A SELF-CLEANING DEVICE FOR POLE MOUNTED SOLAR PV INSTALLATIONS

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This study aims to develop automatic self-cleaning mechanism (SCM) for pole mounted solar installations and to evaluate its performance. Design and fabrication of device allows the SCM to start cleaning cycle after every 24 hours for a period of 20 seconds. It also restricts the SCM to continue the cleaning process during rain or when the battery voltage level is low. The experiments were done at two identical pairs of PV panels tilted at 33° angle, one with SCM and one without, for a period of six weeks in the climatic conditions of Pakistan. Irradiance, dust density and other performance parameters such as maximum power output, short circuit current, open circuit voltage, fill factor and panel efficiency were recorded. The results revealed that with the increasing dust density, the output power, short circuit current and efficiency decreased dramatically for the PV pair without SCM, i.e. by 85%, 80% and 86% respectively. On the other hand, the PV pair having SCM showed fairly a consistent performance due to regular cleaning of the panel surfaces. The proposed SCM is a cost effective mean of removing accumulated dust with a payback period of 2.04 years.

Key words: *Pole mounted solar installation, SCM, soiling, performance*

1. Introduction

Street/road lights consume a considerable amount of electricity on daily basis around the whole world, e.g. in 2010-11, street lightings consumed 1% electricity of India's all electricity consumption [1]. The Clinton Climate Initiative indicated that municipal street lighting can represent from 5% to over 60% of a municipal government's electric bill, depending on the municipality's size, the services it offers, and the efficiency of its public lighting [2]. Similarly, street lightings in Pakistan consumed 441.1 GWh (0.5% of total electricity) in 2015 [3], a country which is currently facing a severe shortage of electricity [4]. In such situation where grid electricity is not available most of the time, alternative energy source such as solar energy can play a vital role in overcoming the on-going energy crises in Pakistan. Fortunately, Pakistan is situated in such a geographical location in Asia where potential for solar energy exists abundantly. Pakistan receives a daily average solar insolation of 5.5 kWh/m^2 with annual mean daily sunshine duration of 8–10 hours throughout the country [5]. Fig. 1 shows the solar radiation map of Pakistan [6]. Realizing the on-going electricity shortage, the local governments of different provinces of Pakistan are encouraging the application of solar energy projects. One of such initiatives is the installation of solar street lighting on the major roads of different cities [7]. Pole mounted solar PV installations are generally exposed to airborne dust due to heavy traffic on the roads. This continuous and rapid accumulation of dust reduces the efficiency of such installations by 85% in a single day and in some cases in few hours. Frequent removal of dust is therefore indispensable for such installation which certainly is not possible by manual means. Majority of pole mounted solar lighting are installed on the high speed roads such as Grand Trunk (G.T) Road. Due to high speed traffic, the airborne dust is always there to threaten the performance of these pole mounted solar installations [8]. Fig. 2 shows a typical pole mounted PV installation on the G.T road in the city of Mureedkay, Pakistan. Manual cleaning of such installations is not easy. It could be seen that considerable airborne dust has accumulated on the surface of both panels. The process of accumulation of dust on the surface of solar panels is called soiling [9]. A number of researchers from across the world have investigated the effect of soiling and cleaning mechanisms on the performance of the solar panels. The rate at which dust accumulates depends on a number of factors such as climatic conditions, tilt angle, environmental conditions such as humidity, wind speed, dew point temperature and local conditions (e.g. industrial exhaust gases) to which the panels are exposed [10]. Hottel and Woertz [11] were pioneers of investigating impact of soiling on

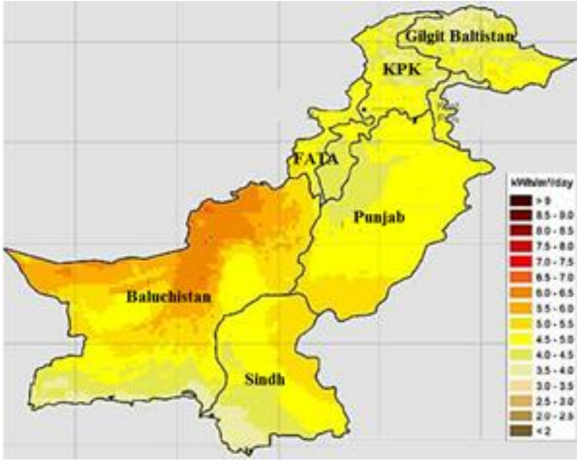

Fig. 1. Solar map of Pakistan [6]

