Experimental study of the impact of dew on soiling and automatic surface-cleaning set-up to optimize the electricity production of PV panels in Polluted atmosphere

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Session 2019-21

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Islamabad, Pakistan

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

The thesis is wholeheartedly dedicated to my beloved parents, **Naheed Kousar,** and **Umar Hayat** who always believed in me and pushing me forward in times when I struggled. I am thankful for their love and measureless support. You have been a driving force throughout this process. Even when my weak soul was withered, they always saw light in me, if today I am capable to stand up is because they always healed my broken bones. Every single equation and effort are dedicated to you.

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Abstract

The performance characteristics of PV modules are significantly affected by environmental factors, particularly by soiling. Dew factor can amplify the deleterious effect of soiling on the performance of PV modules. Therefore, this study investigates the morphological changes caused by dew in dust and proposes a novel automated water-based cleaning system to remove dew-induced dust-off PV modules. The experiment was conducted for the climatic conditions of Islamabad-Pakistan using poly-PV modules. The results showed that soiling losses at tilt angles of 23˚,33˚ and 43˚ degree were 16%, 12%, and 20%, respectively. The proposed cleaning system sprinkles water using flat fan nozzles. The used water was filtered and collected back to storage tank. The power recovered after effective three days of cleaning was 12%, 9.77%, and 18% respectively at tilt angles of 23˚,33˚, and 43˚ degrees. It was observed that cleaning process requires 7.33 ltrs of water to clean surface area of 1.48 m^2. The cleaning process also provide cooling effect to PV modules decreasing front and back surface temperature at tilt angles of 23˚,33˚, and 43˚ degrees by 1.3˚, 0.52˚, and 0.3˚ C and 1.4˚, 0.7˚, and 0.3˚ C. The financial evaluation of the proposed automatic cleaning system indicates that it is feasible for domestic and commercial-sized PV systems.

Keywords: PV module, PV cleaning system, effect of dew on dust, tilt angle, Power, Temperature

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List of Abbreviations

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

Imax …… Maximum current

Vmax …… Maximum voltage

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_{IC} …… Investment Capital

C_{M} …… Maintenance cost

C_{mat} …… Material cost

C_{ACS} …… Addition of the investment capital

C_{E_L} …… Cost of energy losses

COE …… Cost of electricity

E_{D} …… Dusty PV module energy

E_{C} …… Clean PV module energy

Chapter No. 1

Introduction

1.1 Background

Renewable energy sources are replacing fossil fuels rapidly due to climate change and global warming. Continuous increase in fossil fuel prices and their environmental impact is obvious to the world, while solar energy considers to promising glean energy source to replace fossil fuels [1]. The continuous increase in carbon emission results in natural catastrophic events like glacier melting, uneven rain patterns, storms, sea-level rise, heatstroke, and droughts [2]. Electricity generated using renewable rose by 7% in 2020 and is predicted to share 60% of the overall electricity generation by 2030 (World Energy mix 2020- IEA) [3]. Solar energy and wind energy are the fastest-growing renewable energy resources accounting 60% rise in electricity production by renewables [4]. Solar energy is rapidly growing with an estimated potential of 23,000 TW per year of electricity production [5]–[9]. Solar energy conversion efficiency is under development, Although the highest efficiency achieved in commercially available solar PV modules is 29.28% [10]. Soiling is an immense degrading factor that can reduce power to a large extent depending upon the environmental conditions. [11]. Solar PV modules are deployed in series-parallel combinations, therefore, if performance of a single panel is affected by environmental factors it results in affecting the entire production [12]. Recently, researchers are immersed in automatic cleaning due to lower operational costs and more effective cleaning. Some of the commonly used cleaning techniques are water-based cleaning, brush cleaning, wiper-based cleaning, anti-soiling coating, air-blow cleaning, and electrostatic cleaning of solar panels.

1.2 Solar energy potential of Pakistan

Pakistan is located in South Asia with an average solar irradiance per day of 5-7 kWh/m^2 and 8-9 sunshine hours per day [13]. Considering the solar irradiance and sunshine hours in Pakistan, the solar energy market is exponentially growing. Although from 2011 to 2030 electricity demand in Pakistan is expected to increase by 260% [14], therefore, it is predicted that Pakistan will be among the countries with the highest electricity production from solar PV in the future as shown in Figure 1-1 [15][14].

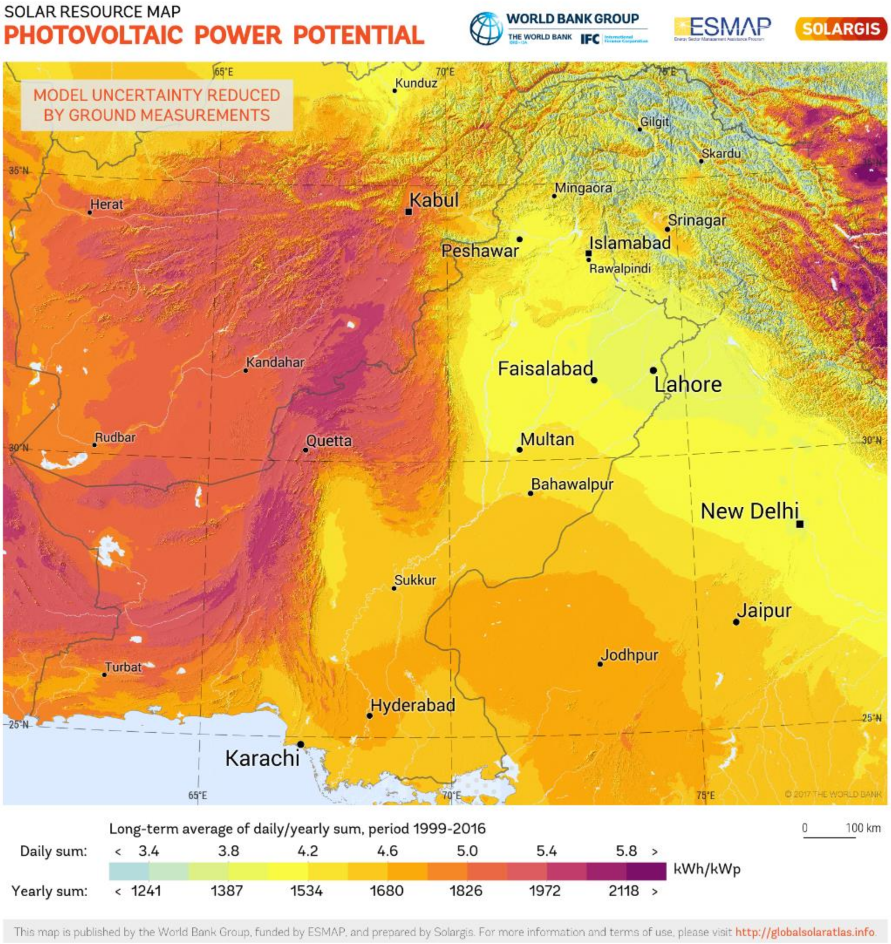


Figure 1-1 Solar PV power potential map of Pakistan[16]

The largest solar farm in Pakistan is the Quaid-e-Azam Solar Power Park (QASP) located in the Cholistan district. QASP is planned for one gigawatt of installed capacity of solar PV system, however, only 100 MW of solar PV plant is deployed till now. Moreover, many other large-scale projects are also commissioned, under process, or inaugurated. Many of the installed solar PV projects are facing drop in the performance due to the soiling effect especially the one installed in the QASP due to the desertic climatic conditions. The poor maintenance and lack of a proper cleaning facility at QASP led to a drop in the performance of the power plant. High dust accumulation is reported on solar panels of QASP. The management has created an artificial lake to provide water for cleaning but without proper infrastructure for cleaning solar panels, this lake is not sufficient and unreliable [17]. Therefore, currently the major issue the solar PV plants are facing is the soiling effect that reduces their power generation capacity to larger extent. Therefore, in the current study this issue has been investigated and the solution has been proposed through a lab scale experimental study.

1.3 Solar Photovoltaic Device

Photovoltaic (PV) Solar panels are the device which is used to produce electricity using solar energy. Solar PV panels are made up of series-parallel combination solar cells. These solar cells are fabricated using semiconductor material by combining P and N-type materials. [18] The upper surface of the solar panel is exposed to solar light, the material absorbs the photons from sunlight and produces flow electron, which is collected through an external circuit. Different types of solar panels is invented up till now three generations of solar PV panels are manufactured but commercially available and mature technology is crystalline solar Panels [18]. The solar photovoltaic technologies which are commercially available can be categorized as:

1.3.1 Monocrystalline PV panels

It is a type of crystalline solar cell having a mono crystal structure, it is the most mature technology of solar panels with an efficiency of approximately 22%. Mono crystalline (mono-PV) are favorable for a temperature of 30 -35 degrees. During fabrication of Mono-crystalline Solar cell due to the round shape of ingots, they have cut on the edge of each cell blackish in color. The efficiency of Monocrystalline is better than polycrystalline solar. Moreover, they are called 1st generation Solar cell technology [19].

1.3.2 Polycrystalline PV panels

Like Monocrystalline solar cells, it is also from the family of crystalline silicon, but the structure of atoms is poly. The sequence of the crystalline structure is slightly different from the Monocrystalline. These types of Solar panels are also considered first-generation solar cells. The operating temperature of Poly-crystalline solar cells is lesser than monocrystalline because of the lower temperature coefficient. The efficiency of polycrystalline solar panels are slightly less than mono silicon approximately 21% commercially available. The solar cell of polysilicon is square with bluish [20].

1.3.3 Amorphous Silicon Panels

The amorphous solar cell is 2nd generation solar cell, and they are from the family of thin-film solar cells. The technology of thin-film silicon is in the developing phase and possess low efficiency than crystalline solar cell while the cost of thin-film solar cell is very low as shown Figure 1-2. It can also be used in the application of flexible materials. Amorphous silicon applications are increasing rapidly [21].

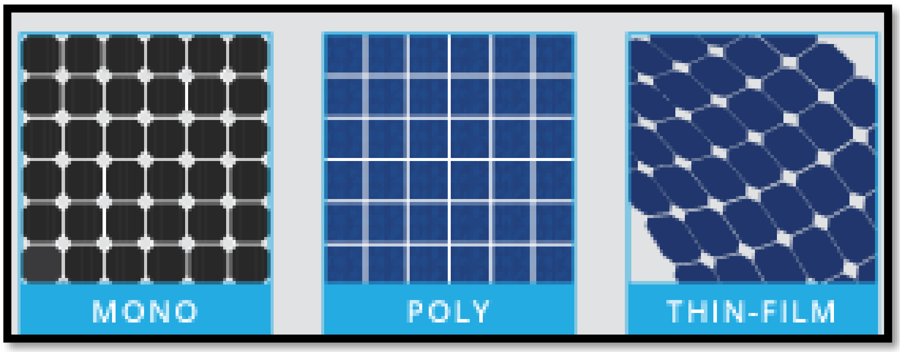


Figure 1-2 Comparison between different technologies of Solar Panels [21]

1.3.4 CIGS Solar Panels

This type of solar cell also belongs to the 2nd Generation Solar Cell. It contains a different type of material combined to obtain the higher efficiency of a solar cell. Copper, indium, gallium, and Selenium are four materials that are used in this type of solar cell. However, they can be manufactured on low temperature and cheap substrate material. The thin-film solar cell has an efficiency of 21%. The combination of different materials reduces cost with improves inefficiency [22].

1.3.5 Cadmium Telluride Solar panel

Cadmium telluride solar cell is a family member of a 2nd generation solar cell with the highest efficiency of the single-junction solar cell of 26%. It is also used widely in commercial projects and is considered to be one of the highest used PV solar cells. Cadmium and telluride materials are used in the manufacturing of solar panels as shown in Figure 1-3. Cadmium telluride is the most widely used 2nd generation solar cell on the commercial level [23].

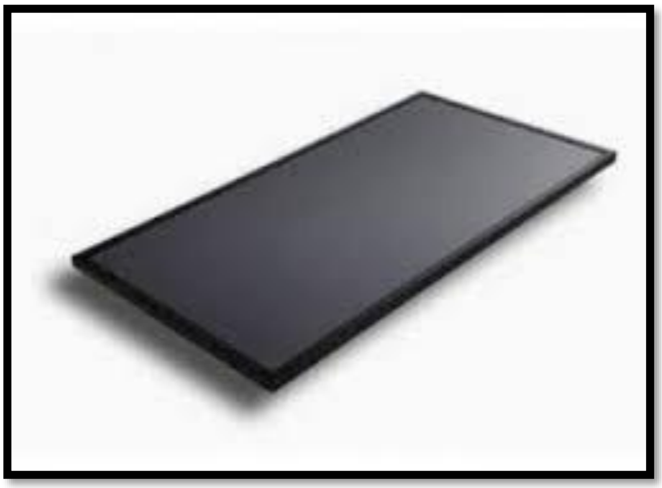


Figure 1-3 CIGS Solar Panels [23]

1.3.6 Multi Junction Solar Cells

The multi-junction solar cell has the highest efficiency of PV solar cell near about 54%, different type of solar cell is stacked together to harness the solar energy effectively. Different material absorbs different type of wavelength in the electromagnetic wave of solar light. This technology is in the developing phase and high cost of the solar cell as compared to a crystalline solar cell. Multi-junction works on the principle of the quantum tunnel where the wave property of photon is used to travel between the potential barrier [24].

1.3.7 Organic Solar Cell

Organic Solar cells are 3rd Generation solar cells; no project or solar cell is commercially available for the organic solar cell as shown Figure 1-4. The Perovskite solar cell has achieved an efficiency of 13% up till now but the lifetime of solar cells is very short approximately 10 years. But the cost of a Perovskite solar cell is much cheaper than a crystalline solar cell [8].

