Experimental investigation of soiling losses and a novel cost-effective cleaning system for conventional PV modules

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Dedication

This thesis is dedicated to my parents, supervisor Dr. Adeel Waqas and elder brother Imran Sheikhuka who taught me how to fight against the struggle of life and support all the decisions and choices I made. I am thankful for their love and measureless support.

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Abstract

Dust accumulation significantly reduces the efficiency of a photovoltaic (PV) module, and the unavailability of an economical and efficient cleaning solution is the persistent problem. Therefore, the focus of this is to investigate the effect of dust on PV performance and proposes a novel cleaning system for the removal of dust from the front surface of PV modules. The outdoor experiment is conducted on the monocrystalline (mono-PV) and polycrystalline (poly-PV) PV modules. Each set contains two PV modules (mono-PV and poly-PV), one set is cleaned every day and the other set left uncleaned throughout the period of the experiment. The cleaning of the PV module is performed using pressurized water, sprayed through a flat-fan nozzle to clean the front surface. The waste-water is collected, filtered and directed back to the storage tank. The cleaning system has a water recovering capacity of 55 % and a water requirement of 1.8 L per m^2 of PV area. It has been analyzed that the output power of the mono-PV module and poly-PV module has decreased by 16.16 % and 11.54 %, respectively after one month with the dust deposition density of 4.6 g/m^2. The cleaning process improves the efficiency of the PV module by 98 % in 35 seconds of operation with a water flow rate of 1.74 L/min. The economic analysis results indicate that the cost of the cleaning system for mono-PV (40 watts) and poly-PV (40 watts) modules are 0.037 USD/month, which is greater than the cost of energy losses 0.005 USD/month It has been evaluated that the proposed cleaning system is cost-effective for commercial size PV modules having a length of around 2 m. Furthermore, the mono-PV module (400-watts) and poly-PV module (355-watts) should be cleaned within 85 days of dust accumulation for optimum energy usage.

Keywords: PV module; Dust accumulation; Dust characterization; Effect of dust; PV module cleaning system; Economic analysis.

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* Annexure I

List of abbreviation

PV	Photovoltaic
Mono-PV	Monocrystalline PV module
Poly-PV	Polycrystalline PV module
QASP	Quaid-e-Azam Solar Power Park
GHG	Greenhouse gasses
c-Si	Crystalline silicon
Voc	Open circuit voltage
Isc	Short circuit current
Vmax	Maximum voltage
Imax	Maximum current
Φ	Latitude angle
FF	Fill-Factor
SEM	Scanning electron microscope
XRD	X-ray diffraction
EDS	Energy Dispersive X-Ray Spectroscopy
O & M	Operation and maintenance
C_{CS}	Cost of cleaning system
C_{intl}	Initial cost
C_{main}	Maintenance cost
C_{mat}	Material cost
C_{WF}	Workforce cost
C_{EL}	Cost of energy losses
CoE	Cost of electricity
$E_{Dirty.pv}$	Dirty PV module energy
$E_{Clean.pv}$	Clean PV module energy
E_{PV}	PV module energy generation
P_{max}	Maximum output power
$P_{max.daily}$	Daily maximum output power

Chapter 1

Introduction

1.1 Background

Due to a rapidly growing world population and technological development, electricity demand and consumption is increasing daily. Most of the global electricity demand is fulfilled by generating it from fossil fuels. With the increasing number of industries and automobiles, the daily global energy utilization is reaching higher values every year. While fossil fuels are major contributors to producing CO_2 gas, which is responsible for global warming and climate change [1]. For this reason, the world has started changing its direction from fossil fuels to renewable energy sources. Solar energy is one of the promising renewable energy resources, which is clean, free, inconsumable, abundant, and safe. Solar energy is one of the cheapest energy sources of electricity generation currently using in the modern world [2]. The solar irradiation can be captured and generate electricity by two types of technology, photovoltaic and solar thermal. Solar PV technology is used to generate electricity by converting solar irradiance into direct current through solar cell made of semiconductors to absorb the solar irradiance and convert it into electrical energy. The solar PV module using the semiconductor solar cells has limited the efficiency of the PV system to 15 – 20 % due to the nature of the material [3].

Solar PV modules have been designed to produce maximum output power and to support the installation process. Many factors determine the optimum yield of the output power of the PV module. Environmental factors are one of the contributing parameters which directly affect the output of the PV module. However, PV performance in such climatic conditions is influenced by several factors such as temperature, wind speed, humidity, rainfall and dust [4]. The solar PV module output power highly depends on the solar irradiance that reaches the solar cells. The low solar irradiance falls on the PV module glass surface result in low output power [5]. Dust effects are the major concern for reducing the output power of the PV module. The airborne dust accumulated on the front surface of the PV module with the passage of time, result in the shading and low exposure of solar irradiance to surface directly. Hence, it reduces the PV module performance [6]. The shading caused by dust deposition on the surface of the PV module is uniform. Soiling can have a large effect on the efficiency of the PV module in desert areas, low rainfall areas or during a sandstorm. The dust particle concentration in the air is important to study the dust effect on the PV panel. The concentration of dust particles or particulate matter originating from air pollution is mainly due to industry, vehicles, construction and agricultural activity. The nearby dusty roads, highways, and fields are also responsible to increase the dust concentration in the air and to settle down on the front surface of the PV module. The air pollution contains hydrocarbon particulates, which are stickier to the surface and influence the PV performance greater than the natural dust particles. The dust particle size is also responsible for the dust concentration in the air. The large size dust particle is heavy and difficult to lift up as compared to small size particles. The more dust in powder form will rise more in the air and responsible for the dust effect [7-10].

1.2 Pakistan’s solar energy potential

Pakistan is a South Asian country with daily solar irradiance of 5.3 kWh/m2/day and eight to nine sunshine hour per day, has favorable climatic conditions for solar PV power generation as shown in Fig. 1-1 [11]. Following the growth of the electricity market, the PV market has been growing exponentially with many solar companies coming into existence every year. The import of solar PV modules is increasing in the local market every year. There is a net metering facility available in the main cities to promote solar PV systems on a large scale. This indicates that Pakistan is becoming a promising country for PV plant installations [12,13].

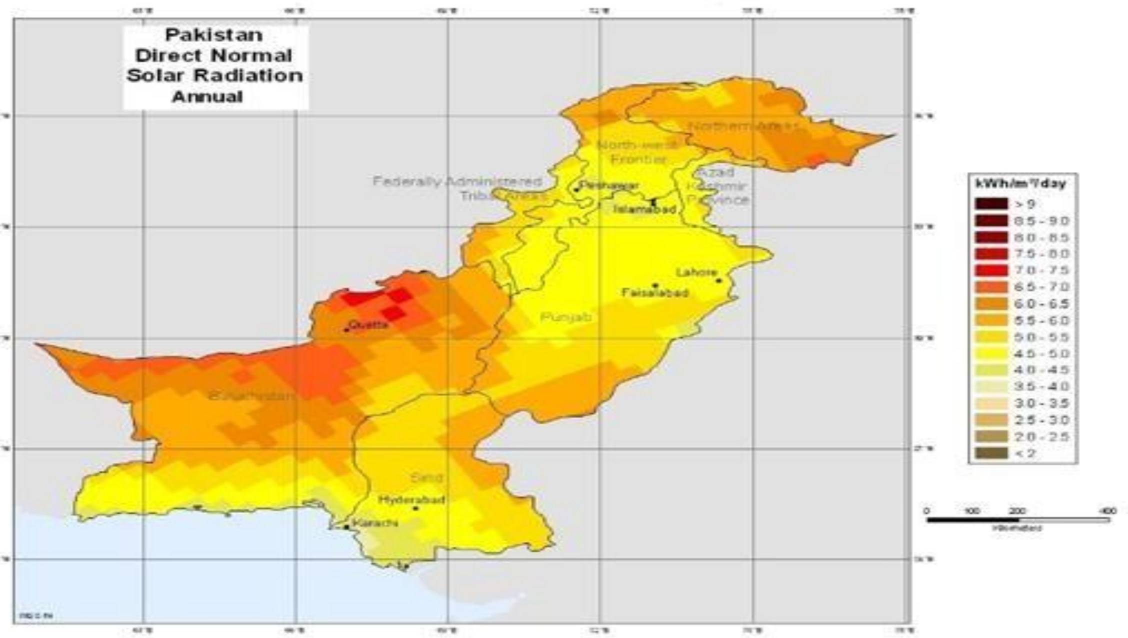


Fig. 1-1: Solar radiations map [14]

The country has the plan to build 1 GW capacity of solar PV plant named Quaid-e-Azam Solar Power Park (QASP) in the Cholistan Desert, Punjab. However, Phase 1 of 100 MW capacity of solar PV plants has been installed and working to date as shown in Fig. 1-2. While there are still many other large solar PV projects that have been commissioned, inaugurated, and under progress. There are some pilot projects installed in different cities of Pakistan facing the soiling effect. QASP is installed on a desert land and facing dust issues. The poor maintenance due to a high rate of dust accumulation has been reported and the cleaning is done manually by water and labor. An artificial lake has been created to fulfill the water requirement. However, it seems inefficient, unreliable, time-consuming and costly solution [15].

1.3 PV devices and systems

The photovoltaic device is used to convert sunlight into electricity using semiconductor material by the photovoltaic effect. PV system is consists of solar modules, each comprising a number of solar cells connected in series and parallel. PV installation can be ground-mounted or rooftop-mounted, wall-mounted or floating on the liquid surface. PV systems have been used in applications as stand-alone installation and grid-connected. PV modules can be manufactured in many different ways depends on the type of material used to make PV cells. The most common material used to construct PV cells is silicon semiconductor material. There are three types of PV cell technologies commercially available that dominate the global solar market and are currently installed worldwide: monocrystalline silicon, polycrystalline silicon, and thin-film as shown in Fig. 1-3 [16,17].

1.3.1 Crystalline silicon wafer-based PV modules

There are two types of crystal silicon (Si) wafer-based PV modules mostly used to generate electricity; one is single crystal Si and the other is multi-crystalline Si cells. Monocrystalline PV modules are made from cylindrical silicon ingots called single crystal that are cut into wafers and have higher efficiency than poly-PV modules. Polycrystalline PV modules are known as multi-crystalline PV modules. The poly-PV cell is made of multi-crystalline silicon, the melted silicon is poured into a square mold to produce polycrystalline shape. Silicon solar cells offer both reasonable prices and good efficiency. It has been found that the large scale production of solar cells during the year 2002 worldwide is up to 500 MWp, consisting of ~40% single-crystal Si and ~51% multicrystalline Si cells and about 8% based on thin-film amorphous Si solar cells. This shows that the mono-PV and poly-PV modules are the major contributors in the world for electricity generation from PV.

1.3.2 Amarphos silicon thin-film PV modules

Another most common technology used for PV modules is amorphous silicon-based solar cells called thin-film solar cells. They are made from thin layers of different semiconductor materials such as cadmium telluride or copper indium gallium diselenide. The advantages of thin-film solar cells are lightweight, flexible and use less energy in production. However, thin-film PV modules require a large area and have low efficiency.

1.3.3 Other advance PV technologies

The advancement in PV technologies has been made over time. At first, there were silicon solar cell based PV modules used to produce electricity. Secondly, the thin-film solar cells being used in PV modules. The third type of PV technology named after the group elements that composed the solar cell called III-V Solar Cells. It has mainly constructed from elements in Group III—e.g., gallium and indium—and Group V—e.g., arsenic and antimony—of the periodic table. The next-generation solar cells are based on many new photovoltaic technologies—such as solar cells made from organic materials, quantum dots, and hybrid organic-inorganic materials (also known as perovskites). These solar cells are very expensive to manufacture and have limited time as compared to silicon-based solar cells PV modules.

Fig. 1-2: QASP located at Bahawalpur [15]

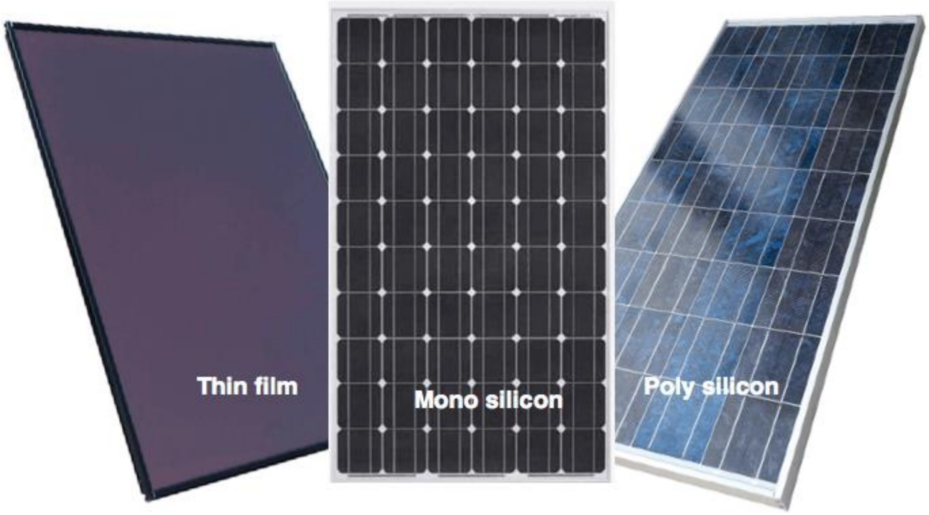


Fig. 1-3: PV module types [18]

1.4 Problem identification

Solar PV has great potential to meet the energy demand and has access to remote locations, but pollution and dust are the major environmental factors that greatly reduce the output power. Dust particles in the air get carried away by the wind and accumulated on the front surface of the PV module. Due to the thick layer of dust accumulated on the front surface prevents the solar irradiance to reach the underneath of glass to the solar cell junction and hence reduces the energy output of the PV module. The current installed solar PV modules lack an integrated cleaning system. Every day, a significant amount of electricity is not harvested due to dust accumulation on the PV module.

1.5 Justification of research

The energy generated from PV is increasing rapidly in recent years. The electricity demand of Pakistan increase by 28 % over the last four years and by 2025, it is expected to increase by 85%. The potential of PV in Pakistan is great and with its growing market. However, it is facing some technical and economic challenges. The selection of this topic is made by taking the following consideration:

- PV growth in the energy market
- Soiling problems facing by PV systems
- Lack of efficient and cost-effective cleaning system
- Solar energy potential in Pakistan
- GHG free power promoting

1.6 Advantages of the cleaning system

These are the following advantages:

- Cost-effective and efficient cleaning system for dust removal
- Time-saving and minimum usage of human resource
- Prevent any damage to the surface from cleaning
- Less maintenance cost and minimum usage of water
- Operate on the PV module power with low energy consumption.
- Recycling of water will save water and cost
- This system will be scalable to large PV farms
- It involves no heavy or complex mechanical structure.

1.7 Scope of the research

The experimental work has been conducted to determine the effect of dust on the electrical performance of the mono-PV and poly-PV module. A novel and cost-effective cleaning system have been proposed to remove the dust from the front surface of the cleaning system. The cleaning system is designed, fabricated and a series of experiments are performed using pressurize water through flat-fan nozzles to investigate its effect on the output power of the PV module. Furthermore, economic analysis has been performed to determine the profitable cleaning frequency of the PV modules. The economic analysis is conducted in terms of the cost of electricity, the cost of the cleaning system, and the total energy generated by clean and dirty PV modules. This study can help to analyze the soiling losses in terms of output energy and cost. Implementing the cleaning system can help to produce more energy, increase its operational life and improves the efficiency of the PV module system.

1.8 Potential for commercialization

Through research, it has been identified that there are three different markets for the proposed solar panel cleaning system

i. Residential solar PV systems
ii. Commercial solar PV system
iii. Large solar PV farms spread on acres

Each market offers different benefits and drawbacks. This cleaning system is more cost-effective on large PV systems. However, the operation and maintenance costs will increase with the PV system size. Although the residential PV systems are greater in number. A small number of solar panels generate relatively low energy than large PV panel arrays, so implementing a cleaning system can operate costly to generate a small amount of electricity on a residential solar PV system. The proposed system is scalable to all types of PV systems having solar panels of length around 2 m. The solar farm market has a large number of solar panels that will increase the profit margin by harvesting a large amount of electricity and minimizes the installation cost of the cleaning system. Commercial PV systems mostly installed on the institutional buildings, industry, parking, departments, and other buildings. Another potential customer is the solar companies, that install commercial PV arrays and willing to implement the cleaning system to generate a significant amount of energy.

1.9 Objectives of the research

The overall broader objective of this research is to develop a novel cost-effective cleaning system to remove the dust from the front surface of the PV module.

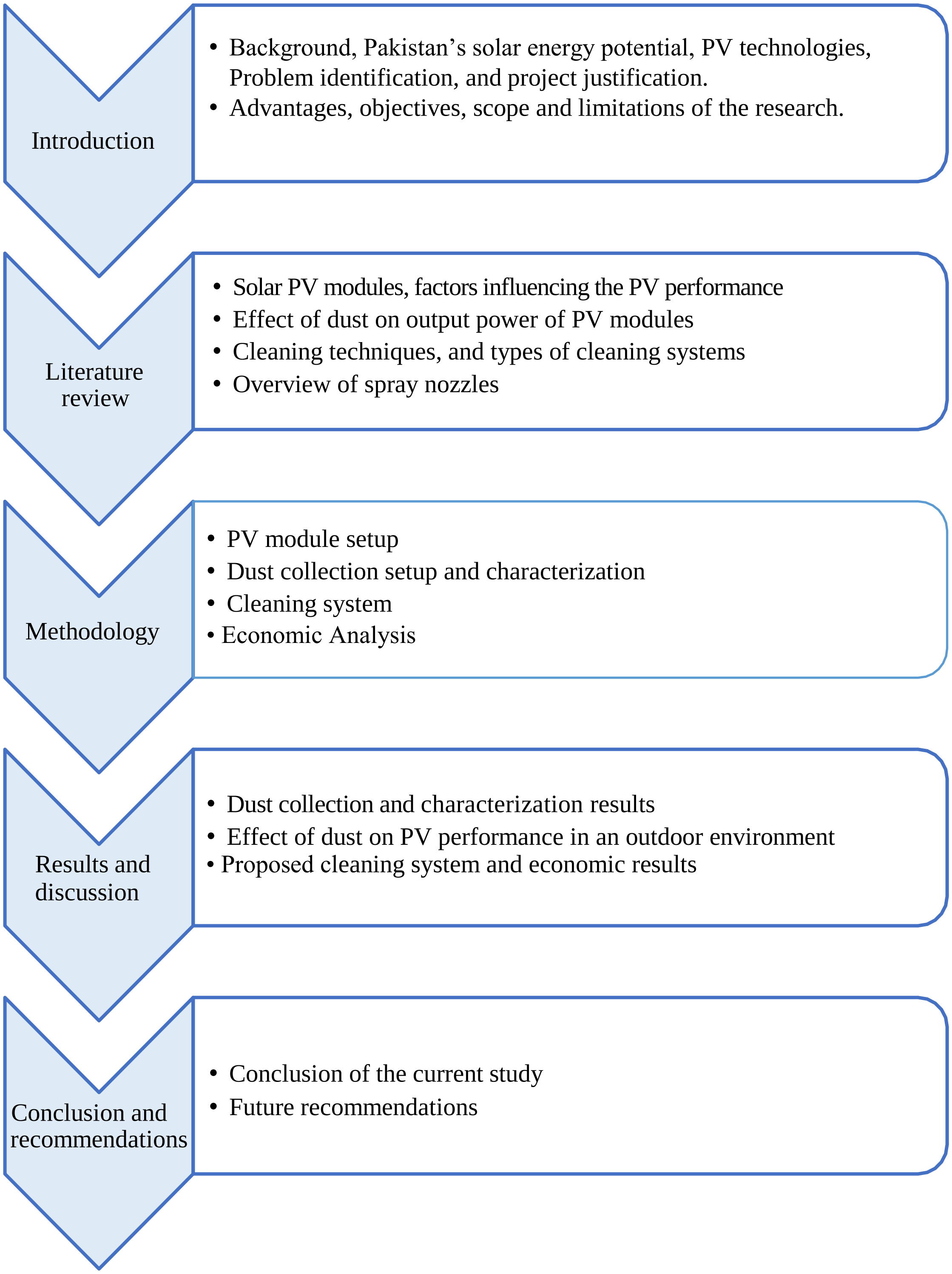
Following are the main objectives of the current study:

i. To measure the particulate matters and solar radiation.
ii. To measure the performance of solar PV modules under the dusty environment.
iii. Analysis of the effect of dust on PV module output power.
iv. Design, fabrication, and experimentation of the PV cleaning system.
v. Economic analysis of the PV cleaning system based on the experiments.

1.10 Limitations of Research

The research is carried out on two types of PV modules, monocrystalline and polycrystalline. The PV cleaning system will function effectively only by using pressurized water as a cleaning agent. The cleaning system is only tested using flat-fan nozzles. However, there are different types of flat-fan nozzles depends on the water flow rate, pressure, and angle that can be used for the cleaning purpose. To clean effectively with the minimum usage of water can be achieved by mixing water with surfactants. The outdoor experiment did not cover the whole year, particularly the winter season, where the dew factor can affect the output power of the PV module differently.