Fig. 2. Pole mounted solar PV installations on GT Road, Mureedkay, Pakistan

solar thermal collectors tilted at 30° in USA for a period of 2 months in 1942. They observed 4.7% degradation in performance with 1% average loss in light transmission to collectors. After three decades, Garg [12] investigated the soiling impact at three different tilt angles, i.e. 20º, 40º and 60º for a period of one month. Ali HM et al., [13] investigated the effect of dust deposition on the performance of monocrystalline and polycrystalline PV modules in Taxila, Pakistan. It was found that monocrystalline and polycrystalline modules showed about 20% and 16% decrease of average output power respectively after 11 weeks of dust deposition. Nahar and Gupta [14] carried out a similar study in India and investigate the soiling phenomenon for the tilt angles 0º, 45º and 90º during a period of 1.5 years. Merrouni et al [15] investigated the effect of soiling on the glass and aluminum in Morocco for a period of three months (Apr-Jun) and found that horizontal mirrors for both glass and aluminum suffered 45% and 33% cleanliness drop respectively; 14% each at +45° mirrors and was remained 3% for -45° and 0°. In another study by Pavan et al [16] concluded power production from PV panels (tilted at 25° angle) on large scale have cleaning dependency. They evaluated 6.9% power loss on sandy soil and 1.1% loss for compact soil. Rao et al [17] had similar research quantifying PV performance losses due to dust accumulation in India. They used two identical panels; one clean and other with 70% dust deposition for each setup. It was observed 30-40% power loss in outdoor test bed and 4-5% power loss for indoor system.

Table 1: Description, advantages and disadvantages of various cleaning methods [18, 19]

Cleaning Method	Description	Advantage	Disadvantage
Natural Means	This involves removal of dust by the natural means such as wind and rain.	This does not involve any labor and operational cost.	Its effectiveness is very low as wind and rain water are not always available.
Manual Mechanical Means	This involves cleaning of solar panel surface with brushes, water etc.	**1.** The effectiveness of this method is high. **2.** This helps in physical inspection of panel surface for any possible cracks.	**1**. Involves high cost. **2.** Not suitable method for pole mounted PV installation. **3.** Risk of life for the cleaning persons, if pole mounted installation.
Nano-films	In this method, the surfaces of the solar cell are covered with a pellucid self-cleaning Nano-film.	No mechanical cleaning is required.	**1.** Not suitable for large PV array installations. **2.** High cost. **3.** Yet not matured technology
Electrostatic removal of dust	This technique helps to lift and transport charged and uncharged dust particles using electrostatic and di-electrophoretic forces.	This does not involve any labor cost.	This method is not suitable for pole mounted PV installations.

From this extensive literature review of soiling and its effects on solar panels efficiency, regular cleaning of panel surface is crucial for its consistent performance. He, et al [18] and Sabah, et al [19] reviewed different methods of cleaning and their effectiveness for the surface of solar panels. These methods include natural method, mechanical method, self-cleaning Nano-film method and electrostatic method. Tab. 1 summarizes the description, major advantages and disadvantages of these methods.

A number of researchers [20-34] had investigated the effect of dust deposition on PV panels using different cleaning methods including Electromagnetic Screens, Nano film coating and mechanical methods for cleaning purpose. Fig. 3 shows overview of such studies made around the globe. It is apparent that most of the research is limited to USA and China in the areas of Electrodynamic Screen and Nano film respectively whereas, a limited research has been undertaken on the mechanical cleaning of solar installations. Further, it has been observed that there is very little published literature available for a cleaning mechanism designed specifically for pole mounted PV installations. This cleaning of pole mounted PV installations is never easy due to their height from the ground level. To address this problem, the need for a Self-Cleaning Mechanism (SCM) for pole mounted solar installations has become indispensable. This research attempts to develop a SCM and to evaluate its performance. This study adds knowledge with original data collected through experiments and would be of high interest for the policy makers, researchers and the operators and owners of solar installation.