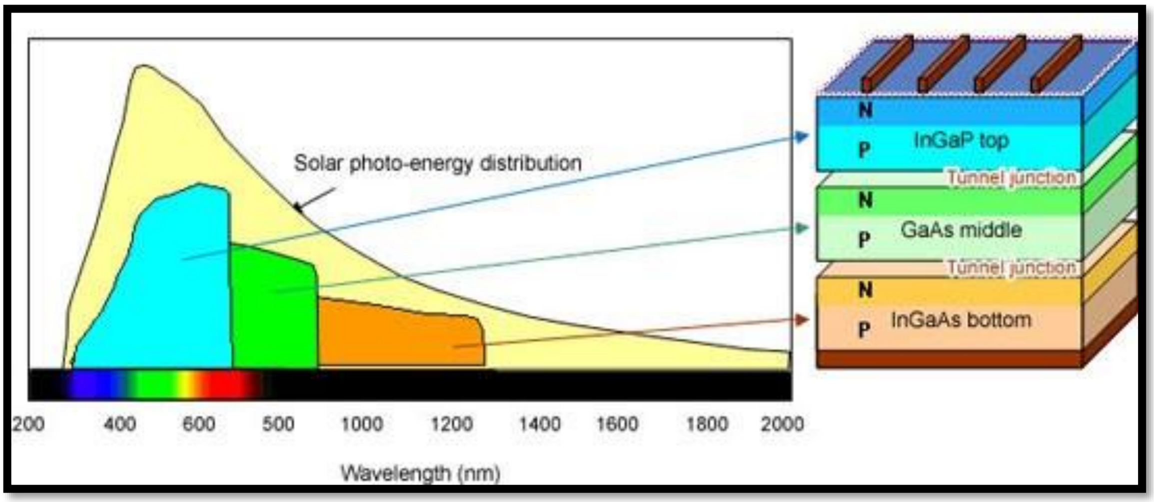


Figure 1-4 Multi Junction Solar Cells [8]

1.4 IV Characteristics of PV Solar Panels

Solar Photovoltaic is another type of technology that converts solar light energy directly to electricity. Solar photovoltaic is made up of Semiconductor material (P and N time), which harnesses the photon and produces the flow of electron (current). The Power produced from the Solar Photovoltaic can be observed through IV characteristics. IV characteristic curves of a solar cell are the graphical representation of the relationship between voltage & current produced by a solar cell under a specific set of irradiance and temperature. IV characteristic curve is used to optimize the solar cell performance to achieve the maximum power point. The graph below shown in the Figure 1-5 is a typical IV curve of PV solar under standard conditions [25]. The power of a PV solar cell is a product of current (I) and voltage (v). If multiplication is performed point to point between voltage and current IV characteristic curve graph is obtained. When no load is connected with a solar cell and voltage in a solar cell is maximum while the current is zero, this voltage is known as Open circuit Voltage (Voc) [26]. When the positive side and negative side of the solar cell are short-circuited and the voltage across the solar cell is zero, however, the current in the solar cell is maximum which is known as Short circuit current (I_{SC}). The maximum span of IV characteristics of a solar cell can be between the open-circuit voltage and short circuit current. Practically these two-point do generate any power but are considered to be limits of IV characteristics while the Maximum point must be located in between these two points [27].

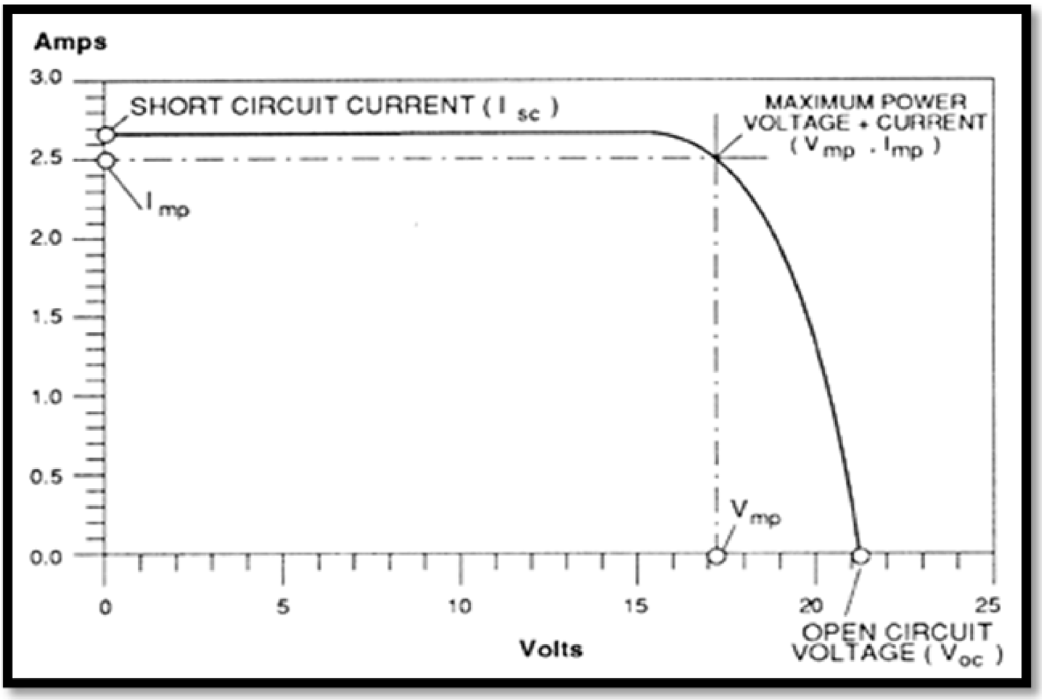


Figure 1-5 IV curve of Solar cell [27]

The point where maximum power is produced by the solar cell is known as the maximum PowerPoint. While voltage at maximum power point is (V_{mp}) and current is (I_{mp}). The most possible position for locating the maximum power point on the IV characteristic curve is near the bend. However, the voltage and current may vary with temperature so the maximum power point will also vary with the temperature of the solar cell.

1.5 Problem identification

Solar PV is a promising renewable energy technology to produce clean and green energy with large resources widespread across the globe. But due to harsh weather, pollution, and dust accumulation, its performance is badly affected. The wind carries the dust particle which is accumulated on the top surface of the solar PV module. These dust particles affect the absorbance of solar irradiance as well as increase the cell and module temperature. Due to soiling the output power produced by solar PV panels is reduced, while the high temperature of the module increases the losses with defects in the solar PV module. The current solar PV modules do not have any cleaning facilities which results in daily large power loss.

1.6 Justification of the research

Pakistan is facing an energy shortage for a couple of decades, and a rapid increase in population has increased the energy demand. The electricity demand in the country is increased by 28% in the last 4- years, moreover it is expected it might increase to 85% by 2025. To overcome the energy shortage in the region Solar energy is a promising solution that can be utilized to overcome the issue of energy shortage. Recently many solar PV farms of megawatt capacity are being installed or commissioned on a commercial and industrial scale for electricity production. Solar PV farms are subjected to different external conditions that reduce the output power. The soiling effect is one of the major adverse factors effecting the power obtained from solar PV. Therefore, this study is conducted to analyze the effect of dew factor on the soiling of the PV panel. It has been observed that very limited number of research is conducted to analyze the effect of soiling under dew conditions. To study the soling condition a lab scale experimental setup is designed to clean the soiling over solar PV panels and study its effects on the PV output. This study will help the upcoming student to research more about the dew effect on the performance of solar panels. The selection of this topic is made by taking the following consideration:

- Solar PV growth in Pakistan's environment
- Power degradation due to soiling
- Lacking cost-effective cleaning system
- Promoting green energy in Pakistan
- Analyzing different factors in the soiling rate

1.7 Scope of Research

This experimental study has been performed to analyse the effect of soiling on the electrical output and temperature of the Poly-PV module. A novel and cost-effective water-based automatic cleaning system have been proposed to clean the soiling over the top surface of solar PV panels. The cleaning system consists of flat fan nozzles which were designed and fabricated to perform cleaning. Automatic cleaning use pressurize water can be performed using the proposed system Furthermore, a recycling system was also proposed with a cleaning system that recycles the water to the tank. The study was also conducted to analyse the effect of dew on the soiling rate. Economic analysis was conducted to obtain the economic feasibility of cleaning concerning the cleaning frequency, moreover, cost of electricity, and cleaning cost to clean and dirty PV modules.

1.9 Objectives of the Research

The primary and the broader objective of this study is to design a cost-effective automatic cleaning system capable of studying the effect of soling factor on the out of the PV panel

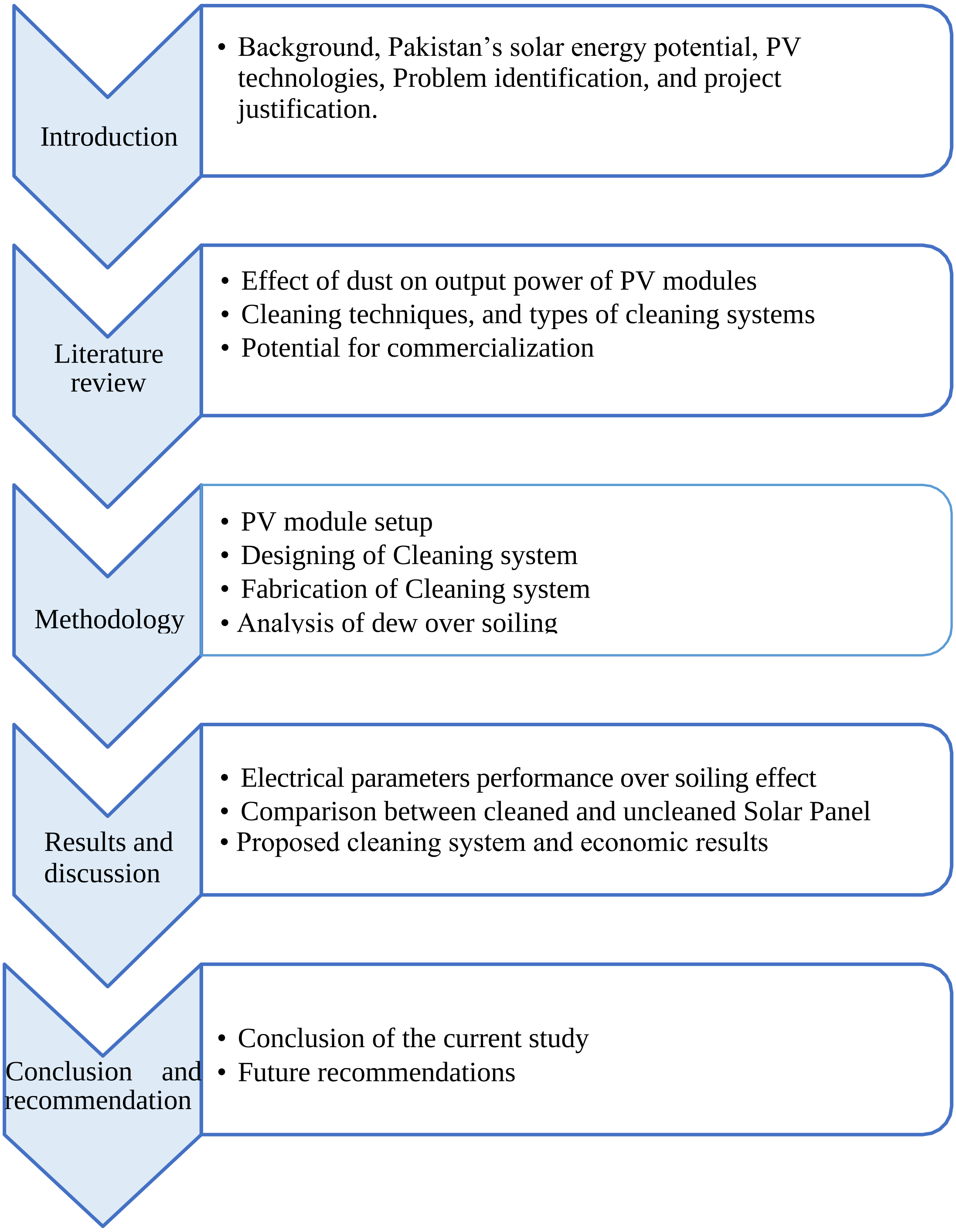
Explicitly following are the objectives of the study:

- To design an experimental setup to measure the soiling rate and under different varying climatic condition.
- To measure the electrical parameters of solar PV panels under dusty conditions and analyze the effect of dew over soiling.
- To analyze the effect of soiling on the temperature of front surface and back surface of the solar PV panel.
- Design, develop and fabricate the experimental setup for the automatic cleaning system.

1.10 Limitations of Research

The research was only conducted on Polycrystalline solar PV panels. The system is effective with 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 depending on the water flow rate, pressure, and angle that can be used for cleaning purposes. Cleaning 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 and icing factor can affect the output power of the PV module.

1.11 Thesis outline



Summary

Solar energy's importance and the problems regarding its efficiency have 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.

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Chapter No. 2

Literature review

2.1 Water-based Cleaning

Water-based cleaning is commonly used to clean the solar panel, moreover, it's the most effective type of cleaning for dry soiling [1]. Water-based cleaning is conventionally performed by installing water sprinklers on top of solar panels, which sprinkles water with pressure over the solar panels to remove the soiling over the surface [2]. Different types of water sprinklers at different positions are installed to vary the water pressure over solar panels. Whereas manual water cleaning can be performed by showering water over solar panels using pipe by a dedicated person. This type of cleaning is a slow process and not recommended for large-scale solar projects [3]. However, the risk of leakage in solar panels can cause damage to the internal circuit leading to a short circuit as shown in Figure 2-1 [4]. Mondal et al. reported that manual water-based cleaning can increase power output by 10% while water sprinkles can increase efficiency up to 25% Heliotex. Moharram et al. reported that cleaning with unpressured water can lead to a decrease in the overall efficiency of the system, experimentally it was observed that 50% of efficiency was reduced over 45 days cleaning with unpressurized water [5], using pressured water with surfactants for cleaning can improve the efficiency of the solar panel by 3%.