Thesis outline



Introduction

- Background, Pakistan’s solar energy potential, PV technologies, Problem identification, and project justification.
- Advantages, objectives, scope and limitations of the research.

Literature review

- Solar PV modules, factors influencing the PV performance
- Effect of dust on output power of PV modules
- Cleaning techniques, and types of cleaning systems
- Overview of spray nozzles

Methodology

- PV module setup
- Dust collection setup and characterization
- Cleaning system
- Economic Analysis

Results and discussion

- Dust collection and characterization results
- Effect of dust on PV performance in an outdoor environment
- Proposed cleaning system and economic results

Conclusion and recommendations

- Conclusion of the current study
- Future recommendations

Summary

Solar energy importance and the problems regarding its efficiency has been briefly discussed in this chapter. Several efficiencies degrading factors have been considered, dust effect and air pollution came out as a major problem in Pakistan. The solar energy potential in the country has been discussed from which solar PV technology is selected due to its advantages in Pakistan‘s scenario. Moreover, the objectives, scope, and limitations of the research are also stated in the end, the organization of the thesis has been discussed in a figurative way.

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Chapter 2

Literature Review

2.1 Solar PV modules

These are solar PV farms that harness solar energy by directly converting solar radiation into electrical energy. There are majorly two types of solar PV modules manufactured from crystalline silicon (c-Si) solar cells commercially installed in the world.

i. Monocrystalline PV modules

ii. Polycrystalline PV modules

2.1.1 Monocrystalline PV modules

Monocrystalline PV modules are made from cylindrical silicon ingots called single crystal that are cut into wafers and have higher efficiency due to the purity of silicon as they can perform well under low irradiation conditions. It has a long life span and a smaller installation area. While it is an expensive technology with low performance at higher temperatures. Fig. 2-1 shows the installation of the monocrystalline solar farm.

Fig. 2-1: Monocrystalline solar PV farm

2.1.2 Polycrystalline PV modules

It is also known as multi-crystalline solar panels, the melted silicon is poured into a square mold to produce polycrystalline shape. This silicon is cooled and then sliced into square wafers. The manufacturing process is simpler and cheaper. They perform well at high operating temperatures. Although it has low efficiency due to low silicon purity and requires large installation area than the mono-PV modules. Fig. 2-2 shows the polycrystalline solar PV farm.

Fig. 2-2: Polycrystalline solar PV farm [2]

2.2 Factors influencing the PV performance

The extensive amount of time and money has been spent to improve the efficiency and lower the cost of solar PV technology. The current research indicates a successful and credible improvement in efficiency and component reliability. However, much less time and money invested to investigate the externalities that can greatly reduce the efficiency of the PV module. Mostly the efficiency of a commercially available PV module is limited up to 20%, which is further reduced by environmental, manufacturing, and installation losses. The efficiency of the PV module can be affected by the following parameters: airborne dust, ambient temperature, solar irradiance, humidity, wind velocity, and installation angle [3].

- **Module temperature**

PV cell made up of semiconductor is very sensitive to temperature. The efficiency and output power of the PV module reduces with the increase of its temperature. This is due to the increase in internal carrier recombination rates caused by increased carrier concentrations. However, the voltage V_{OC} decrease for each degree K rise in temperature is higher than the increase in current I_{SC}. The temperature of a PV module increase with the increase in temperature of air and solar radiation, while the increase in wind speed will reduce the module temperature. The Overall power reduction of the PV module mentioned in the manufacturer datasheet is about 0.4 to 0.5 % per degree rise in temperature.

- **Degradation of PV module**

The manufacturer of the solar PV module usually guarantees a performance life of 25 years with the annual efficiency degradation rate of 0.2 to 0.5%. However, the reduction of efficiency is also mentioned in datasheet due to material degradation with operating duration. The efficiency degradation effect with the passage of time may be caused by chemical, electrical, thermal or mechanical nature [5].

- **Variation in solar radiation due to atmosphere**

The sunlight fall on the PV cell generates electricity by the photovoltaic effect. The performance of a PV module under varying solar radiation differs. The solar radiation can vary under different atmospheric conditions e.g clouds, rain, sandstorm and air pollution. The solar radiation is maximum during sunshine hours, variations in the intensity of solar radiation will impact the following parameters: Isc, Voc, power, FF, and efficiency as shown in Fig. 2-3. However, the PV module converts direct solar radiation into electricity more effectively than diffuse.

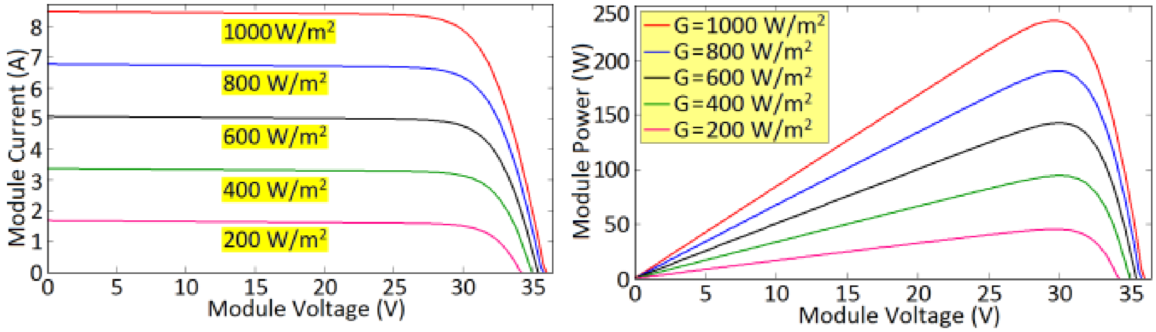


Fig. 2-3: Effect of solar radiation on module output power [3]

- **Shading**

Shading on the PV module is mostly due to trees and building which blocks solar radiation, coming directly from the sun to reach the solar cell. A small amount of shading on the PV module can have a large impact on its output power even a partial shaded cell can significantly reduce the output power as if all cells were shaded. A shaded cell produces much less current than the unshaded, as the cell is connected in series and the same current has to flow through all circuits. The more current generated by unshaded cell will force through a shaded cell and it will be heated and create a hotspot. To avoid that hot-spot heating of PV cells, a bypass diode is used as shown in Fig. 2-4.

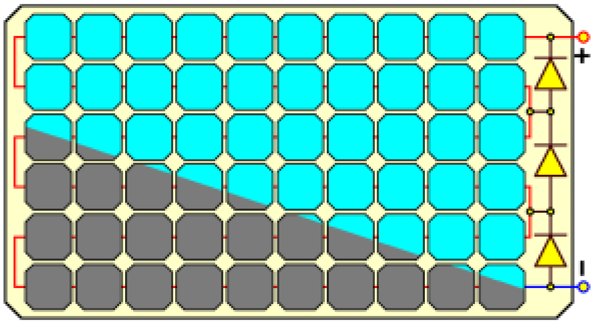


Fig. 2-4: Arrangement of bypass diodes in PV module [3]

- **Hotspot formation**

Hot spot heating occurs in a PV module when its operating current exceeds the reduced short-circuit current (Isc) of a shadowed or faulty cell or group of cells. When such a condition occurs, the affected cell or group of cells is forced into reverse bias and dissipates power, which can cause local overheating [3].

- **Parasitic resistance and Fill-Factor**

The series and shunt resistance of a PV cell are called parasitic resistances resulted in increasing the I^2R losses which eventually decreases the module efficiency. The series resistance (Rs) is the internal resistance of the PV cell e.g. metal contact, impurities, and resistance of the material itself. The shunt resistance (Rsh) represents the leakage resistance due to leakage current. For optimum performance, R_S must be low and R_{SH} must be high as possible [3].

The fill-factor is the ratio of the maximum output power to the product of Voc and Isc. Based on the I-V curve shown in Fig. 2-5, fill-factor can be represented as

$$\boldsymbol{Fill-Factor} = \frac{\mathbf{Vmax\,.Imax}}{\mathbf{Voc\,.Isc}} = \frac{\mathbf{area\ A}}{\mathbf{area\ B}} \qquad (1)$$

Fill-factor is the squareness of the PV cell and area of the largest rectangle which will fit in the I-V curve. A good quality PV module has fill-factor more than 70 %.

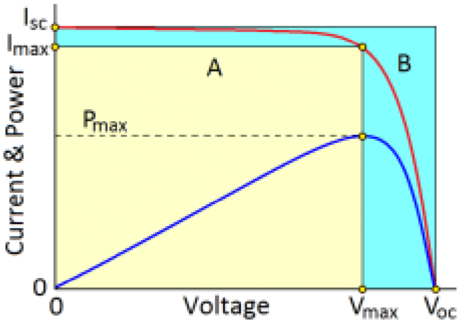


Fig. 2-5: Fill-factor of a module [3]

- **PV module orientation and tilt angle**

The maximum solar radiation falls on the PV module when it is facing exactly perpendicular to the incoming sunlight. This can be achieved through adjusting the array tilt angle (relative to the horizontal ground surface) and azimuth angle (it's east to the west orientation) [6]. The variation in the availability of solar radiations can be best understood from the geometry and the movement of the earth around the sun as shown in Fig. 2-6.

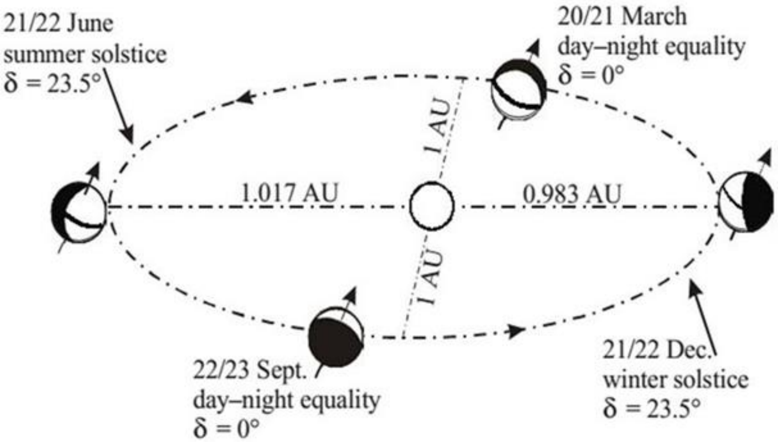


Fig. 2-6: Tilt of earth [7]

The sun position can be defined by two angles; altitude and azimuth angle as shown in Fig. 2-7. In general, the location in the northern hemisphere PV modules must be oriented towards the true south and southern hemisphere PV modules must be oriented towards the true north. At solar noon, the sun is at its highest elevation in the sky and strike intense radiation on earth. The module tilt angle is the angle between the PV module and a horizontal surface. In general, the rule of thumb for the optimum tilt angle set at $\phi \pm 15^{o}$, where, ϕ is the latitude angle, '+' for winter and '-' for the summer season. However, there are three types of PV installation techniques available: dual-axis tracking arrays, single-axis tracking arrays, and fixed tilt angle arrays.

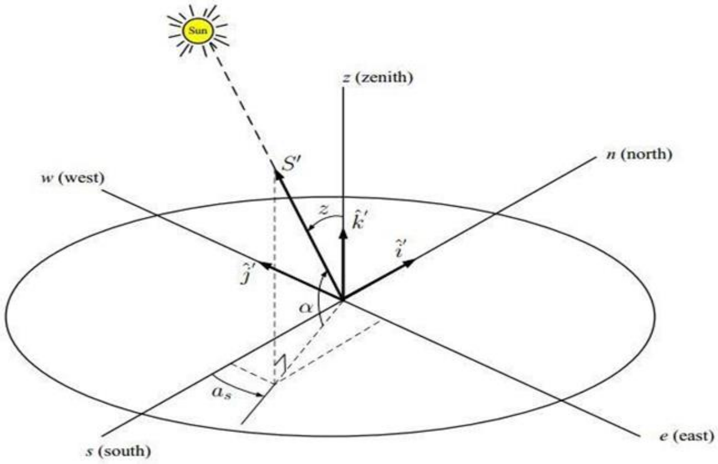


Fig. 2-7. Solar angles [8]

- **Soiling effect**

Soiling is the accumulation of dust, dirt and other contaminated particles present in the air due to air pollution on the front surface of the PV module. A thick layer of dust and dirt tends to block the solar radiation from reaching the PV modules, reduces the output power as shown in Fig. 2-8.

Fig. 2-8: Dust accumulation on PV modules

Dust deposition depends on the particle size, shape, and weight, location, height, wind velocity, weather condition, and module tilt angle. Horizontal installations of PV module avoided to prevent more build-up of dust on the surface and block the solar radiation.

Wind and rain can wash away the dust accumulated on the surface of the PV module. Rooftop PV systems experience lesser soiling effects as compared to ground-mounted systems [4].

2.3 Effect of dust on the output power of PV modules

Soiling effects are the dominating reason for the reduction in the efficiency of a solar PV module [9]. Dust characterization is typically size, distribution, density, composition, and shape. Due to the thick layer of dust accumulated on the front surface, the efficiency of the PV module reduced up to 35 % [10]. Dust particles in the air get carried away by the wind and accumulated on the front surface of the PV module, which prevents the solar irradiance to reach the underneath of glass to the solar cell junction and hence reduces the energy output of the PV module. The transmittance losses of solar radiation at different dust densities are shown in Fig. 2-9.

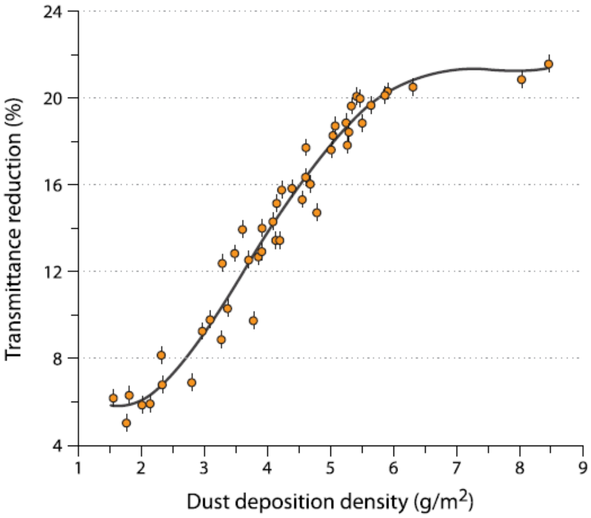


Fig. 2-9: Transmittance reduction at different dust densities [11]

Dust leads to spectrum filtering and therefore reduces the input energy of the PV module in some specified parts of the solar spectrum, depending on the dust particle size and chemical composition. The low speed of wind carries the small size dust particles which tend to block more solar radiation, induce more scattering of light, distributed uniformly with a higher dust accumulation rate, and stick to the surface stronger than the large size dust particles [12,13]. While the large size dust particles can be easily detached off the PV module surface and rolled down from the slope by a low velocity of wind [14]. Moreover, the dust contains charcoal, ash or other lightweight particles, which are more effective towards the reduction of the PV performance [15]. Lu and Zhao (2019) stated that the dust deposition rate is higher on a ground installed PV system than a rooftop installed PV system and the PV module installed at a fixed tilt angle accumulated more dust on the surface than a single or double axis tracking solar PV module system [16]. Alnaser et al. (2018) found that the annual electricity loss of the PV module reached 17 % in the kingdom of Bahrain if it remained uncleaned for the whole year including the natural cleaning [17]. But if it cleaned once a year, its annual electricity loss reaches 7 %. The PV system is shown in Fig. 2-10.

Fig. 2-10: Comparison between clean and dirty PV module output performance [17]

Similarly, Mazumder (2011) observed that the dust density of only 4 g/m² accumulated on the surface can reduce the output power of the PV module by 40 % with the dust particle size ranges between 0.5 μm and 10 μm [18]. Boykiw (2011) found that the effect of dust can decrease the PV efficiency by 5–6 % in 1 week depending on the dust deposition rate [19]. Furthermore, Elminir et al. (2006) found that the dust deposition on the front surface of the PV module can reduce the output power by 17 % per month and the PV system was installed in Egypt at a 45° tilt angle facing south [15]. Jiang et al. (2016) reported that the cleaning frequency of the PV module at 0° tilt angle in the dessert area is about 20 days with the dust deposition density of 2 g/m² and output power reduction of 5 %. The average diameter of the dust particle was 2 μm [20]. The rate accumulation of dust is directly related to the cleaning gap of the PV modules, it depends on the location, height, and other factors as shown in Fig. 2-11.

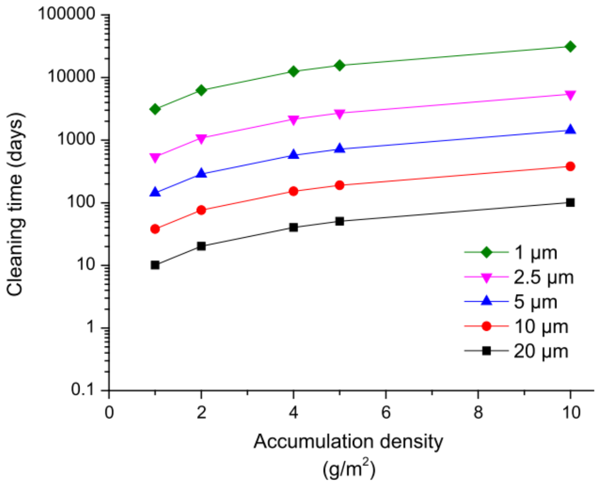


Fig. 2-11: Cleaning time for various dust densities [20].

Hachicha et al. (2019) observed that the dust accumulation strongly depends on the installation angle of the PV module, the high tilt angle accumulates less dust on the front surface of the PV module and results in less reduction in output power. The PV performance analyzed at 0°, 25°, and 45° tilt angles for two weeks and it shows 37.63 %, 14.11 %, and 10.95 % output energy loss, respectively as shown in Fig. 2-12 [21]. Elminir et al. (2006) reported that the dust density at 45° tilt angle was 15.84 g/m² and at 90° tilt angle was 2.48 g/m², collected on the glass sample [15]. The setup can be seen in Fig. 2-13 and results in Fig. 2-14.

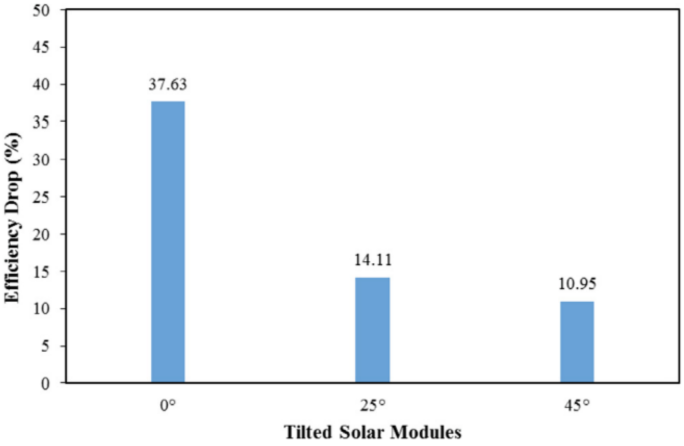


Fig. 2-12: Efficiency drop at different tilted PV modules [21]

Fig. 2-13: Glass samples exposed to the environment for dust collection [15]

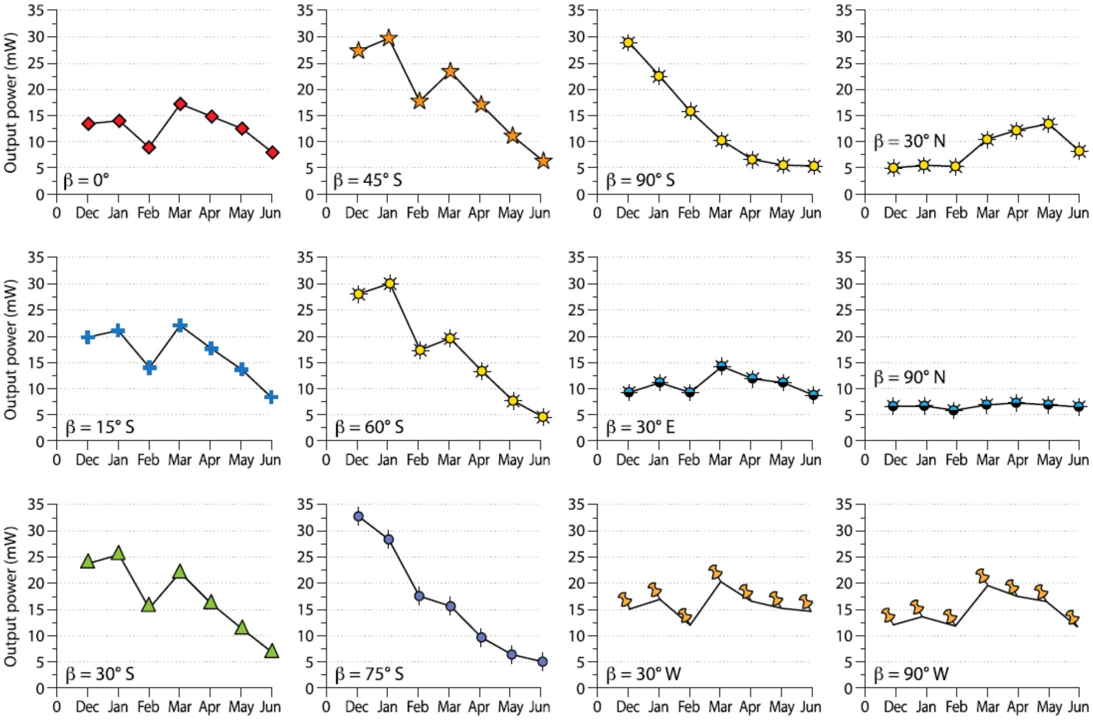


Fig. 2-14: Effect of natural soil on the output power of PV modules [15]

The dust deposition rate depends on the seasonal variation, the accumulation of dust is higher in the duration of a sand storm, high humidity and less rainfall [22]. Therefore, frequent cleaning of the PV module is necessary to prevent soiling losses.