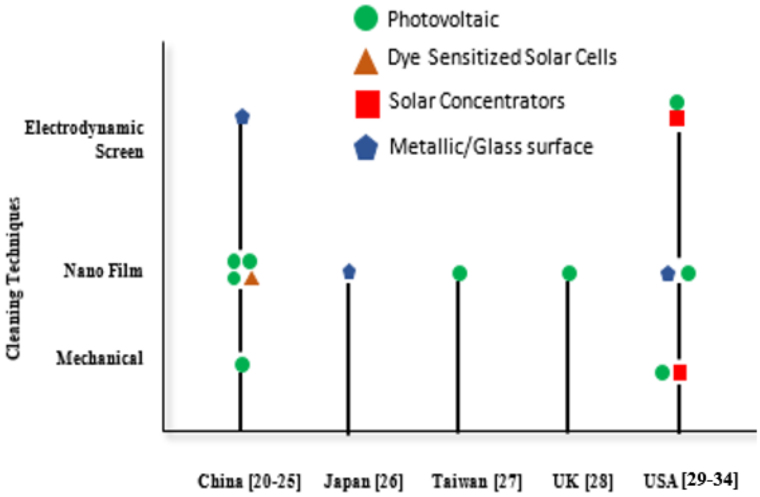

Fig. 3. Overview of solar PV cleaning studies

2. Experimental Setup

2.1. Site selection

Experimental setup was installed on the roof of Mechanical Engineering Department's building at Mirpur University of Science and Technology in the Mirpur city of AJK, Pakistan. This building was selected as it is very close to a high traffic road, and is in the range of the airborne dust which results from heavy traffic. Mirpur city is situated at 33.14° North latitude and 73.77° East longitude.

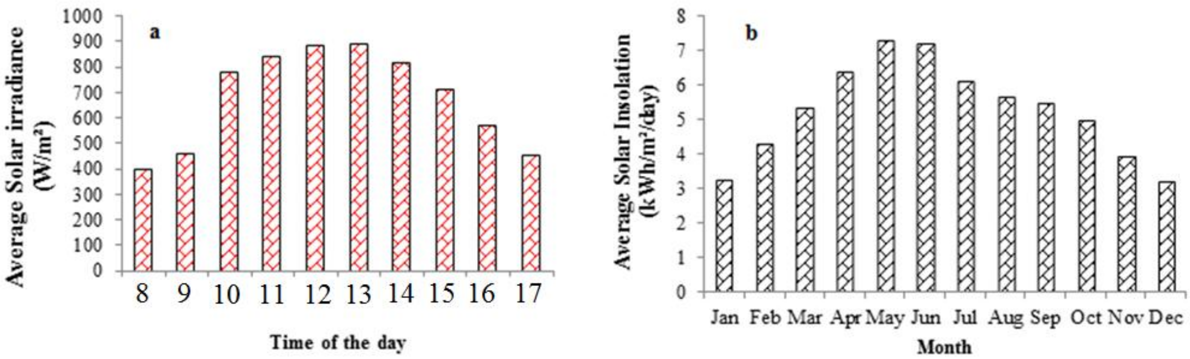

Fig. 4. Average hourly solar irradiance (a) and monthly solar insolation (b) in Mirpur AJK [35]

Table 2: Technical Details of Equipment

Equipment/Item	Technical Details
Solar PV Module	Type: Mono-Crystalline, No. of cells: 12 Cell area: 55x60mm, Rated capacity: 50W; Short Circuit Current: 2.91A, Open Circuit Voltage:22.6V, Module dimensions: 760 × 540 × 40 mm, Estimated life: 25 years
Mounting Structure	Material: Mild Steel, movable along the vertical axis; provides tilt angles between zero and 90°.
Direct Current motor	Type: DC Motor, Voltage: 12V: Rated current : 5 Amperes, Power; 60W, estimated life: 10 years
Cleaning brush	Made of wooden threads/nails screwed to a cast iron strip. The driving end of the brush connects with the shaft of the dc motor. Dimensions: 630 × 40 mm. Estimated life: 2 years
Battery	12V Li-Ion battery – estimated life: 5-6 years
Rain sensor	Model: YL-83 type; operating voltage: 5V, Dimensions: 50 × 30 mm, estimated life: 3 years
Micro-controller	Type: Arduino mega 2560; Arduino is a microcomputer; it has an internal CPU, RAM, IOs interface, estimated life: 15 years

This site has high solar insolation and irradiance. Fig. 4 shows solar insolation and irradiance levels on a surface tilted at 33˚ angle facing south-west. It could be seen that solar insolation at this site goes as high as 7kWh/m^2/day during the summer months with an average value of 4.5-5kWh/m^2/day. Solar irradiance is as high as 900W/m^2 during the peak hours daily.