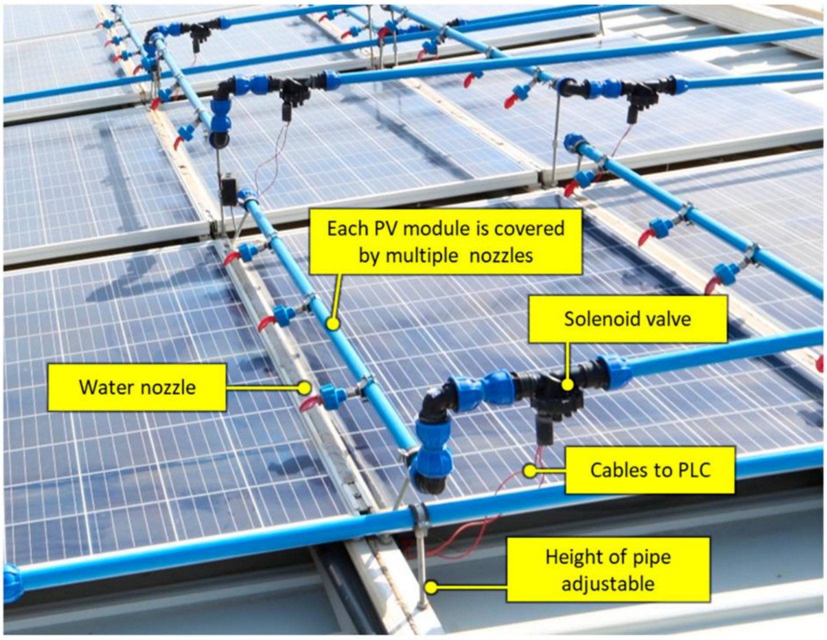

Figure 2-1 Water Based Cleaning system[6]

Amirhosein Hadipour et al. found that the maximum power output of Solar panels is increased up to 25.9%, 27.7%, and 33.3% by spraying water in steady-flow [7]. Jaiganesh et al. experimentally concluded that regular internal cleaning of solar panels can increase the efficiency up to 15-20%[8]. Abdolzadeh et al. employed a system for spraying water over the top surface of solar panels to improve the efficiency as well as cooling of solar panels, it was concluded from the experiment that PV cell efficiency was improved by 1.35%, 1.40, and 3.26% respectively [9]. Elnozahy et al. proposed a prototype of an automatic water system for cleaning and cooling solar panels. The water is sprayed over the surface of the solar panel with reduced surface temperature by 45.5% and 39%. However, solar panel efficiency was also improved by 11.7% [10]. Chaichan et al. concluded from the experiment that uncleaned solar panel has a power reduction of 13% while water was sprayed over the solar panel to improve the power production however, the surfactant should be added to the water for effective cleaning [11]. The major drawback of this type of cleaning is only effective for dry soiling, although bird drops cannot be cleaned through water cleaning. However, it also requires a large amount of water for cleaning.

2.2 Wiper Based cleaning

Wiper-based cleaning is employed in remote areas where availability of water is a concern, it does not require water for cleaning of solar panels. Wipers move over the surface of solar panels to remove the dust particles as shown in Figure 2-2. Prasanthi et al. developed a wiper-based solar panel cleaning system using an arm controller and gear motor, after the cleaning system improved 35% of power losses however, motors to move the wipers were powered through solar panels which take up to 10% of the power [12]. This method is effective to clean soiling on a smaller scale while large power would be required on large scale, moreover, it also involves an active component that will require continuous maintenance for effective operation. Zhang et al. designed a piezo electric-based actuator for cleaning of solar panel using wiper, for dusty environment the wiper has better cleaning efficiency as compared to water-based cleaning [13].

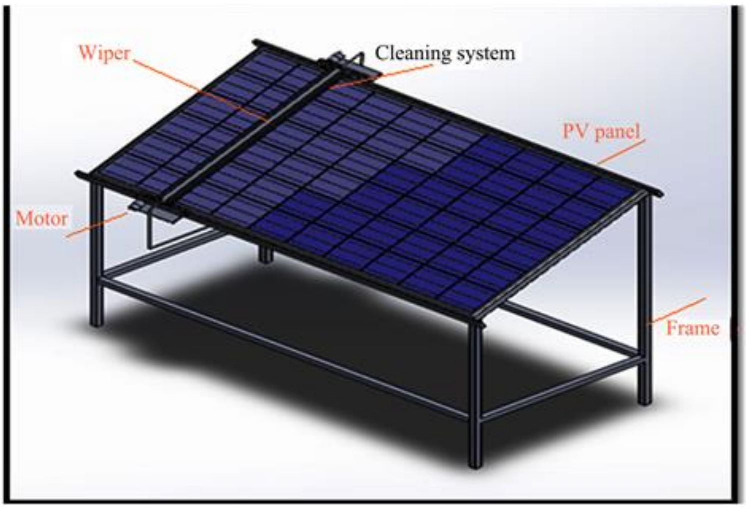

Figure 2-2 Wiper based solar PV cleaning system[14]

It was concluded by the authors that higher pressure is required to drive the wiper across the solar panel in a perpendicular direction, but cleaning efficiency was good and high energy gain was observed after cleaning. Parrott et al. proposed a study related to dry cleaning of solar panels, the proposed prototype type was an automatic robotic cleaning system that includes a wiper made up of silicone rubber [15]. After experimentation, it was observed that performance difference after one week without cleaning was 1.5%, however, after two weeks performance was dropped up to 3%. On a large scale loss of a 1 GW solar plant would be approximately 60 MWh per day, moreover, in economics solar plant will be lost approximately $1 million per year. Al-Housani et al. experimented to observe the performance of the different types of cleaning. Microfiber-based cloth combined with vacuum was most effective with an average energy gain of 7.7% and 3.1% weekly [16], following experiment by [16] was conducted in summers with weekly cleaning. Hudedmani et al. employed an automatic precipitator cleaning system, which resulted in significant improvement of power production [17].

2.3 Brush based Cleaning

Cleaning of solar panels can also be performed through brushing over the surface of the solar panel [18]–[20]. Brush based cleaning system is very effective in cleaning rigid dust particles or bird drops while poor quality brush can cause scratches which can reduce the absorbance of sunlight over solar panel. Shehri et al. proposed a black nylon brush for cleaning of solar panels supported through frame and a shaft to support the brush [21]. DC motor is connected to brush to provide smooth motion powered through DC supply which can control the speed of brush through controlling voltage and current. This system is durable and UV resistant, which provide benefit to this system as compared to other in harsh environment of desert. Dipankar developed a moving water free cleaning system which was deployed for one month to obtain real time values from experiment, author observed 9.05% increase in energy gain with prototype cost of $450 [1] . Jawale et al. conducted experiment to study the effect of brush cleaning over solar panel, authors concluded after experiment that 30-35% of power increase was observed in 8-array solar panels, while also reported that cleaning can be more beneficial if deployed over larger solar farms [22]. Wang et al. conducted a study to observe the relationship between dust particles and brush filament, several cleaning experiments were performed with increase in efficiency of 3.585%, 5.656% and 7.944% for dust density of 2.766 g/m^2, 5.22 g/m^2 and 7.5 g/m^2 with one time cleaning while cleaning twice increase the efficiency of solar panel by 3.9% , 7.03% and 9.12 [23]. Akhtar et al. developed an automatic brush for cleaning system, proposed prototype operated using ultrasonic sensor for dust detection and successfully performed experiments with significant improvement in results [24]. designed a moving brush-based robot which was tested over the solar panels of Zahrani Area, Cleaning was performed using these robots once in every two weeks, overall increase energy gain in period of 14 weeks was about 32% with economic benefit of $4287 in region of Lebanon [25].

Figure 2-3 Automatic brush based solar PV cleaning system[15]

2.4 Air based solar panel cleaning

Air based cleaning is non-contact mode of cleaning with solar panels, high pressure air is blow over the solar panel to remove the dust and other type of soiling [26]. This type of cleaning has a lower efficiency than water-based cleaning in terms of cleaning capacity. Gandhidasan et al. proposed a water free cleaning system for desert environment where availability of water is an issue. The system consists of detachable rollers and air blower [27]. This system requires low and cheap maintenance, which significantly improves the power production of the solar system. Zhang et al. utilize Konda effect to clean the solar panels, the proposed system is closed feedback system operated automatically with dust detection using dust sensor, moreover, proposed system utilizes 20% of power generation but produce 74.08 watts additionally from uncleaned panels [28]. This system is more suitable for places with scarcity of water. Ölmez et al. developed auto powered cleaning robot use blowing air to clean solar panel, this robot is more suitable for environment with low water availability, experimentally the solar panel clean effectively with significant increase in power [29]. King *et al.* proposed a compressed air system for cleaning of solar panels, proposed system is simulated over Ansys software which resulted in 23.2% increase in power production after cleaning [30]. M. King et al. analyzed the performance and temperature of solar panel under soil, moreover designed a compressed air flow system for cleaning and cooling of solar panels. The system was able to increase the power of tested solar panel after cleaning from 567.4 W by 30.7, 33.6 and 36.1% respectively [31].

2.5 Electrostatic based solar panel cleaning

Electrostatic properties of dust particle can be utilized for cleaning of solar panel, although electricity is used to operate electrostatic electrode across of solar panel.[32][33] The solar panel is vibrated by electrostatic cleaning to weaken the dirt bond over the solar panel, and a wiper is used to removes oil from the solar panels. A linear piezoelectric actuator prototype is built and integrated onto a guide that will be attached to a solar panel based on the design, as illustrated in Fig. 5. Kawamoto et al. developed an electrostatic based solar cleaning system using parallel screen electrodes to either side of solar panel to generate electrostatic force, solar panels were effectively clean up to 80% on inclination angle higher than 20° [34]. However, author also recommended that dust accumulation should be more than 5 g/m^2 for effective cleaning. Electrostatic cleaning results are not convincing in low dust density. Altıntaş et al. designed an electrostatic cleaning system which is low cost, highly reliable and lower maintenance system. Through experiment it was observed that electrostatic cleaning effectively clean 80% of dust accumulated over solar panel, however, some of the power is loss in operation of electrostatic electrodes [35].

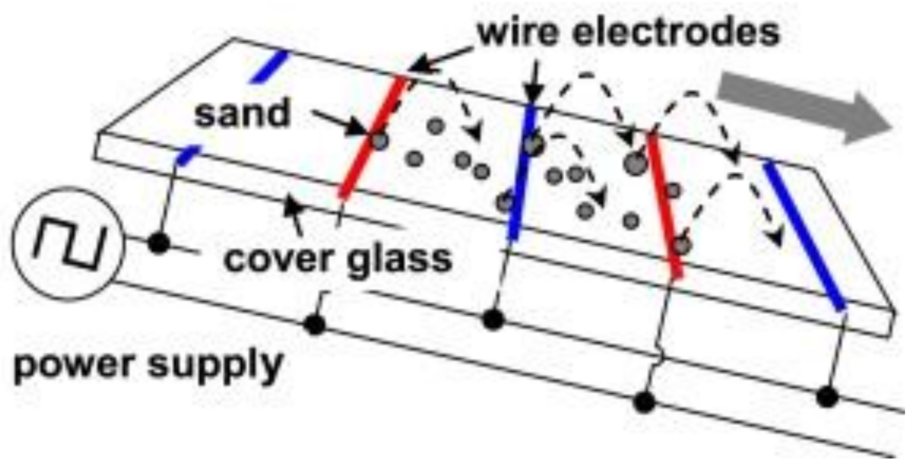

Figure 2-4 Electrostatic based solar PV cleaning system[36]

The variation of voltage across the electrode controls the performance of the electrostatic cleaning system. Kawamoto et al. developed a electrostatic cleaning system which is able to clean 97% of the dust accumulation over the solar panel, although 60% of power was produced by uncleaned solar panels which was recovered up to 90% after electrostatic cleaning [36]. Altıntaş et al. constructed a novel low-cost electrostatic system which requires low maintenance and high effective cleaning of solar panel. Different models of proposed system was experimentally observed with high conversion efficiency [37]. Hashime et al. developed a system to attract the dust particle over the solar panel for cleaning, the proposed system consumed only 10 watts of power. The fraction of power is very small as compared to the overall capacity of solar panels [38].

2.6 Anti-soiling coating for cleaning of solar panel

Traditional cleaning of solar panels is expensive and difficult to implement over the large solar power plant. Anti-soiling coating is self-cleaning technique of solar panels which continuous clean the solar panels. Small layer of different composition of elements deposit over solar panels is termed as anti-soiling coating. Timò et al. synthesized and tested four different type of anti-soiling coating such as TiO_2 super hydrophilic sol-gel films, TiO_2 super hydrophilic e beam films and SiO_2 hydrophobic sol-gel films. These anti soiling layers after testing was able to reduce the transmittance loss to 16% from 50% [39]. Bicer et al. developed an anti-soiling coating for solar cells, the sample with and without anti-soiling coating were tested for fifteen days and observed that sample with anti-soiling coating has better efficiency of energy of 0.61% and exergy 0.07%, moreover, life of solar cells will be improved after anti soiling coating [40]. Polizos *et al.* synthesized a nanostructured anti soiling coating for solar glass, which can improve the glass transmittance by 20% as compared to uncleaned solar glass, Moreover, the uncleaned solar glass has more 17-39% dust as compared to the coated solar glass [41]. Isbilir et al. tested a hydrophobic anti soiling coating, performance of anti-soiling coating is determined by the hydrophobic properties of coating, albeit lifetime of solar panel is achieved for performance [42]. The proposed anti soiling coating was tested with damp heat for 4000 hours; However, coating was not degraded un till 1000 cycles of temperature and 10 cycles of humidity freeze test. Ferrari et al. proposed coating has significantly reduced the soiling rate over solar panels. analyzed the performance of anti-soiling coating under dew conditions, while author synthesized a coating for enhancement of solar panel under dew conditions [43]. Synthesized anti soiling coating was able to reduce the soiling rate and adhesion over solar panel glass under dew conditions which significantly increased the power production.

