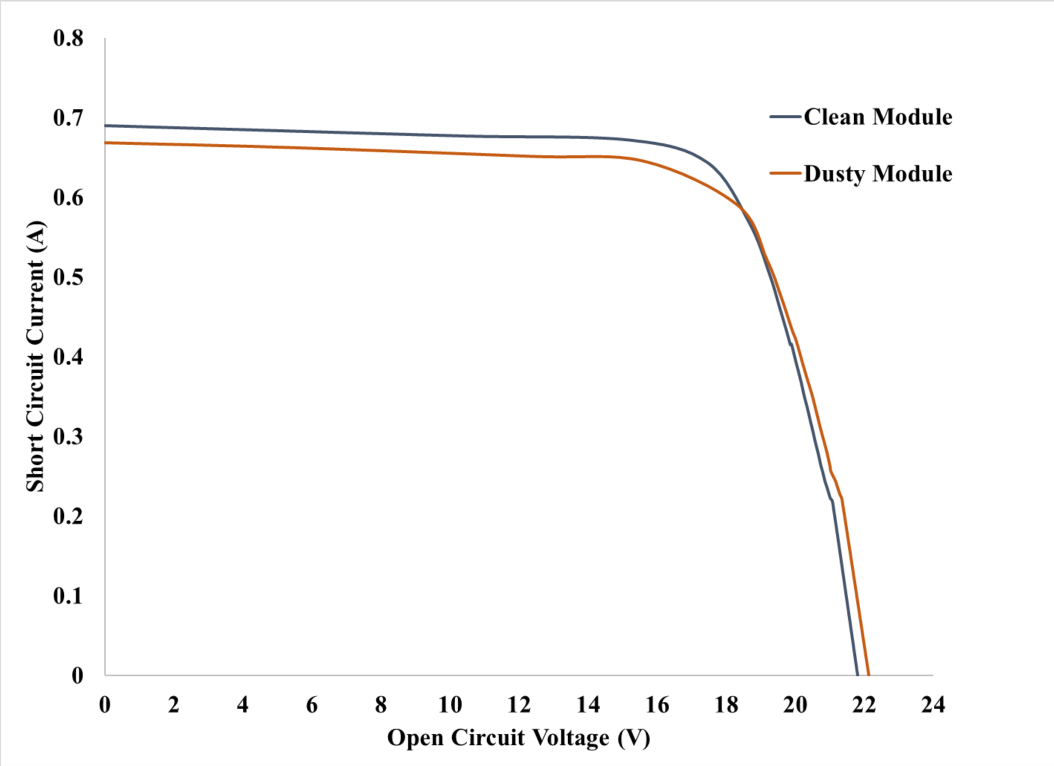

Figure 3. 4 IV characteristics of clean and dusty modules in indoor condition

3.2 Short Circuit current and Temperature data collecting device

To notice the effect of dust current and temperature data was used. For measuring the short circuit current and temperature of clean and dusty module an Arduino based device was made which can store the data with real time. The data logger device is made with an Arduino UNO, Temperature sensor DS18B20, real time clock module RTC DS321, current sensor INA219 & a SD card module for storing the data. In Figure 3.5 a picture is shown of this data logger device with proper connections. Two devices are used for two modules and connected through wires. A programmable code was implemented in Arduino which commands the full device. RTC module helps to get data in real time basis. A micro-SD card was inserted in SD card module to store the data of current, and temperature data. The data was taken with interval of 1 second.

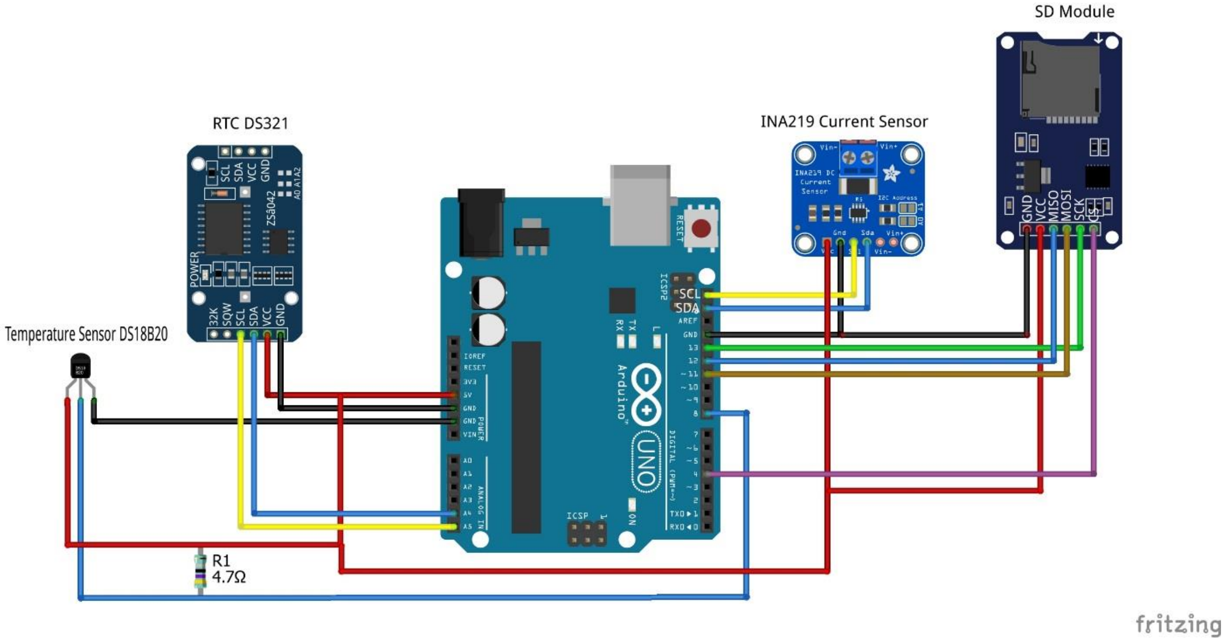

Figure 3. 5 Real time data logger setup

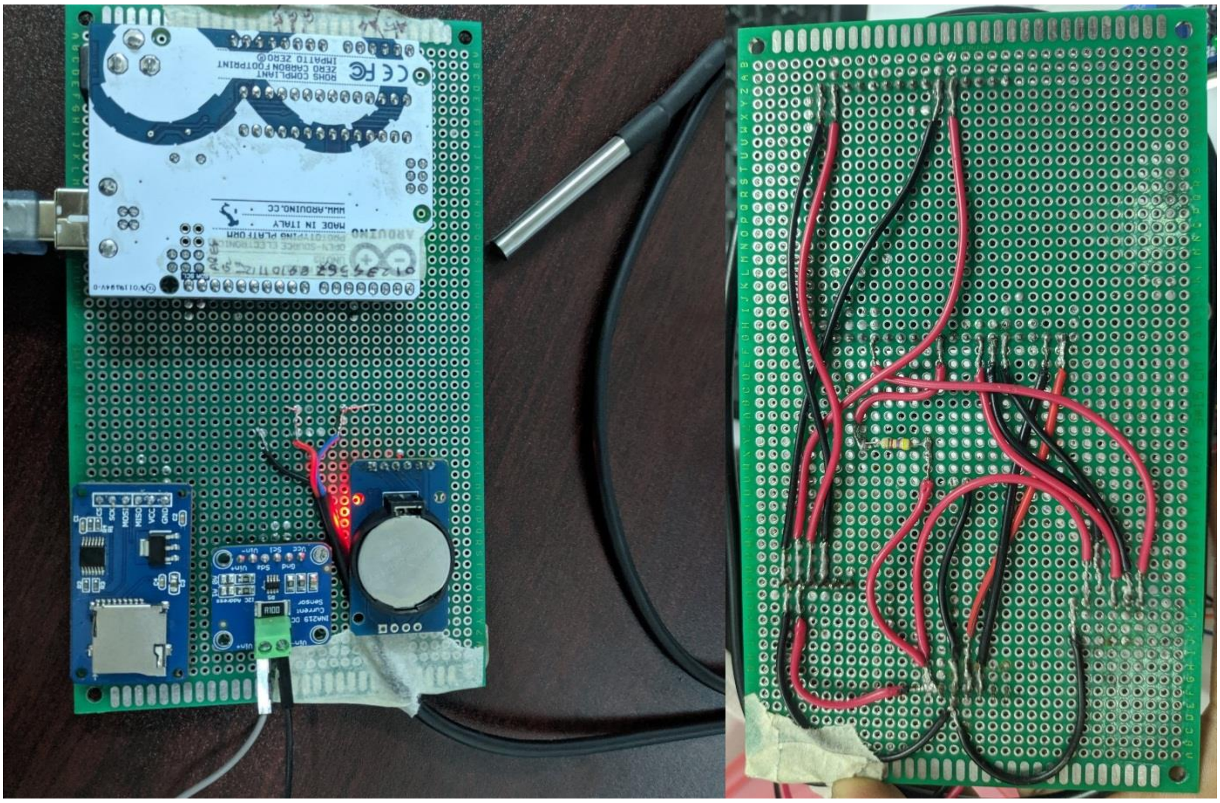

Figure 3. 6 Real time data logger setups

3.2.1 DS18B20 Temperature Sensor

DS18B20 is a programmable temperature sensor. It is generally used to measure temperature. The version used in this project has waterproof features. It can measure from -55°C to 125°C without damaging itself but up to 100°C is recommended. There is no signal loss as it provides digital signal. The sensor can provide temperature information with accuracy of ±0.5°C in the range of -10°C to +85°C. The sensor requires 3V to 5V as input. So, power can be drawn from microcontroller. The sensor has three pins which are GND (Ground), DQ (Data In/Out), V_{DD} (Power Supply Voltage). The DS18B20 Digital Thermometer provides 9 to 12-bit (configurable) temperature readings which indicate the temperature of the device. Temperature data is sent to Arduino from the DS18B20 over a 1-Wire interface, so that only one wire (and ground) needs to be connected from a central microprocessor to a DS18B20. Power for reading, writing and performing temperature conversions can be derived from the data line itself. A pullup resistor(4.7KΩ) between data pin and V_{DD} is needed while connecting the sensor to the microcontroller.

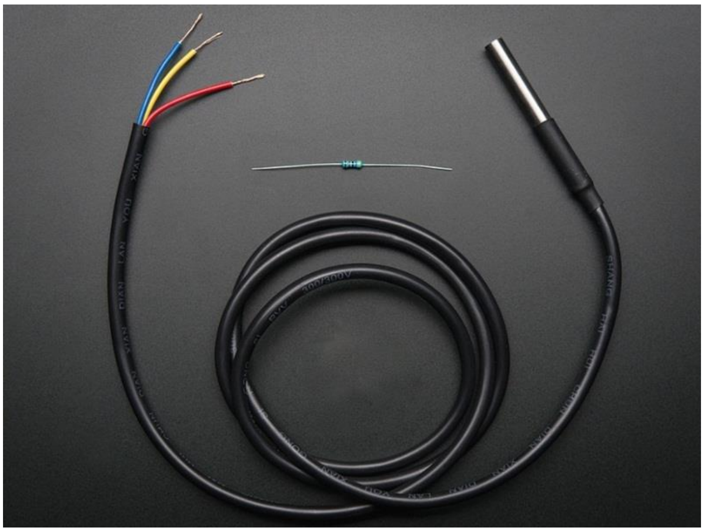

Figure 3. 7 DS18B20 waterproof temperature sensor

3.2.2 DS3231 Real Time Clock

A separate RTC module was used for Arduino Project when the Arduino itself has built-in timekeeper. External clock module was used in the device because Arduino clock reset after disconnect the power source. In DS3231 module a built-in battery is used and so that if power of the device is disconnected RTC module can keep the track of real time with the help of its battery. The DS3231 is a low-cost, highly accurate Real Time Clock which can maintain hours, minutes and seconds, as well as, day, month and year information. Also, it has automatic compensation for leap-years and for months with fewer than 31 days. It needs 4 wires, the VCC and the GND pins for powering the module, and the two I2C communication pins, SDA and SCL. [69]

3.2.3 INA219 Current Sensor

The INA219 is a high-side current shunt and power monitor with an I_2C interface. The INA219 monitors both shunt drop and supply voltage with programmable conversion times and filtering. A programmable calibration value, combined with an internal multiplier, enables direct readouts in amperes. An additional multiplying register calculated power in Watts. The I_2C interface features 16 programmable addresses. The INA219 senses across shunts on buses that can vary from 0V to 26V. The device uses a single +3V to +5.5V supply, drawing a maximum of 1 mA of supply current. The module can measure up to ±3.2A current with ±1% precision and the resolution is ±0.8mA. It uses 0.1ohm 2W shunt resistor to measure current. The INA219 operates from -40°C to +125°C. It has 6 pins where V_{CC} and GND pins are connected to (3V to 5V) source to power the module itself and I_2C pins (SCL & SDA) is connected to microcontroller I_2C pins and Vin+ and Vin- is used to measure the source voltage, supplied current. To measure the source voltage a load is need to connect in the source. Since the device is made for measuring short circuit current, no load is used in this case and because of that the device cannot measure the source voltage.

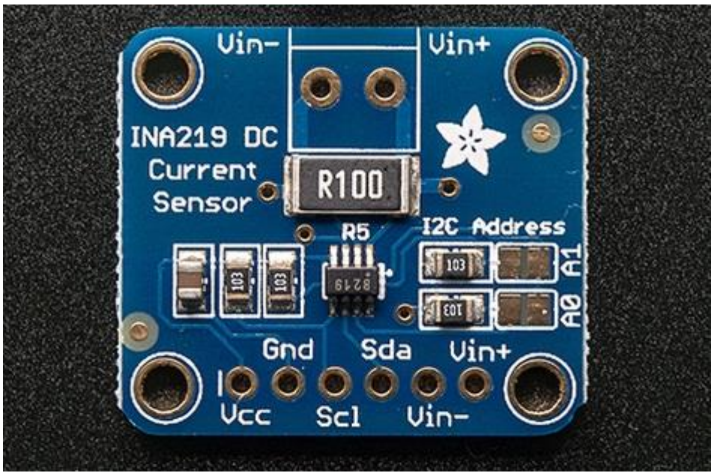

Figure 3. 8 INA219 Current Sensor

3.2.4 SD Card Module

SD and micro-SD cards are one of the most practical ones among the storage devices, which are used in devices such as mobile phones, minicomputers and etc. The SD and micro-SD card modules allows to communicate with the memory card and write or read the information on them. The module interfaces in the SPI protocol and uses 3.3V to 5V. To use these modules with Arduino it needs the SD library. This library is installed on the Arduino application by default. After the installation and coding, all the data from Arduino stores in SD card automatically. In this project, the code is modified in this way so that it stores the short circuit and temperature data by this sequence: Name of the day, date, time, temperature, current, count number and save them in a (.txt) file.