2.2. Technical details of equipment

The proposed SCM consists of two pairs of Solar PV panels with moveable mounting structures, a cleaning brush, a dc motor, a rain sensor, a programmable micro-controller, a 12V rechargeable dc battery and measuring instruments. Details of these components are presented in Tab. 2.

Whole SCM except rain sensor and cleaning brush is installed within a weather proof box (140 × 280 mm) and is capable to sustain severe weather conditions. Its addition to the solar module is expected to improve the mechanical strength of the pole and panels against high wind speed.

The micro-controller has been programmed to start cleaning cycle every day at 12 pm for a 20 second period. Daily cleaning time, i.e. 12 pm has been selected because by this time the dew drops congregated on the panel surface would have vaporized. Secondly, by this time solar radiations are getting to their peak value, therefore cleaning the panel surface just before the peak period will certainly provide better conditions for the panel to generate more energy. The cleaning

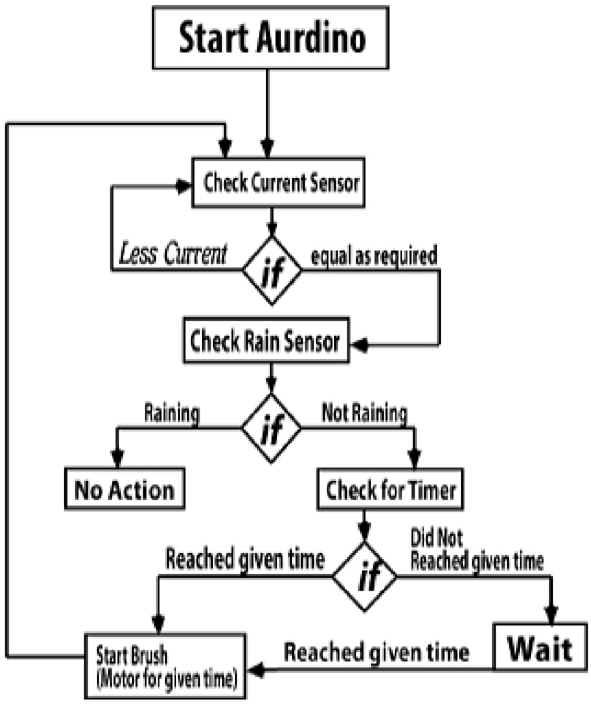

Fig. 5. Flow chart of SCM's cleaning process

period was set to 20 seconds after a series of experiments in which dust was artificially spread over the panels and time was recorded for a complete cleaning of the surface. It was found that the proposed cleaning brush would remove all the dust in 20 seconds. The cleaning time, cleaning period and the cleaning interval, all could be adjusted anytime via re-programming of the micro-controller. Fig. 5 shows a flowchart of the SCM's cleaning process. Pair of PV panels connected in parallel with complete assembly (front and rear sides) of the proposed SCM is shown in Fig. 6.

Precise equipment was used for the measurement of photovoltaic modules parameters. I-V curve analyzer (Model: PROVA 200A) used for the measurement of output parameters of PV modules including maximum power, short circuit current, efficiency and fill factor. It also traces the I-V and P-V curves. The global solar radiations along the plane of PV modules were measured using Pyranometer (operating range 150-1500 W/m^2, accuracy $\pm$ 5 %). Dust accumulation on the surface of PV panels was measured by the weight of dust on the glass plates using sensitive digital weight balance. Six glass plates (110 × 60 mm) were placed at same tilt angle (33º) facing south. Weight of each plate was measured in beginning and after every passing week. At the end of 1st week, panel number one was removed carefully and its weight was measured. Same procedure was repeated till the sixth week where the dust accumulated on panel number six gave the value of dust density over a period of six week.