2.4 PV cleaning techniques

Research has been conducted to investigate the cleaning mechanism currently implemented for dust removal. Currently, there are a number of cleaning solutions that exist for the removal of dust. These are typical systems only feasible on large solar PV farms involve complex built and heavy structure, which has high operating and maintenance cost. However, there is not a clear solution available to the problem. Today, most solar panels are cleaned physically washing with water mixed detergents and labor. This technique is with labor, water, resource and time taking, which can further turn into high operation and maintenance costs. The current installed solar PV modules lack an integrated cleaning system. Every day, a significant amount of electricity not harvested due to the accumulation of dust on the front surface of the PV module. Traditionally the cleaning of PV modules has been performed manually but it has disadvantages such as the risk of staff accident and damage to the PV module, mobility constraints, time-consuming, less efficacy and other influencing factors [23]. While an effective cleaning technique should be cost-effective, reliable, efficient, easy to implement, and automatic [24]. Zorrilla-Casanova et al. [25] stated that the cleaning of the PV module front surface with water is an effective technique than dry cleaning to recover its efficiency but implementing it in a water shortage area like dessert, makes it expensive. Mavroidis et al. [26] designed a robot device for cleaning the PV module arrays by spraying water over its surface, which can further increase its efficiency by up to 15 %. This device is not beneficial because it is an expensive, complex design, and it involves heavy structure and no recycling of water. Anyhow, cleaning of the PV module with water can save the front glass surface from scratches induced by rubbing and cracks by putting weight. Currently, research on the cleaning of the PV module has been carried out, but there is a deficiency of reliable, scalable, and cost-effective cleaning solutions. For the cleaning system to be economical and feasible, the cleaned PV module system must produce more electricity than electricity loss caused by the effect of dust. Faifer et al. (2014) [27] recommended that the cleaning becomes essential for the PV module system when the cost of electricity production losses due to dust is greater than the maintenance and cleaning cost. The economic analysis performed by Yang (2015) [28] reveals that the total cost of electricity production losses of the PV modules caused by dust at the specific deposition rate should be higher than the total cleaning cost. After this, the cleaning technique can be cost-effective for the PV modules. Jiang et al. (2016) has also described the criteria for cleaning that is defined at 5 % reduction in output power of the PV module. The cleaning frequency determined, by Jiang et al., for a conventional PV module is 20 days with the dust density accumulation of 100 µg/m3. However, it is not an economical criterion for the cleaning of PV modules considering the location of current experimental work and therefore it is advisable to conduct real time experiments to determine the cost-effective cleaning solution [29].

There are several cleaning mechanisms employed to tackle the problem, such as manual cleaning with water and labor, mechanical removal of dust by brushing, blowing, vibrating, ultrasonic, electrostatic, hydrophobic coatings and vacuum suction [30,31]. Some of them are discussed here.

2.4.1 Manual cleaning

This method needs a human operator to clean the solar PV modules manually as shown in Fig. 2-15. The manual cleaning can be done with the help of a water shower, mop or any kind of wiper and brushes. The process is very tedious and time taking. There is a risk of panel damage and human security [31].

Fig. 2-15: Manual cleaning [17]

2.4.2 Wiper based cleaning

Wiper based cleaning of PV modules front surface is done with the help of rubber wiper and water pot sprayed and cleaned with wiping action by a robot as shown in Fig. 2-16. The process is related to the vehicle's front glass cleaning system. It can be an automatic or manually operated system. However, this system involves mechanical structure and expensive to build [31].

Fig. 2-16: Automatic wiper based cleaning [31]

2.4.3 Brush based cleaning

The brushing method is used to clean the PV module with the help of a broom or brush that was driven with a machine or robot as shown in Fig. 2-17. This method is inefficient for adhesive dust and the maintenance of the machine is difficult [32].

Fig. 2-17: Brushed based cleaning [33]

2.4.4 Electrostatic cleaning

The electrostatic system consists of two parallel wire electrodes embedded on the glass plate of a PV module and a high-voltage is applied that generates a single-phase rectangular voltage as shown in Fig. 2-18. The alternative electrostatic field generates a standing wave that charges the dust particles and causes a flip-flop motion of the dust particles on the PV module surface and with air, the dust particles rolled down with gravity. However, this technology is not suitable for a large scale of PV systems because it requires a high amount of electrodes to implement and the electrodes create a shadow on the glass surface of the PV module [34].

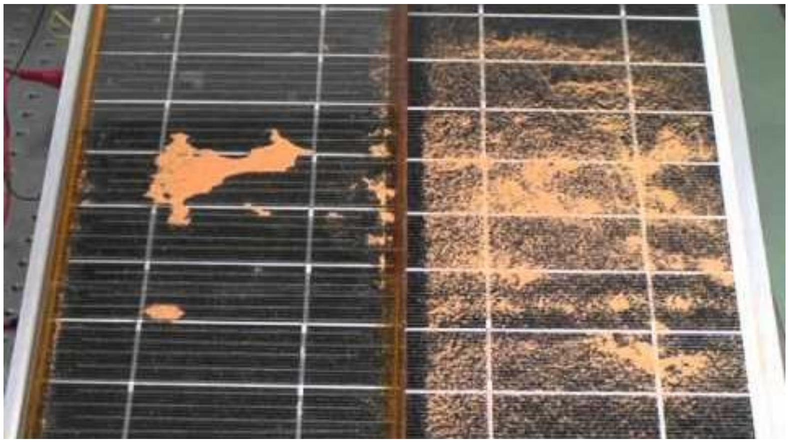


Fig. 2-18: Electrostatic removal of dust [35]

2.4.5 Vacuum suction cleaning

A vacuum suction cleaner is a device that uses an air pump to suck the dust on the front surface of the PV module as shown in Fig. 2-19. However, it requires a human to operate the vacuum cleaner to clean. The electrical supply is required for the vacuum cleaner for cleaning. Cleaning with this device can damage the PV module surface by scratching the surface and reduce the ability of absorption of solar radiation [31].

Fig. 2-19: Vacuum based cleaning [31]

2.4.6 Water sprinkler based cleaning

Water sprinkler is used to clean the dust from the surface, it is an effective technique to clean. The water sprinklers are fitted on the top of the PV module arrays and a pump is required to push the water with speed to spray it on the PV module surface as shown in Fig. 2-20. Water should be clean to wash the PV modules. The energy is required to pump the water only. The system can be automatic or manual controlled.

Fig. 2-20: Cleaning with water sprinklers [36]

2.4.7 Coating based cleaning

The hydrophobic coating acts as an anti-dust coating and reduces the accumulation of dust particles from settling and sticking on the surface of the PV module. It also helps to repel water, slid particles and other liquids. While superhydrophobic coatings make the surface highly water repellent and anti-dust coating. The water droplets fall on the coated surface and it rolls down caring dust particles with it. In this way, the surface remains clean for a long time as shown in Fig. 2-21. the anti-reflecting coating can reduce sunlight reflection and increase the amount of solar radion to be absorbed [37].

Fig. 2-21: Super Hydrophobic Antireflection coating PV modules [37]

Table 2.1: Summary of cleaning technologies for PV module

Reference	**Type of cleaning technology**	**Key findings**	**Comments**
Alnaser et al. [17]	Manual cleaning	The manual cleaning of PV modules produces 16% more electricity than the dirty PV modules for a period of 15 months.	The process is very tedious and time taking. There is a risk of human error, panel damage, and human security
Mohammed et el. [38]	Wiper based cleaning	The efficiency of the PV module is improved by 50%, implementing the wiper based cleaning system	This system involves mechanical structure, motors and actuators, and expensive to build.
B et al. [30]	Brush based cleaning	The automatic cleaning system based on the brush is proved effective towards the dust cleaning and consuming very low power.	Due to the large area of the solar cell array, the cleaning machine is powerful. Lastly, the surfaces of the solar cell may be were damaged by the brush when wiping or rotating the brush over the surface.
Kawanoto and Shibata [34]	Electrostatic cleaning	This technique uses electrostatic force to remove sand from the surface of the PV module. It has been found that more than 90 % of sand particles can be repelled from the slightly inclined surface effectively.	This technology is not suitable for a large scale of PV systems because it requires a high amount of electrodes to implement which is costly and the electrodes create a shadow on the glass surface of the PV module
Arvind el al. [39]	Vacuum suction-based cleaning	An automatic robot device with a vacuum cleaner is tested on the solar panel. The two-stage cleaning mechanism is very effective in removing the upper dust layer.	The electrical supply is required for the vacuum cleaner for cleaning. Cleaning with this device can damage the PV module surface by scratching the surface and reduce the ability of absorption of solar radiation
Heliotex [36]	Water Sprinklers based cleaning	The Heliotex company uses a water sprinkler system with soap and detergents solution to remove the dust effectively. It uses hollow cone spray nozzles and operates at night.	The cleaning with pressurizing water through nozzles is one of the most effective techniques. Using flat-fan nozzles can be more helpful. While it’s a cost-effective cleaning system to install
Mishra et al. [37]	Hydrophobic coatings	By combining the two properties: superhydrophobic and anti-reflective coating, applying on solar PV module front surface can increase the efficiency of solar cells by 25-40 %.	The lifetime of the coating as compared to the PV module is very less and an expensive technique. Hence, This method is not suitable for large PV farms.

2.5 Spraying nozzles overview

A spray nozzle is a device, which makes use of the pressure energy to increase its speed through an orifice and breaks it into drops. The nozzle has either an angled cut or a sloping deflection face to create the fan spray pattern. There are numberless application and type of nozzle are being designed and implemented e.g. applications in many industrial processes. The efficiency of the process is critical for nozzle designing which depends on its quality and other parameters. Different types of spray nozzles required for different applications, the main applications are cooling, coating, washing and scrubbing, and humidification as shown in Fig, 2-22 [40-42].

When selecting the spray nozzles, there are some important factors like the purpose of spraying, type of liquid, direction, width, thickness, and shape of the nozzle. The spraying system will also provide information about the droplet size spectrum, droplet speed, and liquid distribution onto the spray target. Classification of nozzles according to their spray shape and distribution is shown in Fig. 2-23 [43].

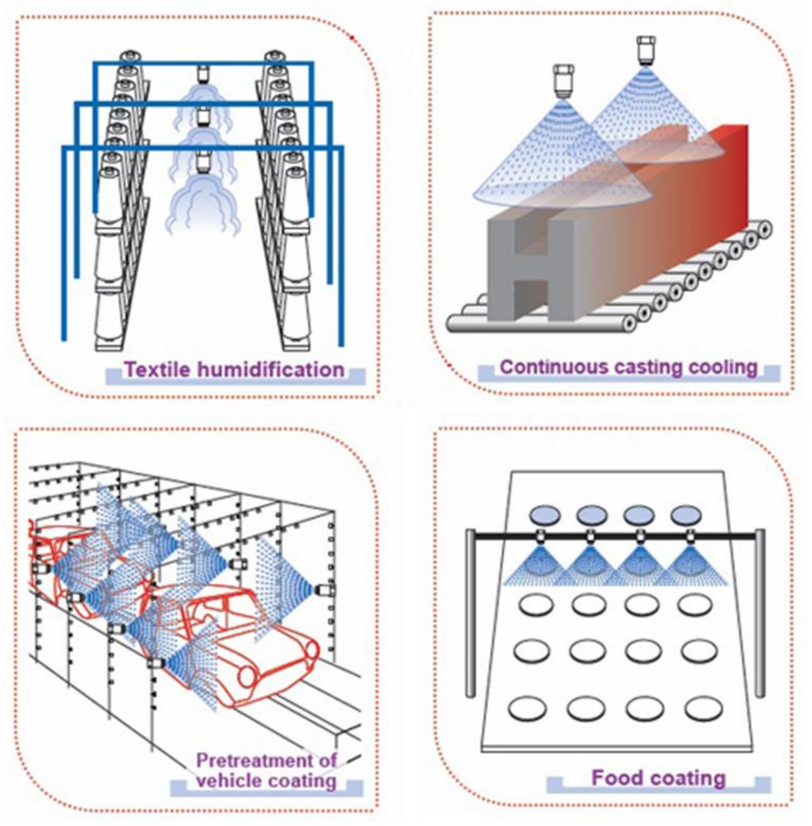


Fig. 2-22: Applications of nozzle spraying [41]

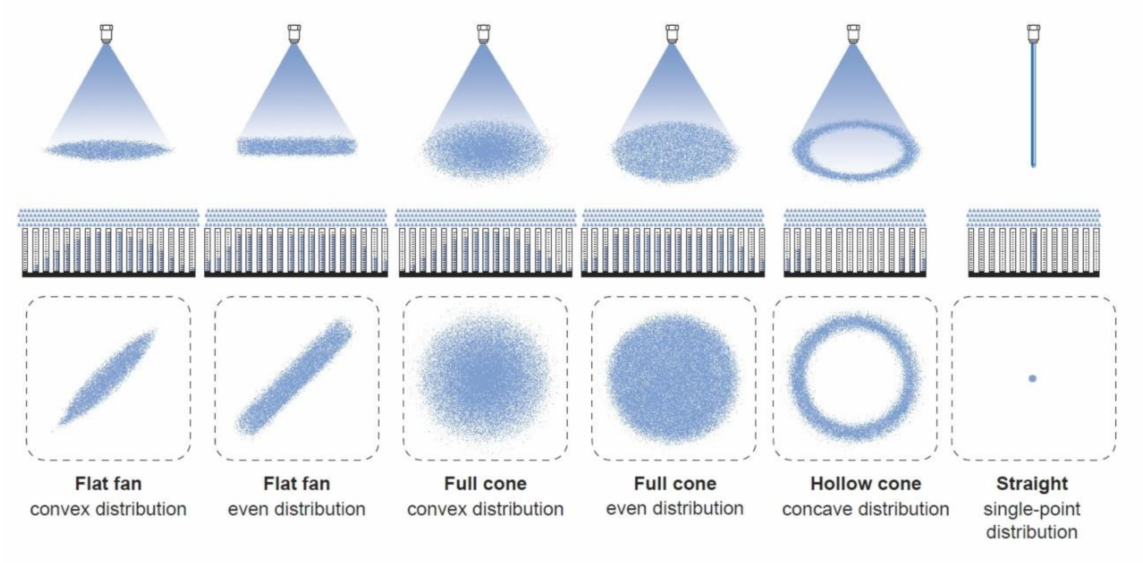


Fig. 2-23: Types of nozzles depend on spray shape [42]

2.5.1 Characteristics of spray nozzle

Some technical features must account for nozzles selection are as follows:

- Nozzle Efficiency
- Droplet size
- Spray angle
- Impact Force
- Spray distribution
- Nozzle feed pressure
- Flow rate/Capacity

2.5.2 Nozzle selection

A flat fan nozzle generates a pillar flow or fan-shaped spray pattern by a strong impact, so it has been widely used for cleaning or washing. Flat fan nozzles are mostly used for efficient surface cleaning and removal of dirt by water. The spray section is rectangular and even spray distribution with high pressure [44].

Flat fan Nozzle are categorized on the basis of these features

- Low pressure/ wide-angle
- High impact
- Dovetail flat fan nozzle

Flat fan nozzles are mostly used for efficient surface cleaning and removal of dirt by water because of the following characteristics:

- Even distribution of water
- Flat surface cleaning
- Pressurize water to remove the dirt
- Wide spray angle with greater impact force to clean the large area of panel front surface
- Minimum usage of water with high efficiency
- Low head loss and no mist spray
- Corrosion resistance to saltwater
- Wide range of flow rates

Flat-fan nozzles are mostly used based on the. its spray pattern and distribution, nozzle tip design and offset angle.

- **Based on spray pattern and distribution**

Standard convex distribution:

In a standard convex spray distribution, the medium section has a larger capacity than the two lateral sections. It is necessary to overlap 50% of the spray range as shown in Fig. 2-24 [45].

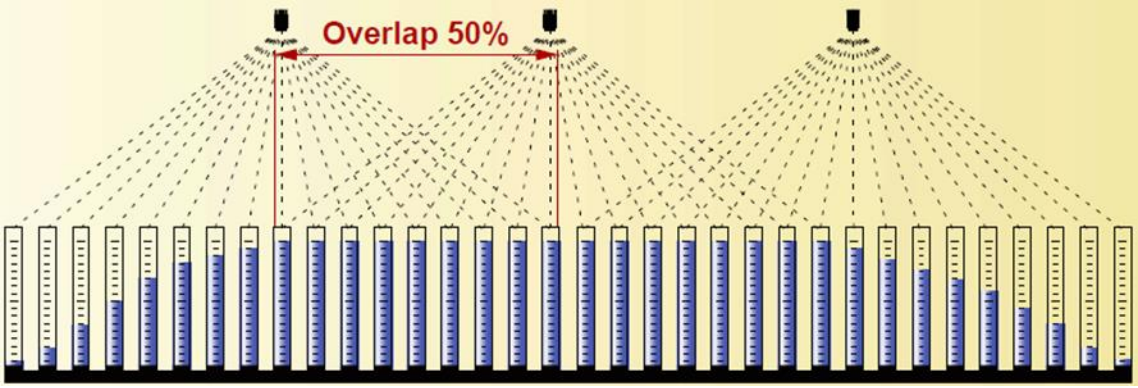


Fig. 2-24: Convex distribution of Flat-fan nozzle [45]

Standard even distribution:

An equal distribution provides a uniform spray and 10% of the spray range overlaps as shown in Fig. 2-25 [45].

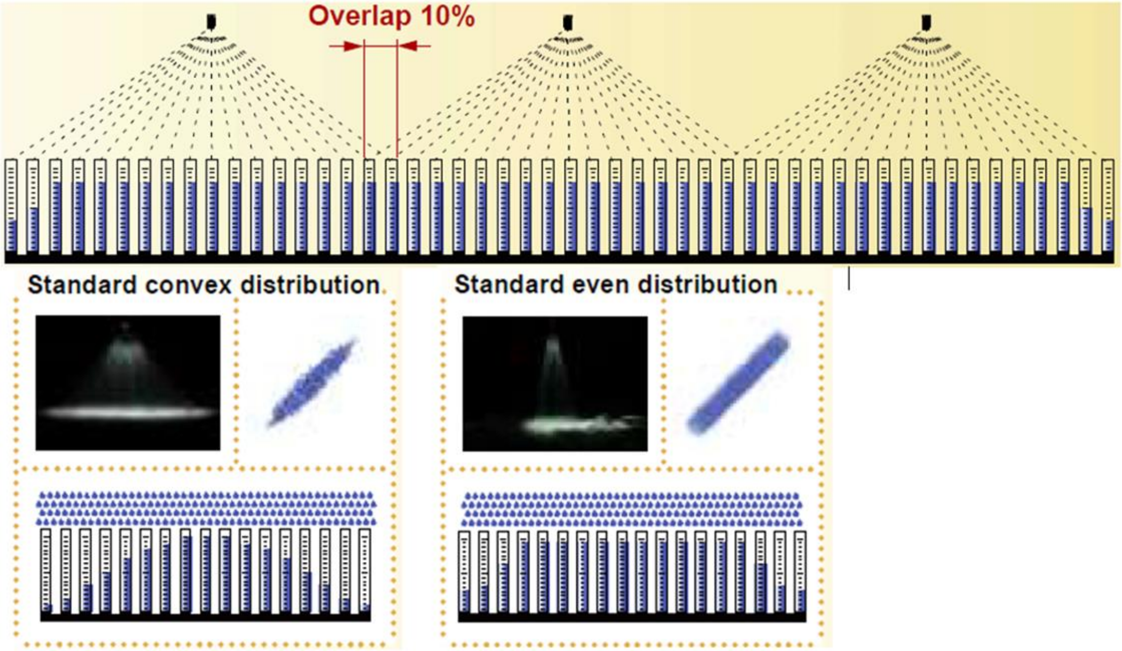


Fig. 2-25: Even distribution of Flat-fan nozzle [45]

- **Equivalent Nozzle Tip Design**

Cat-eyed shaped:

Flat fan nozzle produces cat-eyed shaped spray pattern with different capacities, this type of nozzle tip produces a convex distribution of water as shown in Fig, 2-26. It is used for large capacities and a wide-angle [45].