3.3 Outdoor Experiment

The experiment is done in the rooftop of building 4, BRAC University. The building is about 15th storied and we chose this height so that the shadow cannot make impact in the PV module. In Figure 3.9 and Figure 3.10 the full setup is shown. PV modules are fixed with a 23.77º tilt angle. One module was cleaned in every two days and other one remained dusty. Two data logger devices were connected with the modules. The devices were getting power supply from the university from 7 am to 6 pm every day. In this time two solar module's given data of current, temperature was storing in the SD card by the data logger device.

Figure 3. 9 Experimental Setup on the top of Building 4, BRAC University (Top View)

Figure 3. 10 Experimental Setup on the top of Building 4, BRAC University (Side View)

In Figure 3.11 the block diagram of whole setup is shown. The data was saved in real time in the SD card which were used to measure the performance of the modules.

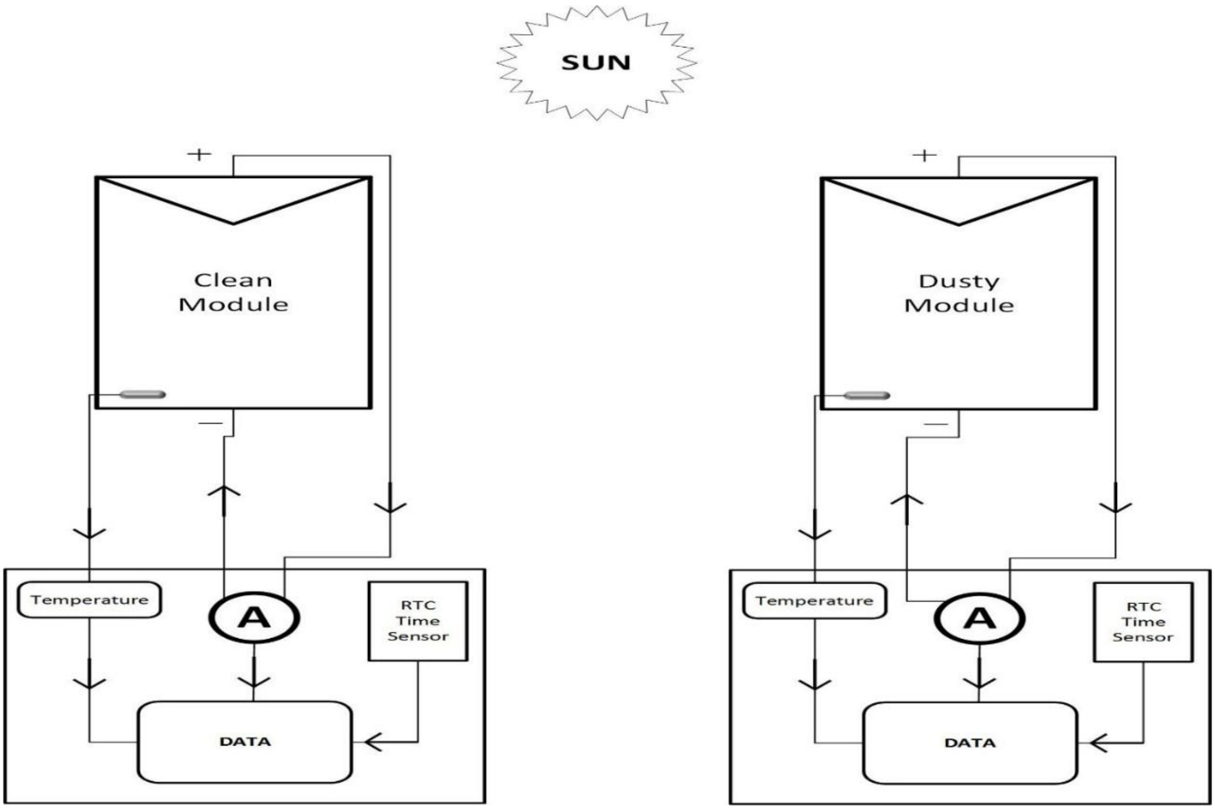

Figure 3. 11 Block diagrams of outdoor full setup

3.4 Data Sorting Method:

Data Sorting means the process of arranging collected data into a meaningful sequence so that it is easier to analyze the data. Sorting the collected data in excel from data logger was the main part. Building's electricity remains turned on from 7 am to 6 pm. During this time data logger continuously takes data from the solar module in every second. The raw data stored in SD card serially as date, time, temperature, current, bus voltage. In average data logger stores about 20000 to 30000 data each day. For this huge amount of data, comparison between the dusty and clean module becomes very complicated. So, a method was used in excel named interpolation to sort this huge amount of data. Basically, interpolation is used when a significant number of data is missed and to cover up those data a limited time period was chosen to get the average data. However, there was no missing data but due to this huge amount of data and to save the time instead of using every second's data it sorts every minute's data. For graphical representation the data of time is taken in X axis and other data (current/temperature) is taken in Y axis. Here a formula was selected in excel named Bessel spline formula. After that, various kind of graphs for each day is shown using excel in the result analysis chapter.

Chapter 4: Result & Analysis

In this chapter, indoor and outdoor test result and their condition resulted from the experiment has been discussed. Collection of data has been incorporated from February 2020 to March 2020 for short circuit current and temperature of clean and dusty modules. Most of the day's data are taken from 7 AM to 7 PM. Data was taken with a 1-minute interval. Figures containing the IV characteristics of both modules (clean and dusty) from the indoor test has been shown and in outdoor short circuit current and temperature results of some combination of sunny, cloudy, and rainy days has been shown.

4.1 Indoor Test Result

Figure 4.1.1 shows the IV characteristics of Clean and Dusty modules which has been used in our experiment. This test was done in a controlled chamber where temperature was almost fixed at 22-25°C and light was provided by 8 filament bulb rating 100W each and total of 800W. This experiment was done in indoor condition. Then the data was taken while load was gradually increased. From the tested result it was found that both results are pretty similar. From this indoor IV test it was found that the power of 137.523W from clean module and 136.399W from Dusty module. Figure 4.1.2 shows the comparative PV curve of both modules. The MPP was recorded from the test were 11.240648W for clean module and 10.979214W for dusty module. With the increase of load the open circuit voltage varies from (0-21.8) V for clean module and (0-22.13) V for dusty module and short circuit current varies from (.69-0) A for clean module and (0.668-0) A for dusty module. Voltage (V_M) at maximum power point for clean module was 17.3V and current (I_M) was 0.6497A and for dusty module V_M was 17.7V and I_M was 0.62029A.

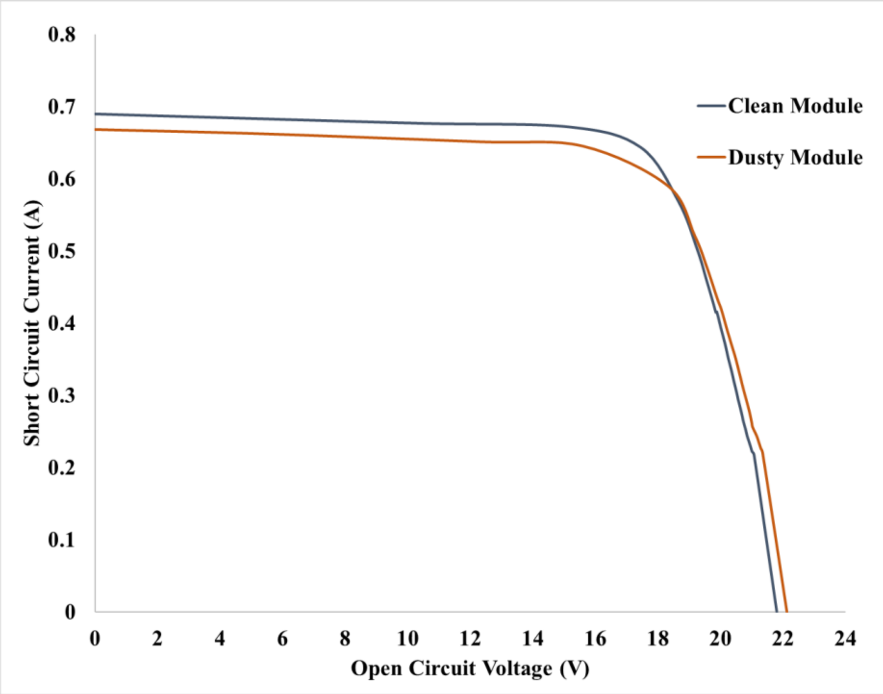

Figure 4.1.1 IV Characteristics of Clean & Dusty Module

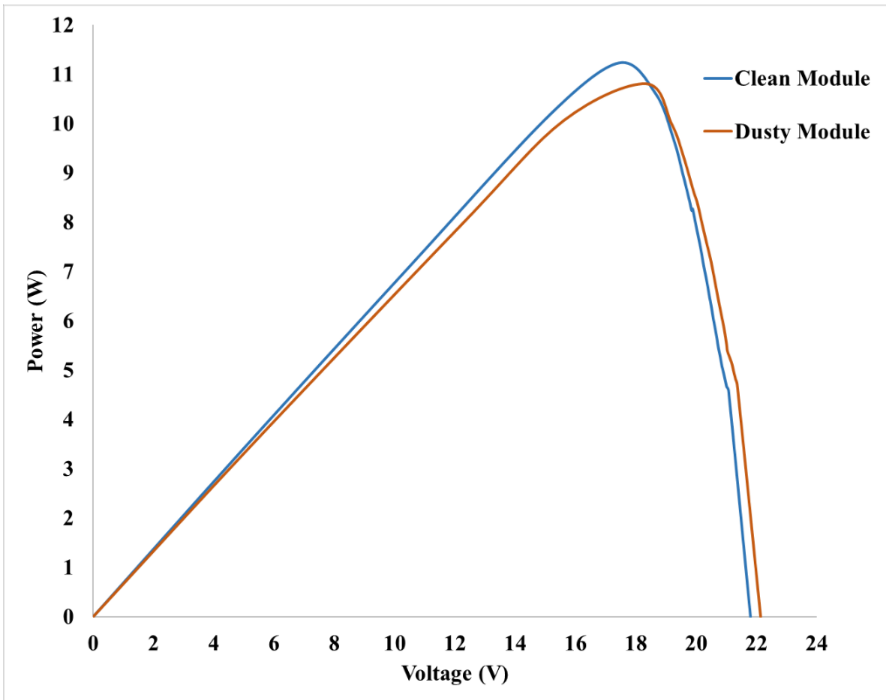

Figure 4.1.2 PV curve of Clean and Dusty Module in Indoor condition

4.2 Short Circuit current and module Temperature of different days

Figure 4.2.1 shows the short circuit current and temperature of clean and dusty module of 27th February,2020 which was a cloudy day. Because of clouds, the modules could not get proper sunlight in that day and that's why the curves have more ups and downs. Unlike sunny day, the output short circuit current of both the modules was very less and were less than 500mA till 09:00AM. After that the current started to increase gradually at about 10:30 Short circuit current (SC) was about 875mA after that SC decreased due to clouds. The maximum current was recorded at 12:16PM for clean module 957.2mA and for dusty module 918.7mA. Overall current difference between clean and dusty modules were 4.67% where clean module had the higher short circuit current than dusty module.

From the temperature curve it was seen that before 10AM both module's temperature was increasing and reached up to 35°C and then decreased drastically later. Maximum temperature was recorded for clean module was 37.44°C and 38.69°C for dusty module. Overall temperature of dusty module was 3.51% higher than clean module.

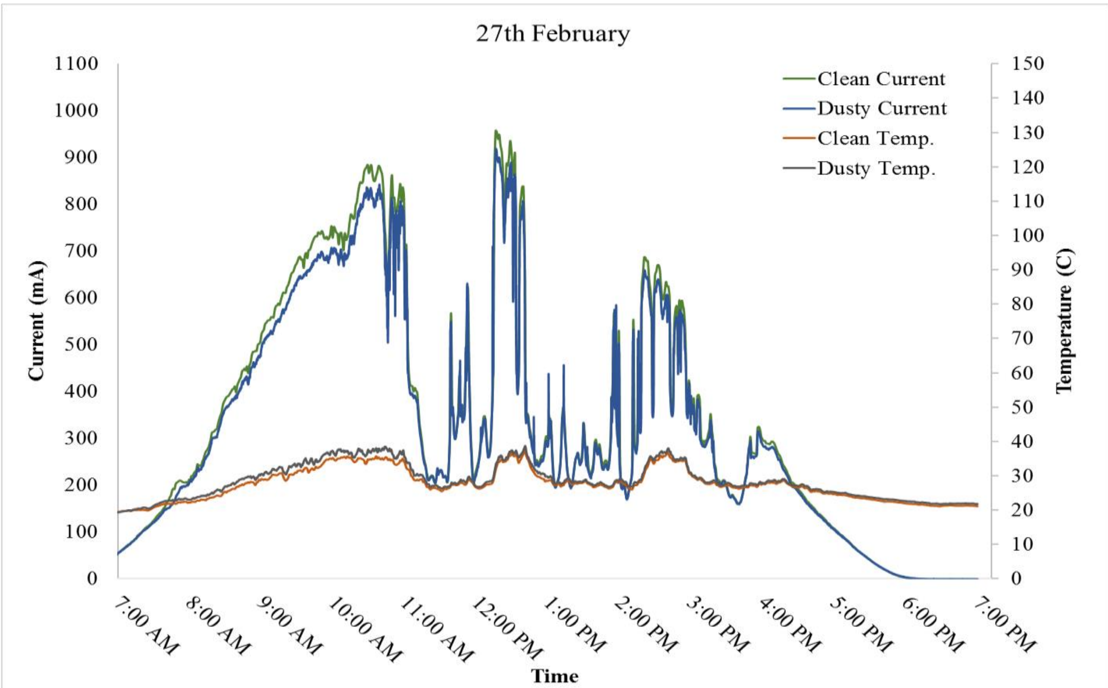

Figure 4.2.1 Graph of Short Circuit Current and Temperature of modules

Figure 4.2.2 shows the short circuit current and temperature graph of both clean and dusty modules of 28th February, 2020. It was a sunny day and short circuit current increased gradually over time. From 10:00AM to 3PM the current reading was recorded above 700mA and maximum current at 12:02 PM resulted 1341.3mA from clean module and 1245.7mA from dusty module. Maximum temperature was recorded at 02:32PM to be 43.63°C from clean module and 46.06°C from dusty module. The overall short circuit current of clean module was higher than dusty module by 7.40% and the temperature of dusty module was higher than clean module by 3.58%. Reason of getting higher temperature from dusty module was dusty surface absorbed more heat than clean surface. Clean surface reflects the heat better than dusty surface but absorbs more light from the sun.