2.3 Calculation of PV panel's performance

Systematic series of measurements were conducted for a period of six weeks. Maximum power depends on the maximum current and voltage for specific time and is given by Eq. (1):

$$P_m = V_m \times I_m \qquad (1)$$

Where, P_m is the maximum power, V_m is the maximum voltage and I_m represents the maximum current. Percentage efficiency of PV module was calculated using Eq. (2),

$$\eta_{module} = \left(\frac{P_m}{G \times A}\right) \times 100 \qquad (2)$$

η_{module} represents the module efficiency, G is the global solar irradiance in W/m^{2}and A is the aperture area of PV module. Fill factor is a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power and can be represented as,

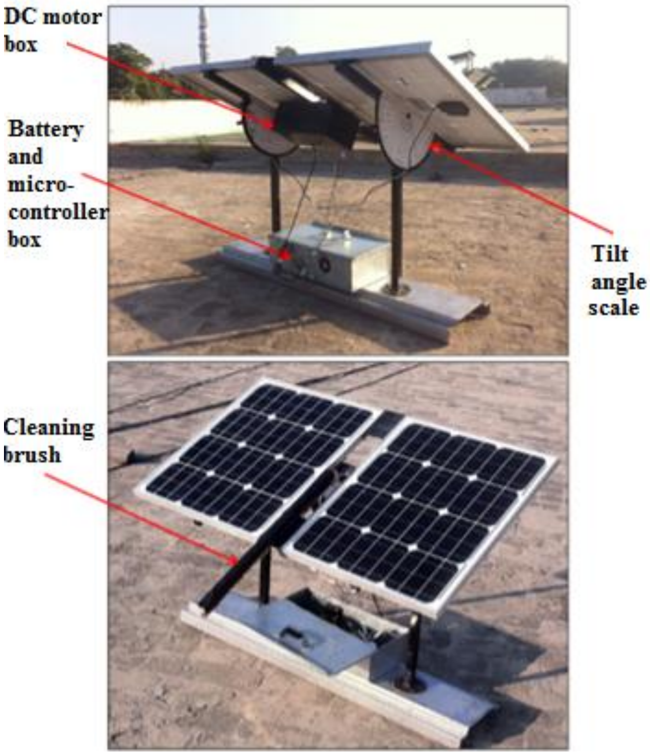

Fig. 6. Experimental setup of proposed SCM (Front and rear side of PV panel pair having SCM)

$$FF = \left(\frac{V_m \times I_m}{V_{oc} \times I_{sc}}\right) \qquad (3)$$

where FF is the fill factor, V_{oc} is the open circuit voltage and I_{sc} is the short circuit current of PV module. V_{oc} is the potential difference between two terminals of solar panel when these are not connected to any circuit. Short circuit current (I_{sc}) is the current value without any resistance in the path of current flow. I-V and P-V curves were obtained for I-V curve analyzer. Readings of all these parameters for both pairs were recorded on daily basis at 12pm. All the daily values were then converted to weekly average values for each week in order to compare these with the weekly dust density.

3. Results and Discussion

Readings were recorded on weekly basis and are shown in Tab. 3.

Table 3: Weekly readings of different parameters

Week	Dust	PV Pair with SCM					PV Pair without SCM				
No.	Density	P_{max}	I_{sc}	V_{op}	FF	Eff	P_{max}	I_{sc}	V_{op}	FF	Eff
	gm/cm²	Watt	Amp	V		%	Watt	A	V		%
Week 0	0	70	4.83	19.40	0.73	7.20%	70	4.8	19.15	0.74	7.20%
Week 1	0.58	67	4.26	19.40	0.73	6.69%	67	4.17	19.15	0.74	6.67%
Week 2	1.45	67	4.17	19.38	0.747	6.70%	60	3.75	19.20	0.76	5.99%
Week 3	2.65	63	3.92	19.37	0.715	6.29%	50	3.05	19.07	0.71	5.03%
Week 4	3.87	66	4.08	19.64	0.76	6.63%	43	2.61	19.20	0.75	4.32%
Week 5	5.45	58	3.38	19.59	0.795	5.82%	29	1.63	19.27	0.77	2.86%
Week 6	6.9	58	3.38	19.59	0.75	5.82%	9	0.561	19.20	0.72	0.81%

3.1. Dust accumulation and dust composition

Dust accumulation was measured using digital weight balance for the period of a six week, i.e. from 6 September 2016 to 18 October 2016 on weekly basis. Fig. 7 shows the dust density (mg/cm^2) on weekly basis for the period of six week. It is apparent that dust density increased consistently till the end of 6th week. No raining was observed during this period, i.e. from 6 September 2016 to 18 October 2016. Dust accumulation in the last two weeks was observed higher compared to first four weeks. This is probably because, during the last two weeks, some grinding works in the parking area near this building was carried out which caused a lot of airborne dust in surrounding that ultimately accumulated on the panels. To find the composition of dust, a sample of collected dust was tested using hydrometer method at Soil Test Laboratory of University of Engineering and Technology, Taxila. The tests showed that sample dust contains 32% fine sand (diameter > 0.07 mm), 60.5 % silt (diameter 0.06 - 0.002 mm) and 7.5 % clay (diameter < 0.002 mm).