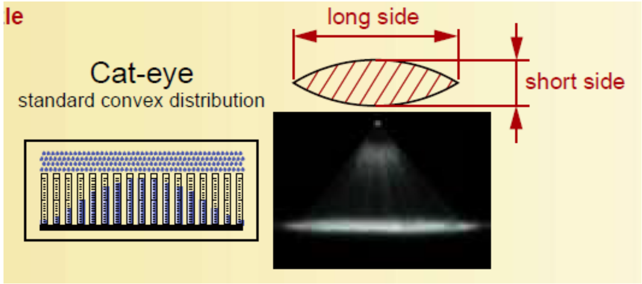


Fig. 2-26: Cat-eyed shape pattern [45]

Parabolic shape:

Flat fan nozzle produces a rectangular-shaped spray pattern with different capacities, this type of nozzle tip produces even distribution of water as shown in Fig. 2-27. It is used for even distribution of high-pressure water [45].

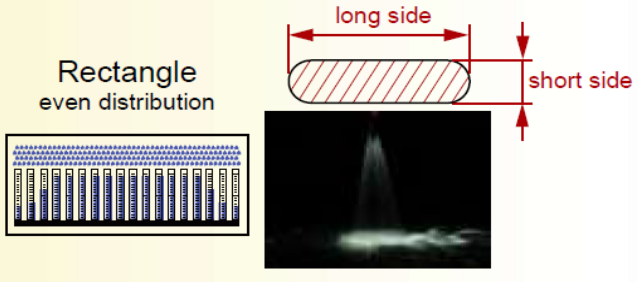
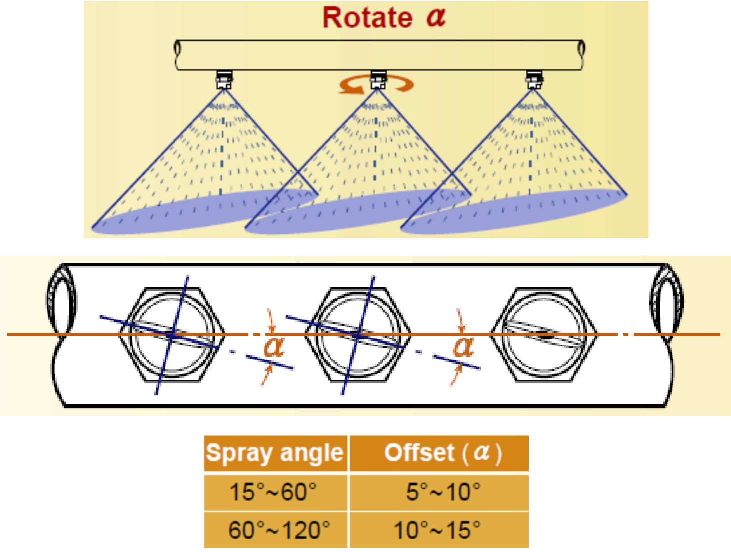


Fig. 2-27: Rectangular shape pattern

- **Offset**

Offset angle is used to avoid overlapping and interference of showering the water. The offset angle depends on the spray range of the nozzle as shown in Fig. 2-28 [45].



Spray angle	Offset (α)
15°~60°	5°~10°
60°~120°	10°~15°

Fig. 2-28: Offset spray angle for Flat-fan nozzle [45]

Summary

Mostly two types of PV modules used for installation are monocrystalline and polycrystalline PV module. The commercial PV module efficiency is limited up to 20% due to its semiconductor material nature. Its efficiency further reduces by environmental, location, installation, manufacturing and other factors. Dust is a major environmental concern that greatly reduces the output power of the PV modules. There are several cleaning techniques and systems available to tackle the problem. However, there is a lack of clear, integrated and suitable cleaning system for all kinds of PV systems.

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Chapter 3

Research Methodology

This research proceeds with the designing of a suitable experimental setup and procedure to conduct the experiment. The proposed experimental setup has been developed to study the effect of dust and cleaning system on the energy generation of PV modules. The schematic of the proposed experimental setup is shown in Fig. 3-1. To further explore the effect of dust, it has been characterized for surface morphology, elemental composition and particle size analysis. The economic analysis using different parameters pretends to find a cost-effective and feasible cleaning solution for the removal of dust, accumulated on the front surface of the PV module. The flow diagram fo the process is shown in Fig. 3-2.

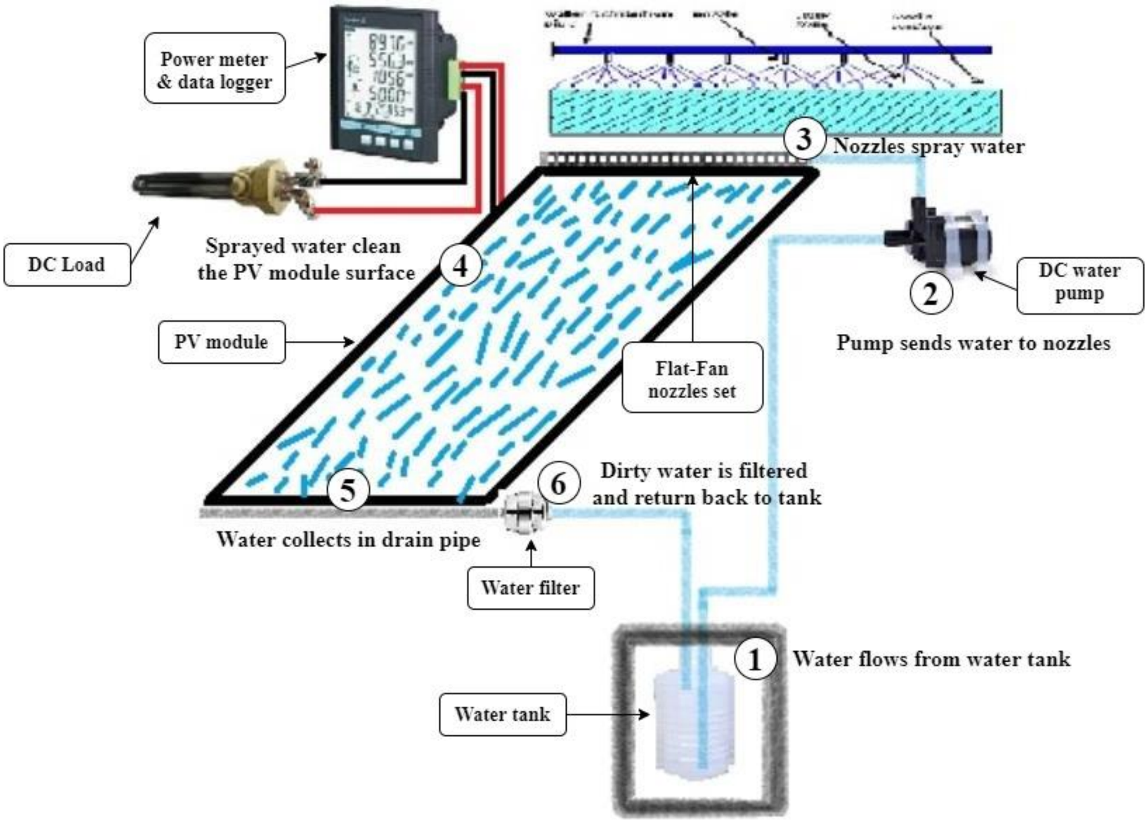

Fig. 3-1: Schematic diagram of the proposed setup

The outdoor experiments are conducted on the rooftop of the USPCASE, NUST, Islamabad building for two months from 1st July 2019 to 31st August 2019. The data is collected and analyzed for only clear days when the daily solar radiation is almost the same for each day so that the effect of dust on the PV performance is not affected by other factors such as the sandstorm, rainfall, and cloudy days. In this way, a clear understanding of the effect of dust on the output performance of PV modules can be seen through results [1]. This setup is designed and built to study the effect of dust and pollutant on the electricity production of PV modules, present in the atmosphere. The experiment involves testing of a novel water cleaning system to remove the dust. The experimental setup consists of a PV modules setup, and a dust collection setup, and a cleaning system.

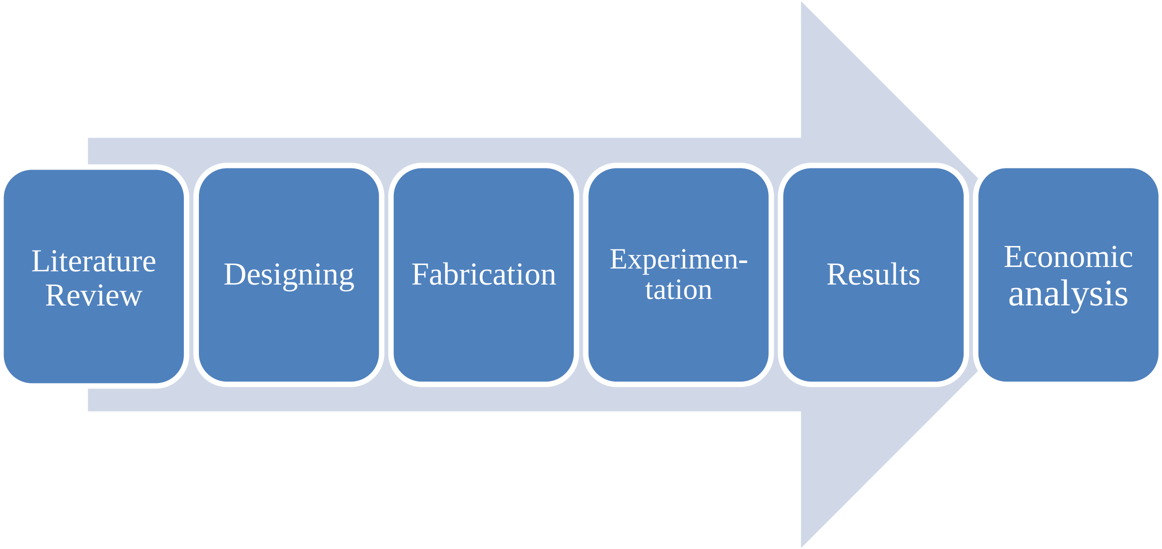

Fig. 3-2: Flow diagram

3.1 PV modules setup

The PV module setup consists of two mono-PV modules (40 watts), two poly-PV modules (40 watts), an adjustable mounting stand, DC bulbs as a load connected to the PV modules, and a DC power meter data logger which is used to record daily energy generation by each PV module as shown in Fig. 3-8a. A pyranometer is placed on the same plane as that of the PV modules in order to get the solar radiation data as shown in Fig. 3-3. The PV modules installed at the tilt angle of 34.5° facing south, as the location (Islamabad) has a latitude of 33.7°. The type of PV module technology used in this experiment is the mono-PV and poly-PV module with the electrical specifications given in Table 3-1. The dust is naturally accumulated on the front surface of PV modules to study its effect on the output power. Two sets, each set contains two PV modules (mono-PV and poly-PV), have been used to conduct the experiment. Each set has a dimension of 0.98 (L) m x 0.67 (W) m x 0.035 (T) m and an area of 0.66 m². One set is left dirty and the other set is cleaned (using the proposed cleaning system as discussed in section 2.3) every day at 10 am in the morning for a duration of 2 months as shown in Fig. 3-4. The output energy (Wh) of clean and dirty PV module sets has been recorded each day by using a DC power meter data logger as shown in Fig. 3-5.

Fig. 3-3: LI19 pyranometer | Hukseflux

Table 3-1: Electrical and physical specifications of the PV modules

Parameters	***Mono***	***Poly***
Model no.	SLS-M6U (39)	SH-40
Maximum Power (P_{max})	40 W	40 W
Voltage at maximum power (V_{mp})	19.5 V	17.28V
Current at maximum power (I_{mp})	2.14 A	2.31 A
Open circuit voltage (V_{oc})	24.96 V	21.6 V
Short circuit current (I_{sc})	2.37 A	2.47 A
Power tolerance	0.0-5.0 %	0.0-3.0 %
Max series fuse rating	15 A	15 A
Operating Temperature	-40°C to +85°C	-40°C to +90°C
Weight	4 kg	5.75 kg
Dimensions length (L) x width (W) x thickness (T)	0.64 x 0.51 x 0.035 m	0.67 x 0.45 x 0.033 m
Test conditions	1000 W/m², AM 1.5, 25°C	1000 W/m², AM 1.5, 25°C

Fig. 3-4: Clean and dirty PV modules

Fig. 3-5: DC power meter data logger

3.2 Dust collection set up and characterization

The dust collection setup consists of a steel stand, six pieces of glass, and a digital weight balance. While the glass piece has 2 mm thickness and 0.0216 m² of the area is used to collect the dust. The steel stand has 3 rectangular small frames with adjustable tilt angles (set at 15°, 34°, and 60°) as shown in Fig. 3-6. The 15° tilt angle is selected because this angle is suggested for a roof slope of a PV installation on parking area, 34° is the tilt angle of PV module setup and 60° tilt angle is selected for a higher value of tilt angle to study the dust accumulation variation. Each small frame contains 2 pieces of glass with numbering to identify different samples. The accumulated dust has been weighed by a digital weight balance (Radwag AS 220.R2) as shown in Fig. 3-7, this device can measure 0.1 mg of dust with weight ranges from 10 mg to 200 g. The steel frame is placed next to the PV module setup, facing south as that of the PV module's setup.

Fig. 3-6: Dust collection setup.

Fig. 3-7: Digital weight balance

The dust samples (glass plates) have been collected at different tilt angles for the same duration and under the same environmental exposure to measure the dust density. Initially, the clean glass plates weighed before the start of dust accumulation using digital weight balance and each day the small amount of dust gets accumulated on the surface area of glass plates, weighed every two or three days later. The rate of dust deposition on a surface area is measured in terms of dust density, which is defined as the dust weight divided by the surface area. The area of a glass piece is known, and the dust weight can be measured by an increase in the mass of the glass plates, during the time period of dust accumulation.

Dust characterization is necessary in order to investigate the effect of dust on the PV performance. Every location has its own type of dust with unique characteristics. Each type of dust blocks a different percentage of solar irradiance with same dust density[2]. The collected dust is initially characterized for particle size, mineralogical composition, surface morphology, and compound analysis. BT-9300ST Laser Particle Size Analyzer is used to analyze the particle size ranging from 0.1 um to 1000 um. Surface morphology and elemental composition are determined by Tescan VEGA3 XM SEM and Oxford Instruments X-Max 50 EDS, operated at 20 kV beam voltage. The structural analysis is done by Bruker D8 advanced X-Ray Diffractometer with a Bragg-Bentano θ:2θ configuration in a range of 20°-60° using CuKα as a radiation source [3].

3.3 Cleaning system

The cleaning system is designed using the effective cleaning technique with a minimum usage of water by recycling it. The cleaning system consists of a 1 m long steel pipe with a diameter of 0.016 m installed on the top of the PV module set shown in Fig. 2a. The steel pipe has eight flat-fan nozzles with a convex spray pattern connected to it with the spacing of 0.12 m to overlap 50 % of spray pattern for uniform distribution of water, sprayed on the front surface of the PV module. The flat-fan nozzle (model VP110 015) having a maximum water flow rate of 0.45 L/min, maximum pressure of 0.2 MPa and spray angle of 110° has been used. A dc diaphragm pump of 36-watt power capacity with a maximum water flow rate of 4 L/min and a maximum pressure of 0.65 MPa is used to pump the water through flat-fan nozzles. Fig. 3-8b shows the design of the proposed cleaning system including nozzle selection, spacing, and placement integrated with the dc centrifugal water pump to provide optimum cleaning. The cleaning system is powered by a dry lithium-ion battery (18 Ah, 12 V) placed in the experimental setup. There is a water flow meter connected between the pump and nozzle pipe to measure the water flow rate of the cleaning system, ranging from 0.1 GPM to 5 GPM. The water is collected from the surface of the PV module through a water collector pipe. The collected water is filtered by one stage charcoal filter so that the water can be reused for cleaning. The filtered water prevents blocking the nozzle hole. The one-stage granular activated coconut shell carbon filter has a diameter of 0.06 m, filtration of 5 microns, and capacity of 10,000 L. A water tank of 20 liters capacity is used to collect and store the water.

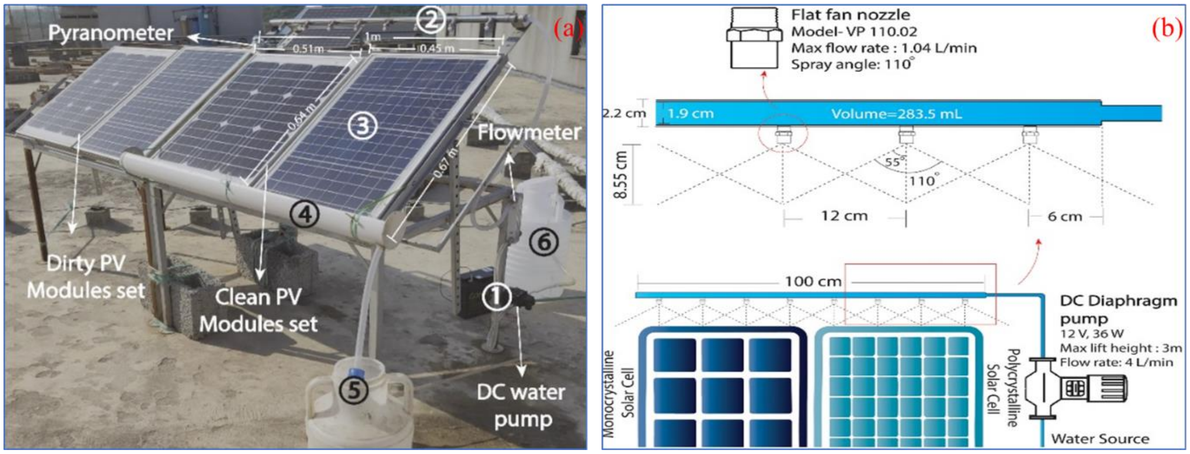

Fig. 3-8**:** (a) PV module setup with the cleaning system (b) Cleaning system design using flat-fan nozzles.

This cleaning system uses the pressurized water to safely clean the front surface of the PV module and recycle the water by collecting it through the drain pipe and then filter it back to the water tank. The cleaning of PV modules begins from centrifugal pump which starts injecting water from tank to the nozzles pipe. The water nozzles installed at the upper side of the modules, spray water on the front surface of the PV module and clean the surface effectively. The dirty water from the cleaned surface of PV is collected in a water collector pipe. After that the dirty water moves to the filter for recycling. The one-stage filter placed next to the water collector pipe will filter the water and send it into drain pipe. In the last step, the filtered water from drain pipe goes into the water tank where it restarts the cleaning cycle. This cleaning cycle of water is shown in Fig. 3-8a and in Fig. 3-9 with the step number to make all the sequence clear. Recycling of water is expected to minimize the water shortage problem in the desert area for the cleaning of PV modules. Flat-Fan nozzles are used for evenly cleaning of the PV module front surface with water.

3.4 Economic Analysis

The economic analysis of the cleaning system is conducted by the comparison of the cost recovered by producing more electricity by PV system through cleaning the surface during its lifetime and the cost of cleaning [4]. The cost of the cleaning system is mainly comprising of initial cost and operational and maintenance (O & M) cost. O & M cost is due to the water required for cleaning, energy required to operate and water filter replacement. Initially the cost of cleaning system will add up in the capital amount of PV system installation however with more electricity production from the clean PV module system can save the cost for a longer period [5,6]. The cleaning of PV modules is expected to save significant energy to reduce the payback period.