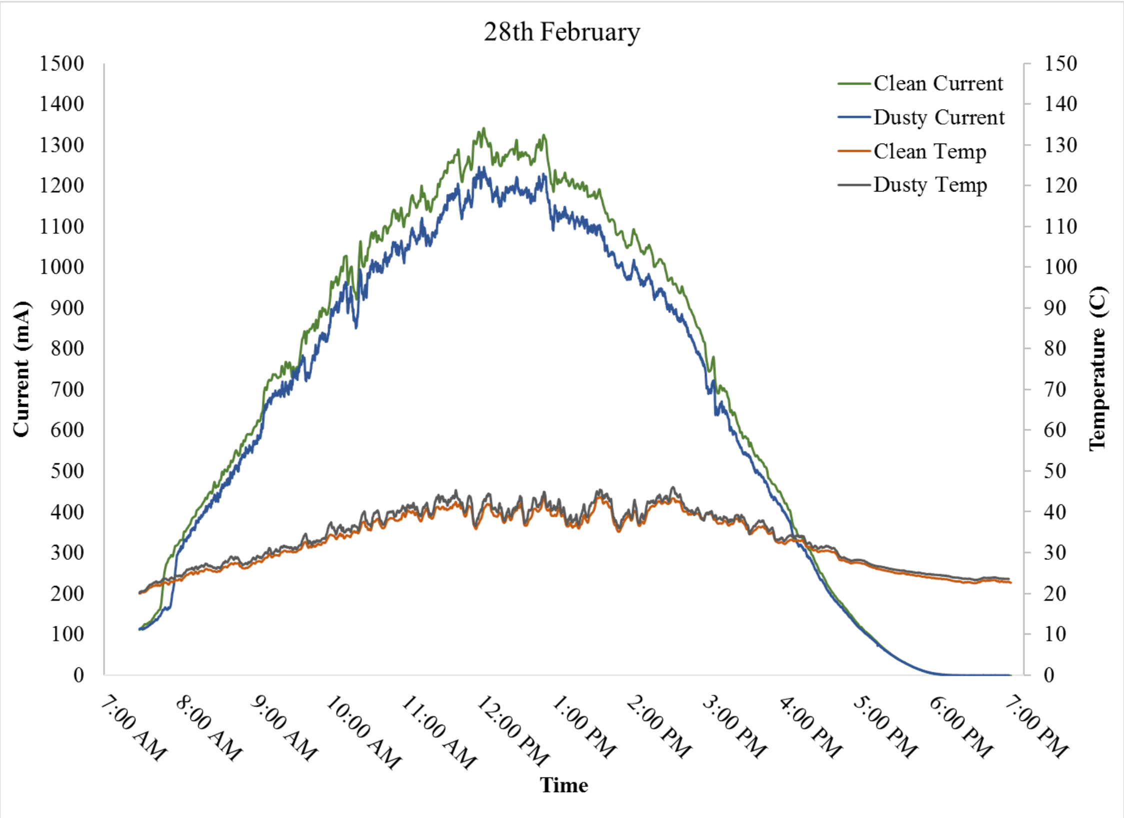

Figure 4.2.2 Graph of Short Circuit current and Temperature of modules

Figure 4.2.3 shows the short circuit current and temperature graph of both clean and dusty modules of 29th February, 2020. It was a sunny day and short circuit current increased gradually over time. From 10:00AM to 2PM the current reading was recorded above 850mA and maximum current at 12:28 PM resulted 1275.1mA from clean module and maximum current 1183.9mA at 12:29 PM and from dusty module. Maximum temperature was recorded at 12:28PM to be 47.56°C from clean module and maximum temperature was recorded at 12:31PM to be 48.69 °C from dusty module. The overall short circuit current of clean module was higher than dusty module by 7.66% and the temperature of dusty module was higher than clean module by 2.44%. Reason of getting higher temperature from dusty module was dusty surface absorbed more heat than clean surface. Clean surface reflects the heat better than dusty surface but absorbs more light from the sun.

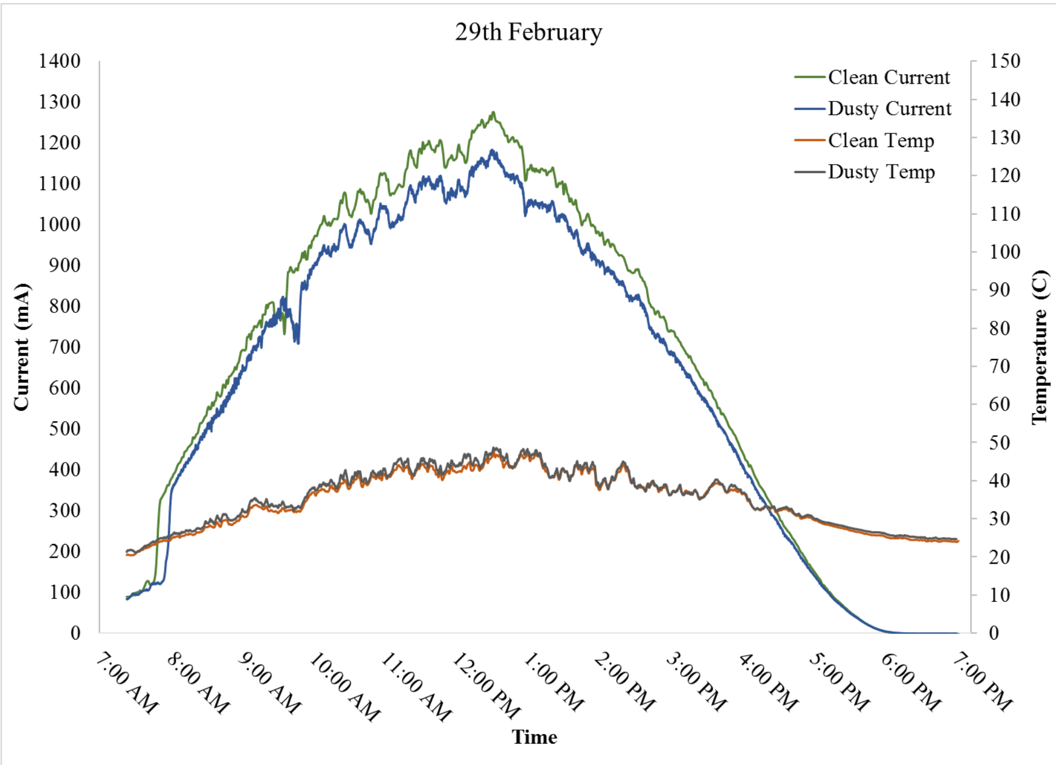

Figure 4.2.3 Graph of Short Circuit current and Temperature of modules

Figure 4.2.4 shows the short circuit current and temperature graph of both clean and dusty modules of 1st March 2020. It was a sunny day and short circuit current increased gradually over time. From 10:00AM to 3PM the current reading was recorded above 700mA and maximum current at 12:06 PM resulted 1080.08mA from clean module and 1004.42 mA from dusty module. Maximum temperature was recorded at 11:00PM to be 44.71°C from clean module and 47.0°C from dusty module. The overall short circuit current of clean module was higher than dusty module by 7.40% and the temperature of dusty module was higher than clean module by 2.43%. Reason of getting higher temperature from dusty module was dusty surface absorbed more heat than clean surface. Clean surface reflects the heat better than dusty surface but absorbs more light from the sun.

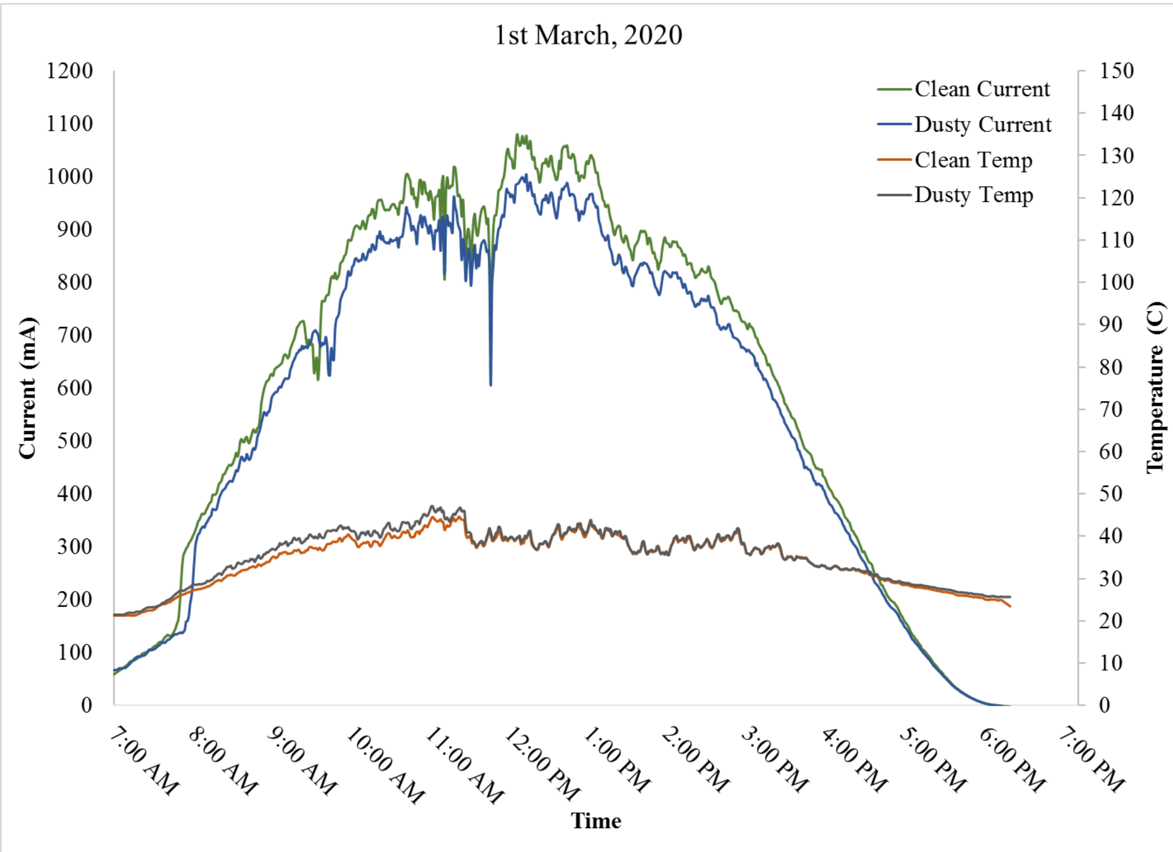

Figure 4.2.4 Graph of Short Circuit current and Temperature of modules

Figure 4.2.5 shows the short circuit current and temperature graph of both clean and dusty modules of 2nd February 2020. It was also a sunny day and there were very few scattered clouds. After 9AM short circuit current crossed 500mA and remained above that till 3PM. Dusty module's short circuit current followed clean module's current by maintaining little difference. The maximum short circuit current recorded at 11:50AM and it was 1100.03mA for clean module and 981.6mA for dusty module. Short circuit current difference increased drastically between the modules after 9:30AM and it maintained till 2:30PM. The overall short circuit current of clean module was higher than dusty module by 11.85%. From the temperature curve we have noticed that the surface temperature of dusty module was higher than clean module. Temperature also increased gradually with time and the maximum temperature was recorded at 11:14AM which was 41.9°C for clean module and 43.25°C for dusty module. Overall temperature of dusty module was 1.97% higher than clean module.

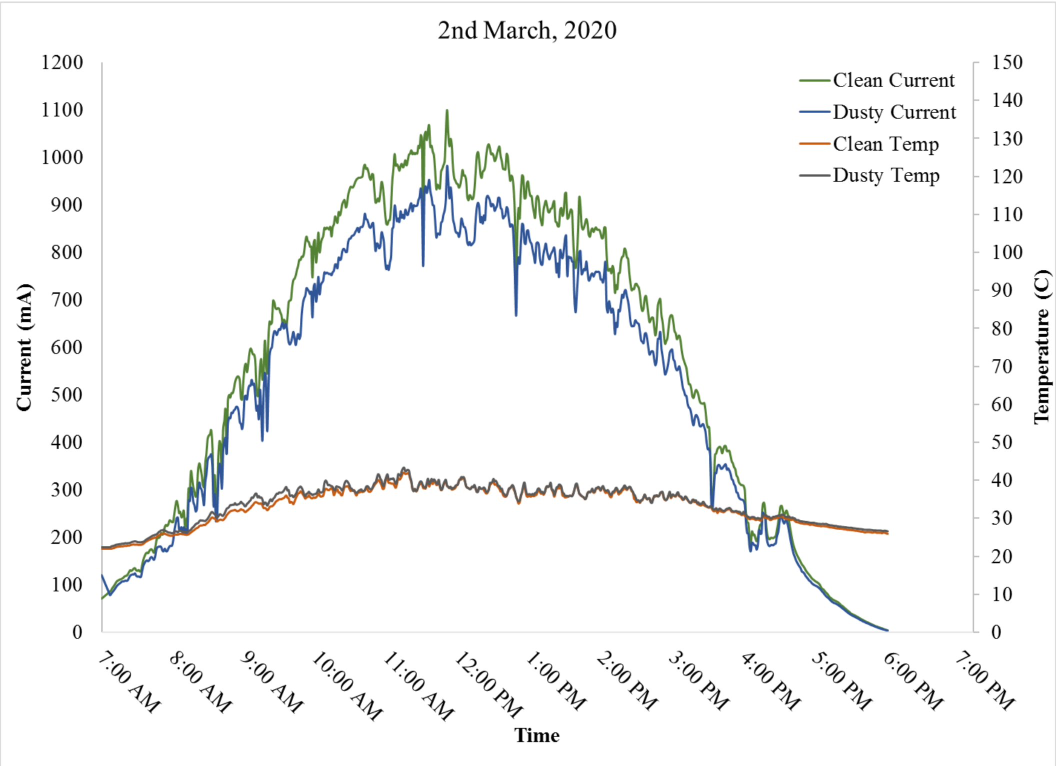

Figure 4.2.5 Graph of Short Circuit current and Temperature of modules

Figure: 4.2.6 shows the short circuit current and temperature of clean and dusty module of 3rd March2020 which was a cloudy day. Because of clouds, the modules could not get proper sunlight in that day and that's why the curves have more ups and downs. Unlike sunny day, the output short circuit current of both the modules was very less and were less than 400mA till 10:00AM. After that the current jump to almost 1175mA due to the absence of clouds and getting direct light from the sun. The maximum current was recorded at 12.43PM for clean module 1406.54mA and for dusty module 1285.41mA. From 10:30AM to 3:00PM both modules maintained almost 60-70mA current difference. Overall current difference between clean and dusty modules were 7.74% whereas clean module had the higher short circuit current than dusty module.