2.7 Advance automated cleaning system

Technology advancement is rapidly growing, internet of things and robotic are rapid growing emerging technologies. Cleaning system for solar panel can utilized advance technology for effective operation. Recent development of advance cleaning system shows effective results, Jaradat *et al.* developed a fully automatic moving robot for cleaning of solar panel, which move over solar panel to clean dust using rollers with brush connected to robot. Proposed robot was able to clean 80% of the dust from the solar panel. In future system can be modified for better motion by connecting quadrotor [44]. Noh *et al.* manufactured an automatic self-operated cleaning robot, which can improve the current of solar panel by 50% through cleaning. However, power was also improved through cleaning [45]. Patil et al. [46]. Yousaf et al. developed Internet of things based automatic cleaning system, which improved the energy by 32% after cleaning. The system was controlled by Internet of things with low consumption of electricity [47]. Author also proposed that motion of automatic system can be improved in future by implemented rack and pinion system. Using a PIC microcontroller, this article discusses the design structure for water-based automated cleaning of solar PV modules [4].

Figure 2-5 Robotic solar PV cleaning system[48]

To minimize hotspots and shading effects, the writer cleaned the solar PV module with water and a wiper. The model was created with the intention of cleaning the PV module in two ways: the first technique was to sprinkle water over the PV module, and the second method was to use a wiper that was also programmed to clean the water droplet over the PV module after rainfall. The entire system is automated, and sensor based. The author found that good cleaning can be accomplished with water and a wiper, but that water flow over the PV module requires greater power. The authors highlight the power loss caused by soiling on PV modules and provide a cleaning system solution, as well as a brief comparison of alternative cleaning procedures for PV modules [49]. The electro dynamic cleaning system for standing wave electric curtains is very efficient at high gas pressure, and there is no mechanical movement in the whole system to avoid scratching the PV module's surface. This system's limitation is that when gas pressure drops, so does the system's efficiency. The dust particle size has a significant impact on the system cleaning procedure. Electro dynamic screening for multiphase electric cleaning systems is very efficient and can be used on a wide range of surfaces. There is no mechanical movement in the entire system, thus the PV module's surface is not damaged.

2.8 Problem encountered by current cleaning system

Solar panel performance is adversely affected by the soiling effect. To overcome the losses due to soiling, PV panels should be regularly cleaned. PV panels are cleaned using different cleaning techniques such as water cleaning, wiper cleaning, brush cleaning, electrostatic cleaning, and air-based cleaning. These cleaning techniques are not highly efficient due to various problems. Water-based cleaning is the most effective and commonly used cleaning technique, even though excessive water is required to clean the PV panels efficiently. In remote areas where cleaning is frequently required availability of water is a major concern. Wiper cleaning required motors to move the wiper across the PV system for cleaning, these motors consume power to operate. However, the power consumes by motors to rotate wipers reduces the efficiency of the wiper cleaning. The electrostatic cleaning technique is an advanced form of cleaning, electrodes are installed on both sides of the solar panel. This type of cleaning system is not efficient for a dusty environment as well as installation cost is higher than other conventional cleaning techniques.

Brush cleaning is a water-free cleaning system technique; however, it produces micro scratch which can decrease the operational lifetime of front glass as well as reduces the transmittance of the PV panels. Air cleaning is rarely used cleaning technique due to lower cleaning efficiency as well as high energy consumption of the compressors. The problems encountered by all techniques reduce their cleaning efficiency however, water-based cleaning has better cleaning efficiency as well as lower issues and power consumption.

Table 2-1 Comparison between different cleaning methods

Reference	**Year of Publication**	**Journal name**	**Type of cleaning technology**	**Key findings**	**Comments**
Salehi[50]	2022	Journal of Alloys and Compounds	Anti-soiling Coating	Anti-soiling coating help to increase the transmittance from 90.5% to 96%	Anti-soiling coating is effective as self-cleaning for solar panels.
Nahar[51]	2022	Solar Energy	Wiper cleaning	Wiper and water-based cleaning combinedly used to recover power loss due to soiling by harvesting the rainwater.	Availability of water is major concern for water-based cleaning; therefore, rainwater was collected to clean solar PV panels.
Swain[52]	2021	Electric Power Components and Systems	Brush cleaning	Brush cleaning is a type of water free cleaning, experimental result shows that after one day of brush cleaning the output electrical efficiency was increased from 10.63% to 13.20%.	the experiment of brush-based cleaning can produce micro scratches on glass of PV panels, which can reduce light absorption in longer time frame.
Altıntaş et el. [37]	2021	Energy	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.
Heliotex [53]	2020		Water Sprinklers based cleaning	The Heliotex company uses a water sprinkler system with soap and detergents solution to remove the dust	The cleaning with pressurizing water through nozzles is one of the most effective techniques. Using flat-fan nozzles can be more

				effectively. It uses hollow cone spray nozzles and operates at night.	helpful. While it’s a cost-effective cleaning system to install
Michele[54]	2020	mechatronics	Advance automated cleaning system	The robot was test over tilt angle of 30˚ with effective cleaning using brush.	The AACS are more effective than conventional brush cleaning with advance feature to move around solar panel.
Kawanoto et al. [35]	2019	Electrostatic	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 number of electrodes to implement which is costly and the electrodes create a shadow on the glass surface of the PV module
Bari et al.[55]	2018	International Journal of Advances in Scientific Research and Engineering	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 damaged by the brush when wiping or rotating the brush over the surface.
Hudedmani et al. [17]	2017		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
Arvind el al. [56]	2017	2014 Texas Instruments India Educators' Conference (TIIEC)	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
Gwon et al. [43]	2014	Nano Research	Hydrophobic coatings	By combining the two properties: superhydrop-hobic 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.

Summary

Solar PV losses due to soiling is a significant degrading factor, to reduce the impact of soiling on performance on the solar PV module different cleaning techniques are opted. The most efficient and commonly used cleaning technique is water-based cleaning. Other techniques which are opted to clean the solar PV modules are brush cleaning, electrostatic cleaning, air cleaning, wiper cleaning, and anti-soiling coating.

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Chapter No. 3

Research Methodology

The experimental study was conducted in Islamabad-Pakistan. Islamabad has an average air quality index of 44 AQI and average humidity of RH 61%. The environment get polluted during the dry season that greatly affect the output of the installed PV systems. Islamabad's daily solar data show that the direct normal irradiation is 4.3 kWh/m^2, global horizontal irradiation is 4.6 kWh/m^2, and solar PV electricity potential is 4.5 kWh/kW$_p$ [1]. During January and February (which are the dry months), the experimental setup was placed on the roof of the Centre for Advanced Studies in Energy (CASEN), NUST, Islamabad, for three tilt angles 23˚,33˚, and 43˚. The experiment on each angle was performed for three days.

Figure 3-6 Unclean and Clean PV module attached with automatic cleaning system

In this research a test bench was assembled to perform the critical analysis of the effect of soiling on the performance of solar PV modules. During the experiments the effect of dew factor on dust morphology was also studied as shown in the Figure 3-1. Furthermore, different characterization technique such as Energy Dispersive X-ray Spectroscopy (EDS) Scanning Electron Microscope (SEM), and Particle size analyzer was performed to examine the morphology, elemental structure, and practical size on dew-induced soil.

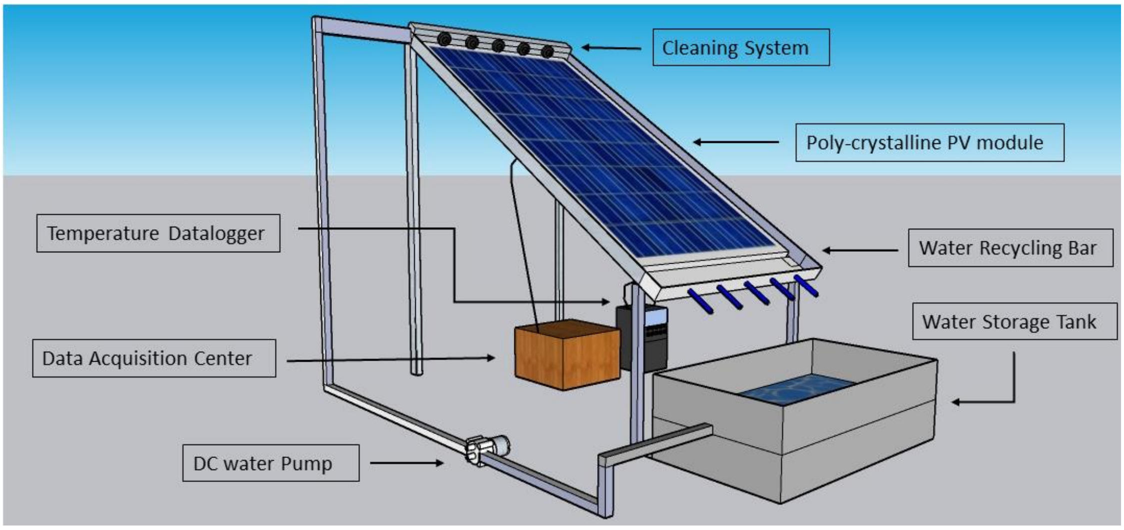

Figure 3-7 Schematic Diagram of Proposed System

The experimental setup for the cleaning of the PV module is automatically operated through programming to eliminate the human interface for cleaning of solar PV modules. The proposed setup can perform automatic water-based cleaning and recycling of water to remove dust from the top surface of solar PV modules as and when required. The schematic of the proposed experimental setup is shown in Figure 3-2.

3.1 Design of Experimental Setup

As shown in Figure 3-1 & 3-2 the experimental setup consists of three major parts, data acquisition station (datalogger), PV module, and an automatic cleaning system. The data acquisition station is connected with a tier 1 metrological station installed on the top roof of the building to collect the weather data. Two solar PV modules used are poly-crystalline with a rated output capacity of 175 watt and an area of 1.048 m^2 while other specifications of the PV module are provided in the below Table 1. The experimental setup contains two identical poly-PV modules, one poly-PV module is connected to the cleaning system, while the other poly-PV module is without the cleaning system. These PV modules were installed on a movable steel stand to experiment with different tilt angles as shown in Figure 3-1 & 3-2.

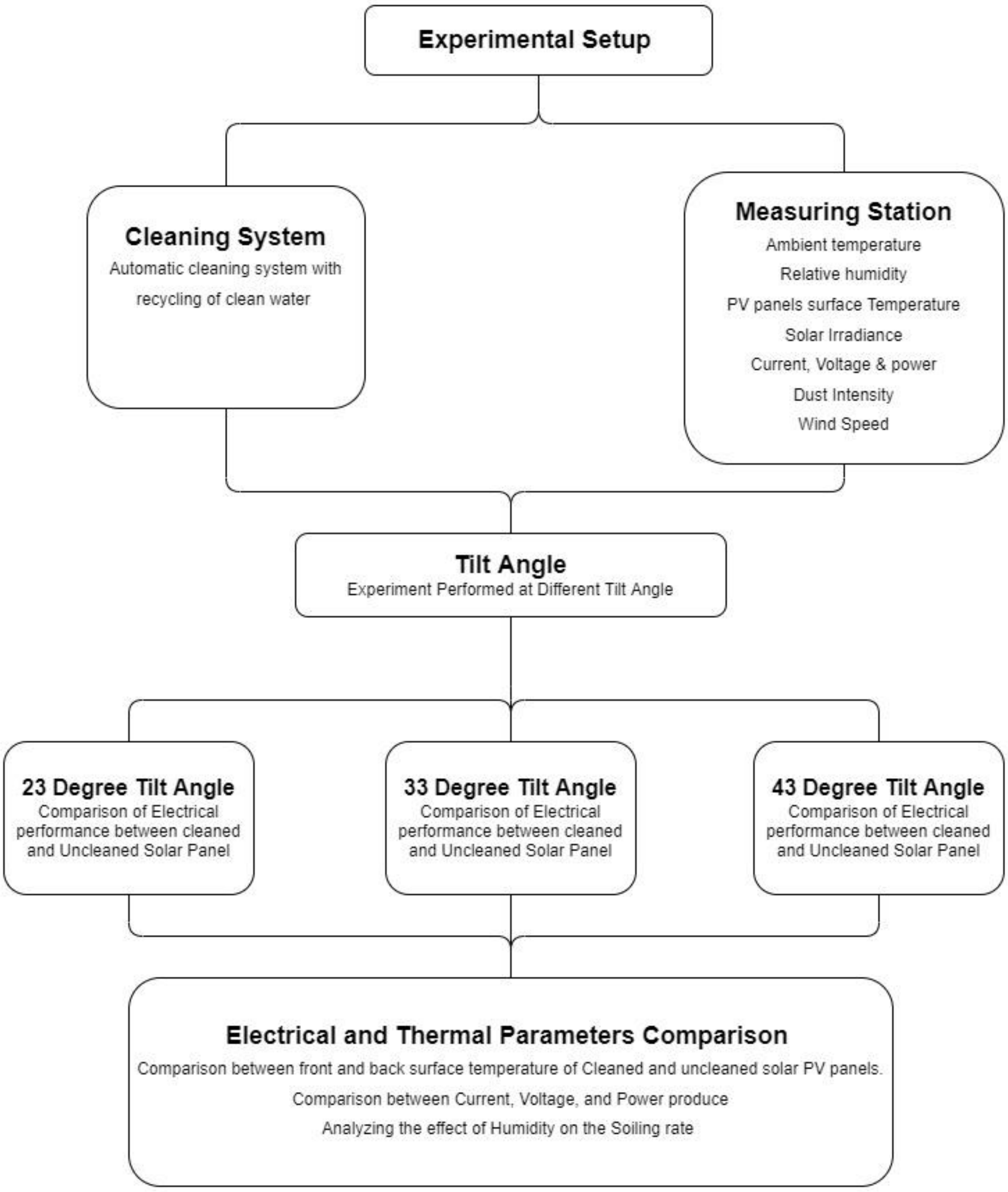

Figure 3-8 Flow chart of proposed study

3.2 Data acquisition station

Data acquisition system is integrated with a solar module to record electrical and thermal parameters such as voltage, current, power, humidity, back and front surface temperature, dust intensity, and ambient temperature. Arduino voltage sensor (0-25 volts) is used to record the voltage of solar PV modules, although the current is measured through Arduino current sensor (ACS712 20A). The output power produced by the solar module is calculated using equation (1).

$$\text{Power (P)} = \text{Voltage (V)} \times \text{Current (I)} \quad (1)$$

EXTECH 12-channel datalogger with k-type beat thermocouple is used to record the front and rear surface temperature of the PV module. The dust intensity is recorded using Sharp GP2Y1010AU0F optical dust sensor. To control the flow of water through the Arduino board, the motor controller (BTS7960 43A) is integrated with a water pump for efficient automatic cleaning and motor operation. The flow diagram of data acquisition station is shown and explained in Figure 3-3.