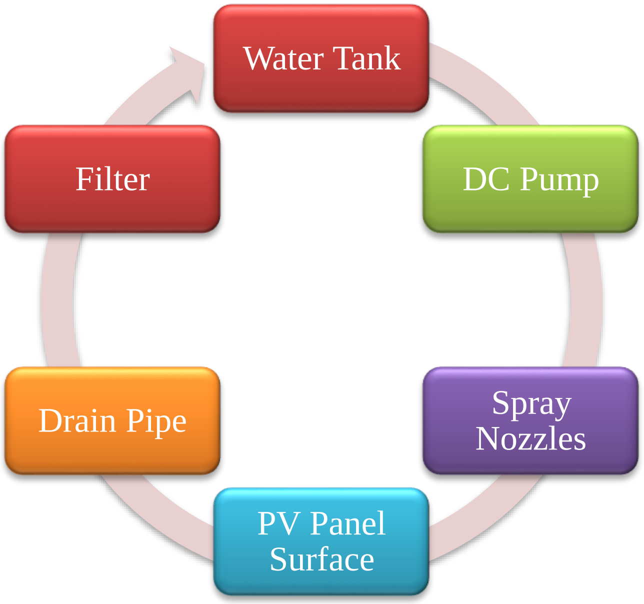

Fig. 3-9: Cleaning cycle

The frequency of cleaning action is determined based on the dust deposition rate and daily output energy loss. The cost of the cleaning system (C_{CS}) is the summation of the initial cost (C_{intl}) and maintenance cost (C_{main}) as in Eq. (1), maintenance cost depends on the material cost (C_{mat}) and workforce cost (C_{WF}) as in Eq. (2). The cost analysis of the proposed cleaning system for 1 m width and the cost analysis of the PV module system has been calculated for 25 years according to the manufacturer datasheet and values have been reported in Table 3-2 and Table 3-3 respectively.

$$C_{CS} = C_{intl} + C_{main} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$C_{main} = C_{mat} + C_{WF} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Table 3-2: Cost analysis of the cleaning system (1 m width)

System components	Quantity	Total cost (USD)
Water tank (20 liters)	1	1.28
Diaphragm dc pump	1	7.7
Water filter	1	1.28
Flat fan nozzles	2 sets	2.56
1m SS pipe with pipe fitting and fabrication	1 m	8.33
Plastic pipe	1.52 m	1.28
Total		22.43

Table 3-3: Consideration for economic analysis

Item	Value
PV systems and cleaning systems lifetime (years)	25
Cleaning system cost (USD)	11.2
Mono PV module 40-watt cost (USD)	17.3
Poly PV module 40-watt cost (USD)	16
Steel stand frame cost (USD)	4
PV installation & commissioning cost (USD)	1.6

The cost of electricity losses (C_{EL}) is calculated in Eq. (3) by using energy losses and electricity cost per kWh (CoE) of the PV system. The energy loss is the difference between the clean PV module energy ($E_{Clean.PV}$) and the dirty PV module energy ($E_{Dirty.PV}$) as calculated in Eq. (4) [7]. The electricity cost per unit (USD/kWh) is calculated by dividing the total cost of the system over the total energy (E_{PV}) generated by the PV system for the specific duration as in Eq. (5). For the cleaning system to be feasible and economical, the CoE of the PV module with a cleaning system must be less than the CoE of the PV module without a cleaning system [8].

C_{EL} = Energy loss x CoE ………………….……….. (3)

Energy loss = $E_{Clean.pv}$ - $E_{Dirty.pv}$ ……………..……. (4)

CoE = Total cost of the PV system / E_{PV} ….……… (5)

Summary

The proceeds with the designing of an experimental setup that includes PV module setup, dust collection setup, and cleaning system. The fabrication of these is done to start the experiment. The experiments are tested on monocrystalline and polycrystalline and recorded the data. The dust characterization is done to understand the nature of particles and their effect on the performance of PV modules. After that, the proposed cleaning system is tested on the dirty PV module. The economic analysis is defined to find the cleaning system's financial feasibility and the energy losses cost.

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Chapter 4

Results and Discussion

The obtained results have been divided into subcategories as mentioned below. The first part reports the dust collection and characterization. The second part describes the effect of dust on PV performance by comparing the clean and dirty PV module output power and the cleaning system efficiency is discussed. Finally, the economic analysis has been performed.

4.1 Dust collection and characterization

The atmospheric dust collected on the glass sheet with the passage of time is weighed to get the dust density, which shows the daily dust accumulation at different angles. It is experimentally investigated that the dust density after 30 days at tilt angle of 60°, 34.5° and 15° are 3.179 g/m^2, 4.618 g/m^2 and 5.522 g/m^2 with the daily dust deposition rate of 0.106 g/m^2, 0.154 g/m^2 and 0.184 g/m^2, respectively as shown in Fig. 4-1. It can be concluded that the deposition of dust on the glass surface with a low tilt angle is greater than the high tilt angle due to low gravity. This shows that the PV module installation with a lower tilt angle is likely to reduce more output power due to high dust accumulation on the surface. Et al observed the 20% reduction in transmittance and 5 g/m2 of dust accumulation after 45 days of outdoor exposure. It was also found that the mono-PV module tilted at the location altitude of 25° and the output power has been reduced by 6% after 5 weeks of dust accumulation [1].

The small amount of dust collected from the surface of the PV module installed at the tilt angle of 34.5° facing south has been used for the dust characterization to understand the dust particle size, elemental and chemical composition, and surface morphology. Dust particle size and chemical composition have an important impact on PV performance [2]. The Results obtained from laser particle size analyzer shows that the particle size distribution by volume of the dust is in the range of 0.5 um to 200 um as shown in Table 4-1. It is found that the 87 % portion of the dust particle size ranges from 2 um to 45 um which indicates that the particle size is small as shown in Fig. 4-2. Similarly in literature, (Hachicha et al., 2019; Javed et al., 2017) reported that the dust particles have different sizes, shapes and distributed randomly in the range of 1.6 um to 38.4 um, in which 95 % of the dust particle was below 25 um [3-4]. Kazem and Chaichan (2016) reported that in dust particle size analysis, the bulk of grain size lies between 2 - 63 um [5]. While in the current study the dust particles lie in the range of 2 um to 45 um. It has larger grain size than this study reported. It is generally observed that the smaller particles are uniformly distributed with a high accumulation rate and create more scattering of light than larger particles, this will contribute towards the degradation of PV performance [6].

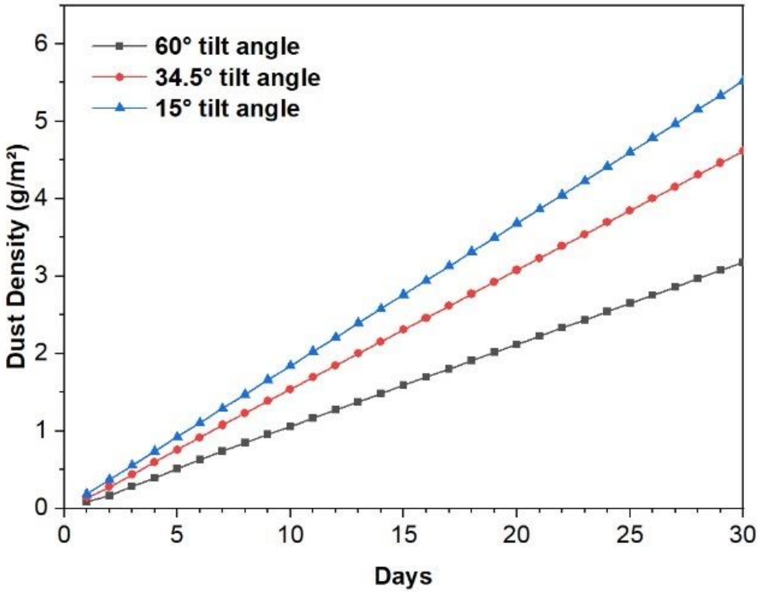

Fig. 4-1: Deposition of dust at different tilt angles.

Table 4-1: Dust size distribution per volume percentage

Dust particle diameter (um)	Volume percentage (%)
0-0.5	0.61
0.5-1	2.89
1-2	7.48
2-5	18.03
5-10	18.14
10-20	21.47
20-45	22.02
45-75	5.81
75-100	2.02
100-200	1.53

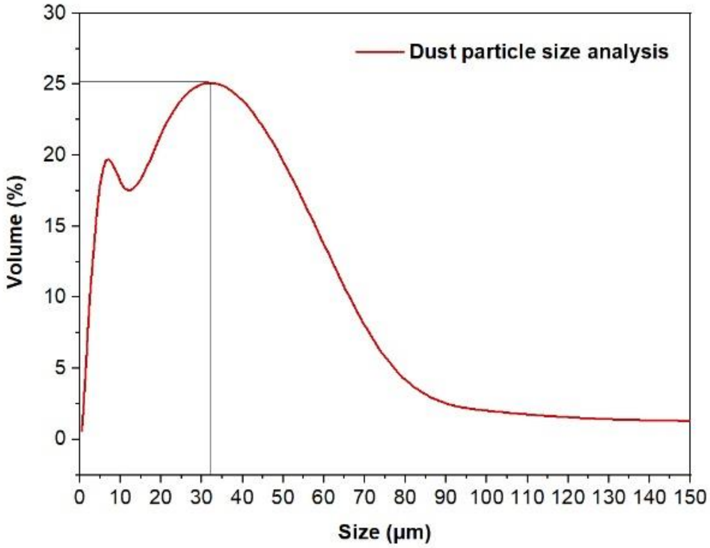

Fig. 4-2: Dust particle size distribution

The surface morphology of dust is analyzed by performing the topographical inspection on the sample using SEM, as reported in Fig. 4-3a, which shows that the dust particles have different sizes, random shapes, and irregular distribution. The elemental composition of the collected dust sample is performed by the EDS, as it is important in terms of particle adhesion to the surface. The obtained spectrum in Fig. 4-3b demonstrates that the oxygen dominates with 48.36 % composition, followed by carbon, calcium, and silicon with the elemental composition of 25.26 %, 10.46 %, and 8.56 %, respectively. Small traces of aluminum, iron, magnesium, sulfur, copper, and titanium are also found. In literature [4], the author reported EDS results of the dust sample collected from the rooftop, which shows that the oxygen is a major element contributed 46.1 % followed by carbon 20.3 %, calcium 10.5 %, and silicon 10.2 % with the small traces of magnesium, iron, aluminum, copper, sodium, potassium, sulfur, and chlorine. Javed et al., (2017) found that the calcium is the most abundant element followed by silicon, iron, magnesium and aluminum. Calcite, dolomite, and quartz were the major minerals present in the dust. It was also found that the dust particles size decreases with the increase in outdoor exposure time [3]. The elemental concentration in airborne dust is site-dependent and depends on the pollutants and the emission sources such as transportation, construction, and industrial waste in the surroundings.

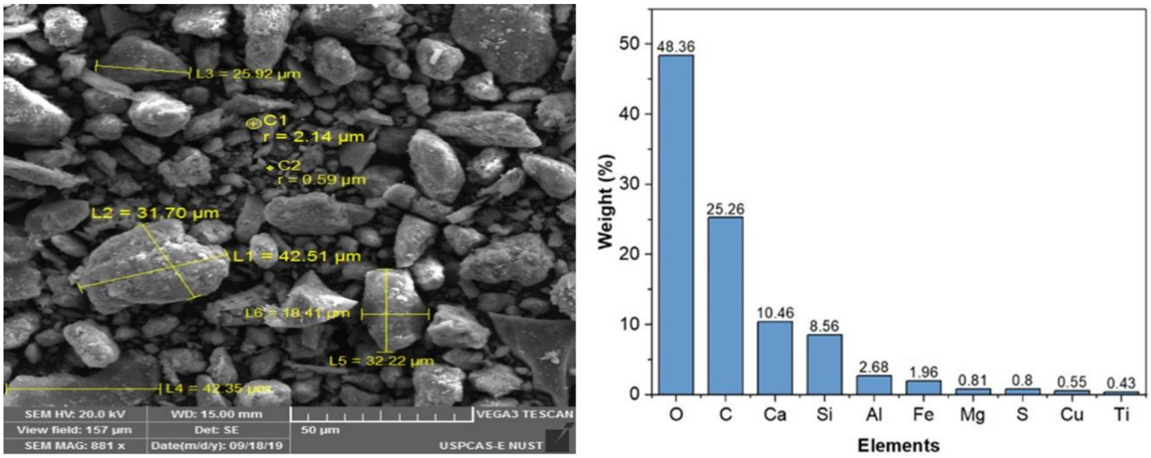

Fig. 4-3: a) SEM image of dust b) EDS spectrum of dust

The mineralogical analyses of dust performed by the X-ray Diffraction, the peak intensities formed by the attenuation of X-ray scattering from the sample to the X-ray detector in Fig. 4-4 shows that the dust particles are mainly composed of quartz, calcite and silicon sulfide. The obtained XRD results are compared with the literature [4], it is found that the major mineral composition of the dust sample contains SiO_2, CaO, and Fe_2O_3 minerals in the test. Kazem and Chaichan (2016) found that dust contain 86 % portion of SiO2 and CaO [4]. It is also observed that the major portion of calcite shows the involvement of human activities near the site. In general, the atmospheric dust contains six different minerals (quartz, illite, kaolinite, gypsum, calcite, and dolomite) that can be recognized from the X-ray diffraction patterns of samples mounted on glass slides, silicon plates, and Ag-filters [7].

4.2 Effect of dust on PV performance in an outdoor environment

The rate of decrease in the PV module's performance mainly depends on the rate of dust accumulated on its surface area. The performance of dirty and clean PV modules over a whole day is observed for the entire period of experimentation. To simplify the analysis of the results, days with approximately constant weather conditions i.e. maximum daily solar irradiation (6 kWh/m^2/day to 7 kWh/m^2/day) and almost the same energy output, were selected. The parameters used to study the effect of dust on PV module output are dust density, daily energy output, and output energy loss.

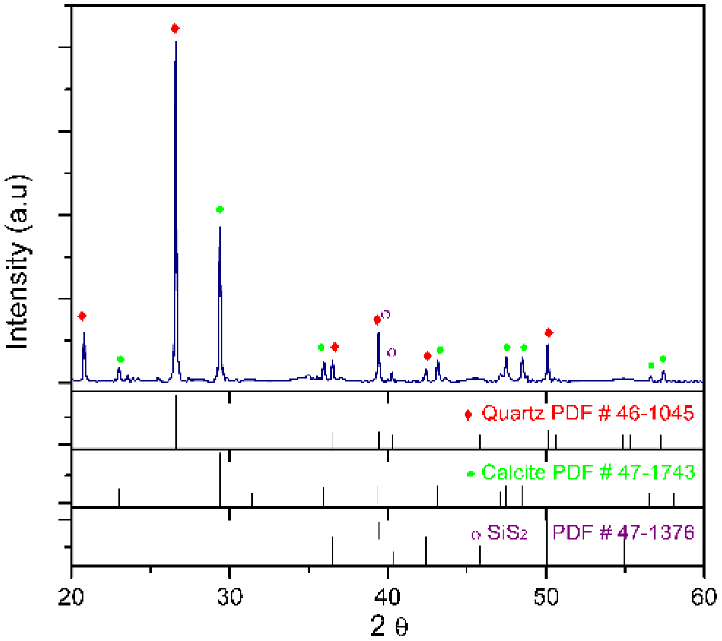

Fig. 4-4: XRD of the dust sample

The effect of dust on output power is experimentally observed on both mono-PV and poly-PV modules. The graph in Fig. 4-5 shows that the layer of dust on the surface of the PV module reduces more output power of the mono-PV module than the poly-PV module because the mono-PV cell is made up of single-crystal which drops more power on the shading of dust than poly-PV cell made up of multi-crystalline structure [8]. It is found that the output power loss of the mono-PV module is 36.75 % and the poly-PV module is 26.25 % at 10.5 g/m² of dust density. The experiment is conducted on the PV module at the installation angle of 34.5°, and the effect of dust on PV performance at different dust density is observed and analyzed. Besides the dust density to the output power loss plot shown in Fig. 4-5, it has been observed that the output power loss varies with different tilt angles of PV modules, on which the dust density depends. It has been determined from the experimental data that the output power loss of dirty mono-PV at the different installation angles of 60°, 34.5°, and 15° is found to be 11.13 %, 16.16 %, and 19.33 %, respectively, while the output power loss of dirty poly-PV at 60°, 34.5° and 15° is found to be 7.95 %, 11.55 %, and 13.8 %, respectively.

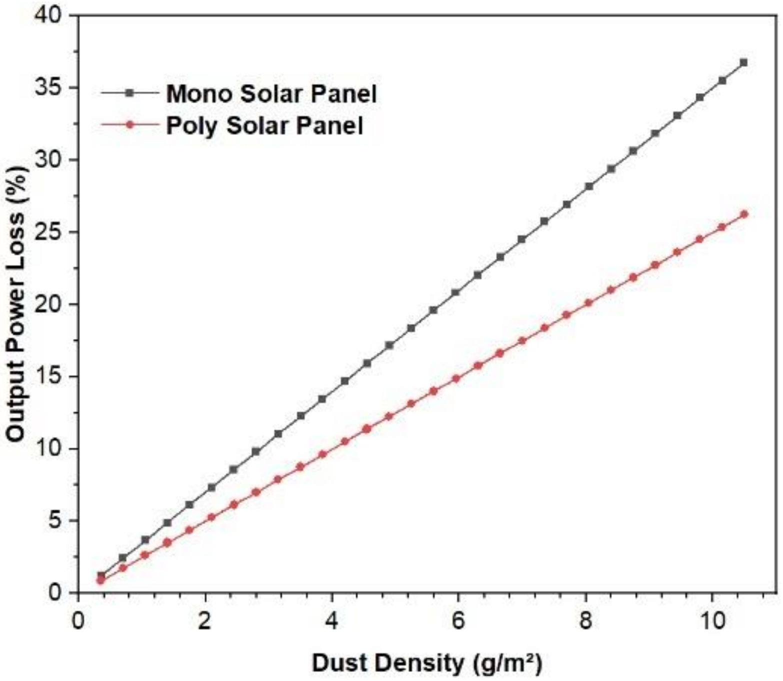

Fig. 4-5: Output power loss due to dust accumulation.

All the reported data has been analyzed in the span of 30 days without rainfall and plots are shown in Fig. 4-6 which shows that the maximum output power loss observed is 19.33 % at tilt angle 15° of the mono-PV module and minimum output power loss observed is 7.95 % at a tilt angle of 60° of poly PV module. The fixed installation angle of PV modules is mostly set according to the latitude of the location, from which the maximum solar radiation can be harvested in the whole year. The experimental results show that the average daily output power loss of 0.54 % is observed in the mono-PV module and 0.38 % in the case of the poly-PV module at the installation angle of 34.5° with an average daily dust deposition rate of 0.154 g/m².

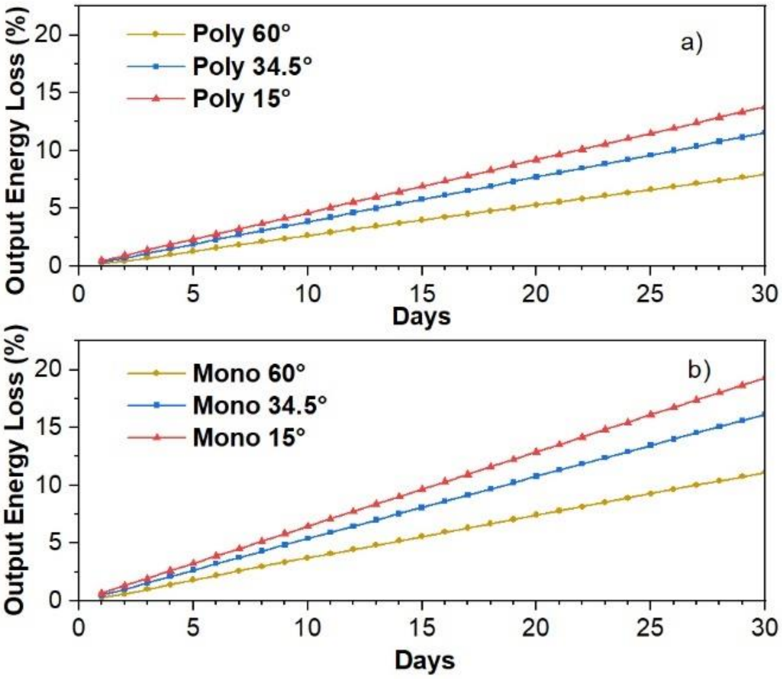

Fig. 4-6: Output energy loss; a) mono PV module b) poly PV module.

The effect of dust on the electricity production has been observed by the comparison of the dirty and clean PV modules output power. The normalized maximum power output (Pmax/Pmax.daily) is measured for different dust densities as shown in Fig. 4-7. It is found that the daily energy generation of both mono-PV and poly-PV modules is directly related to the daily solar radiation. The energy generation of clean and dirty PV modules is the same on the first day of the experiment when both have clean front surfaces. The dust starts to deposit on the surface of PV modules with the passage of time, one set of PV modules is cleaned on daily basis in the morning while the other set of PV modules is left uncleaned and recorded the daily output energy of both sets for 30 days. The daily energy production of clean PV modules remains the same in 30 days while the dirty PV modules energy production starts declining and reduces every day until dirty mono PV module reaches 16.16 % and dirty poly PV module reaches 11.54 % of output power loss.

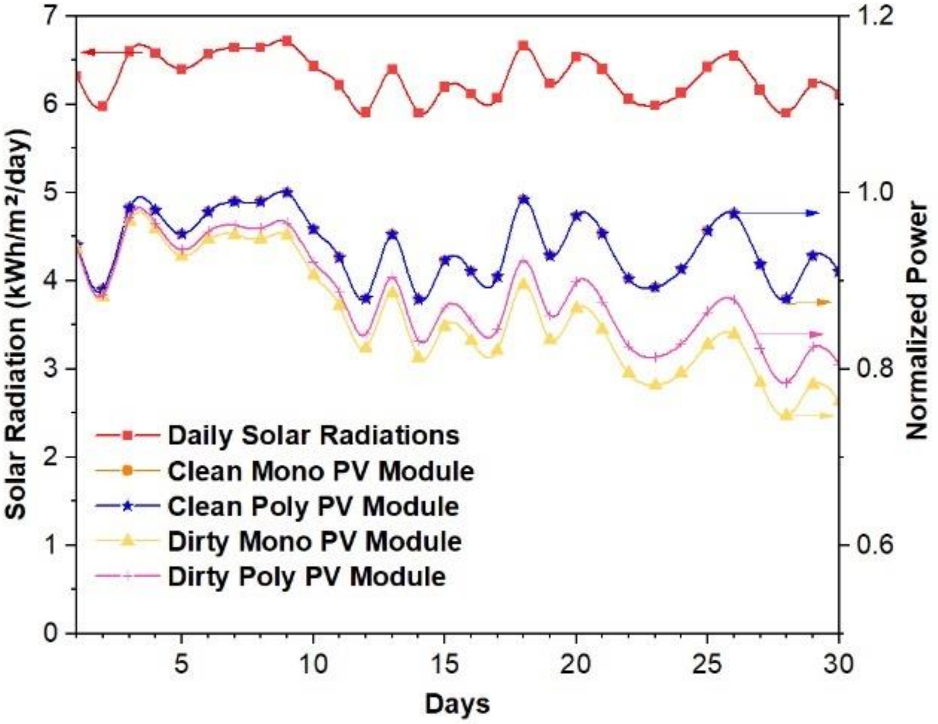

Fig. 4-7: Comparison of the energy output of PV modules.