Form the temperature curve it was seen that before 10AM both module's temperature was less than 30°C and then increased drastically to almost 40°C due to the absence of clouds. Maximum temperature was recorded for clean module was 44.27°C and 45.26°C for dusty module. Overall temperature of dusty module was 1.84% higher than clean module.

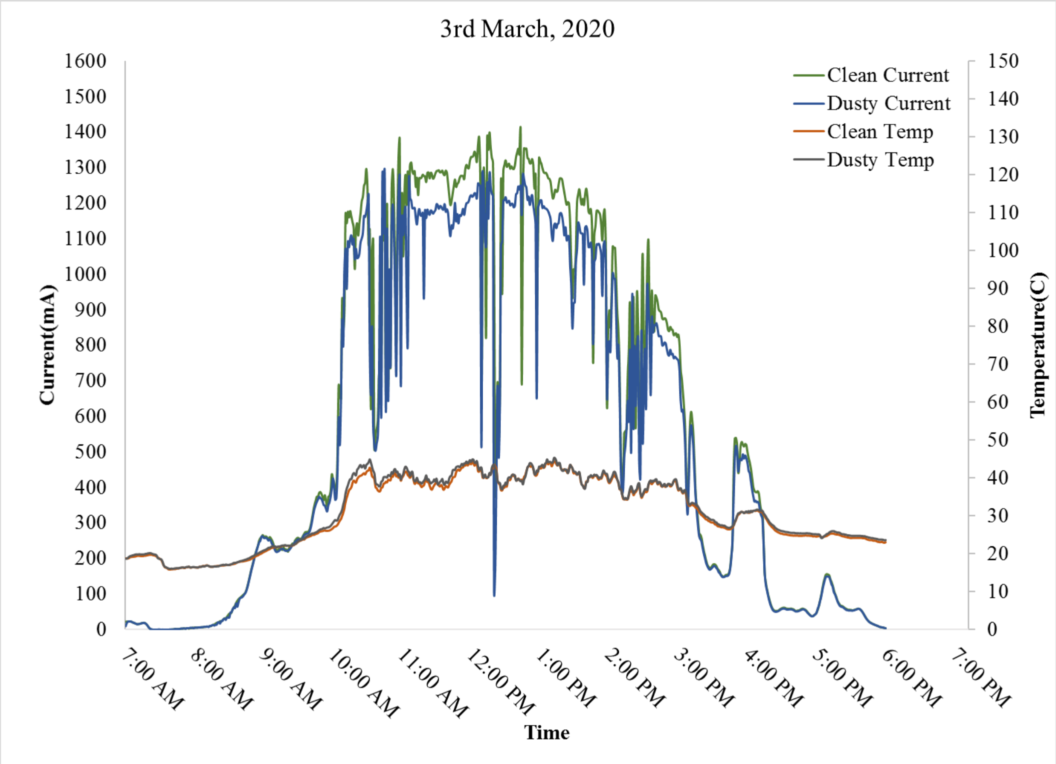

Figure 4.2.6 Graph of Short Circuit current and Temperature of modules

From Figure: 4.2.7 performance of clean and dusty solar module was observed. The figure shows the short circuit current and temperature of both modules of 8th March2020. It was also a cloudy day with partly sunny weather. In that day, because of clouds from both modules did not give any short circuit till 11:30AM after that it was getting noticeable amount of current with interval. The short circuit current difference for both modules were much less than other days because the dusty module got washed by rain and was giving almost same reading compare to the clean module. The maximum short circuit current recorded at 12:19PM for clean module was 1329.47mA and 1243.52mA for dusty module. Overall current of clean module was 5.42% higher than dusty module.

Like current graph temperature curve also have huge ups and downs. Temperature was lower than normal days as expected because of cloudiness weather. Maximum temperature for clean module was recorded 44.87°C and for dusty module was 45.82°C. Overall temperature of dusty module was 1.68% higher than clean module. From the data it is also noticeable that the overall temperature if significantly less because of the clearness of both modules.

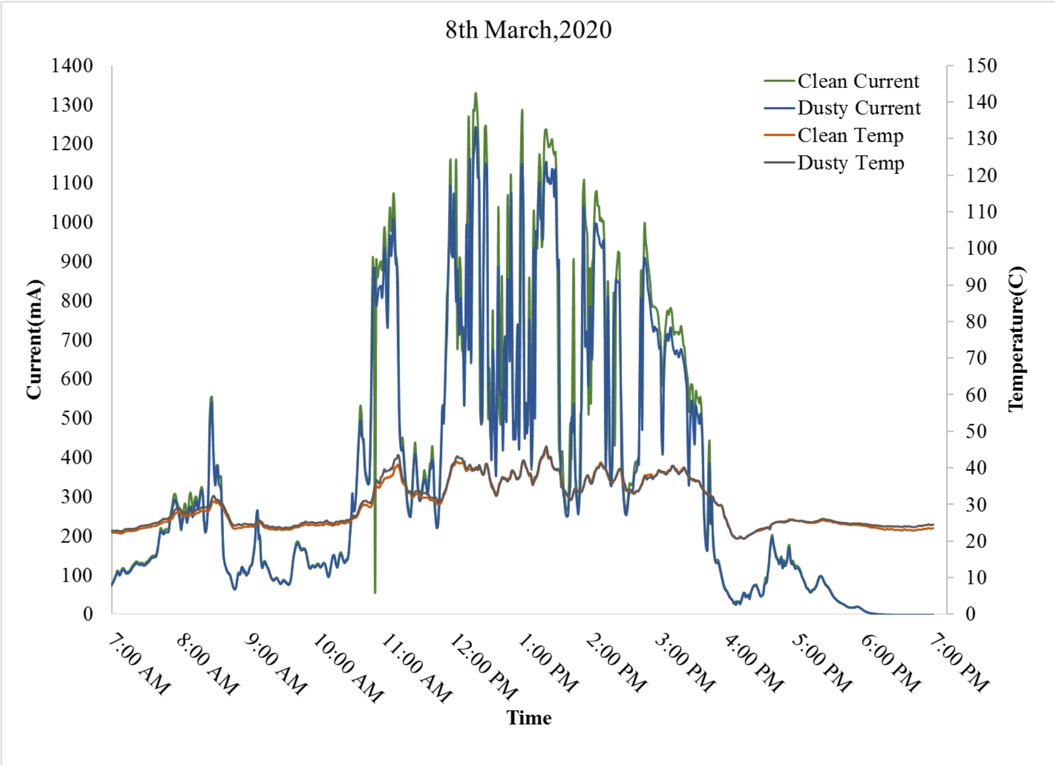

Figure 4.2.7 Graph of Short Circuit current and Temperature of modules

Figure 4.2.8 shows the short circuit current and surface temperature data of both clean and dusty modules of 9th March2020. It was a sunny day with few amounts of scattered clouds. Short circuit current was higher than previous day for both modules. In that day, after 12:00PM sometimes we got almost zero short circuit current because of clouds. From 8:30AM to 3:30PM Short Circuit current was above 500mA for both modules and maintained a current difference of 60 to 80 mA. Maximum short circuit current was recorded at 11.38AM for clean module which was 1400.34mA and for dusty module was 1304.42mA. Overall short circuit current of clean module was 8.27% higher than dusty module.

From the temperature curve of figure 4.2.5 we can see that the temperature was also higher than previous day. Maximum temperature of the module surface recorded at 11:00AM for clean module was 43.76°C and for dusty module was 44.61°C. Overall temperature of dusty module was 0.34% higher than clean module.

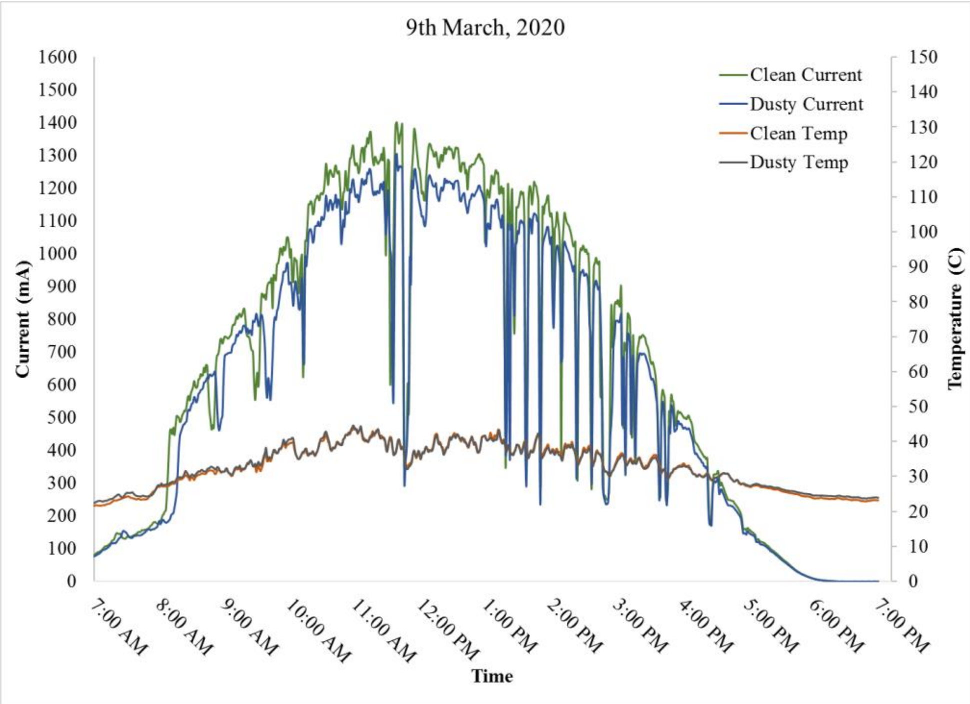

Figure 4.2.8 Graph of Short Circuit current and Temperature of modules

Figure 4.2.9 shows the short circuit current and surface temperature graph of clean and dusty module of 10th March 2020. It was almost a perfect sunny day. That's why it resulted showing good performance from the modules. Looking at the short circuit current graph, it does not show huge ups and downs and maintaining a noticeable difference, both modules have provided good short circuit current. Maximum short circuit current of clean module was recorded at 11:25 AM and was 1336.99 mA and for dusty module it was 1237.32 mA. Overall short circuit current of clean module was 8.13% higher than dusty module.

From the temperature graph it was seen that the surface temperature of both modules was almost identical. From 7:00AM temperature started increasing and continued to increase till 10:00AM then the temperature dropped a little bit because of the shadow of clouds. Maximum temperature recorded for clean module at 11:50AM and it was 42.39°C and for dusty module it was 42.12°C. Overall temperature of dusty module is 0.60% higher than clean module.

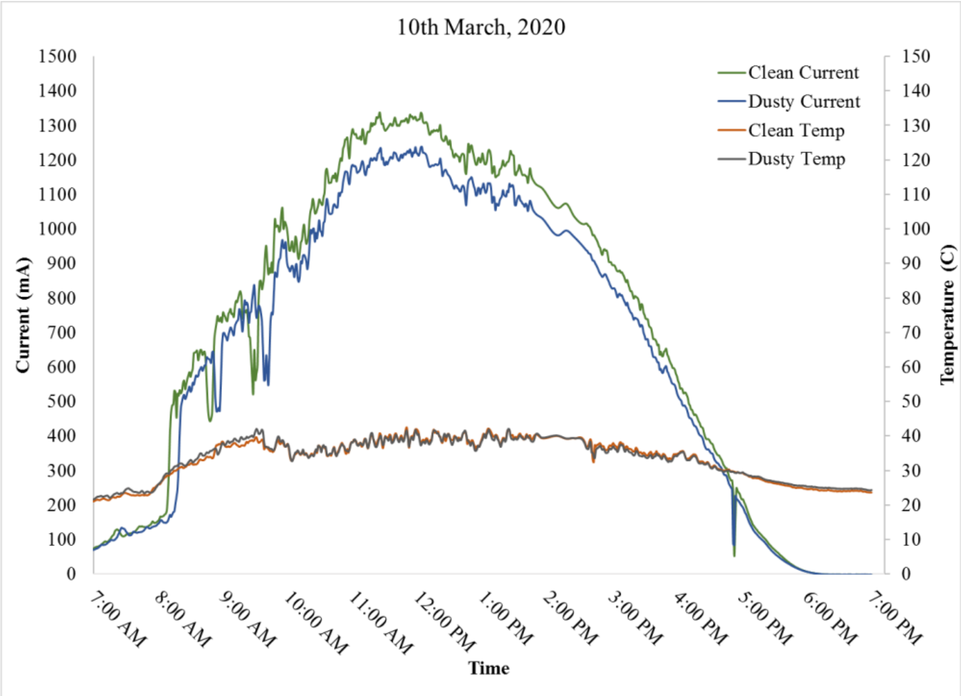

Figure 4.2.9 Graph of Short Circuit current and Temperature of modules

Figure 4.2.10 shows the short circuit current and temperature graph of both clean and dusty module of 11th march 2020. It was a sunny day with white cloudy sky. Both short circuit current and temperature was like a typical sunny day with little ups and downs. Data was taken from 7:00AM to 7:00PM and from 7:00AM the short circuit current start to increase and after 10:00AM current has crossed 1000mA and all the time dusty module has provided slightly less short circuit current. Maximum SC recorded from clean module at 12:10PM was 1333.95mA and from dusty module was 1212.65mA. Overall SC of clean module is 9.91% highr than dusty module.

Temperature graph shows that with time temperature also increases. Clean module has less surface temperature than dusty module. Maximum temperature of dusty module recorded at

1:36PM and it was 45.83°C and for clean module it was 45.15°C. Overall temperature of dusty module is 2.18% higher than clean module.