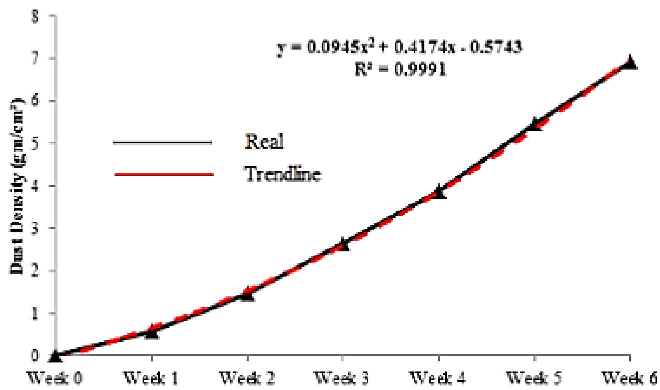

Fig. 7. Dust density for six weeks

3.2. Solar PV Performance Parameters

Fig. 8 shows variation of different output parameters of solar modules with respect to variation in the dust density.

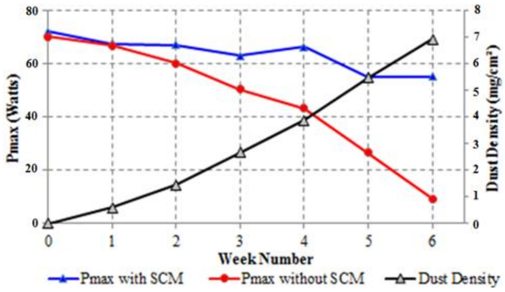

Fig. 8A. Weekly dust density Vs maximum

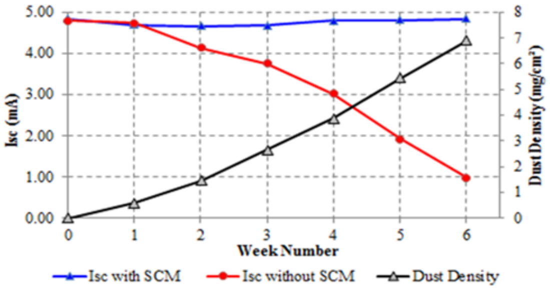

Fig. 8B. Weekly dust density Vs I_{sc}

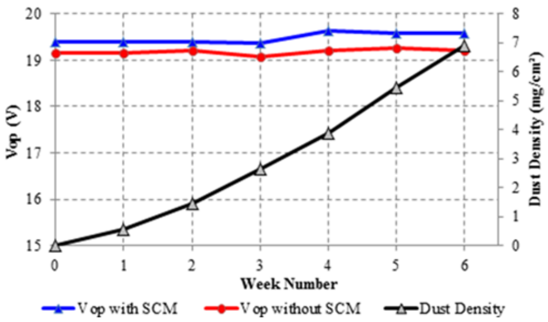

Fig. 8C. Weekly dust density Vs open circuit voltage

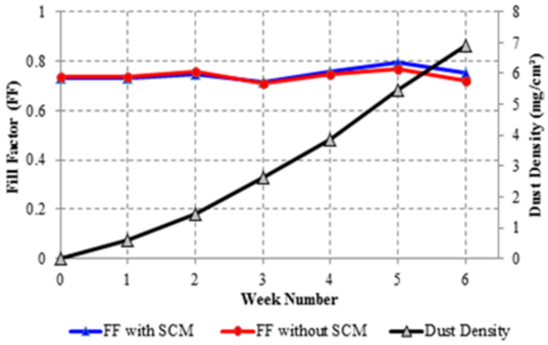

Fig. 8D. Weekly dust density Vs fill

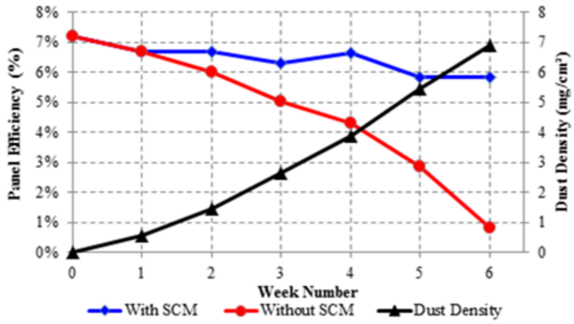

Fig. 8E. Weekly dust density Vs efficiency

It is apparent from Fig. 8 (A, B & E) that with the increasing dust density, maximum power (P_{max}), short circuit current (I_{sc}) and efficiency (η) of the PV pair without SCM have identical decreasing trend and were recorded (85%, 80% and 86% respectively) lower than that of PV pair having SCM. This confirms that these three parameters i.e. maximum power (P_{max}), short circuit current (I_{sc}) and efficiency (η) are strongly influenced by the soiling effect. As shown in Fig. 8 (C) variation in Open Circuit Voltage, "V_{oc}" remained fairly negligible and was recorded between 19.5 – 20.2V for both PV pair. This shows that dust density does not affect the V_{oc} significantly. From Fig. 8 (D) it is obvious that dust does not have a significant effect on the FF. However, FF of the PV pair with SCM was observed 4% higher than that without SCM. Overall variation of FF during six week study period was observed 11%. Fig. 9 (a) and Fig. 9 (b) show the weekly I-V and P-V curves for the solar panel pair without automatic SCM. It is apparent that with increasing dust density, short circuit current went on decreasing which caused maximum power to drop on weekly basis. Over the six weeks of study period, short circuit current dropped by 80%, i.e. from 4.8 Amp to 0.98 Amp whereas very little drop in the open circuit voltage (V_{oc}) drop was observed. Similarly, peak power consistently dropped during this period. A drop of 80% in maximum power was observed at the end of study period. Fig. 10 (a) and Fig. 10 (b) show the weekly I-V and P-V curves for the solar panel pair with automatic SCM. It is apparent that both the Short Circuit Current and power of the panels remained quite consistent during the study period due to regular cleaning of the panel surface.