4.3 Water Cleaning System

The cleaning of the dirty PV module set (Dimensions: 0.55 m (L) x 1 m (W) x 0.035 m (T), Area = 0.55 m²) is performed by spraying water through flat-fan nozzles using the designed cleaning system. In the experiment outcomes, the cleaning system takes 35 secs to completely clean the dirty PV modules set and recover the output power by 98 %. The water flow rate of the cleaning system measured by the water flow meter is found to be 1.735 L/min or 0.475 GPM in the presence of flat-fan nozzles, while the maximum water flow rate of the water pump is 4 L/min. The water requires to clean the set is calculated to be 1 liter, from which it can also be concluded that the area of 1 m² requires 1.8 L of water for cleaning, the energy consumed by the cleaning system for 35 seconds of operation is calculated to be 0.3 Wh with the power capacity of 36 watts. These results of the cleaning system have been verified by cleaning the set 10 times on different days and taking the average of it. The cleaning of PV modules is done in the morning to minimize the evaporation of water. The water recovered after the cleaning and collected in the water tank is found to be 550 ml. It has been observed that the recycling of water is 55 % of the total water used to clean, which is considered low because most of the water droplets sprayed through the flat-fan nozzles carried by the wind and some of the water evaporates.

4.4 Economic analysis

The economic analysis has been performed considering the radiation data, dust characterization, dust deposition rate, energy production, energy losses, cost of the PV module, and cost of the cleaning system, according to the literature [9]. The economic analysis results for the recorded data indicate that the cost of the cleaning system for mono-PV (40 watts) and poly-PV (40 watts) modules are 0.037 USD/month, which is greater than the cost of energy losses 0.005 USD/month. For a 2-month period of the study reveals that the cost of electricity per unit (USD/kWh) of the PV module with the cleaning system which is 0.04 USD/kWh for mono-PV and 0.023 USD/kWh for poly-PV greater than the electricity per unit cost of the mono-PV and poly-PV module system without the cleaning system which is 0.028 USD/kWh and 0.022 USD/kWh. This shows that the cleaning system is not feasible for the 40-watt panel.

This cleaning system with a width of 1 m can also be implemented on a commercial size PV module that can provide feasible economic analysis, considering the same cleaning criteria and cleaning efficiency with extra water requirements according to the area of the PV module. For commercial scale, the maximum power capacity of the PV module found for mono-PV is 415 watts [10] with the dimension of 2.02 m (L) x 1 m (W) x 0.035 m (T) and for poly-PV is 355 watts [11] with the dimension of 2.02 m (L) x 1 m (W) x 0.035 m (T), the cost is given in Table 4-2. The energy production and energy losses of commercial size PV modules having 1 m width have been predicted for 4 months. The first 2 months of energy generation values for clean and dirty commercial size PV modules have been calculated from the results of small size PV modules used in the experiment taken as a reference. For the next 2 months of energy generation, the values are predicted from the previous trend linearly and considering the same procedure and parameters. For this scenario, the economic analysis results indicate that the cost of the cleaning system becomes less than the cost of the energy losses for the PV module system after some time in Fig. 4-8. The cost of electricity per kWh is also become cheaper for the commercial size PV modules with the cleaning system than without the cleaning system as shown in Fig. 4-9. In terms of cost, the cleaning system for mono and poly PV module is economically feasible after cumulative energy loss and consecutive dust accumulation with no rainfall of 50 and 83 days. There is a need for the cleaning system and more than 3 months of energy losses would be uneconomical for both types of PV modules without the installation of the cleaning system as already observed by other researchers [12]. Therefore, the cleaning system is recommended for a large-scale commercial PV system.

Table 4-2: Consideration for economic analysis

Item	Value
PV systems and cleaning systems lifetime (years)	25
Cleaning system cost (USD)	22.43
Mono PV module 415-watt cost (USD)	170
Poly PV module 355-watt cost (USD)	128.4
Steel stand frame cost (USD)	8
PV installation & commissioning cost (USD)	3.2

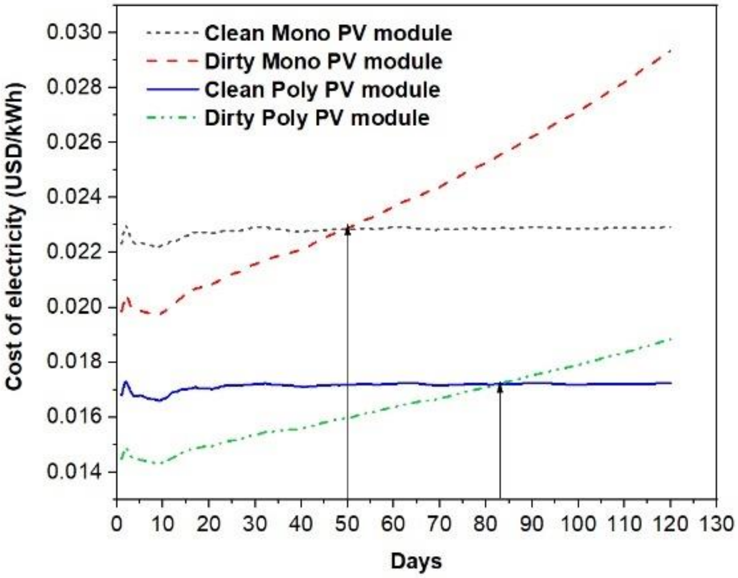

Fig. 4-8: Electricity cost comparison.

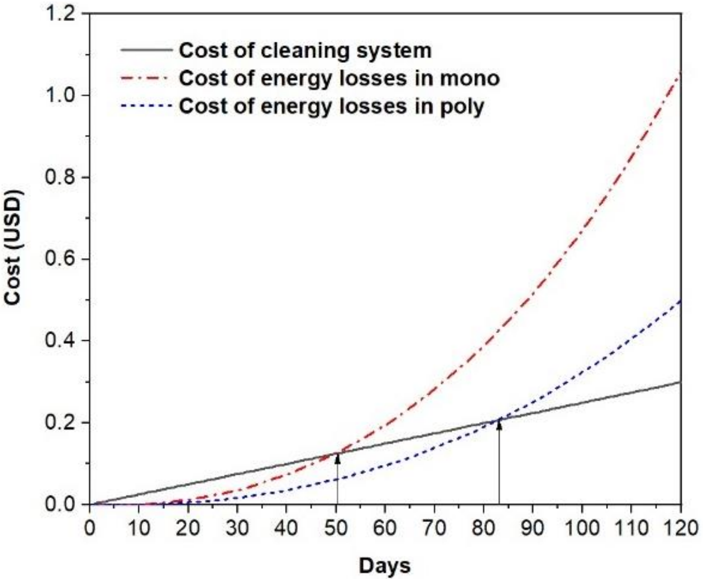

Fig. 4-9: Cost of cleaning system and energy losses

Summary

The obtained results have been briefly discussed in this chapter. The results have been divided into subcategories as mention in this chapter. The first part reports the dust collection and characterization to explore the dust density and understand the dust particle size, composition, and morphology. After that, the outdoor experiment is designed and conducted to study the effect of dust on PV performance by comparing the clean and dirty PV module output power, and the cleaning system is used to effectively clean the dust from the surface. In last, the economic analysis has been performed to find the proposed cleaning system cost-effective.

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Chapter 5

Conclusion and Recommendations

5.1 Conclusion

A Soiling loss is one of the challenging issues for the PV module system to operate efficiently under Pakistan weather conditions. This study has investigated the performance of the PV module affected by the dust accumulation in an outdoor experiment and the influence of cleaning using a cost-effective home-made cleaning system. The experiment has been performed employing the experimental setup for dust settling on the PV modules surface, to observe the output power variation, cleaning of modules by pressurized water and finally economic analysis. The main findings of this work are summarized in the following points:

- Dust accumulation depends on the tilt angle of the PV module surface. A high tilt angle accumulates less dust on the surface due to gravity than a low tilt angle surface. After 2 months of outdoor exposure, the daily dust deposition rate found to be 0.184 g/m^2 at 15° tilt angle and 0.106 g/m^2 at 60° tilt angle.
- The dust characterization results show that most of the dust particle ranges from 2 um to 45 um in size, has random shapes, and contain a high percentage of carbon, silicon, and oxygen. The dust has small particles with high influence on PV performance.
- The results indicate that after one month of uncleaned PV modules installed at 34.5° tilt angle contributes a 16.16 % loss in output power of mono-PV module and 11.54 % loss in a poly-PV module, with 4.6 g/m^2 dust density.
- A linear relationship found between output power loss and dust density with the output power drop of 3.5 % per g/m^2 for the mono-PV module and 2.5 % per g/m^2 for the poly PV-module is observed.
- The daily output power loss rate of the mono PV module (0.53 %/day) is higher than the poly PV module output power loss rate (0.38 %/day) with the dust deposition rate of 0.153 g/m^2/day. Hence this shows that the mono PV module drops more power on shading due to dust accumulation as compared to the poly PV module.

- The cleaning recovers 98 % efficiency of the PV module in 35 seconds of operation performed using water with a flow rate of 1.735 L/min. The cleaning system has a water recycling capacity of 55 % and a water requirement of 1.8 L/m^2 for surface cleaning.
- The proposed cleaning system design can be scalable to all commercial size arrays and it can also operate in industrial areas and almost any dusty/low rainfall area that contains ash, smoke, and cement particles in the dust. The system is low maintenance with minimum human intervention involved.
- This cleaning system is found to be cost-effective for commercial size PV modules. Hence, the commercial size mono PV module (400 watts) should be cleaned before 50 days of dust accumulation and the poly PV module (355 watts) should be cleaned before 85 days of dust accumulation with the proposed cleaning system to avoid the extra cost of energy losses.

5.2 Future Recommendations

The cleaning system is recommended and economical only for large/commercial-scale PV modules. The cleaning of the PV module surface can be more efficient by modifying the nozzle design and more water can be recycled. The use of surfactants in water can help to reduce water usage and clean the dust effectively. The proposed automatic dust cleaning system of solar PV modules has the potential to overcome the difficulties arise in the traditional cleaning techniques and produces an effective, non- abrasive cleaning to avoid the irregularities in productivity due to the deposition of dust. However, the outdoor experiment did not cover the whole year especially the winter season, where the dew factor can be counted and affect the dust deposition. The cleaning frequency should also be tested under the dew factor. Therefore, further studies can be carried out to combine the effect of dust and dew factor along the year and hence the cleaning system can be improved. To advance and globalize this cleaning technique, an extensive collaboration of researchers is recommended.

Annexure I

Experimental investigation of soiling losses and a novel cost-effective cleaning system for PV modules

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Abstract

Dust accumulation significantly reduces the efficiency of a photovoltaic (PV) module, and the unavailability of an economical and efficient cleaning solution is the persistent problem. Therefore, the focus of this study is to investigate the effect of dust on PV performance and proposes a novel cleaning system for the removal of dust from the front surface of PV modules. The outdoor experiment is conducted on the monocrystalline (mono-PV) and polycrystalline (poly-PV) PV modules. Each experimental set contains two PV modules (mono-PV and poly-PV), one set is cleaned every day and the other set left uncleaned throughout the experimental time period. The cleaning of the PV module is performed using pressurized water, sprayed through a flat-fan nozzle to clean the front surface. The wastewater is collected, filtered and directed back to the storage tank. The cleaning system has a water recovering capacity of 55 % and a water requirement of 1.8 L per m² of PV area. It has been analyzed and observed that the output power of the mono-PV module and poly-PV module has decreased by 16.16 % and 11.54 %, respectively after one month with the dust deposition density of 4.6 g/m². The cleaning process improves the efficiency of the PV module by 98 % in 35 seconds of operation with a water flow rate of 1.74 L/min. It has been evaluated that the proposed cleaning system is cost-effective for commercial size PV modules having a length of around 2 m. Furthermore, the mono-PV module (400-watts) and poly-PV module (355-watts) should be cleaned within 85 days of dust accumulation for optimum energy usage.

Keywords: PV module; Dust accumulation; Dust characterization; Effect of dust; PV module cleaning system; Economic analysis

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1. Introduction

Solar energy is one of the promising renewable energy resources, due to its versatility of use, for stand-alone and utility-scale production of energy, and ease of installation. Pakistan is one of the resource-rich countries in terms of solar energy. Pakistan receives an average of 5.3 kWh/m²/day (1.93 MWh/m²/year) of solar global insolation (Mirza et al., 2003). Solar PV has great potential to meet the energy demand and has access to remote locations, but pollution and dust are the major environmental factors that greatly reduce the output power.

In 2017, 95 % of the solar PV modules were manufactured from crystalline silicon (c-Si) solar cells made of multicrystalline and monocrystalline silicon (Philipps and Warmuth, 2018). The solar cells convert solar irradiance into direct current electricity through the photovoltaic effect. Mostly the efficiency of commercially available PV modules is up to 20 %, which is further reduced by environmental, manufacturing, and installation losses (Fu et al., 2016). The efficiency of a solar PV module is limited due to weather conditions, so it is essential to take care of the parameters like ambient temperature, solar irradiance, airborne dust, humidity and wind speed (Meral and Dinçer, 2011).

Soiling effect is the dominant reason for the reduction in the efficiency of a solar PV module (Sayyah et al., 2014). Due to the thick layer of dust accumulated on the front surface, the efficiency of the PV module reduced up to 35 % (Kazem and Chaichan, 2016; Zaihidee et al., 2016). Dust particles in the air get carried away by the wind and accumulated on the front surface of the PV module, which avoids the solar irradiance to reach the underneath of glass to the solar cell junction and hence reduces the energy output of the PV module. Dust leads to spectrum filtering and therefore reduces the input energy of the PV module in some specified parts of the solar spectrum particularly in visible region, depending on the dust particle size and chemical composition. The low speed of wind carries the small size dust particles which tend to block more solar radiation and induce more scattering of light. Small size dust particles distributed uniformly with a higher dust accumulation rate, and stick stronger to the surface than the large size dust particles (Qasem et al., 2014; Tanesab et al., 2015). While the large sized dust particles can easily detach and rolled down from the surface by low velocity of wind due to gravity and slope of the PV module (Jiang et al., 2018). Moreover, the dust contains charcoal, ash and other lightweight particles, which are more effective towards the reduction of the PV performance (Elminir et al., 2006). Lu and Zhao (2019) stated that the dust deposition rate is higher on a ground installed PV system than on a rooftop installed PV system. Also, it was observed that more dust accumulated on PV module installed at a fixed tilt angle compared to the a single or double axis tracking solar PV module system. Alnaser et al. (2018) observed that the annual electricity loss of the PV module reached 17 % in the kingdom of Bahrain if it remained uncleaned for the whole year and 7 % electricity loss, if it cleaned once a year. Similarly, Mazumder (2011) observed that the dust density of only 4 g/m² accumulated on the PV surface can reduce the output power of the PV module by 40 % with the dust particle size ranging between 0.5 -

10 μm. Boykiw (2011) concluded that the effect of dust can decrease the PV efficiency by 5–6 % in a week depending on the dust deposition rate. Furthermore, Elminir et al. (2006) conducted an experimental study on PV module installed at 45° tilt angle facing south in Egypt to analyze the effect of dust. It was observed that the dust deposition on the front surface of the PV module can reduce the output power by 17 % per month. Jiang et al. (2016) reported that the cleaning frequency of the PV module at 0° tilt angle in the dessert area is about 20 days with the dust deposition density of 2 g/m² and output power reduction of 5 %. The average diameter of the dust particle was 2 μm. Hachicha et al. (2019) observed that the dust accumulation strongly depends on the tilt angle of the PV module, the high tilt angle accumulates less dust on the front surface of the PV module and results in less reduction in output power. The PV performance was analyzed at 0°, 25°, and 45° tilt angles for two weeks and it showed 37.63 %, 14.11 %, and 10.95 % output energy loss, respectively. Elminir et al. (2006) reported that the dust density at 45° tilt angle was 15.84 g/m² and at 90° tilt angle was 2.48 g/m², collected on the glass sample. The dust deposition rate depends on the seasonal variations also. The accumulation of dust is higher during the durations of a sand storm, high humidity and less rainfall (El-Nashar, 2009). Therefore, frequent cleaning of the PV module is necessary to prevent soiling losses.

Every year, a growth of 34 % in the installation of the PV module system has been reported from 2015 to 2017 globally. Recently, Pakistan imported more than 950 megawatts (MW) of power capacity solar panels during the financial year 2017-2018 (Lalani, 2018). The currently installed solar PV modules lack an integrated cleaning system. Every day, a significant amount of electricity is lost due to the accumulation of dust on the front surface of the PV module. There are several cleaning mechanisms employed to tackle the problem, such as manual cleaning with water and labor, mechanical removal of dust by brushing, blowing, vibrating, ultrasonic, electrostatic, hydrophobic coatings and vacuum suction (B et al., 2018). Traditionally the cleaning of PV modules has been performed manually but it has disadvantages such as the risk of physical injury to work force, damage to the PV module, mobility constraints, time-consuming, less effective and other influencing factors (Syafaruddin et al., 2017). An effective cleaning technique should be reliable, efficient, easy to implement, and cost-effective (Burke et al., 2016). Zorrilla-Casanova et al. (2011) stated that the cleaning of the PV module front surface with water is an effective technique than dry cleaning to recover its efficiency but implementing it in a water shortage area like dessert, makes it expensive. Mavroidis et al. (2009) designed a robot device for cleaning the PV module arrays by spraying water over its surface, which can further increase its efficiency up to 15 %. This device is less beneficial because it is an expensive, complex design, and it involves heavy structure and no recycling of used water. The cleaning of the PV module with water can save the front glass surface from scratches induced by rubbing and cracks by putting weight. Currently, research on the cleaning of the PV module has been carried out, but there is a deficiency of reliable, scalable, and cost-effective cleaning solutions. For the cleaning system to be economical and feasible, the cleaned PV module system must produce more electricity than electricity loss caused by the effect of dust. Faifer et al. (2014) recommended that the cleaning becomes essential for the PV module system when the cost of electricity production losses due to dust is larger than the maintenance and cleaning cost. Jiang et al. (2016) has also described the criteria for cleaning that is defined at 5 % reduction in output power of the PV module. The cleaning frequency determined, by Jiang et al., for a conventional PV module is 20 days with the dust density accumulation of 100 µg/m^3. However, it is not an economical criterion for the cleaning of PV modules considering the location of current experimental work and therefore it is advisable to conduct real time experiments to determine the cost-effective cleaning solution.

The economic analysis performed by Yang (2015) reveals that the total cost of electricity production losses of the PV modules caused by dust at the specific deposition rate should be higher than the total cleaning cost. After this, the cleaning technique can be cost-effective for the PV modules. The cleaning system lifetime and degradation rate are important in terms of life cycle cost so that the cleaning system life should be equal to the PV system life. Generally, it is stated in the manufacturer data sheet ("mono-PV Module-400," 2019) that the lifetime of the PV module is almost 25 years with the annual output efficiency degradation at the rate of 0.2 % to 0.5 %.

In this study, a cost-effective novel cleaning system is proposed to remove the dust from the front surface of the PV modules at different tilt angles and hence to enhance the PV system performance. Moreover, the dust collection and characterization are done to find the dust accumulation rate and nature of the dust particle. The experimental work is conducted to determine the effect of dust on the electrical performance of the mono-PV and poly-PV module. A cleaning system has been designed & fabricated, and a series of experiments are performed to investigate its effect on the output power of the PV modules. This cleaning system is introduced using pressurize water with the ability to recycle it. Furthermore, economic analysis has been performed to suggest a financial methodology to determine a profitable cleaning frequency of the PV modules. The economic analysis is conducted in terms of the cost of electricity, the cost of the cleaning system, and the total energy generated by clean and dirty PV modules for the specific period. This study can help to analyze the soiling losses in terms of output energy and cost. Effectuating the cleaning system can help to produce more energy, increases operational life and improves the efficiency of the PV module system. The objective of the proposed cleaning system is to save time, cost, manpower, water, and electricity.