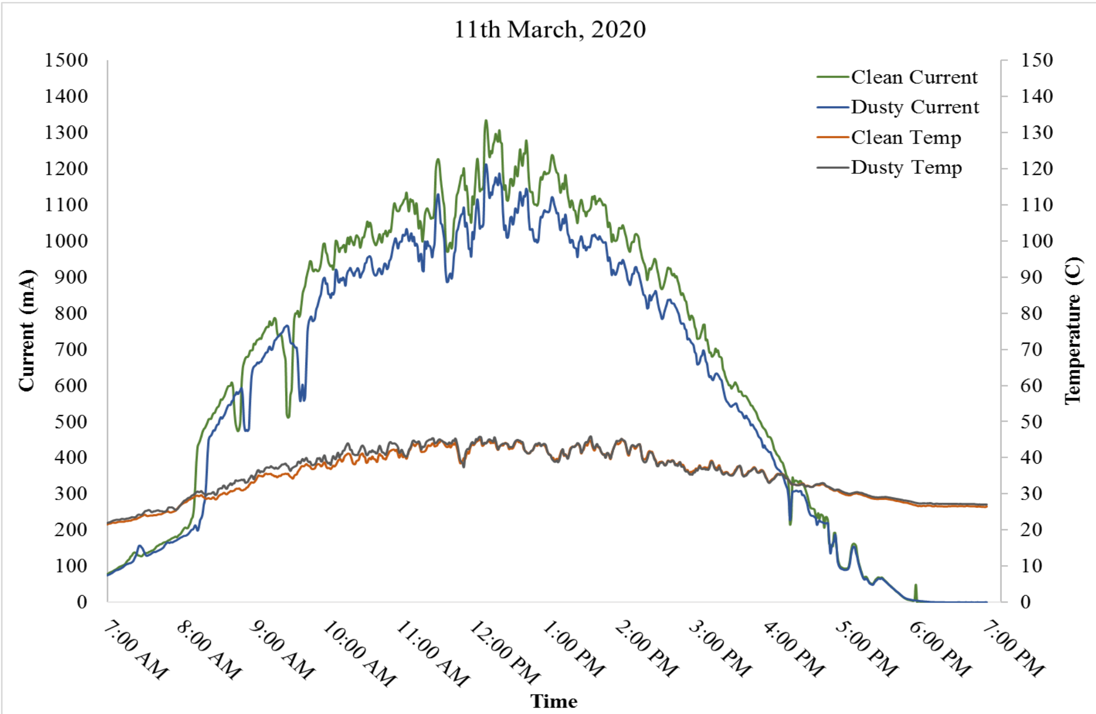

Figure 4.2.10 Graph of Short Circuit current and Temperature of modules

Figure 4.2.11 shows the short circuit current and temperature graph of clean and dusty modules of 15th March 2020. It was a sunny day. Short circuit current started increasing gradually with the time for both modules but dusty module had little less current as usual. SC crossed 1000mA for both modules at around 10:00AM. After 11:30AM SC of clean module was more than 1200mA and for dusty module it was around 1100 -1200mA and after 12:20PM SC reduced drastically because of sudden appearance of clouds which remained almost till 1:30PM. Maximum current recorded from clean module at 12:44PM was 1384.2mA and from dusty module was 1263.93mA. Overall SC of clean module was 9.24% higher than dusty module.

Temperature graph also shows that surface temperature of both modules started increasing with time. After 11:30AM temperature dropped almost 8°C for both modules because of clouds.

Dusty module's surface temperature is higher than clean module as always because of dust accumulation. Maximum surface temperature recorded at 12:20PM for dusty module was 42.6°C and for clean module was 42.54°C. Overall surface temperature of dusty module is 0.89% higher than clean module.

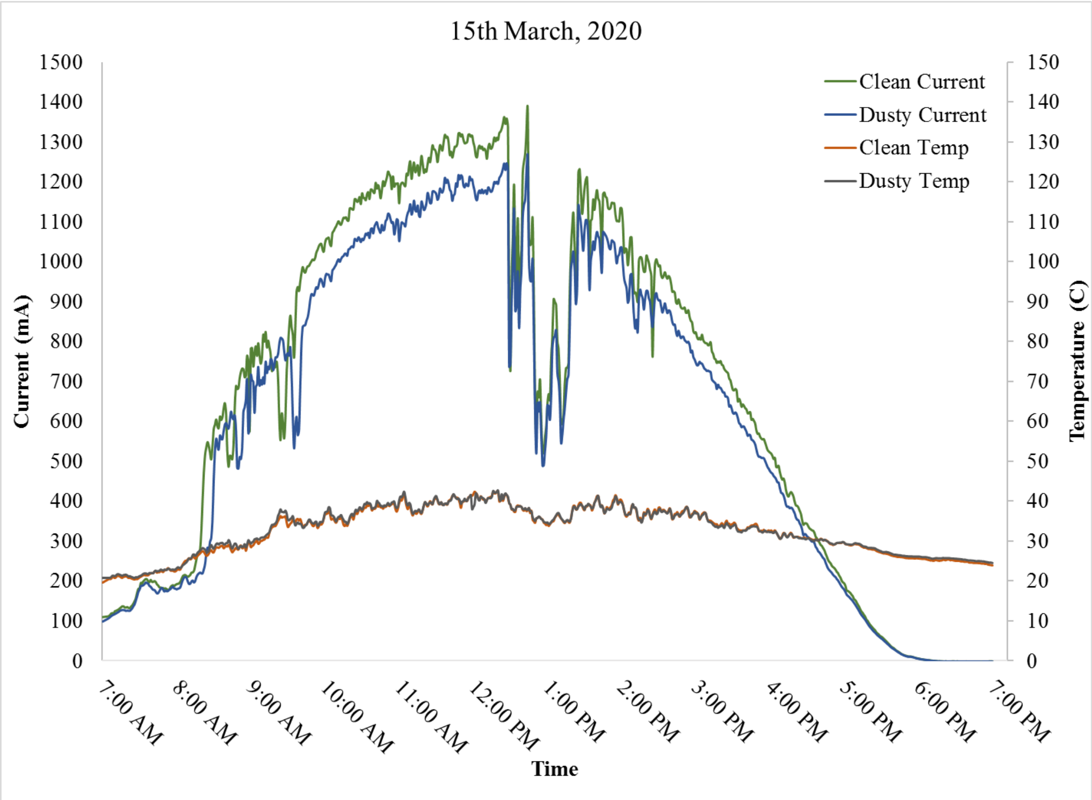

Figure 4.2.11 Graph of Short Circuit current and Temperature of modules

4.3 Short Circuit Current comparison of Clean and Dusty modules of different days

Figure 4.3.1 shows the average short circuit current of clean and dusty module of different days. From the collected data, here are some data of different days and all of them are taken from 7:00AM to 7:00PM. From the figure it is seen average current for each day is not same because sunlight of each day was not same but it can be seen that in almost every day, clean module had the higher average SC current. From all the collected data it was seen that clean module had 7.865% higher average short circuit current than dusty module. From mentioned days, the highest current was found on 16th March2020.

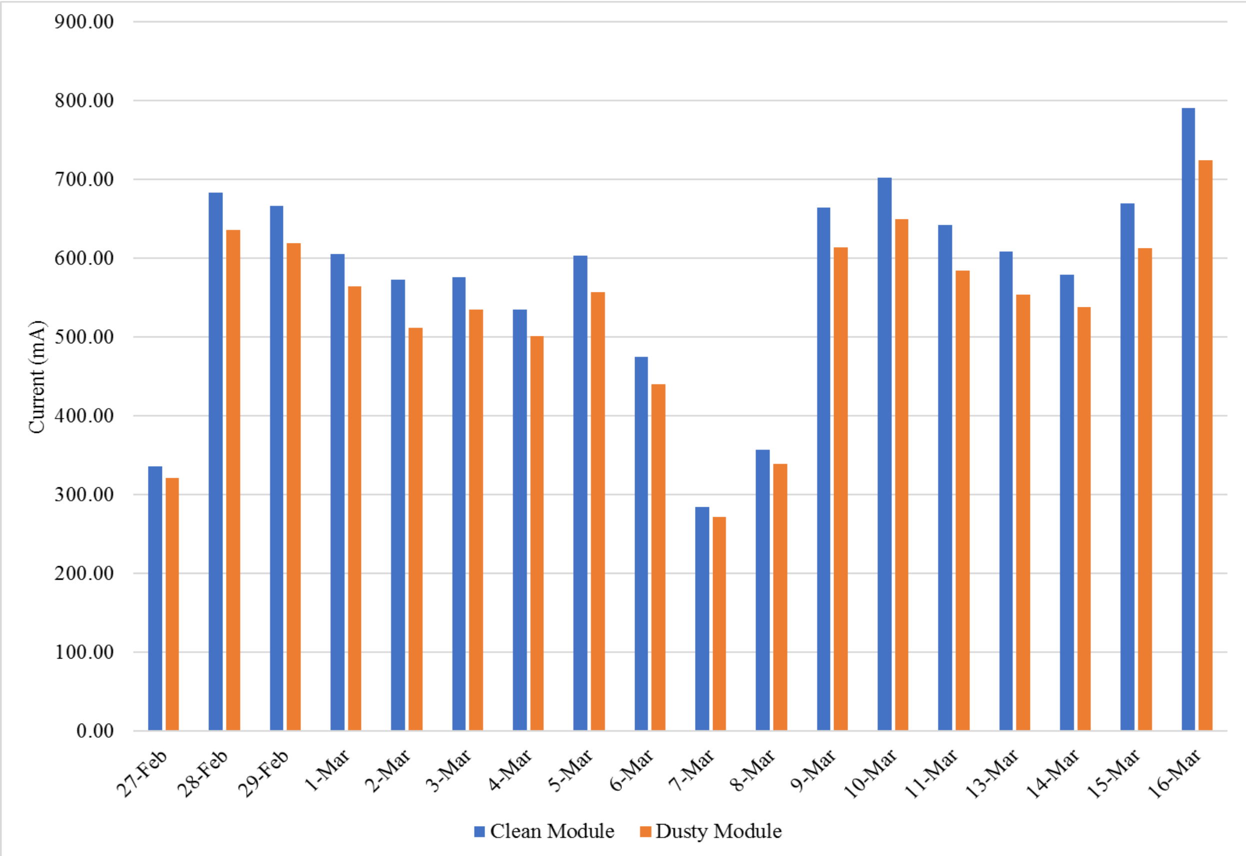

Figure 4.3.1 I_{SC} Comparison of different days

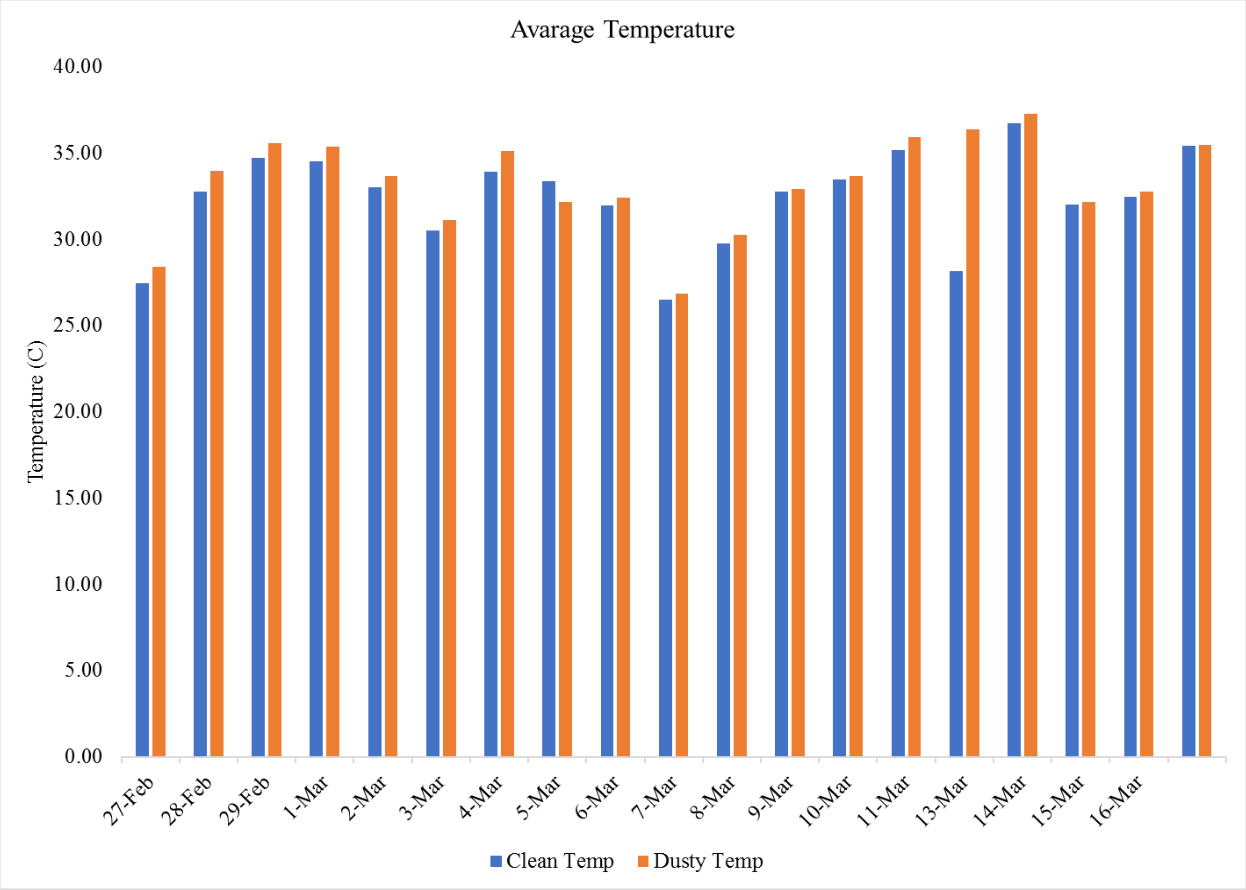

Figure 4.3.2 Temperature Comparison

Figure 4.3.3 shows the short circuit current of clean and dusty module of different days at 12pm. From the figure it is seen that SC current for each day is not same because sunlight of each day was not same but it can be seen that in almost every day, clean module had the higher SC current at 12pm except for 8th march,2020. From all the collected data it was seen that clean module had on average 7.819%higher current than dusty module at 12pm. From mentioned days, the highest difference in SC current was found on 16th March2020.