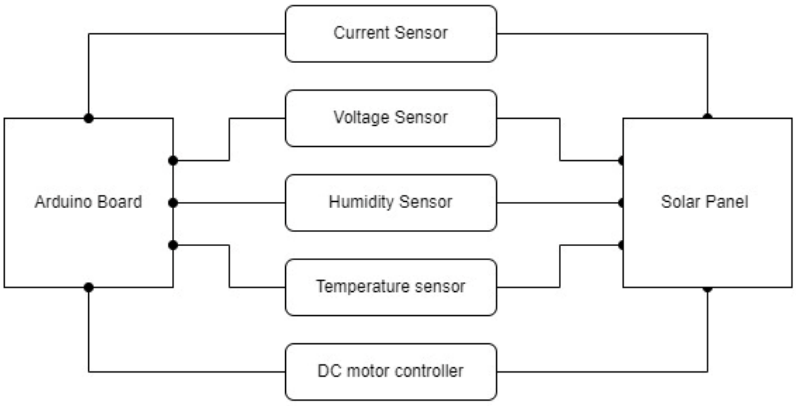

Figure 3-9 Data Acquisition Station flow chart

Table 3-1 Polycrystalline PV module parameters

Parameters	***Polycrystalline***
Maximum Power (P_{max})	175 W
Maximum Power Voltage (V_{mp})	17.90 V
Maximum Power Current (I_{mp})	8.40 A
Open circuit voltage (V_{oc})	22.40 V
Short circuit current (I_{SC})	9.19 A
Module Efficiency	14.99 %
Maximum system voltage (V_{max})	1000 V DC
Fuse rating	15 A
Temperature range	-40°C to +90°C
Weight	12 kg
Dimensions (W x L x T)	28.5 in x 57 in x 1.5 in
Fire-resistance rating	Class C

3.3 Automatic Cleaning system

The automatic cleaning system consists of 0.762 m long bar of steel attached at the upper side of the polycrystalline solar module as shown in Figure 3-1. The cleansing bar has eight openings on which flat-fan nozzles are attached to provide a convex spray pattern with 50% overlapping for a uniform flow of water for effective cleaning. The distance between each flat fan nozzle is 0.14 meter. Flat-fan nozzle can generate a water flow of 0.49 ltr/min with approximate pressure of 2.1 bars having a spraying angle of 48^{o}. A DC water pump of 36 W rating with a rated flow rate of 5 ltr/min and approximate pressure of 6.8 bars is used to extract the water from the storage tank to the nozzles as shown in Figure 3-1. The DC diaphragm pump and data acquisition station are powered through a dry lead-acid battery (18Ah, 12V). The dirty water from the recycling bar is filtered through a Whatman filter with a pore size of 12 mm.

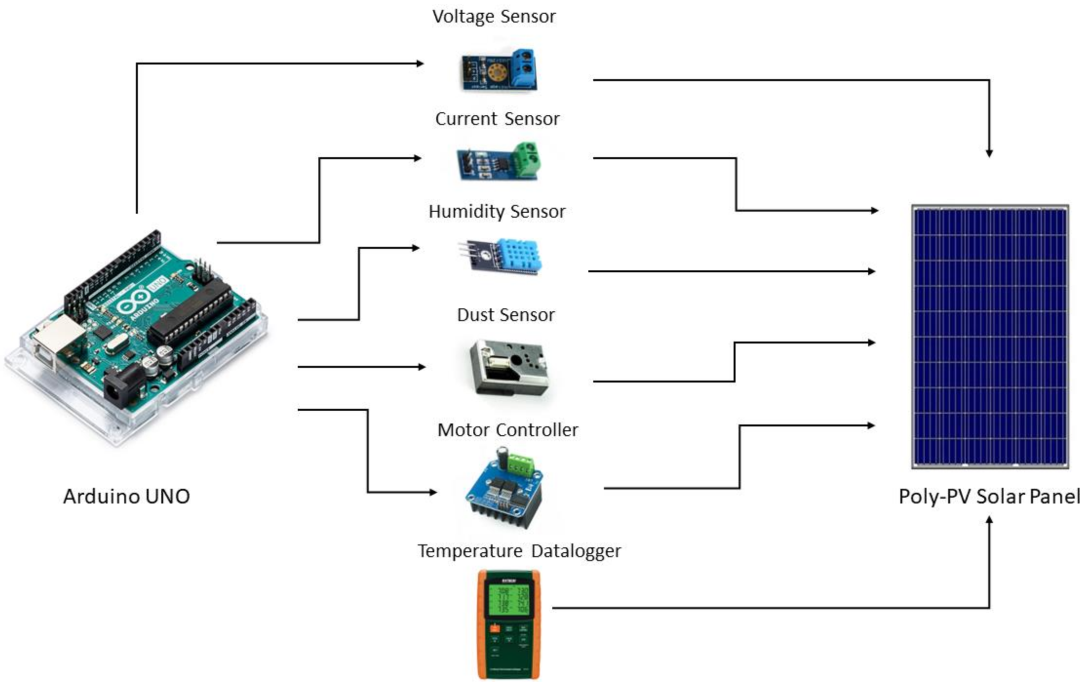

Figure 3-10 Data Acquisition Station flow chart

The cleaning of the PV module is done before or after sunlight hours to avoid the thermal stresses caused by the water droplets [2]. Arduino board was programmed to clean the solar module automatically, although the experiment is conducted for consecutive 3-4 days at different tilt angle, the dust accumulation at different tilt angles ranges between 167.33 mg/m^2 per day. Arduino board controls the operation of the DC diaphragm water pump using BTS7960 motor controller. The pressurized water is sprinkled over the solar modules which are collected and filtered on a recycling bar connected to the lower end of the PV module. The automated cleaning operation begins with the Arduino board sending a signal to the DC diaphragm water pump through the BTS7960. After receiving a signal, the DC diaphragm begins water supply to the flat fan nozzle which sprinkles pressurized water over the front surface of the solar PV panel. The water transports dust particles and other pollutants to the recycling bar, where they are filtered using a one-stage Whatman filter before draining back into the storage tank as shown in Figure 3-1.

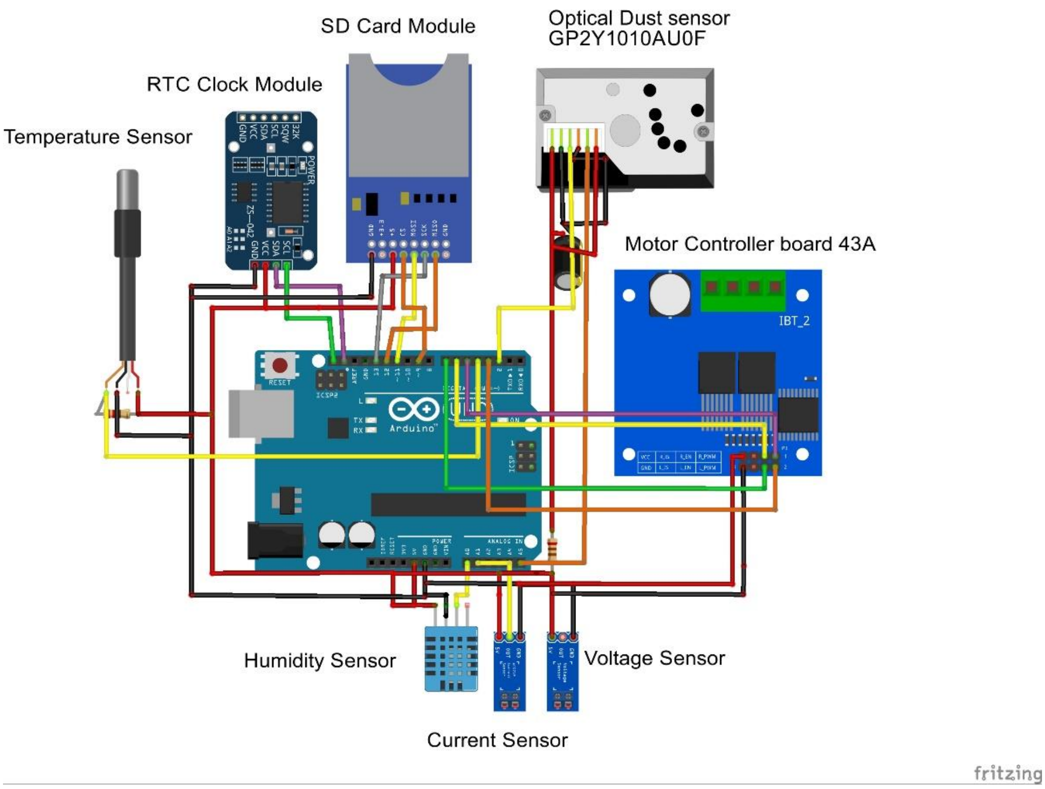

Figure 3-11 Circuit Diagram of Data Acquisitions center

3.4 Economic Analysis

The viability of the proposed automatic cleaning system is investigated through economic analysis. The analysis is performed by comparing the cost of the system with the cost of improved power production by solar PV over its operational lifetime. The overall cost of an automatic cleaning system consists of initial capital cost and maintenance cost. The proposed model can be installed with the PV system, and it will increase the overall initial capital but will produce more electricity.

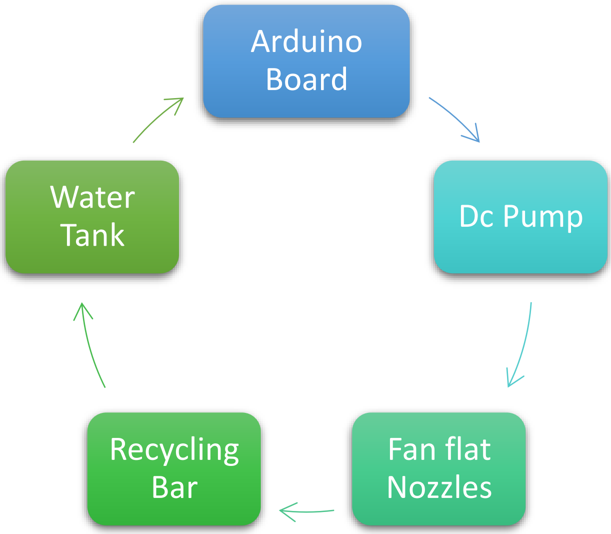

Figure 3-12 Cleaning process cycle

The payback period of solar PV modules is improved with the cleaning system while the cleaning frequency is adjustable according to the dust density as shown in Figure 3-7. The equation for the cost of an automatic cleaning system is given below and different parametric values considered for calculation are tabulated in Table 3-2. In equation 2 C_{ACS} is the addition of the investment capital (C_{IC}) and maintenance cost (C_M).

$$C_{ACS} = C_{IC} + C_M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Table 3-2 Component cost of cleaning system

Components	**Quantity**	**Total cost (USD)**
Storage tank (30 liters)	1	6
DC water pump	1	6
Arduino and motor controller	1	5
Whatman filter	1	0.6
Nozzles	7 pieces	3.2
30 inches SS steel pipe	30 inches	8
Rubber pipe	2 m	2
Total		30.48

The loss of electricity cost due to the dirty module is calculated using eq. (3), while the loss in energy is determined by subtracting clean solar PV module energy (E_C) from dusty solar PV module energy (E_D) as shown in eq (4). The per-unit cost of electricity (USD per kWh) is determined using equation (5). The economic feasibility of an automatic cleaning system is positive if the cost of the electricity of an unclean solar PV module (COE) is less than the cost of electricity of a clean solar PV module [3].