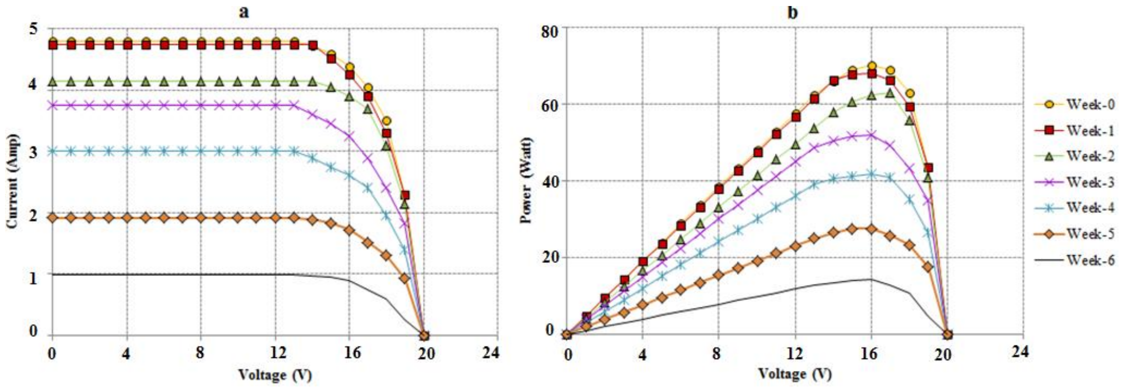

Fig. 9. I-V curves (a) and P-V curve (b) for the pair of panels without SCM

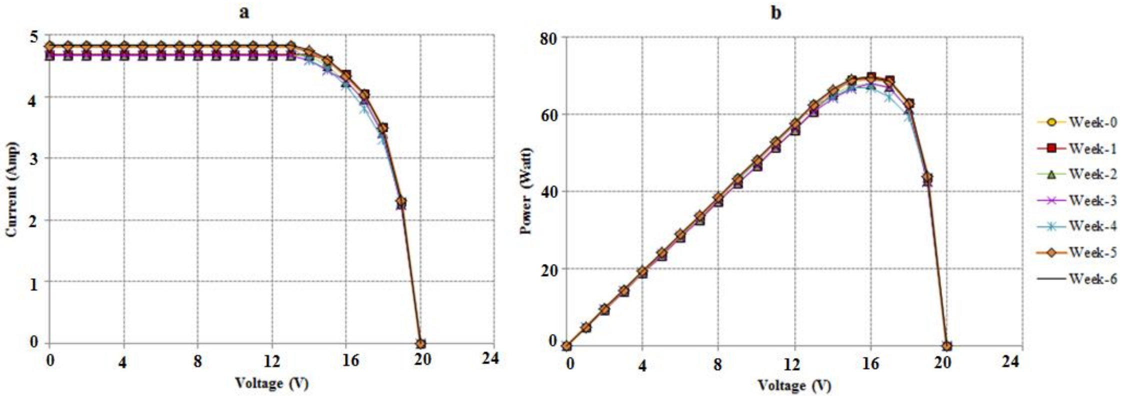

Fig. 10. I-V curves (a) and P-V curve (b) for the pair of panels with SCM

3.3. Economic Analysis

An economic analysis has been done based on the readings collected during six weeks period and on the following assumptions. **(a)** Same pattern of dust density repeats after every six week period (i.e. rain cleans the surface of both panels after every six weeks); **(b)** Average sunshine hours are 8 during winter months (Nov-Mar) and 12 during summer months (Apr-Oct). **(c)** Daily electricity consumed by SCM remains constant for all days of the year.

Tab. 4 shows a simple economic analysis whereas Fig. 11 shows weekly power generation by PV modules (with and without SCM) based on aforementioned assumptions.

Table 4: Economic analysis of proposed SCM for PV modules

Parameter	PV Module with SCM	PV Module without SCM	Difference
Weekly power generation (kWh) for winter months @ 8 sunshine hours/day	90.4	69	24%
Weekly power generation (kWh) for summer months @ 12 sunshine hours/day	151	110	27%
Total annual generation, (kWh)	241	179	26%
Total cost of Self Cleaning Mechanism		PKR. 2,800	
Annual savings @ Rs.22/kWh		PKR. 1,364	
Simple payback period		2.05 Years	

As shown in Tab. 4, SCM modules generate 26% higher electricity compared to PV modules without SCM. Under real conditions (i.e. PV module installed near a high traffic road), this difference of power generation could be much larger due to frequent and rapid dust accumulation on the PV modules surfaces. Secondly, in summer months, power generation from modules having SCM will be much higher than that having no SCM. A difference of 50% in generation from both PV modules (with and without SCM) will result in a payback period of one year.