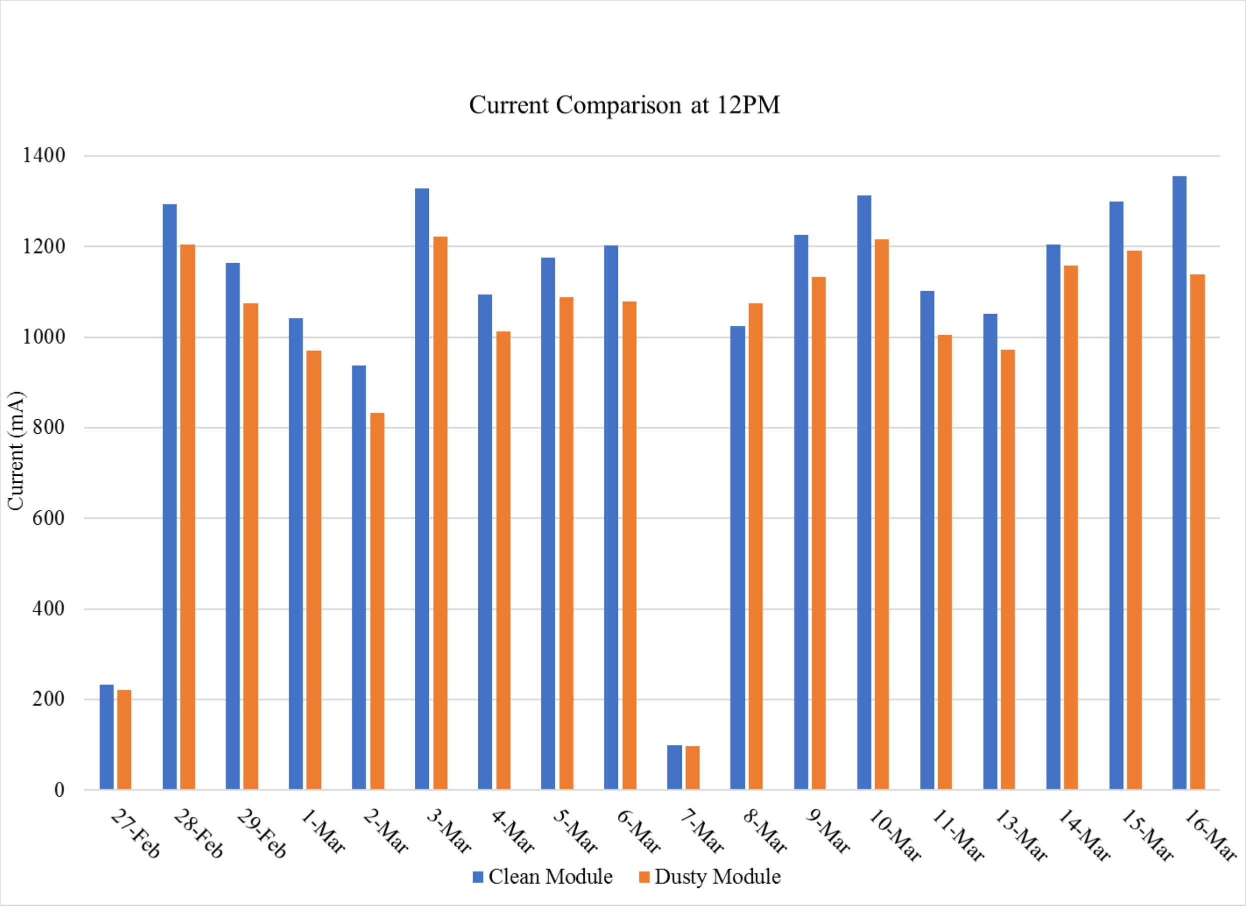

Figure 4.3.3 I_{SC} comparison at 12pm of different days

Figure 4.3.4 shows the temperature of clean and dusty module of different days at 12pm. From the figure, it is seen that temperature for each day is not same because sunlight of each day was not same but it can be seen that in most of the days, dusty module had the higher temperature at 12pm except for 2^{nd}, 5th, 10th, 15th and16^{th} march, 2020. From all the collected data it was seen that dusty module had on average 0.683% higher temperature than dusty module at 12pm.

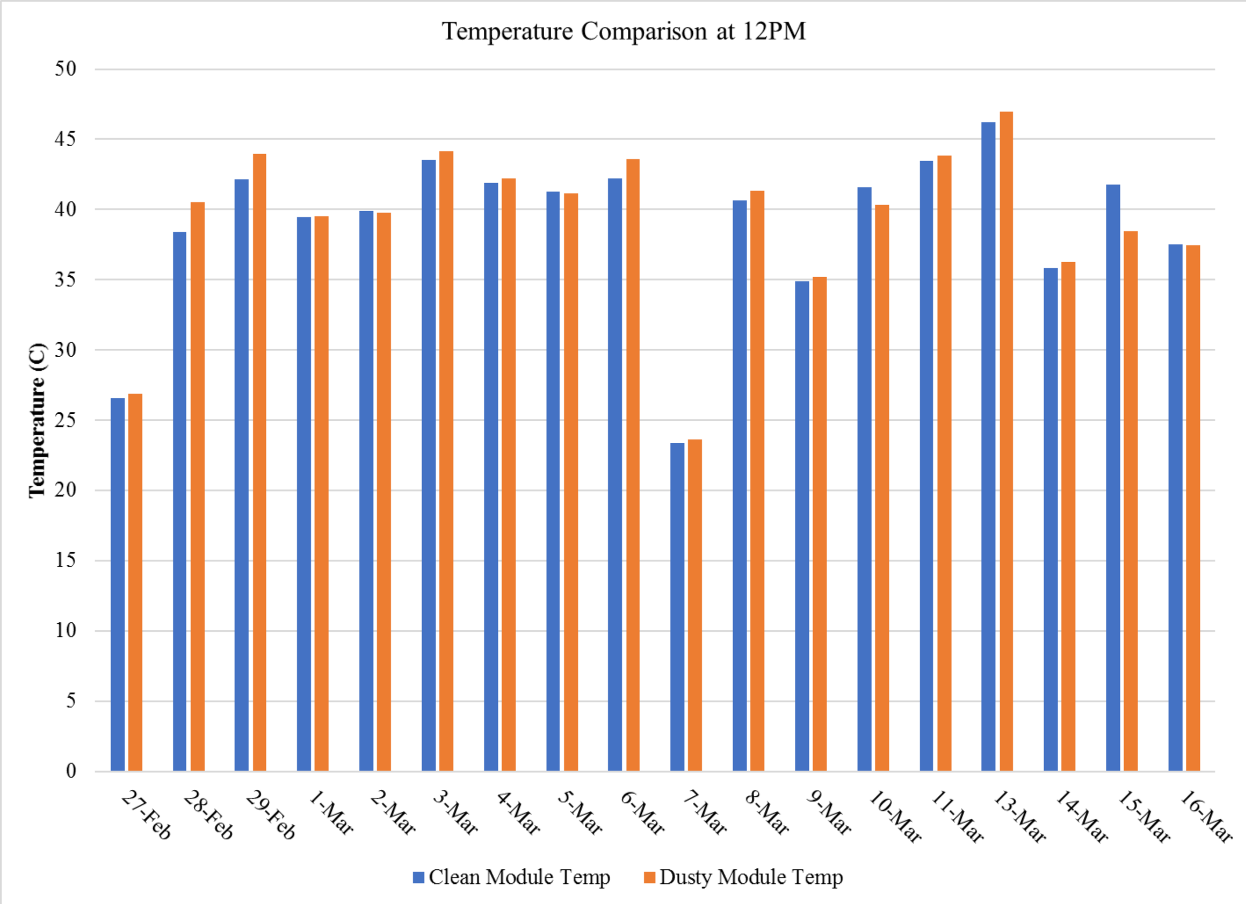

Figure 4.3.4 Comparison of temperature at 12pm.

Figure 4.3.5 shows the sunny and cloudy short circuit current difference between clean and dusty module of different days at 12PM. From the figure, it was seen that for clean module during the sunny days average SC current was 1184.629mA and in cloudy days average SC current was 639. 7025mA.So, during the Sunny days clean module had 85.18% higher SC current than cloudy days.

In the dusty module it was seen that at 12PM for sunny days average SC current was 1087.0014mA and in cloudy days average SC current was 617. 3725mA. So, during the Sunny days it had 76.07% higher SC current than cloudy days.

Note: Here (27th February,6th,7th march and 8th march 2020) were considered as cloudy days except for these days all were sunny days.

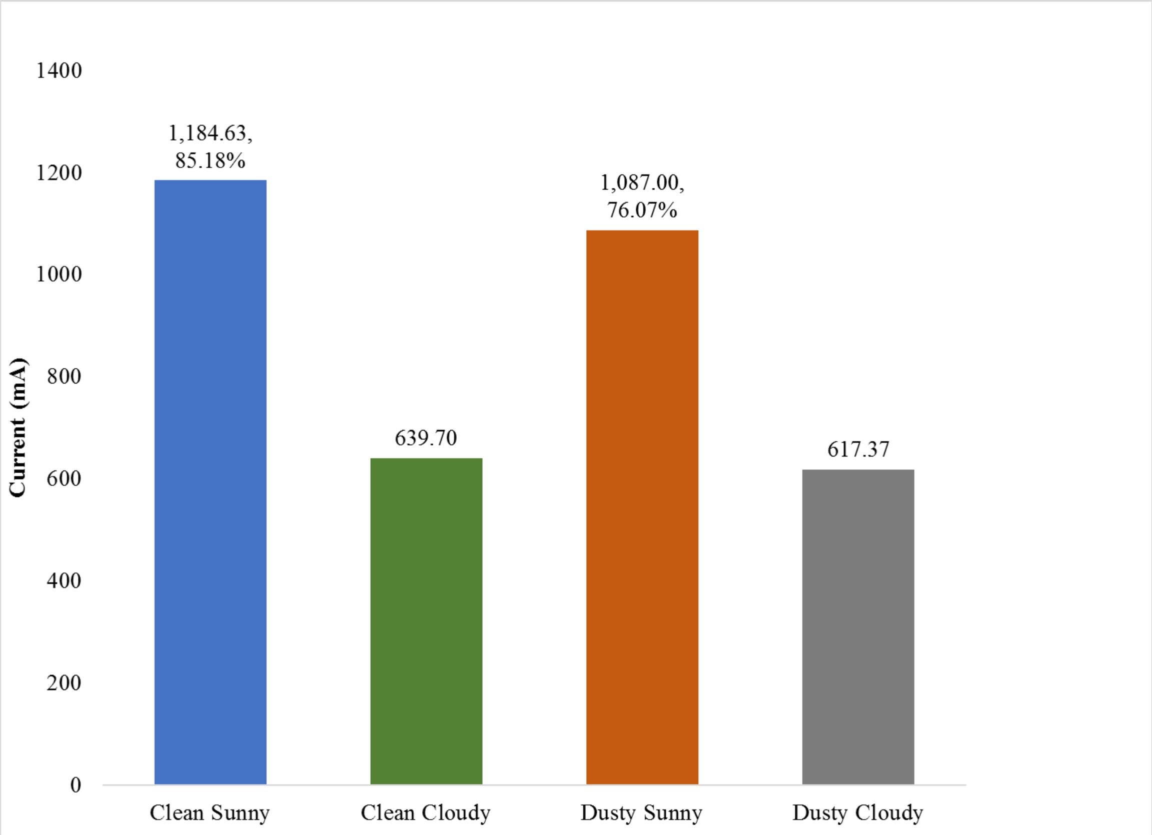

Figure 4.3.5 Sunny vs. Cloudy comparison

Overall, it was observed that around 100mA current difference was seen between the clean and dusty module. Clean solar panel was giving higher current than the dusty one. It was noticed that for subsequent sunny days current difference was increasing slightly because of increased dust accumulation. These differences were not shown because of rainfall and clouds effect. Along with the dust there were few other factors which were also affecting the performance such as temperature and cloud mostly. When the temperature was higher the current reading was lower. Overall, average current difference in percentage was measured around 7.865% and average temperature difference was measured around 1.442%. Considering the time at 12pm for all the days the clean module had about 7.819% SC current more and 0.682% higher temperature than the dusty module during that time. In sunny days, clean module's short circuit current was 8.981% higher than dusty module and for cloudy days clean module's SC current was 3.617% higher than dusty module. Moreover, if suddenly cloud was covering the solar panel with shadow it resulted in drastic drop in current reading as both shadow and heat was affecting the performance of the solar panel. However, rain helped dusty panel by cleaning it and therefore it gave good current reading like the clean one for someday.

4.4 Solar Irradiance and Energy comparison

In this section, comparison between theoretical and practical irradiance has been shown. Theoretical solar irradiance was calculated using ($I = I_0 cos\delta cos\theta$) for fixed axis. Clean and dusty module were used to get practical data. Also, comparison among theoretical calculated solar energy and incident energy of different modules have been shown here. From short circuit current, energy was calculated by comparing the module's current of 12PM with theoretically calculated energy at 12PM.

4.4.1 Irradiance Comparison

Figure 4.1.1 shows the solar irradiance of clean and dusty module along with theoretical Irradiance of 8th March. It was a cloudy day and solar radiation received by both modules was much less than calculated theoretical irradiance. Overall irradiance of clean and dusty module was almost same and both modules had less irradiance than theoretical irradince.

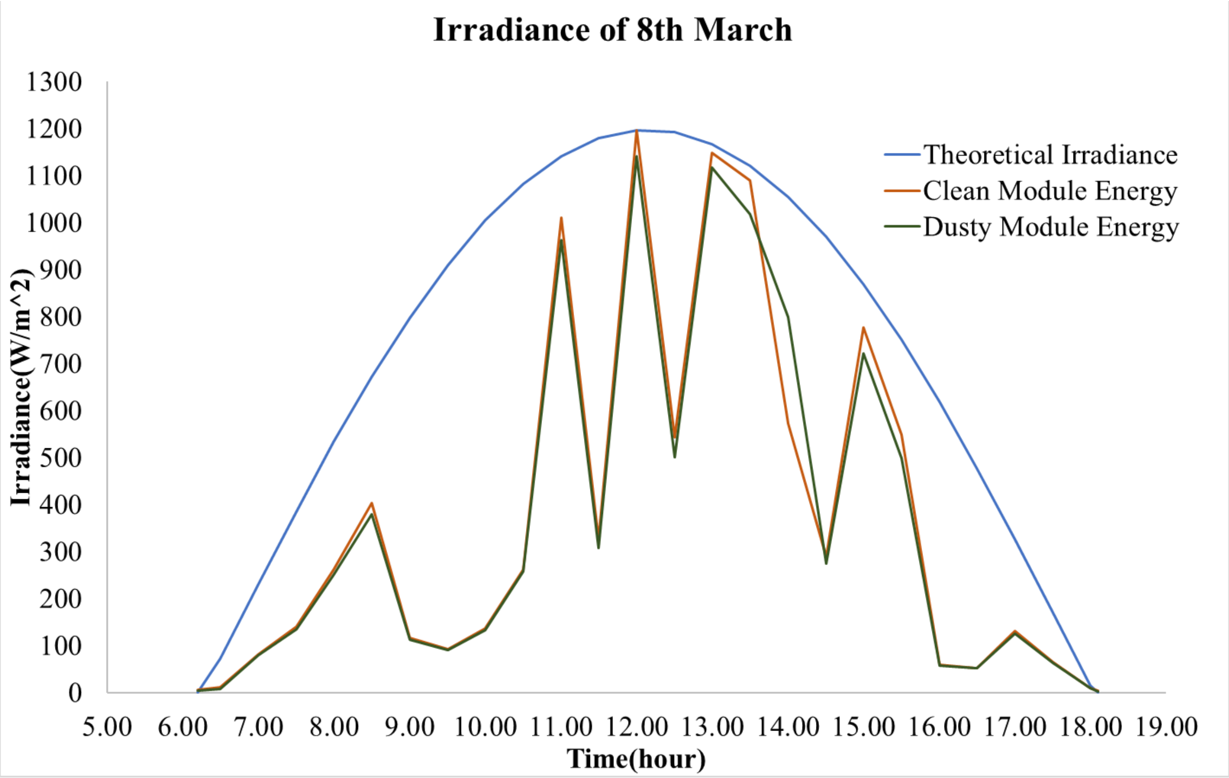

Figure 4.4.1 Solar Irradiance of 8th march (Cloudy Day

Figure 4.4.2 shows the irradiance of clean and dusty module along with the theoretical irradiance of 10th march. It was almost a sunny day and irradiation received by the module was higher than 8th March. Clean module had higher irradiance than dusty module. Clean module's irradiation was close to the calculated theoretical irradiation and dusty module had less than that.