Table 3-3 Financial parameters of cleaning system

Item	Value
Operation lifetime of solar PV panels	20-25
Automatic cleaning system initial capital (USD)	26.48
Polycrystalline solar PV module (175W) cost (USD)	35
Solar PV steel frame cost (USD)	6.5
System installation and commissioning cost (USD)	2.5

C_{E_L} = Energy loss x COE ………………….……….... (3)

Loss in Energy = E_C - E_D ……………...…….......... (4)

COE = Cost of Electricity / E_{PV} …..…………………. (5)

Summary

The experimental setup consists of automatic cleaning system, measuring station, and solar PV panel, the system is installed on the rooftop of USPCAS-E building in NUST, Islamabad. The experiment was conducted on Polycrystalline solar PV panel for three different angles and data of different electrical and thermal parameters were recorded in Measuring station SD Card. Moreover, Economic analysis of the automatic cleaning is performed to obtain the economic feasibility of cleaning system in term of cost.

References

[1] A. Gholami, I. Khazaee, S. Eslami, M. Zandi, and E. Akrami, "Experimental investigation of dust deposition effects on photo-voltaic output performance," *Sol. Energy*, vol. 159, no. August 2017, pp. 346–352, 2018, doi: 10.1016/j.solener.2017.11.010.

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Chapter No. 4

Results and Discussion

The results obtained from the experiments have been categorized into different subsections as specified below:

The first section compares dew-induced dust with dew-free dust to analyse properties such as particle size, structural composition, and morphology using different characterization techniques. The second section is related to influence of dew-induced dust on the performance of solar PV modules. Lastly, third section describes about the economic analysis of the proposed cleaning system to determine the viability of the system.

4.1 Dust characterization and Analysis

Dust density over the solar PV modules is measured using the Sharp optical dust sensor (GP2Y1010AU0F) at tilt angles of 23°, 33°, and 43°, the measured dust density at these tilt angles were 629 mg/m^2, 487 mg/m^{2,} and 392 mg/m^2 respectively. The average daily deposition rate of dust for these tilt angles is 209 mg/m^2, 162 mg/m^2, and 131 mg/m^2 as shown in figure 4-1. However, the deposition rate over solar PV panels depicts that with a higher tilt angle the dust accumulation is minimum due to gravity while for a lower tilt the deposition rate is higher.

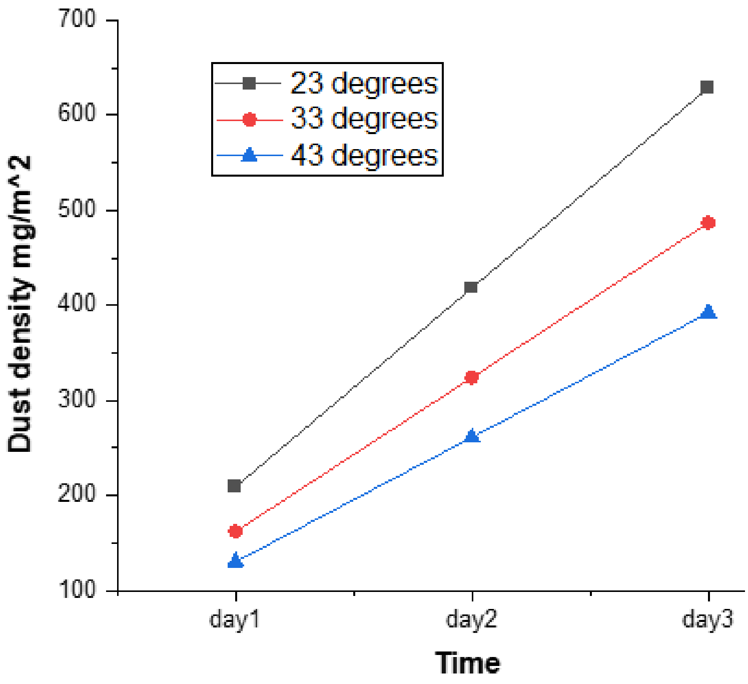


Figure 4-1 Daily dust density at different tilt angles

The dew that fell on the front surface of the solar PV module has influenced the dust accumulated too. The deposited dust from the PV module was collected for characterization to examine the morphological and elemental composition of the dust particles. The particle size of the dew-induced dust and dew-free dust were analysed using Bettersize 9300 ST laser particle size analyser.

Table 4-1 Particle size distribution of dew-induced dust

Dust particle diameter (μm)	Volume percentage	Volume percentage
	With Dew	*Without Dew*
0.2-0.5	11	4.46
0.5-1	23.66	17.02
1-2	19.47	18.67
2-5	20.97	21.71
5-10	10.05	14.34
10-20	8.28	13.33
20-45	5.79	9.1
45-75	0.74	1.26
75-100	0.04	0.08

The structural size of dew-induced dust ranges from 0.2 µm to 100 µm as shown in Table 4-1. Overall, the particle size distribution of dew-induced dust is smaller because 94% of the particle size ranges between 0.2 µm to 20 µm as shown in figure 4-2. Moreover, the particle size of dew-free dust also ranges between 0.2 µm to 100 µm, with 89 % of the particle size ranging between 0.2 µm to 20 µm as shown in Table 5. Considering, the particle size analyser data small agglomeration is observed in dew-induced dust particles, resulting in particle contraction to a smaller size as shown in Figure 4-2. Moreover, small dust particles have a higher deposition rate than large dust particles, which will have a detrimental effect on light absorption by solar PV modules. [1].

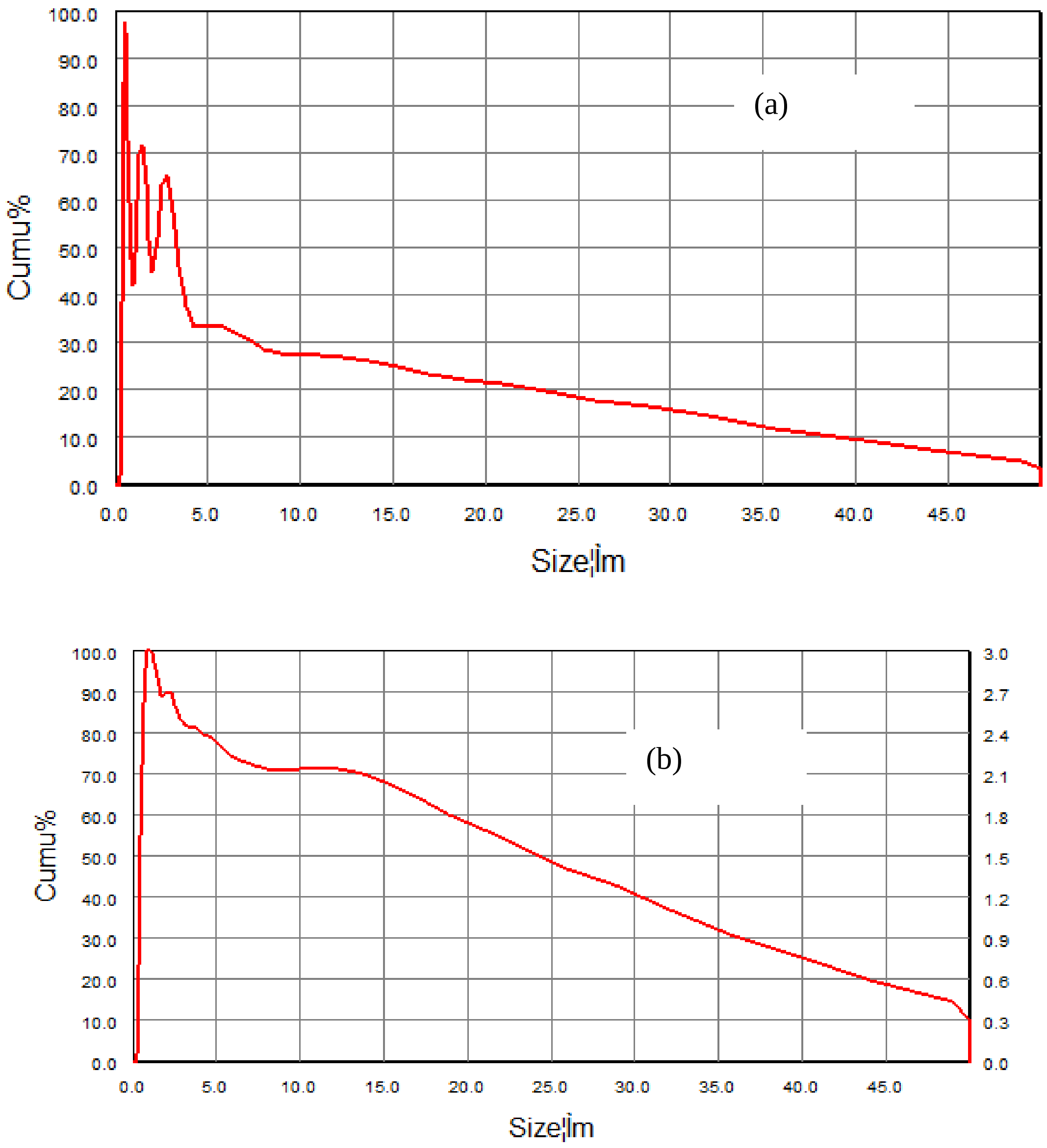


Figure 4-2 Particle size distribution of dew-induced dust and dew-free dust

Scanning Electron Microscope (SEM) imaging and Energy Dispersive X-ray Spectroscopy (EDS) were used to examine the morphology and elemental composition of dust particles. The SEM imaging of dust particles reveals that the particles vary in size, shape, and elemental composition as shown in Figure 4-3. The elemental compositions of dew-induced dust and dew-free dust are comparable with minor differences in element concentrations as shown in Figure 4-4. The particle size of dew-induced dust is more compact as compared to the dew-free dust due to the absorption of moisture from dew by the dust particles as shown in Figure 4-5.

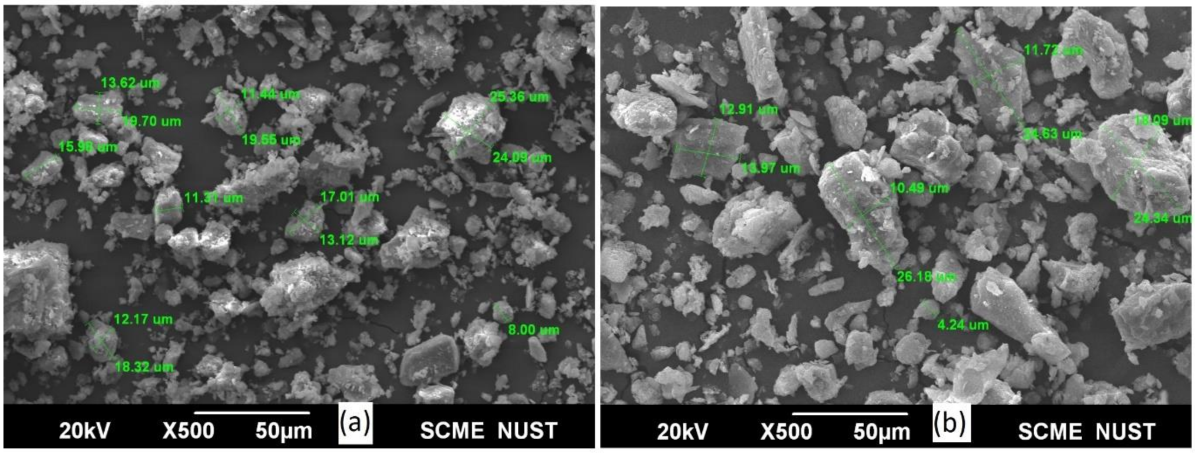
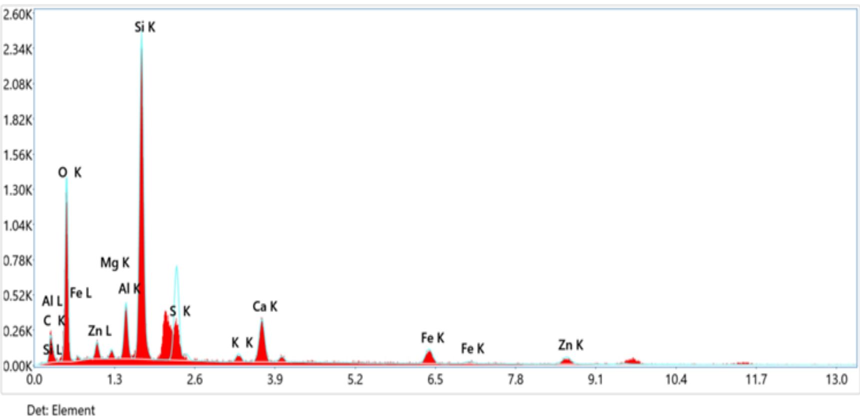


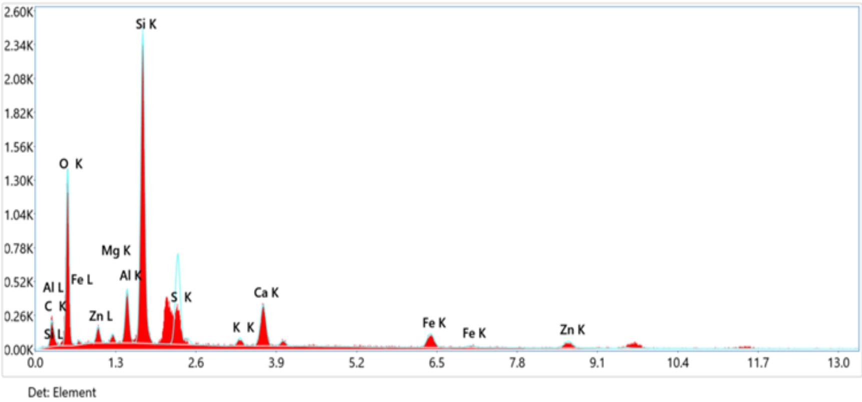
Figure 4-3 (a) SEM image of dew-induced dust (b) SEM image of dew-free dust

The EDS spectrum of dew-free dust indicates that dust particles are primarily composed of oxygen 40.8% followed by silicon, sulphur, calcium, and zinc with 24%, 9.8%, 6.9%, and 5.3% respectively as shown in Figure 4-4, while the EDS spectrum of dew -induced dust indicates that it is primarily composed of oxygen 46.8% followed by silicon, Aluminium, calcium, and iron with 24%, 9.8%, 6.9%, and 5.3% respectively as shown in Figure 4-5, although many more elements were found in lower concentrations. Both samples of EDS spectra were comparable, although their concentrations were slightly different. Dust particle elemental composition is influenced by its geographical location, weather conditions and nearby emissions such as industrial pollutants, vehicle gases, and other pollutants in the atmosphere.[1]



Element	Weight %	MDL	Atomic %
C K	1.7	4.99	3.2
O K	40.8	0.47	57.6
Mg K	0.9	0.26	0.8
Al K	4.5	0.22	3.8
Si K	24.0	0.19	19.3
S K	9.8	0.24	6.9
K K	1.1	0.26	0.6
Ca K	6.9	0.30	3.9
Fe K	5.0	0.47	2.0
Zn K	5.3	0.81	1.8

Figure 4-4 EDS results of dew-induced dust



Element	Weight %	MDL	Atomic %
C K	1.7	4.99	3.2
O K	40.8	0.47	57.6
Mg K	0.9	0.26	0.8
Al K	4.5	0.22	3.8
Si K	24.0	0.19	19.3
S K	9.8	0.24	6.9
K K	1.1	0.26	0.6
Ca K	6.9	0.30	3.9
Fe K	5.0	0.47	2.0
Zn K	5.3	0.81	1.8

Figure 4-5 EDS results of dew-free dust

4.2 Effect of Dust on PV performance

The experiments were conducted to investigate the influence of dew-induced dust on electrical and thermal parameters from three different tilt angles 23°, 33°, and 43°. The experiments were carried out on clear days during January and February with steady weather conditions. Different parameters which were analysed to study the effect of dew-induced dust are voltage, current, power, and surface temperatures.