2. Methodology

This research proceeds with the designing of a suitable experimental setup and procedure to conduct the experiment. The proposed experimental setup has been developed to study the effect of dust and cleaning system on the energy generation of PV modules. To further explore the effect of dust, it has been characterized for surface morphology, elemental composition and particle size analysis. The economic analysis using different parameters pretends to find a cost-effective and feasible cleaning solution for the removal of dust, accumulated on the front surface of the PV module.

The outdoor experiments are conducted on the rooftop of the USPCASE, NUST, Islamabad building for two months from 1st July 2019 to 31st August 2019. The data is collected and analyzed for only clear days when the daily solar radiation is almost the same for each day so that the effect of dust on the PV performance is not affected by other factors such as the sandstorm, rainfall, and cloudy days. In this way, a clear understanding of the effect of dust on the output performance of PV modules can be seen through results (Gholami et al., 2018). This setup is designed and built to study the effect of dust and pollutant on the electricity production of PV modules, present in the atmosphere. The experiment involves testing of a novel water cleaning system to remove the dust. The experimental setup consists of a PV modules setup, and a dust collection setup, and a cleaning system

2.1. PV modules setup

The PV module setup consists of two mono-PV modules (40 watts), two poly-PV modules (40 watts), an adjustable mounting stand, DC bulbs as a load connected to the PV modules, and a DC power meter data logger which is used to record daily energy generation by each PV module as shown in Fig. 2a. A pyranometer is placed on the same plane as that of the PV modules in order to get the solar radiation data. The PV modules installed at the tilt angle of 34.5° facing south, as the location (Islamabad) has a latitude of 33.7°. The type of PV module technology used in this experiment is the mono-PV and poly-PV module with the electrical specifications given in Table 1. The dust is naturally accumulated on the front surface of PV modules to study its effect on the output power. Two sets, each set contains two PV modules (mono-PV and poly-PV), have been used to conduct the experiment. Each set has a dimension of 0.98 (L) m x 0.67 (W) m x 0.035 (T) m and an area of 0.66 m². One set is left dirty and the other set is cleaned (using the proposed cleaning system as discussed in section 2.3) every day at 10 am in the morning for a duration of 2 months. The output energy (Wh) of clean and dirty PV module sets has been recorded each day by using a DC power meter data logger.

Table 1

Electrical and physical specifications of the PV modules.

Parameters	***Mono***	***Poly***
Model no.	SLS-M6U (39)	SH-40
Maximum Power (P_{max})	40 W	40 W
Voltage at maximum power (V_{mp})	19.5 V	17.28V
Current at maximum power (I_{mp})	2.14 A	2.31 A
Open circuit voltage (V_{oc})	24.96 V	21.6 V
Short circuit current (I_{sc})	2.37 A	2.47 A
Power tolerance	0.0-5.0 %	0.0-3.0 %
Max series fuse rating	15 A	15 A
Operating Temperature	-40°C to +85°C	-40°C to +90°C
Weight	4 kg	5.75 kg

Dimensions length (L) x width (W) x thickness (T)	0.64 x 0.51 x 0.035 m	0.67 x 0.45 x 0.033 m
Test conditions	1000 W/m², AM 1.5, 25°C	1000 W/m², AM 1.5, 25°C

2.2. Dust collection setup and characterization

The dust collection setup consists of a steel stand, six pieces of glass, and a digital weight balance. While the glass piece has 2 mm thickness and 0.0216 m² of the area is used to collect the dust. The steel stand has 3 rectangular small frames with adjustable tilt angles (set at 15°, 34°, and 60°) as shown in Fig. 1. The 15° tilt angle is selected because this angle is suggested for a roof slope of a PV installation on parking area, 34° is the tilt angle of PV module setup and 60° tilt angle is selected for a higher value of tilt angle to study the dust accumulation variation. Each small frame contains 2 pieces of glass with numbering to identify different samples. The accumulated dust has been weighed by a digital weight balance (Radwag AS 220.R2), this device can measure 0.1 mg of dust with weight ranges from 10 mg to 200 g. The steel frame is placed next to the PV module setup, facing south as that of the PV module's setup.

Fig. 1. Dust collection setup.

The dust samples (glass plates) have been collected at different tilt angles for the same duration and under the same environmental exposure to measure the dust density. Initially, the clean glass plates weighed before the start of dust accumulation using digital weight balance and each day the small amount of dust gets accumulated on the surface area of glass plates, weighed every two or three days later. The rate of dust deposition on a surface area is measured in terms of dust density, which is defined as the dust weight divided by the surface area. The area of a glass piece is known, and the dust weight can be measured by an increase in the mass of the glass plates, during the time period of dust accumulation.

Dust characterization is necessary in order to investigate the effect of dust on the PV performance. Every location has its own type of dust with unique characteristics. Each type of dust blocks a different percentage of solar irradiance with same dust density (Kawamoto and Guo, 2018). The collected dust is initially characterized for particle size, mineralogical composition, surface morphology, and compound analysis. BT-9300ST Laser Particle Size Analyzer is used to analyze the particle size ranging from 0.1 um to 1000 um. Surface morphology and elemental composition are determined by Tescan VEGA3 XM SEM and Oxford Instruments X-Max 50 EDS, operated at 20 kV beam voltage. The structural analysis is done by Bruker D8 advanced X-Ray Diffractometer with a Bragg-Bentano θ:2θ configuration in a range of 20°-60° using CuKα as a radiation source (Queralt et al., 2001).

2.3. Cleaning system

The cleaning system is designed using the effective cleaning technique with minimum usage of water by recycling it. The cleaning system consists of a 1 m long steel pipe with a diameter of 0.016 m installed on the top of the PV module set shown in Fig. 2a. The steel pipe has eight flat-fan nozzles with a convex spray pattern connected to it with the spacing of 0.12 m to overlap 50 % of spray pattern for uniform distribution of water, sprayed on the front surface of the PV module. The flat-fan nozzle (model VP110 015) having a maximum water flow rate of 0.45 L/min, maximum pressure of 0.2 MPa and spray angle of 110° has been used. A dc diaphragm pump of 36-watt power capacity with a maximum water flow rate of 4 L/min and a maximum pressure of 0.65 MPa is used to pump the water through flat-fan nozzles. Fig. 2b shows the design of the proposed cleaning system including nozzle selection, spacing, and placement integrated with the dc centrifugal water pump to provide optimum cleaning. The cleaning system is powered by a dry lithium-ion battery (18 Ah, 12 V) placed in the experimental setup. There is a water flow meter connected between the pump and nozzle pipe to measure the water flow rate of the cleaning system, ranging from 0.1 GPM to 5 GPM. The water is collected from the surface of the PV module through a water collector pipe. The collected water is filtered by one stage charcoal filter so that the water can be reused for cleaning. The filtered water prevents blocking the nozzle hole. The one-stage granular activated coconut shell carbon filter has a diameter of 0.06 m, filtration of 5 microns, and capacity of 10,000 L. A water tank of 20 liters capacity is used to collect and store the water.

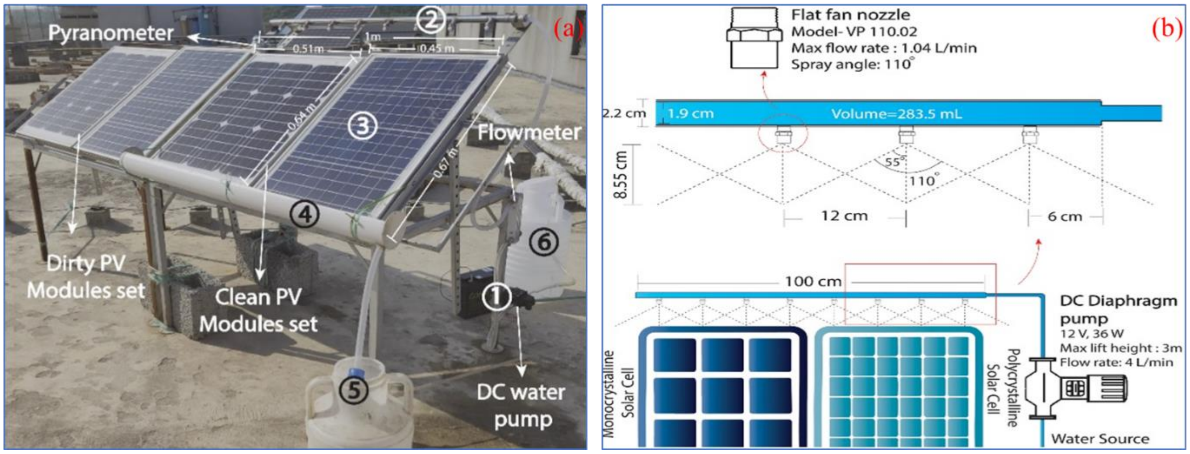

Fig. 2. (a) PV module setup with the cleaning system (b) Cleaning system design using flat-fan nozzles.

This cleaning system uses the pressurized water to safely clean the front surface of the PV module and recycle the water by collecting it through the drain pipe and then filter it back to the water tank. The cleaning of PV modules begins from centrifugal pump which starts injecting water from tank to the nozzles pipe. The water nozzles installed at the upper side of the modules, spray water on the front surface of the PV module and clean the surface effectively. The dirty water from the cleaned surface of PV is collected in a water collector pipe. After that the dirty water moves to the filter for recycling. The one-stage filter placed next to the water collector pipe will filter the water and send it into drain pipe. In the last step, the filtered water from drain pipe goes into the water tank where it restarts the cleaning cycle. This cleaning cycle of water is shown in Fig. 2a with the step number to make all the sequence clear. Recycling of water is expected to minimize the water shortage problem in the desert area for the cleaning of PV modules. Flat-Fan nozzles are used for evenly cleaning of the PV module front surface with water.

2.4. Economic Analysis

The economic analysis of the cleaning system is conducted by the comparison of the cost recovered by producing more electricity by PV system through cleaning the surface during its lifetime and the cost of cleaning (Fathi et al., 2017). The cost of the cleaning system is mainly comprising of initial cost and operational and maintenance (O & M) cost. O & M cost is due to the water required for cleaning, energy required to operate and water filter replacement. Initially the cost of cleaning system will add up in the capital amount of PV system installation however with more electricity production from the clean PV module system can save the cost for a longer period (Kazem and Chaichan, 2019; Tanesab et al., 2016). The cleaning of PV modules is expected to save significant energy to reduce the payback period.

The frequency of cleaning action is determined based on the dust deposition rate and daily output energy loss. The cost of the cleaning system (C_{CS}) is the summation of the initial cost (C_{intl}) and maintenance cost (C_{main}) as in Eq. (1). Maintenance cost depends on the material cost (C_{mat}) and workforce cost (C_{WF}) as in Eq. (2). The cost analysis of the proposed cleaning system for 1 m width and the cost analysis of the PV module system has been calculated for 25 years according to the manufacturer datasheet and values have been reported in Table 2 and Table 3 respectively.

$C_{CS} = C_{intl} + C_{main}$ …………………………………. (1)

$C_{main} = C_{mat} + C_{WF}$ …………...……….……..…...….. (2)

Table 2

Cost analysis of the cleaning system (1 m width).

System components	Quantity	Total cost (USD)
Water tank (20 liters)	1	1.28
Diaphragm dc pump	1	7.7
Water filter	1	1.28
Flat fan nozzles	2 sets	2.56
1m SS pipe with pipe fitting and fabrication	1	8.33
Plastic pipe	1.52 m	1.28
Total	1.6	22.43

Table 3

Consideration for economic analysis.

Item	Value
PV systems and cleaning systems lifetime (years)	25
Cleaning system cost (USD)	11.2
Mono PV module 40-watt cost (USD)	17.3
Poly PV module 40-watt cost (USD)	16
Steel stand frame cost (USD)	4
PV installation & commissioning cost (USD)	1.6

The cost of electricity losses (C_{EL}) is calculated in Eq. (3) by using energy losses and electricity cost per kWh (CoE) of the PV system. The energy loss is the difference between the clean PV module energy ($E_{Clean.PV}$) and the dirty PV module energy ($E_{Dirty.PV}$) as calculated in Eq. (4) (Faifer et al., 2014). The electricity cost per unit (USD/kWh) is calculated by dividing the total cost of the system over the total energy (E_{PV}) generated by the PV system for the specific duration as in Eq. (5). For the cleaning system to be feasible and economical, the CoE of the PV module with a cleaning system must be less than the CoE of the PV module without a cleaning system (Kazem and Khatib, 2013).

C_{EL} = Energy loss x CoE …………………………... (3)

Energy loss = $E_{Clean.pv}$ - $E_{Dirty.pv}$ ………………...…… (4)

CoE = Total cost of the PV system / E_{PV} …..……… (5)

3. Results and Discussion

The obtained results have been divided into subcategories as mentioned below. The first part reports the dust collection and characterization. The second part describes the effect of dust on PV performance by comparing the clean and dirty PV module output power and the cleaning system efficiency is discussed. Finally, the economic analysis has been performed.

3.1. Dust collection and characterization

The atmospheric dust collected on the glass sheet with the passage of time is weighed to get the dust density, which shows the daily dust accumulation at different angles. It is experimentally investigated that the dust density after 30 days at tilt angle of 60°, 34.5° and 15° are 3.179 g/m², 4.618 g/m² and 5.522 g/m² with the daily dust deposition rate of 0.106 g/m², 0.154 g/m² and 0.184 g/m², respectively as shown in Fig. 3. It can be concluded that the deposition of dust on the glass surface with a low tilt angle is greater than the high tilt angle due to low gravity. This shows that the PV module installation with a lower tilt angle is likely to reduce more output power due to high dust accumulation on the surface. Said and Walwil (2014) observed the 20% reduction in transmittance and 5 g/m^2 of dust accumulation after 45 days of outdoor exposure. It was also found that the mono-PV module tilted at the location altitude of 25° and the output power has been reduced by 6% after 5 weeks of dust accumulation.

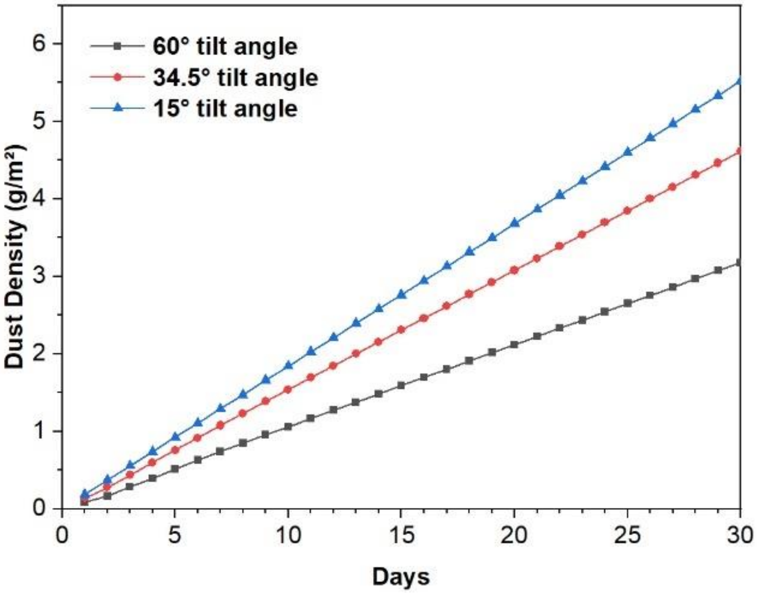

Fig. 3. Deposition of dust at different tilt angles.

The small amount of dust collected from the surface of the PV module installed at the tilt angle of 34.5° facing south has been used for the dust characterization to understand the dust particle size, elemental and chemical composition, and surface morphology. Dust particle size and chemical composition have an important impact on PV performance (Abderrezek and Fathi, 2017). The Results obtained from laser particle size analyzer shows that the particle size distribution by volume of the dust is in the range of 0.5 um to 200 um as shown in Table 4. It is found that the 87 % portion of the dust particle size ranges from 2 um to 45 um which indicates that the particle size is small as shown in Fig. 4. Similarly, (Hachicha et al., 2019; Javed et al., 2017) reported that the dust particles have different sizes, shapes and distributed randomly in the range of 1.6 um to 38.4 um, in which 95 % of the dust particle was below 25 um. Kazem and Chaichan (2016) reported that in dust particle size analysis, the bulk of grain size lies between 2 - 63 um, while in the current study the most of dust particles lie in the range of 2 um to 45 um. It is generally observed that the smaller particles are uniformly distributed with a high accumulation rate and create more scattering of light than larger particles, this may contribute towards higher degradation of PV performance (Tanesab et al., 2015).

Table 4

Dust size distribution per volume percentage.

Dust particle diameter (um)	Volume percentage (%)
0-0.5	0.61
0.5-1	2.89
1-2	7.48
2-5	18.03
5-10	18.14
10-20	21.47
20-45	22.02
45-75	5.81
75-100	2.02
100-200	1.53

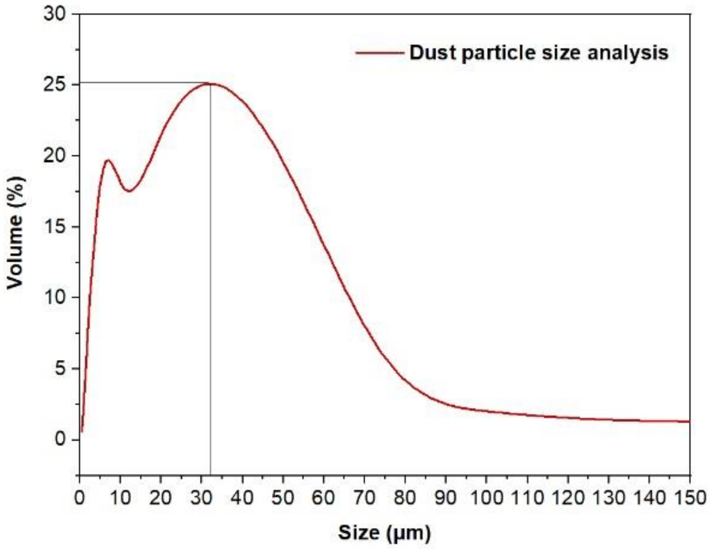

Fig. 4. Dust particle size distribution

The surface morphology of dust is analyzed by performing the topographical inspection on the sample using SEM, as reported in Fig. 5a, which shows that the dust particles have different sizes, random shapes, and irregular distribution. The elemental composition of the collected dust sample is performed by the EDS, as it is important in terms of particle adhesion to the surface. The obtained spectrum in Fig. 5b demonstrates that the oxygen dominates with 48.36 % composition, followed by carbon, calcium, and silicon with the elemental composition of 25.26 %, 10.46 %, and 8.56 %, respectively. Small traces of aluminum, iron, magnesium, sulfur, copper, and titanium are also found. In literature (Hachicha et al., 2019),the author reported EDS results of the dust sample collected from the rooftop, which shows that the oxygen is a major element contributed 46.1 % followed by carbon 20.3 %, calcium 10.5 %, and silicon 10.2 % with the small traces of magnesium, iron, aluminum, copper, sodium, potassium, sulfur, and chlorine. Javed et al., (2017) found that the calcium is the most abundant element followed by silicon, iron, magnesium and aluminum. Calcite, dolomite, and quartz were the major minerals present in the dust. It was also found that the dust particles size decreases with the increase in outdoor exposure time. The elemental concentration in airborne dust is site-dependent and depends on the pollutants and the emission sources such as transportation, construction, and industrial waste in the surroundings.

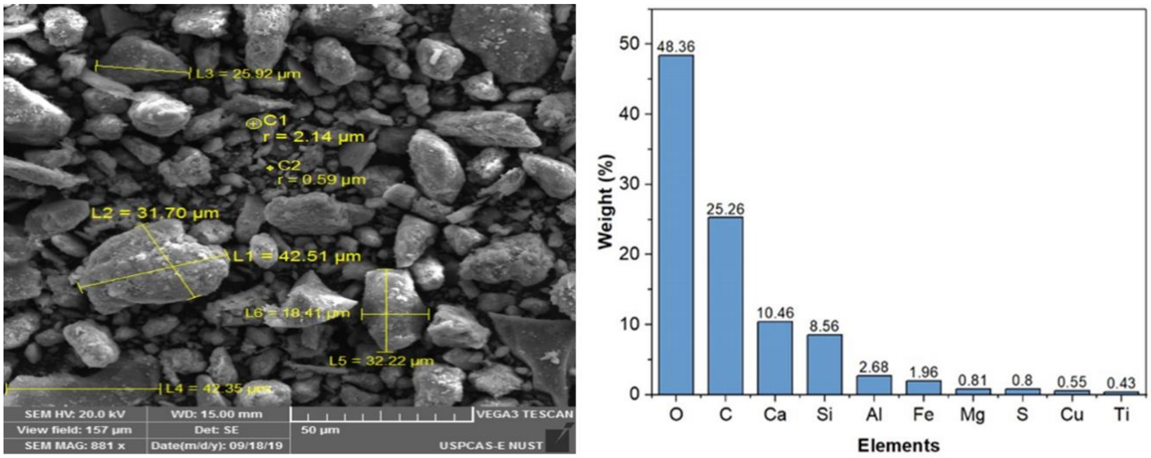

Fig. 5. a) SEM image of dust b) EDS spectrum of dust

The mineralogical analyses of dust performed by the X-ray Diffraction, the peak intensities formed by the attenuation of X-ray scattering from the sample to the X-ray detector in Fig. 6 show that the dust particles are mainly composed of quartz, calcite and silicon sulfide. The obtained XRD results are compared with the literature (Hachicha et al., 2019), it is found that the major mineral composition of the dust sample contains SiO$_2$, CaO, and Fe$_2$O$_3$ minerals in the test. (Queralt et al., 2001). Kazem and Chaichan (2016) found that dust contain 86 % portion of SiO2 and CaO. It is also found that the major portion of calcite shows the involvement of human activities near the site. In general, the atmospheric dust contains six different minerals (quartz, illite, kaolinite, gypsum, calcite, and dolomite) that can be recognized from the X-ray diffraction patterns of samples mounted on glass slides, silicon plates, and Ag-filters (Queralt et al., 2001).