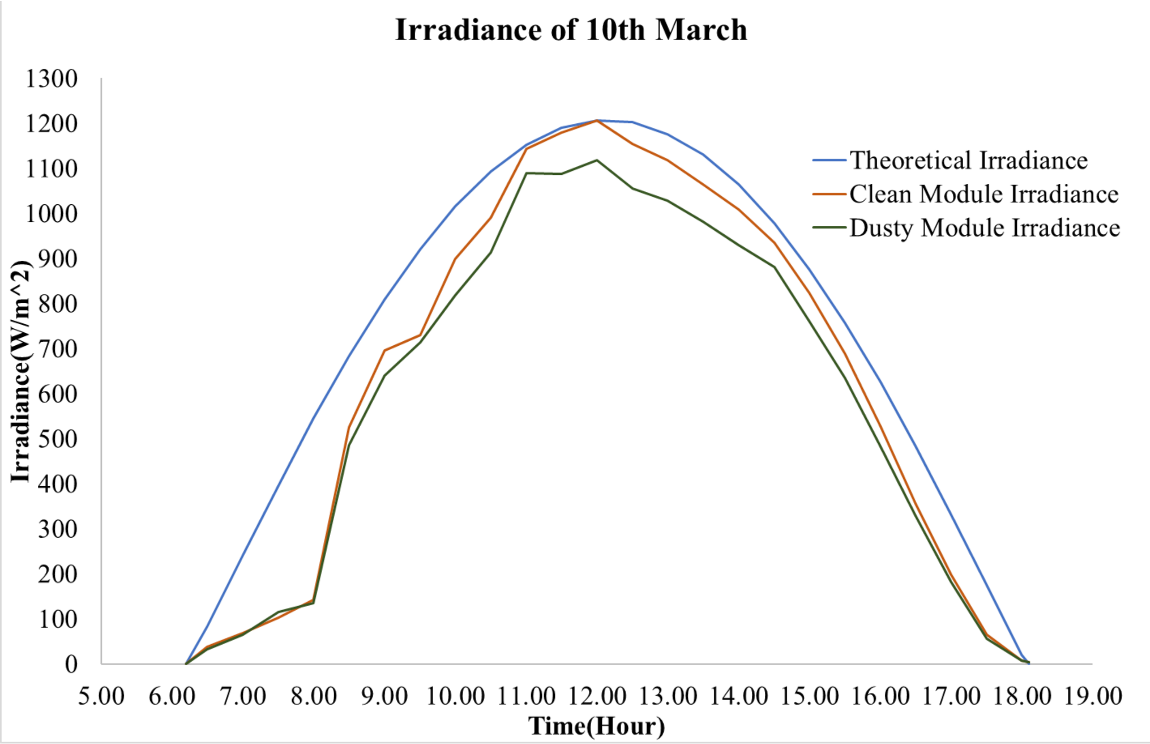

Figure 4.4.2 Solar Irradiance of 10th March (Sunny Day)

Figure 4.4.3 also shows the irradiance of both modules along with theoretical irradiance of 15th March. It was also a sunny day and irradiation received by both modules ware higher than cloudy days. Irradiotion received by clean module was higher than dusty module. After 12PM irradiation receiving dropped suddenly for both module because of clouds.

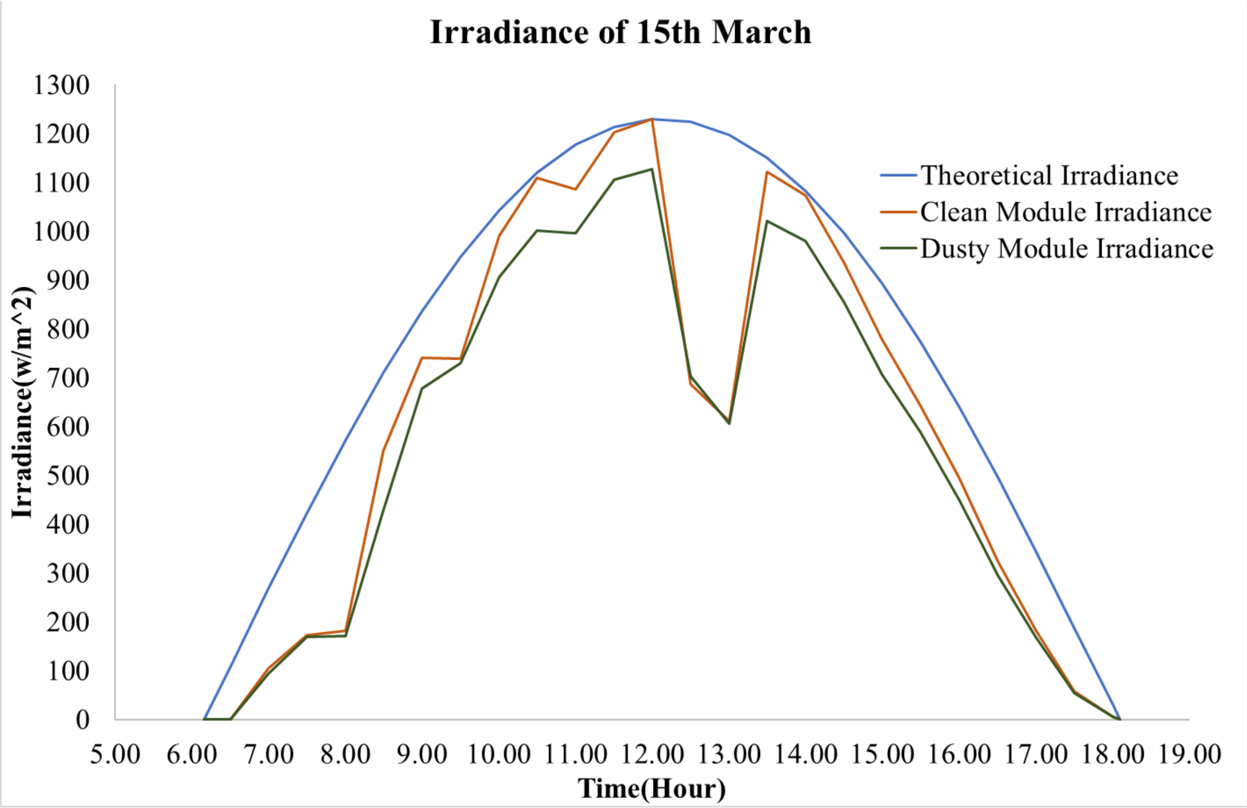

Figure 4.4.3 Solar Irradiance of 15th March (Sunny Day)

4.4.2 Energy Comparison

Figure 4.4.4 shows the incident energy of clean and dusty module along with calculated theoretical energy of 8th march. On this day, theoretical calculated energy was 8968.82Wh/m^2 where clean module's incident energy was 4662.22 Wh/m^2 and dusty module's energy was 4551.84 Wh/m^2. Dusty module had 2.367% less energy than clean module because dusty module got less solar radiation because of dust layer on the surface of dusty module.

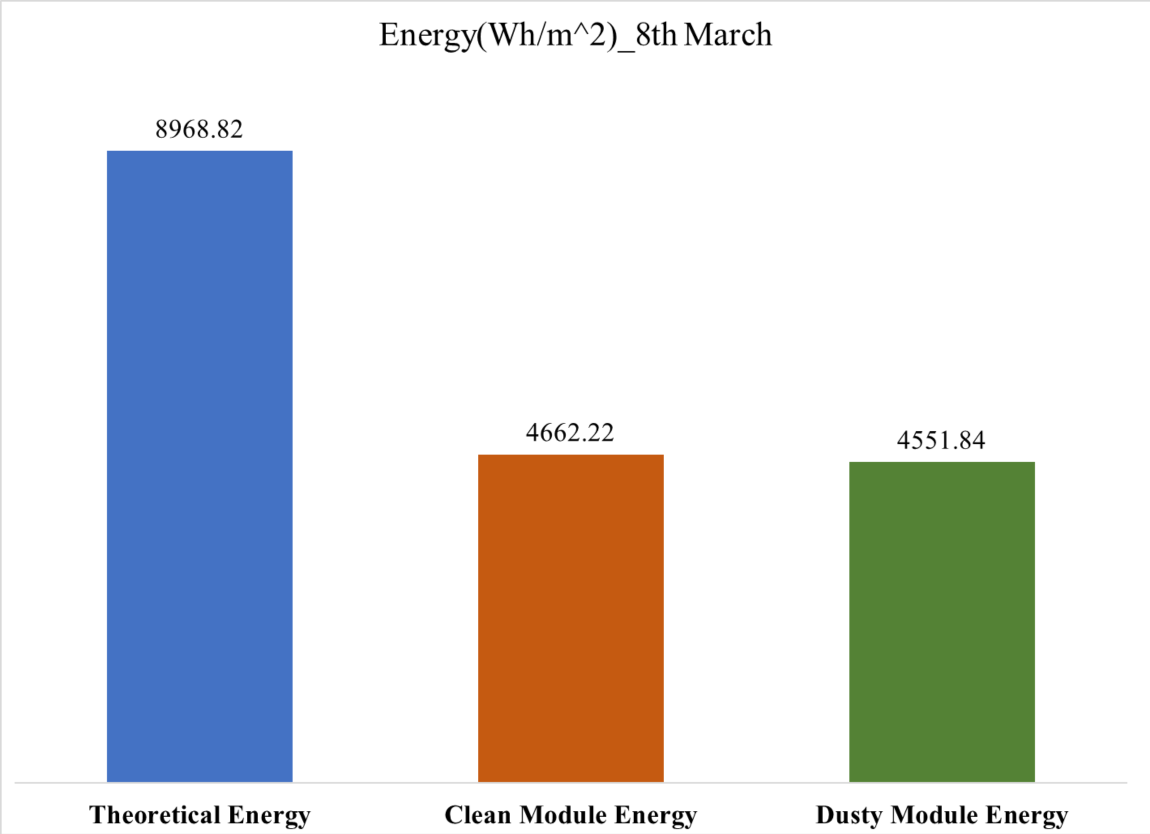

Figure 4.4.4 Incident Energy of different module on 8th March

Figure 4.4.5 shows the comparison of incident energy on clean and dusty module along with theoretical calculated solar radiated energy per squre meter on 10th March. In this day calculated radiated energy was 9076.82 Wh/m^2 where clean module had 7749.12 Wh/m^2 and dusty module had 7272.75 Wh/m^2. Dusty module had 6.147% less energy than clean module.

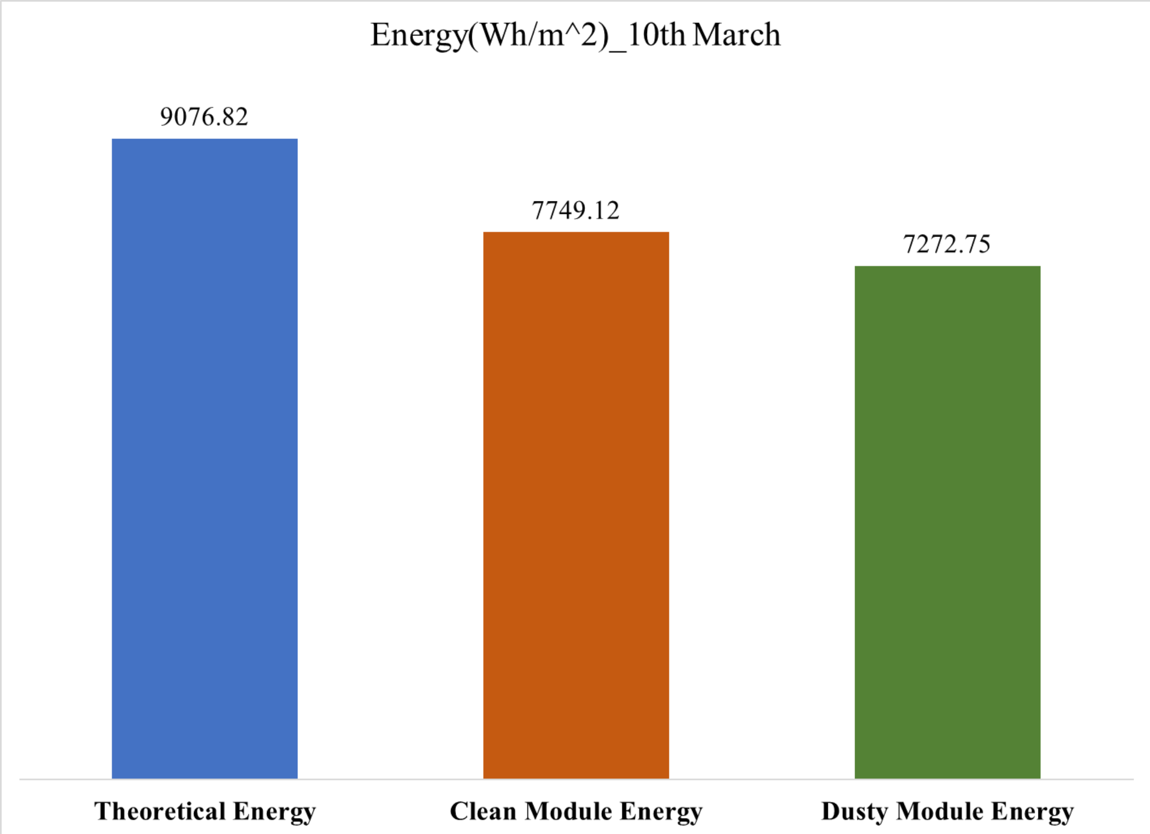

Figure 4.4.5 Incident Energy of different module on 10th March

Figure 4.4.6 also shows the comparison of incident energy on clean and dusty module along with theoretical calculated solar radiated energy per squre meter on 15th March. In this day calculated radiated energy was 9333.89 Wh/m^2 where clean module had 7509.83 Wh/m^2 and dusty module had 6919.94 Wh/m^2. Dusty module had 7.855% less energy than clean module.