4.2.1 Effect of Dust on PV Voltage

Voltage is an important factor determining the performance of solar PV module. The effect of dew-induced dust on voltage is observed at three different tilt angles. The voltage difference between the clean and unclean modules is not significant as compared to current, since the voltage is mostly impacted by temperature; however, changes in irradiance have a small impact on voltage as shown in Figure 4-6. It has been observed that dew-induced dust can reduce output voltage by 6.5%, 5.7%, and 5.2% at a tilt angle of 23°, 33°, and 43°. Water-based cleaning increased the system output voltage by 5.8, although the average voltage of 0.7% was increased on day 2 as compared to day 1 on all tilt angles and a voltage of 0.23% increased on day 3 as compared to the voltage produced on day 2.

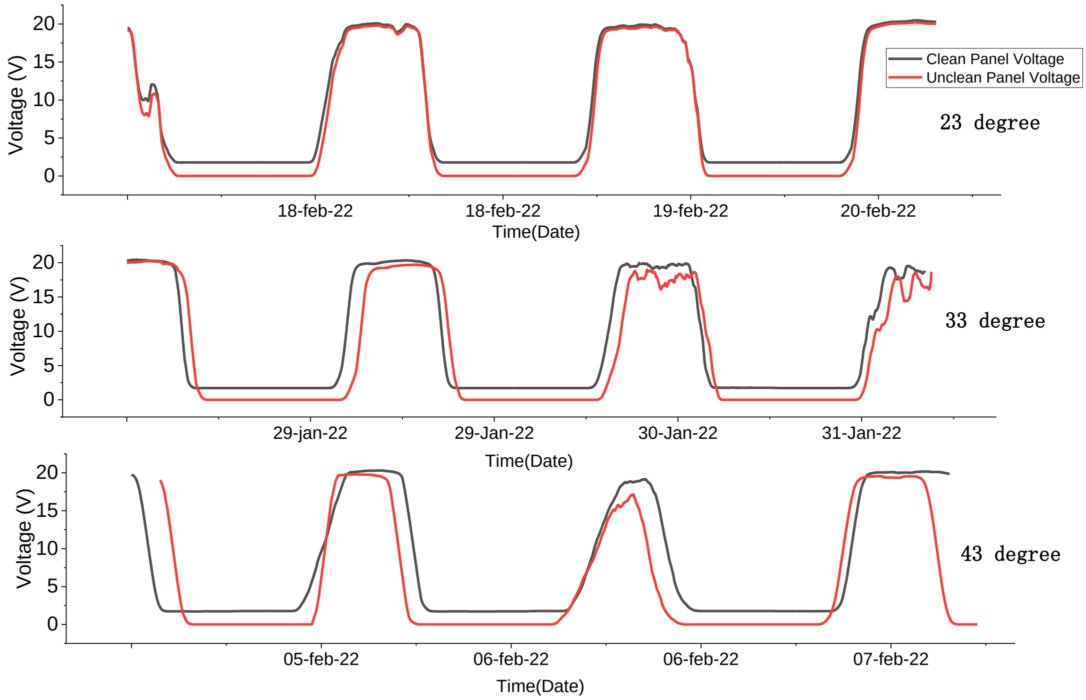


Figure 4-6 Clean and unclean solar PV module voltage at a different angle

4.2.2 Effect of Dust on PV Current

Current production by solar PV modules is majorly dependent on the irradiance, although large variation in irradiance can result in variation of current produced by PV module. Dust deposited on the glass of a solar PV module can have a significant impact on current output since it reduces the irradiance absorbed by the solar PV module. The largest improvement in the PV current was recorded for a 43° tilt angle and the lowest current was recorded for a 23° tilt angle. Current at 23°, 33°, and 43° tilt angle was improved by 15%, 12%, and 13% respectively after water-based cleaning, while the average improvement in current between day 1-2 and day 2-3 of the experiment was 1.7% and 0.8% as shown in Figure 4-7. Further, the average current enhanced by automated water-based cleaning at various angles was 13.27 %.

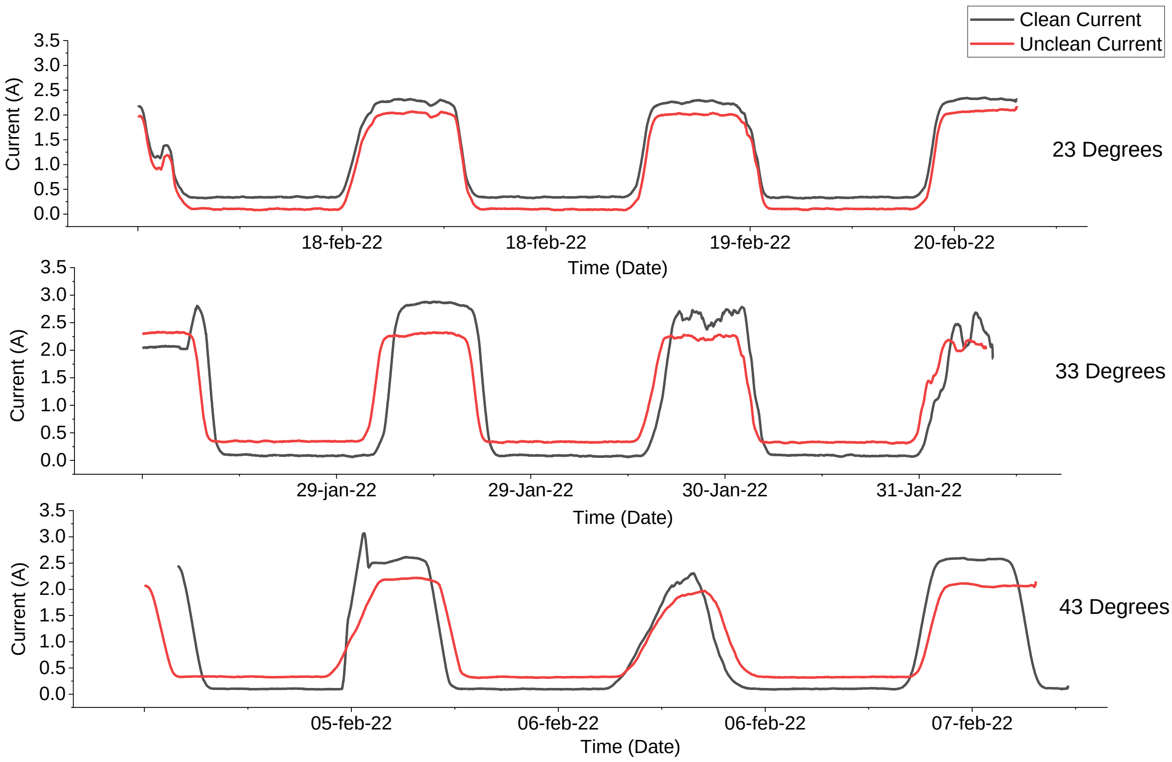


Figure 4-7 Clean and unclean Solar PV module Current at a different angle

4.2.3 Effect of Dust on PV Power

The power output of PV module is a product of current and voltage, different factors affecting these parameters also influence the power output of PV module, this experiment also investigates the effect of soiling on the power output. The experimental results show that the power output of the clean module at tilt angles of 23°, 33° and 43° was improved by 12%, 9.77%, and 18% respectively, after water-based cleaning as shown in Figure 4-8. It was found that power loss due to soiling at a tilt angle of 23°, 33° and 43° was 16%, 12%, and 20%. The water-based cleaning was effective to recover power loss due to dust accumulation by 75%, 81.47%, and 90% at a tilt angle of 23°, 33° and 43°. The highest power gain was obtained for 43° of 18%, while the lowest power gain was obtained for 33°. The average power loss due to soiling is 13.27 % at all tilt angles with an average soiling rate of 167.33 mg/m^2 per day. The relationship between power loss and dust accumulation is linear; the more dust accumulates, the greater will be output power loss. [2]. As a result, it is advised that solar PV modules be cleaned at regular intervals for high electricity yields.

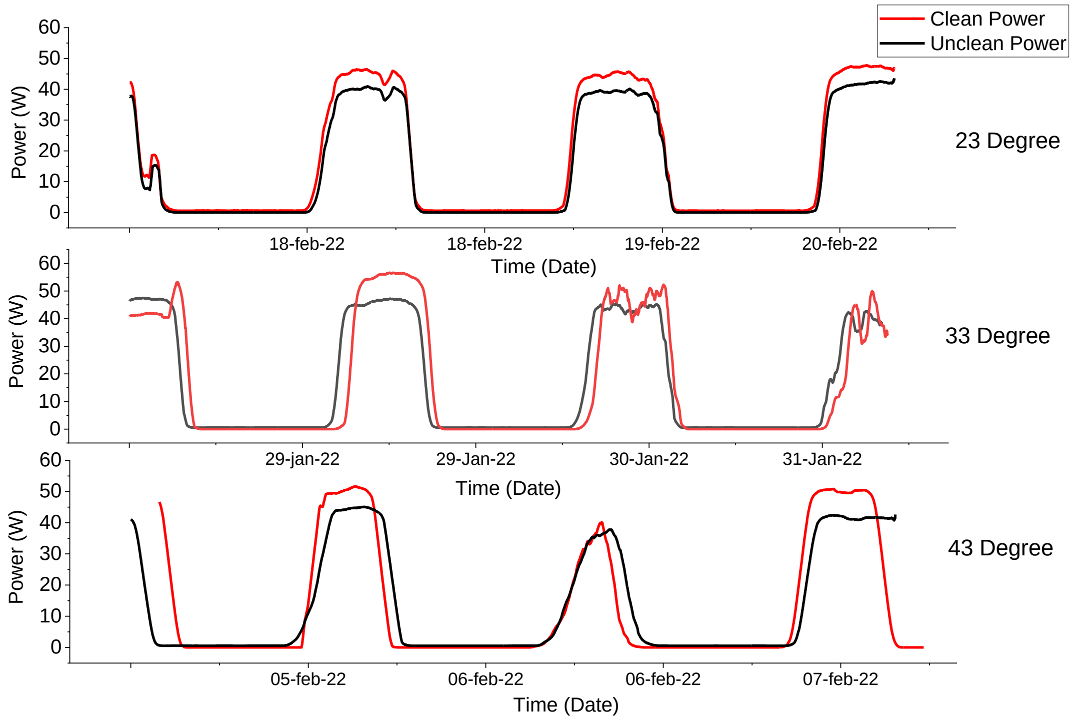


Figure 4-8 Clean and unclean Solar PV module Power at a different angle

4.2.4 Solar PV Module Temperature

The rate of dust accumulation on the front glass of the solar PV module affects the change in front and back surface temperature. The front and back surface temperature of clean and unclean solar PV modules were observed for three different tilt angles, The front surface temperature of the clean module was reduced through cleaning at 23°, 33°, and 43° tilt angles by 0.8°, 0.52°, and 0.3° C as shown in Figure 4-8. Therefore, water-based cleaning improves the thermal characteristics of solar PV modules, which aids in enhancing performance of PV module in high-temperature environments. It was also found in the experiment that after cleaning back surface temperature of clean solar PV module at tilt angles of 23°, 33°, and 43° was reduced by 1.2°, 0.7°, and 0.3° C. The average front and back surface temperature of clean and unclean solar PV modules is shown in table 4-2.

Table 4-2 Poly-PV module average front and back surface temperature at different tilt angles

Tilt Angle	**Clean Solar PV module**		**Unclean solar PV module**	
	Average Front Surface Temperature	**Average Back Surface Temperature**	**Average Front Surface Temperature**	**Average Back Surface Temperature**
23°	23.3	23.5	24.1	24.9

33˚	19.12	19.9	19.64	20.3
43˚	19.5	21.9	19.8	22.2

During sunshine hours the maximum temperature of PV module was reduced after the cleaning process at a tilt angle of 23˚, 33˚, and 43˚ by 1˚,1.3˚, and 1.3˚ C as shown in Figure 4-9, furthermore, the maximum rear surface temperature of PV module was reduced by 1˚,1.5˚, and 1.5˚ C as tabulated in Table 4-3. Experimental results show that cleaning has a cooling impact on the solar PV module, allowing it to lower the average and maximum surface temperatures.