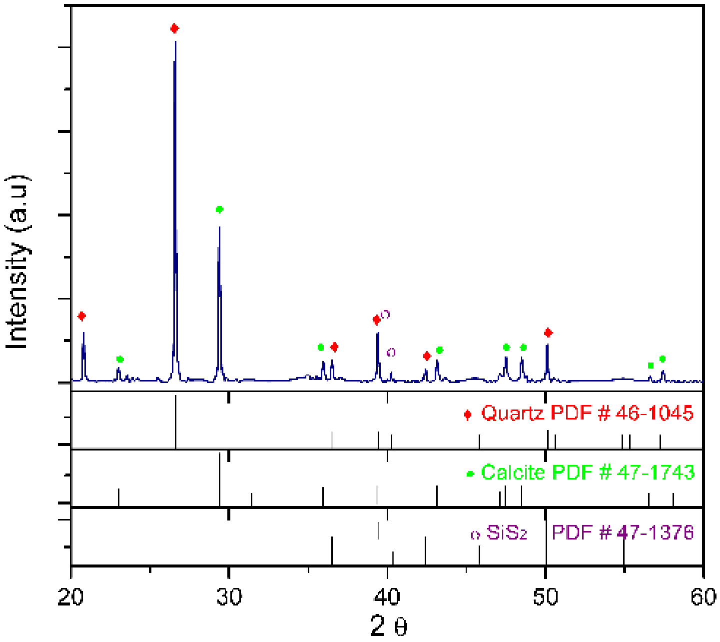

Fig. 6. XRD of the dust sample

3.2. Effect of dust on PV performance in an outdoor environment

The rate of decrease in the PV module's performance mainly depends on the rate of dust accumulated on its surface area. The performance of dirty and clean PV modules over a whole day is observed for the entire period of experimentation. To simplify the analysis of the results, days with approximately constant weather conditions i.e. maximum daily solar irradiation (6 kWh/m²/day to 7 kWh/m²/day) and almost the same energy output, were selected. The parameters used to study the effect of dust on PV module output are dust density, daily energy output, and output energy loss.

The effect of dust on output power is experimentally observed on both mono-PV and poly-PV modules. The graph in Fig. 7 shows that the layer of dust on the surface of the PV module reduces more output power of the mono-PV module than the poly-PV module because the mono-PV cell is made up of single-crystal which drops more power on the shading of dust than poly-PV cell made up of multi-crystalline structure (Edalati et al., 2015). It is found that the output power loss of the mono-PV module is 36.75 % and the poly-PV module is 26.25 % at 10.5 g/m² of dust density. The experiment is conducted on the PV module at the installation angle of 34.5°, and the effect of dust on PV performance at different dust density is observed and analyzed. Besides the dust density to the output power loss plot shown in Fig. 7, it has been observed that the output power loss varies with different tilt angles of PV modules, on which the dust density depends. It has been determined from the experimental data that the output power loss of dirty mono-PV at the different installation angles of 60°, 34.5°, and 15° is found to be 11.13 %, 16.16 %, and 19.33 %, respectively, while the output power loss of dirty poly-PV at 60°, 34.5° and 15° is found to be 7.95 %, 11.55 %, and 13.8 %, respectively.

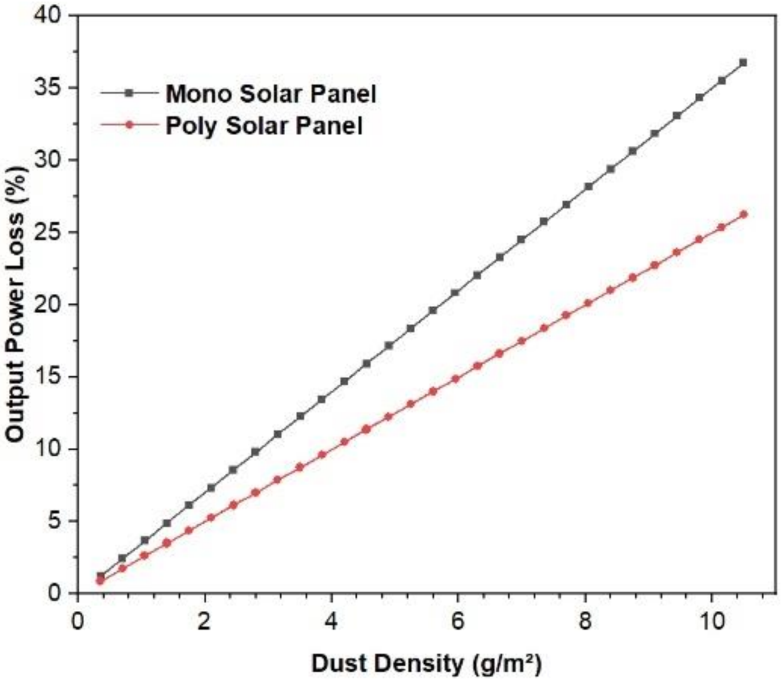

Fig. 7. Output power loss due to dust accumulation.

All the reported data has been analyzed in the span of 30 days without rainfall and plots are shown in Fig. 8 which shows that the maximum output power loss observed is 19.33 % at tilt angle 15° of mono-PV module and minimum output power loss observed is 7.95 % at tilt angle of 60° of poly PV module. The fixed installation angle of PV modules is mostly set according to the latitude of the location, from which the maximum solar radiation can be harvested in the whole year. The experimental results show that the average daily output power loss of 0.54 % is observed in the mono-PV module and 0.38 % in the case of the poly-PV module at the installation angle of 34.5° with an average daily dust deposition rate of 0.154 g/m².

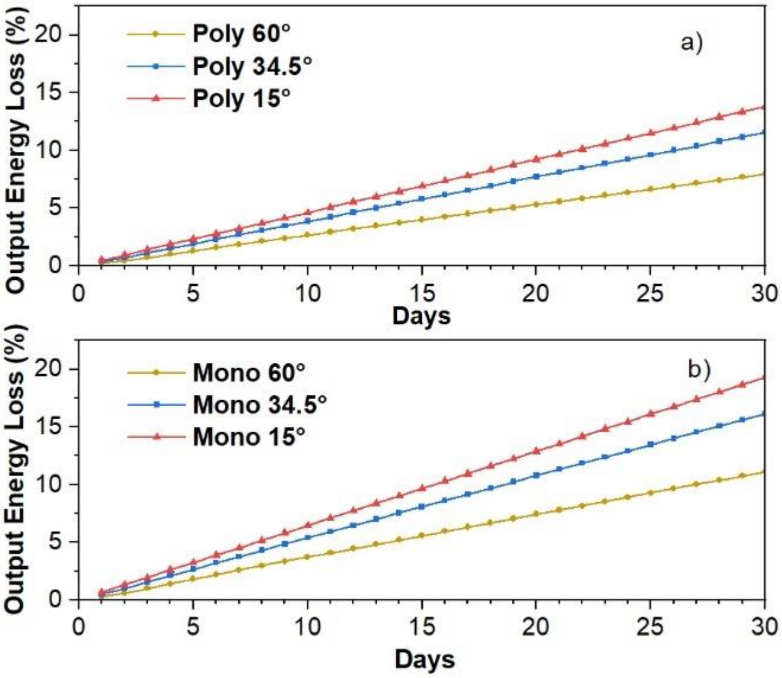

Fig. 8. Output energy loss; a) poly PV module b) mono PV module

The effect of dust on the electricity production has been observed by the comparison of the dirty and clean PV modules output power. The normalized maximum power output ($P_{max}/P_{max.daily}$) is measured for different dust densities as shown in Fig. 9. It is found that the daily energy generation of both mono-PV and poly-PV modules is directly related to the daily solar radiation. The energy generation of clean and dirty PV modules is the same on the first day of the experiment when both have clean front surfaces. The dust starts to deposit on the surface of PV modules with the passage of time, one set of PV modules is cleaned on daily basis in the morning while the other set of PV modules is left uncleaned and recorded the daily output energy of both sets for 30 days. The daily energy production of clean PV modules remains the same in 30 days while the dirty PV modules energy production starts declining and reduces every day until dirty mono PV module reaches 16.16 % and dirty poly PV module reaches 11.54 % of output power loss.

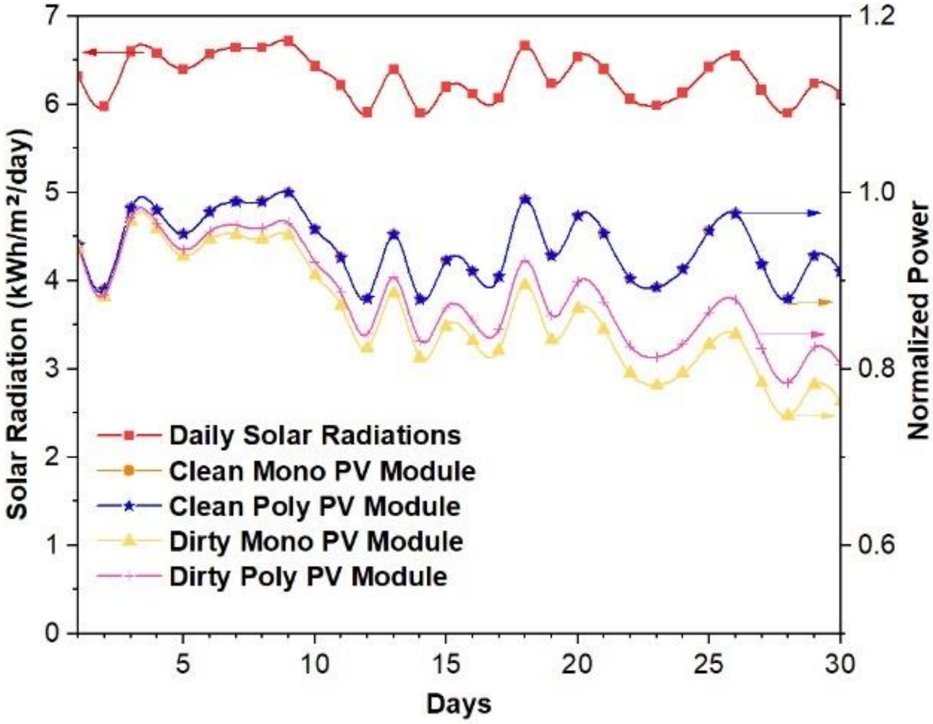

Fig. 9. Comparison of the energy output of PV modules.

3.3. Water Cleaning System

The cleaning of the dirty PV module set (Dimensions: 0.55 m (L) x 1 m (W) x 0.035 m (T), Area = 0.55 m²) is performed by spraying water through flat-fan nozzles using the designed cleaning system. In the experiment outcomes, the cleaning system takes 35 secs to completely clean the dirty PV modules set and recover the output power by 98 %. The water flow rate of the cleaning system measured by the water flow meter is found to be 1.735 L/min or 0.475 GPM in the presence of flat-fan nozzles, while the maximum water flow rate of the water pump is 4 L/min. The water requires to clean the set is calculated to be 1 liter, from which it can also be concluded that the area of 1 m² requires 1.8 L of water for cleaning. The energy consumed by the cleaning system for 35 seconds of operation is calculated to be 0.3 Wh with the power capacity of 36 watts. These results of the cleaning system have been verified by cleaning the PV modules 10 times during different days and taking the average of it. The cleaning of PV modules is done in the morning to minimize the evaporation of water. The water recovered after the cleaning and collected in the water tank is found to be 550 ml. It has been observed that the recycling of water is 55 % of the total water used to clean, which is considered low because most of the water droplets sprayed through the flat-fan nozzles carried by the wind and some of the water evaporates.

3.4. Economic analysis

The economic analysis has been performed considering the radiation data, dust characterization, dust deposition rate, energy production, energy losses, cost of the PV module, and cost of the cleaning system, according to the literature (Pillai and Naser, 2018). The economic analysis results for the recorded data indicate that the cost of the cleaning system for mono-PV (40 watts) and poly-PV (40 watts) modules are 0.037 USD/month, which is greater than the cost of energy losses 0.005 USD/month. For a 2-month period of the study reveals that the cost of electricity per unit (USD/kWh) of the PV module with the cleaning system which is 0.04 USD/kWh for mono-PV and 0.023 USD/kWh for poly-PV greater than the electricity per unit cost of the mono-PV and poly-PV module system without the cleaning system which is 0.028 USD/kWh and 0.022 USD/kWh. This shows that the cleaning system is not feasible for the 40-watt panel.

This cleaning system with a width of 1 m can also be implemented on a commercial size PV module that can provide feasible economic analysis, considering the same cleaning criteria and cleaning efficiency with extra water requirements according to the area of the PV module. For commercial scale, the maximum power capacity of the PV module found for mono-PV is 415 watts (“mono-PV Module-400,” 2019) with the dimension of 2.02 m (L) x 1 m (W) x 0.035 m (T) and for poly-PV is 355 watts (“Poly-PV module-355,” 2019) with the dimension of 2.02 m (L) x 1 m (W) x 0.035 m (T), the cost is given in Table 5. The energy production and energy losses of commercial size PV modules having 1 m width have been predicted for 4 months. The first 2 months of energy generation values for clean and dirty commercial size PV modules have been calculated from the results of small size PV modules used in the experiment taken as a reference. For the next 2 months of energy generation, the values are predicted from the previous trend linearly and considering the same procedure and parameters. For this scenario, the economic analysis results indicate that the cost of the cleaning system becomes less than the cost of the energy losses for the PV module system after some time in Fig. 10. The cost of electricity per kWh is also become cheaper for the commercial size PV modules with the cleaning system than without the cleaning system as shown in Fig. 11. In terms of cost, the cleaning system for mono and poly PV module is economically feasible after cumulative energy loss and consecutive dust accumulation with no rainfall of 50 and 83 days. There is a need for the cleaning system and more than 3 months of energy losses would be uneconomical for both types of PV modules without the installation of the cleaning system as already observed by other researchers (Mostefaoui et al., 2018). Therefore, the cleaning system is recommended for a large-scale commercial PV system.

Table 5

Consideration for economic analysis.

Item	Value
PV systems and cleaning systems lifetime (years)	25

Cleaning system cost (USD)	22.43
Mono PV module 415-watt cost (USD)	170
Poly PV module 355-watt cost (USD)	128.4
Steel stand frame cost (USD)	8
PV installation & commissioning cost (USD)	3.2

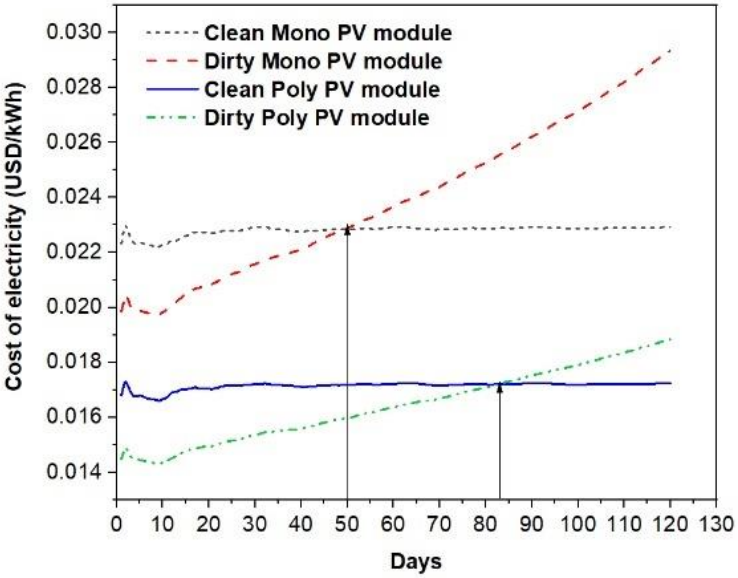

Fig. 10. Electricity cost comparison.

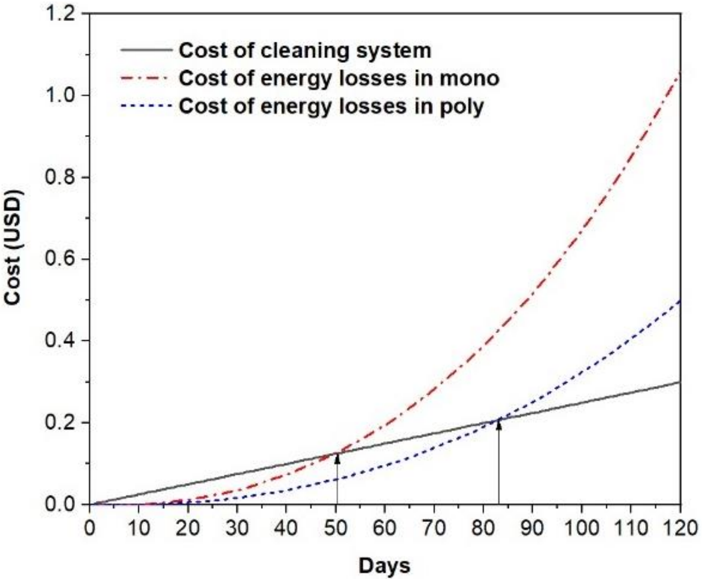

Fig. 11. Cost of cleaning system and energy losses.

4. Conclusion and recommendations

Soiling losses is one of the challenging issues for the PV module system to operate efficiently under Pakistan weather conditions. This study has investigated the performance of the PV module affected by the dust accumulation in an outdoor experiment and the influence of cleaning using a cost-effective home-made cleaning system. The experiment has been performed employing the experimental setup for dust settling on the PV modules surface, to observe the output power variation, cleaning of modules by pressurized water and finally economic analysis. The main findings of this work are summarized in the following points:

- Dust accumulation depends on the tilt angle of the PV module surface. A high tilt angle accumulates less dust on the surface due to gravity than a low tilt angle surface. After 2 months of outdoor exposure, the daily dust deposition rate found to be 0.184 g/m^2 at 15° tilt angle and 0.106 g/m^2 at 60° tilt angle.
- The dust characterization results show that most of the dust particle ranges from 2 um to 45 um in size, has random shapes, and contain a high percentage of carbon, silicon, and oxygen. The dust has small particles with high influence on PV performance.
- The results indicate that after one month of uncleaned PV modules installed at 34.5° tilt angle contributes a 16.16 % loss in output power of mono-PV module and 11.54 % loss in a poly-PV module, with 4.6 g/m^2 dust density.
- A linear relationship found between output power loss and dust density with the output power drop of 3.5 % per g/m^2 for the mono-PV module and 2.5 % per g/m^2 for the poly PV-module is observed.
- The daily output power loss rate of the mono PV module (0.53 %/day) is higher than the poly PV module output power loss rate (0.38 %/day) with the dust deposition rate of 0.153 g/m^2/day. Hence this shows that the mono PV module drops more power on shading due to dust accumulation as compared to the poly PV module.
- The cleaning recovers 98 % efficiency of the PV module in 35 seconds of operation performed using water with a flow rate of 1.735 L/min. The cleaning

system has a water recycling capacity of 55 % and a water requirement of 1.8 L/m^2 for surface cleaning.

- The proposed cleaning system design can be scalable to all commercial size arrays and it can also operate in industrial areas and almost any dusty/low rainfall area that contains ash, smoke, and cement particles in the dust. The system is low maintenance with minimum human intervention involved.
- This cleaning system is found to be cost-effective for commercial size PV modules. Hence, the commercial size mono PV module (400 watts) should be cleaned before 50 days of dust accumulation and the poly PV module (355 watts) should be cleaned before 85 days of dust accumulation with the proposed cleaning system to avoid the extra cost of energy losses.

The cleaning system is recommended and economical only for large/commercial-scale PV modules. The cleaning of the PV module surface can be more efficient by modifying the nozzle design and more water can be recycled. The use of surfactants in water can help to reduce water usage and clean the dust effectively. The proposed automatic dust cleaning system of solar PV modules has the potential to overcome the difficulties arise in the traditional cleaning techniques and produces an effective, non-abrasive cleaning to avoid the irregularities in productivity due to the deposition of dust. However, the outdoor experiment did not cover the whole year especially the winter season, where the dew factor can be counted and affect the dust deposition. The cleaning frequency should also be tested under the dew factor. Therefore, further studies can be carried out to combine the effect of dust and dew factor along the year and hence the cleaning system can be improved. To advance and globalize this cleaning technique, an extensive collaboration of researchers is recommended.

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