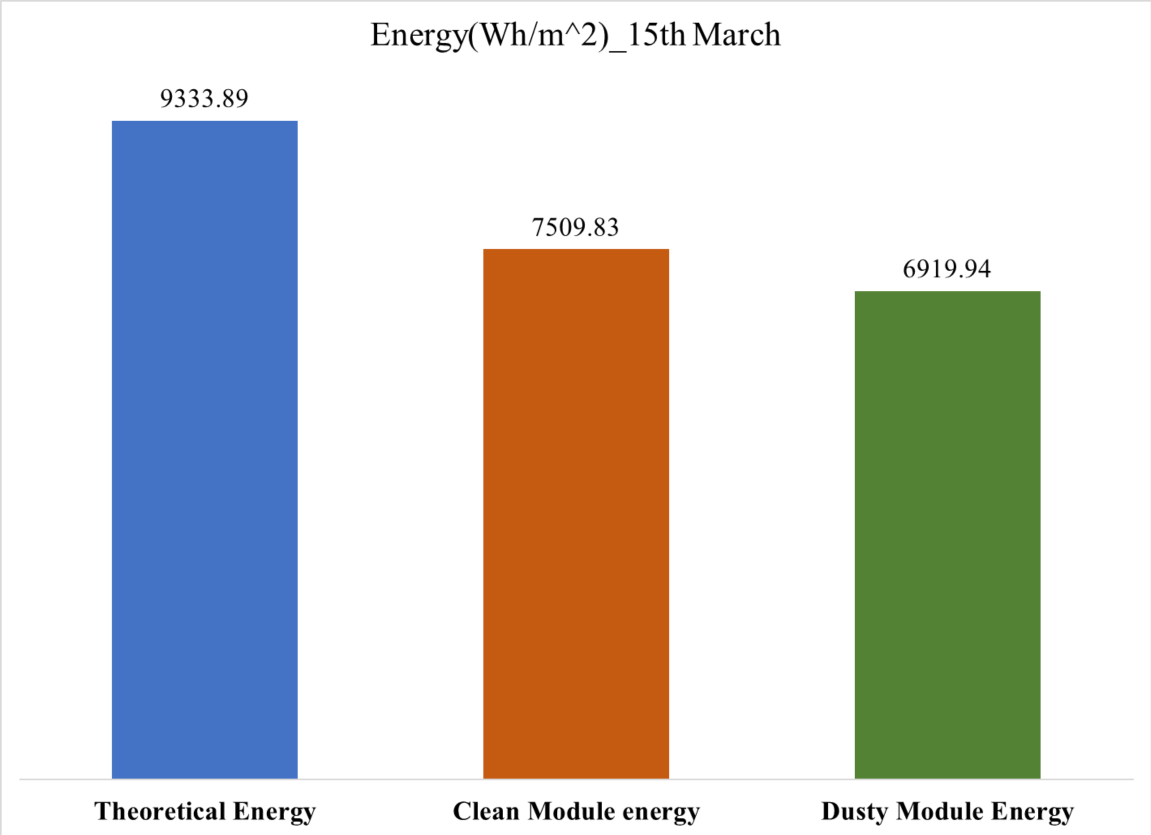

Figure 4.4.6 Incident Energy of different module on 10th March

Figure 4.4.7 shows the energy comparison of the clean and dusty modules along with theoretical energy in March 2020. On march about almost 7 days were cloudy and the remaining 24 days were sunny. Theoretical calculated energy on March is 283710.32 Wh/m2 where for sunny days it was 220928.58 Wh/m2 and for the dusty module, it was 62781.74 Wh/m2. Clean module's total energy output on March was 215742.88 Wh/m2 where for sunny days it was total 183107.37 Wh/m2 and for cloudy days and for cloudy days it was total 32635.51 Wh/m2. On the other hand, the dusty module's total output energy in the march was 202175.18 Wh/m2 where for sunny days it was 170312.31 Wh/m2 and cloudy days it was 31862.87 Wh/m2. In addition, the clean module produced 6.711% more energy in the march than the dusty module.

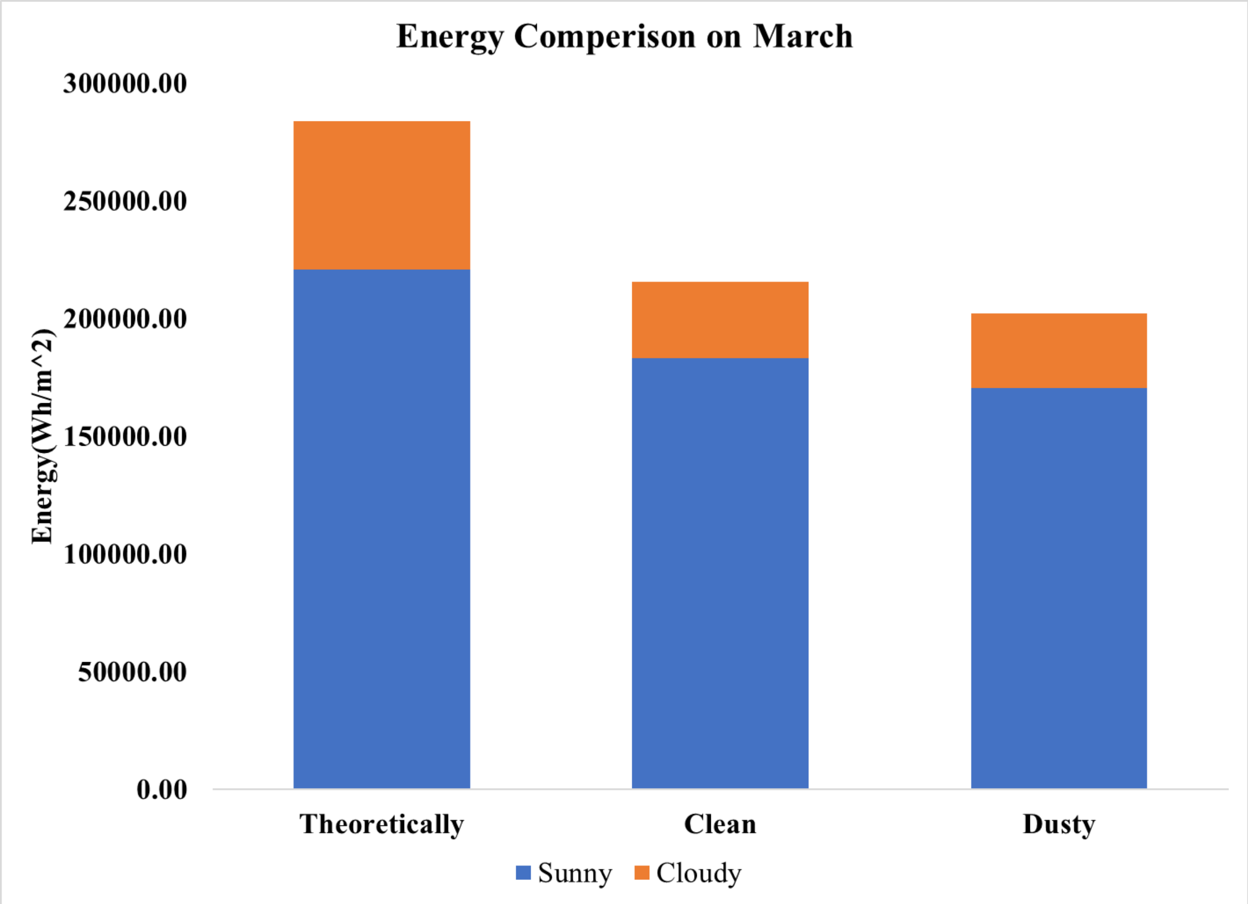

Figure 4.4.7 Energy Comparison on March

Observation: From the above-mentioned graph, it is shown that the average output energy from the clean module is 6959.44Wh/m2 and the dusty module is 6521.78Wh/m2 per day. Moreover, practically clean module resulted in 23.957% less incentive energy than the theoretical value and in terms of the dusty module, it showed 28.739% less. Finally, it was observed that the dusty module was producing on an average 0.298% less energy than the clean module each day because of the increased amount of dust accumulation.

Chapter 5: Conclusion and future works

5.1 Conclusion

This examination researches comparative performance analysis due to dust accumulation impact on two available photovoltaic modules under the same environment. The presentation is estimated depending on the short circuit current. The fundamental outside boundaries were considered as follows: dust, temperature, cloud. All the information is gathered during the time Feb to March 2020. Here, both sunny and rainy days data has been studied and plotted. As it is known that during February and March rain may come any time so it has caused some problems with short circuit current reading as due to rain dusty module was getting washed up along with the clean module. Therefore, it had similar results with the clean module. The Clouds were also causing problems during these rainy days.

In this study dust, temperature, rain, and cloud as environmental parameters were considered which affects both PV modules. Moreover, the comparison between both module's irradiance (Practical irradiance) with theoretical solar irradiance which was calculated by the fixed axis method was done in this experiment.

5.2 Future Works

Present work describes how clean and dusty modules perform at the same height. In the future dust impact on different altitudes can be analyzed. More devices are ready for performing dust impact on PV modules in different heights but due to covid-19, it was not possible to work on that. In the future, a pyranometer can be used to get more accurate irradiance. In terms of device improvement, open-circuit voltage and short circuit measuring features can be added to it so that energy calculation can be done directly from the data. Cloud storing and monitoring features can be added to the device. Finally, the study of seasonal variation on the solar module can also be studied in outdoor condition.

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Appendix:

A. Solar Module Specifications

Model	SP20-18-M
Rated Maximum Power (Pmax)	20W
Tolerance (Tol)	0 ~ +3%
Voltage at Pmax (Vmp)	17.35V
Current at Pmax (Imp)	1.16A
Open Circuit Voltage (Voc)	21.16V
Short Circuit Current (Isc)	1.27A
Nominal Operating Cell Temperature (NOCT)	47±2’C
Maximum System Voltage	1000VDC
Maximum Series Fuse Rating	10A
Operating Temperature	-40°C to +85°C
Application Class	Class A
Cell Technology	Mono-Si
Weight (Kg)	1.92
Dimensions (mm)	510°360°25
Manufacture	China
Technical performance data recorded at Standard Test Conditions (STC) Am= 1.5 E=1000W/m^2 TC=25°C	

B. Mat lab Codes:

1) The following code has been used to find the solar irradiance

```
function I=Intensity(n,T,q)

d=23.45*(sind((360/365)*(n-80)));

Sr=12-((1/15)*(acosd(-tand(d)*tand(q))));
```

```
Ss=12+((1/15)*(acosd(-tand(d)*tand(q))));

ws=acosd((-tand(d)*tand(q)));

t=Ss-Sr;

w=(-ws+(((2*ws)/t)*(T-Sr)));

A=asind((sind(d)*sind(q))+(cosd(d)*cosd(q)*cosd(w)));

Z=(90-A);

I=1367*cosd(d)*cosd(Z);

End
```

C. Arduino Code used in data logger devices

```
#include <OneWire.h>

#include <DallasTemperature.h>

#include <SPI.h>

#include <SD.h>

#include <SD.h>

#include <SPI.h>

#include <DS3231.h>

#include <Wire.h>

#include <Adafruit_INA219.h>

const int chipSelect = 4;

#define ONE_WIRE_BUS 8
```

```
OneWire oneWire(ONE_WIRE_BUS);

DallasTemperature sensors(&oneWire);

float Celsius = 0;

File myFile;

DS3231  rtc(SDA, SCL);

Adafruit_INA219 ina219;

unsigned long previousMillis = 0;

unsigned long interval = 100;

//const int chipSelect = 4;

float shuntvoltage = 0;

float busvoltage = 0;

float current_mA = 0;

float loadvoltage = 0;

float energy = 0;

File TimeFile;

File VoltFile;

File CurFile;

int logNo = 1;



void setup() {
```

```
  sensors.begin();  //temp_sensor begin
  rtc.begin();      //time sensor begin
  ina219.begin();


  Serial.begin(9600);
  while (!Serial) {
    ; // wait for serial port to connect. Needed for native USB port only
  }


  Serial.print("Initializing SD card...");


  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    while (1);
  }
  Serial.println("card initialized.");
}


void loop() {
```

```
//temperature
  sensors.requestTemperatures();
  Celsius = sensors.getTempCByIndex(0);
// Log data Sequence
  String dataString = "";
  dataString = String(logNo);
  logNo++;


// INA
  ina219values();
File dataFile = SD.open("datalog.txt", FILE_WRITE);
// if the file is available, write to it:
if (dataFile) {
  dataFile.print(rtc.getDOWStr());
  dataFile.print(",");
  dataFile.print(rtc.getDateStr());
  dataFile.print(",");
  dataFile.print(rtc.getTimeStr());
  dataFile.print(",");
  dataFile.print(Celsius);
```

```
  dataFile.print(",");
  dataFile.print(current_mA);
  dataFile.print(",");
  dataFile.print(busvoltage);
  dataFile.print(",");
  dataFile.print("Log No: ");
  dataFile.println(dataString);
  dataFile.close();
// print to the serial port too:
  Serial.print(rtc.getDOWStr());
  Serial.print(" ");
  Serial.print(rtc.getDateStr());
  Serial.print(", ");
  Serial.print(rtc.getTimeStr());
  Serial.print(", temp: ");
  Serial.print(Celsius);
  Serial.print("C, ");
  Serial.print("Current: ");
  Serial.print(current_mA);
  Serial.print(" mA, ");
```

```
    Serial.print("Bus Voltage: ");
    Serial.print(busvoltage);
    Serial.print(" V");
    Serial.print(", Log No: ");
    Serial.println(dataString);
  }
  // if the file isn't open, pop up an error:
  else {
    Serial.println("error opening datalog.txt");
  }
  delay(2000);
}
  void ina219values() {
  shuntvoltage = ina219.getShuntVoltage_mV();
  busvoltage = ina219.getBusVoltage_V();
  current_mA = ina219.getCurrent_mA();
  }
```