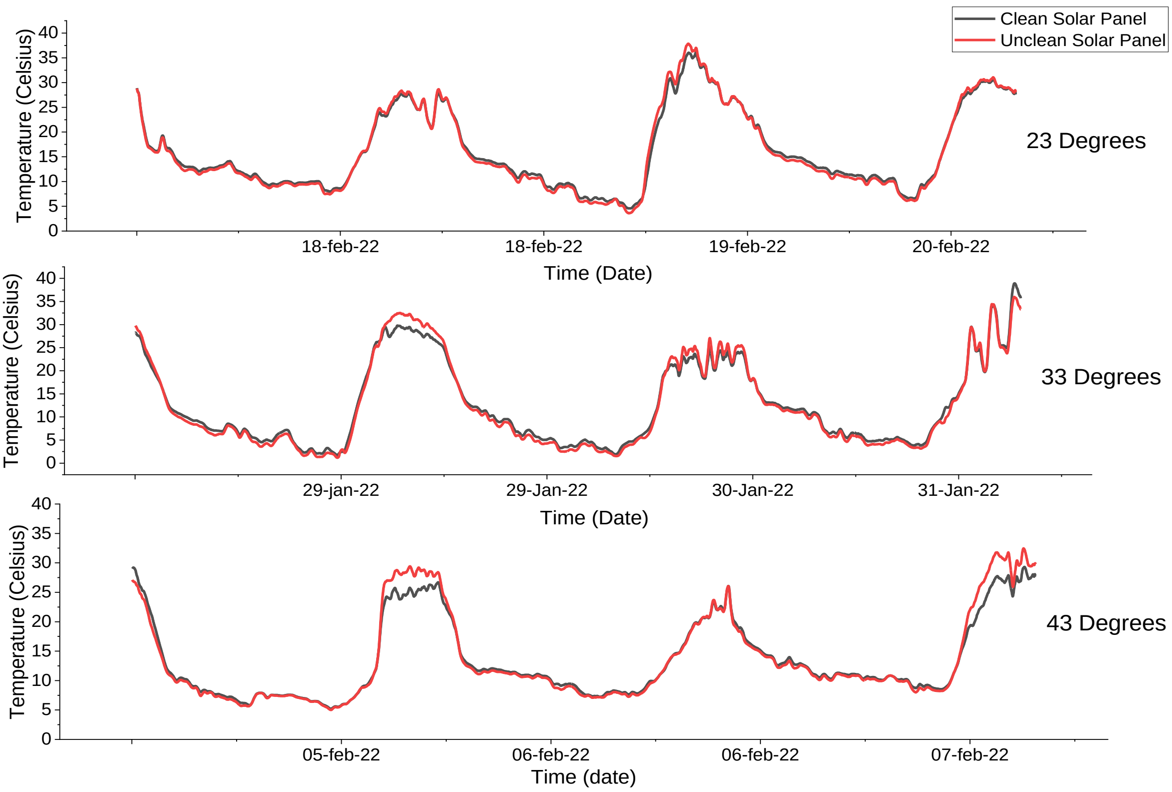


Figure 4-9 Front surface temperature of clean and unclean solar PV module at different tilt angles

Table 4-3 Poly-PV module Maximum front and back surface temperature at different tilt angles

Tilt Angle	Clean Solar PV module		Unclean solar PV module	
	Max. Front Surface Temperature	**Max. Back Surface Temperature**	**Max. Front Surface Temperature**	**Max. Back Surface Temperature**
23°	37.9	43	38.9	44
33°	38.7	45.2	49.4	46.7
43°	33.2	44.9	34.5	46.4

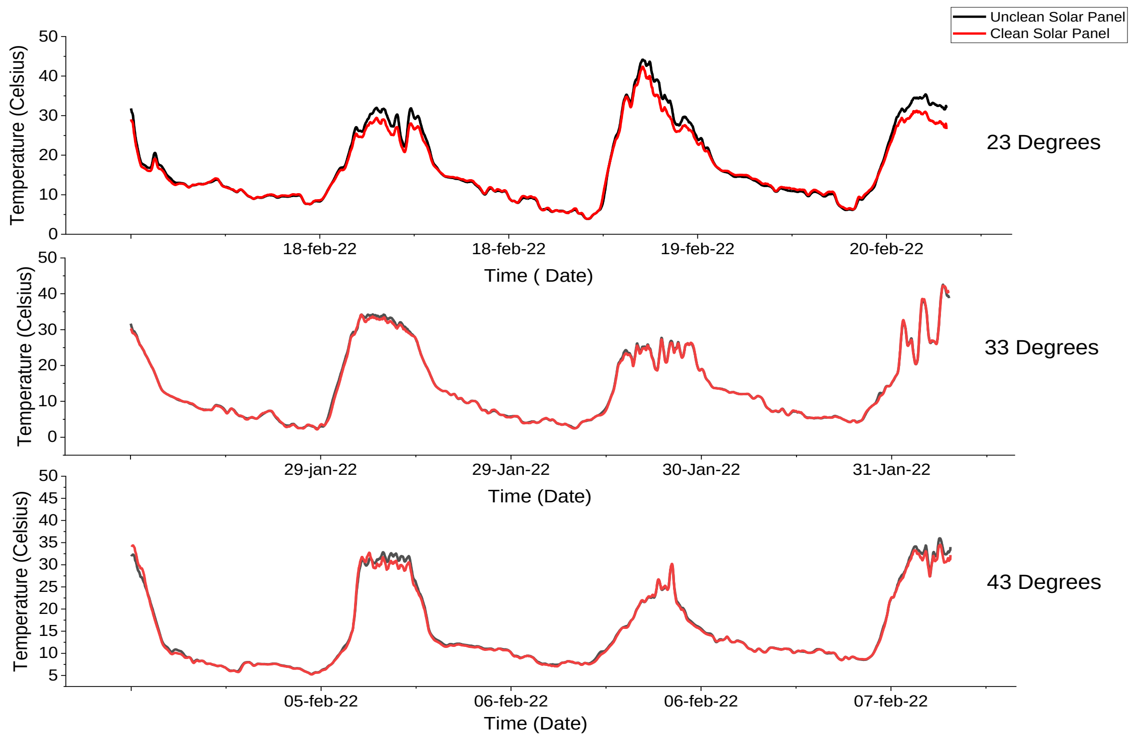


Figure 4-10 Back surface temperature of clean and unclean solar PV module at different tilt angles

4.3 Automatic Water Cleaning System

The set of experiments at different tilt angles were performed on a polycrystalline solar PV module of 1.05 m^2 area to clean dew-induced dust with an automatic cleaning system, Moreover, an Arduino board was used to control the cleaning method. The water cleans 98% of the solar PV module area in five minutes of operation, recovering up to 85 % of the power loss. During the cleaning process, the water flow rate was 1.465 ltr/min recorded using a flow meter, whereas the maximum flow rate of the diaphragm water pump is 5 ltr/min with an operating power of 36 W. To clean 98% of the area of PV module 7.325 ltr of water is required, which may remove a substantial quantity of dust accumulated on the PV module. During the experiment the cleaning process was performed on dew-induced dust and dew-free dust, the quantity of water required to clean dew-induced dust was larger than the quantity of water required to clean dew-free dust because of caking process adhesion of dust on the front surface of PV module. To clean 98% of the area of a solar Module (1.027 m^2), 7.325 Liters of water is required, which may remove a substantial quantity of dust accumulated on the PV module. The water pump uses 3 Wh of energy to operate for 5 minutes and has an operating power of 36 W. Furthermore, the cleaning process was repeated once a day before sunrise for three days to prevent evaporation and heat stress on the front surface. The water that was recovered after cleaning of the PV module through recycling bar 90%, while 10% was lost during each set of the cleaning process.

4.4 Economic analysis

To evaluate the viability of the automatic cleaning system, an economic analysis was conducted using the cost of the electricity produced by the solar PV module with a cleaning system and the cost of the cleaning system. The total cost of the solar PV module with a cleaning system is USD 65.48 and the solar PV module without a cleaning system cost USD 35. Therefore, the per-watt cost of the module without a cleaning system is USD 0.2, while the cost of solar PV module with a cleaning system is USD 0.3741. After performing the economic analysis, the cost recovered from additional power after cleaning is USD 0.0332 per day, resulting in a payback period of 2.51 years in Islamabad for additional cleaning system costs. The operating cost of the system is negligible since it is automatically operated using an Arduino board; also, the economic feasibility of the proposed system is relatively viable since the cost of the system is recovered in a short time.

Summary

This chapter discusses the results obtained from the experiment. The results are categorized into different subcategories as mentioned above. In initial section of the chapter the dust compositional analysis has been performed utilizing results from different characterization techniques. After performing the outdoor experiment electrical and thermal parameters of the clean and unclean panel are observed and compared to observe the effect of cleaning system.

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Chapter No. 5

Conclusion and Recommendations

5.1 Conclusion

This study investigates the effect of dew-induced dust on electrical and thermal parameters of polycrystalline solar PV module under outdoor conditions along with the impact of water-based cleaning using a low-cost automatic cleaning system. The key findings of the research work are summarised below:

- SEM imaging and EDX spectrum reveals that small agglomeration of dust particle were formed after dew effect, while overall particle size of dew-induced dust and dew-free dust ranges between 0.2 µm to 20 µm. The elemental composition of the dust mainly contains oxygen, silicon, aluminum, sulphur, zinc, and many other elements in small proportion. Although the weight concentration of different elements was reduced after dew effect.

- The rate of dust accumulation on solar PV modules is influenced by the tilt angle, at a higher tilt angle, the rate of dust accumulation is lower as compared to a lower tilt angle. The average dust accumulation per day at tilt angles of 23˚,33˚, and 43˚ were 209 mg/m^2, 162 mg/m^2, and 131 mg/m^2.
- The voltage at tilt angles 23˚,33˚, and 43˚ was decreased by 6.5%, 5.7%, and 5.2% with an average decrease of 5.8% in three days. Voltage loss due to soiling was greater at lower tilt angles as compared to higher tilt angles.
- Clean solar PV module has 15%, 12%, and 13% more current at tilt angles of 23˚,33˚, and 43˚ than unclean solar PV module. Current loss has a linear relation with soil deposition on the front surface of solar panel, at a lower tilt angle, current loss due to dust deposition was higher as compared to the higher tilt angles.
- The power output of solar PV module was improved by 12%, 9.77%, and 18% respectively, at tilt angles of 23˚,33˚, and 43˚ after cleaning process. Although the power loss at different dust density of 629 mg/m^2, 487 $mg/m^{2,}$ and 392 mg/m^2 was 16%, 12% and 20%. The average power loss at different tilt angles was 13.27% with an average dust accumulation of 167.3 mg/m^2 per day.

- At tilt angles of 23˚,33˚, and 43˚, the front surface temperature of an unclean PV module was greater than that of a clean PV module, with a front surface temperature difference of

0.8°, 0.52°, and 0.3° C, respectively. The difference in back surface temperature between clean and unclean solar PV modules at tilt angles of 23°,33°, and 43°, was 1.2°, 0.7°, and 0.3° C respectively. Experiment results show that cleaning has a cooling impact on the solar PV module lowering front and back surface temperature.

- The automated cleaning system increases efficiency by 85% with 5 minutes of daily operation utilizing pressured water through flat fan nozzles. After filtering through Whatman filter paper, the recycling system recovers 85% of the water to the storage tank.

5.2 Future Recommendations

The proposed system can be implemented on large scale commercial size solar PV system. Although cost of microcontroller can be reduced by using different microprocessors. Different type of nozzle design can reduce the water quantity as well as less time of operation. The use of surfactants can be added to waters to remove soil more efficiently. The proposed experiment was performed on polycrystalline solar panel Although it can be implemented on monocrystalline solar panels. The experiment was performed for short period of time and only in winter season, hence it can be performed for large period as well as in other three seasons. Experiment can also be conducted for different type of soil to observe the electrical and thermal parameters.

A Solar PV Surface-Cleaning Setup to Optimize the Electricity Output of PV modules in a polluted Atmosphere

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Abstract

The performance characteristics of PV modules are significantly affected by environmental factors, particularly soiling. Dew factor can amplify the deleterious effect of soiling on the performance of PV modules. Therefore, this study investigates the morphological changes caused by dew in soil and proposes a novel automated water-based cleaning system to remove dew-induced dust-off PV modules. The experiment was conducted for the climatic conditions of Islamabad-Pakistan using poly-PV modules. The results showed that soiling rates at tilt angles of 23˚,33˚ and 43˚ degree are 16%, 12%, and 20%, respectively. The proposed cleaning system sprinkles water using flat fan nozzles. The used water was filtered and collected back to storage tank. The power recovered after effective three days of cleaning was 12%, 9.77%, and 18% respectively at tilt angles of 23˚,33˚, and 43˚ degrees. It was observed that cleaning process requires 7.325 ltrs of water to clean surface area of 1.4772 m^2. The cleaning process also provide cooling effect to PV modules decreasing front and back surface at tilt angles of 23˚,33˚, and 43˚ degrees by 1.3˚, 0.52˚, and 0.3˚ C and 1.4˚, 0.7˚, and 0.3˚ C. The financial evaluation of the proposed automatic cleaning system indicates that it is feasible for domestic and commercial-sized PV systems.

Keywords:

PV module.

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