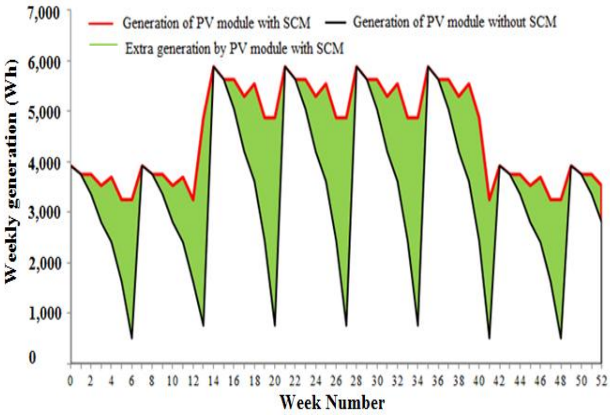

Fig. 11. Weekly power generation by PV modules

4. Conclusions and Recommendations

Road side pole mounted solar PV installations are exposed to heavily airborne dust which adversely affects the panel's performance. Manual removal of such accumulated airborne dust is expensive and involves higher maintenance costs. In this study, we have developed an automatic self-cleaning mechanism (SCM) for pole mounted PV installations and have tested its performance. Two PV pairs, one with SCM and the other without SCM, tilted at an angle of 33º were placed on the roof of a building that is very close to a main road for a period of six weeks. Readings of their essential performance parameters were recorded on daily basis. The following conclusions could be drawn from this study.

I. Automatic cleaning or regular manual cleaning of panel surface is highly necessary to avoid or minimize the soiling effect.
II. Increasing dust density has a significant negative effect on the power, short circuit current and the efficiency of the PV panels (in this case, reduction in the P_{max} (85%), I_{sc} (80%) and Efficiency (86%) was observed for the panel pair without SCM).
III. Dust density does not increase linearly with respect to time but is somewhat exponential. Local conditions may result in a sudden and rapid increase in the soiling effect thus reducing the overall performance of the PV panels.
IV. Dust accumulation does not affect the FF and V_{oc}.
V. The PV module with proposed SCM could produce 26% to 50% higher electricity compared to a simple PV module.

Finally, it is recommended that the developed SCM should be tested on a road side mounted pole for a longer period in order to evaluate its performance under real conditions.

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