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# The effect of weather conditions on the efficiency of PV panels in the southeast of UK

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ABSTRACT

Increasing installation of photovoltaic (PV) systems and demand for more accurate prediction of their operational performance in the UK has prompted the research that aims to establish the relationships between output efficiencies, weather parameters and deposited solid particles on the panel surface. The direct use of efficiency figures quoted by PV manufacturers, normally based on measurements taken in clean laboratory environments of 25 °C and at standard air density, is often not appropriate as field studies demonstrated the actual outputs could be reduced by as much as 60% in dusty or polluted climate without regular cleaning. The experimental investigations and case studies took place in the town of Brighton in the southeast of the UK. Experimental simulations of dry dust cover were carried out in the laboratory to establish the effect of dust density to light transmittance. The effect of dust deposit on panels subjected to the climatic elements was studied using a set of outdoor glass units configured at different tilt angles placed on a roof, which were subsequently analysed in the laboratory after exposures between one and four weeks. Effects of climatic parameters on the performance of PV panels were examined through detailed analysis of the performance of two existing PV installations in relation to their weather exposure. Results for the indoor experiments showed that even a small amount of fine particles could reduce light transmittance by as much as 11%. Distribution analysis of dust collected from the exposed glass units revealed particles sizes were smaller than 400 microns with the highest frequency under 20 microns but the impact on solar transmission through the glass was mere 5% after exposure of four weeks due to the frequent rainy days. Amongst a wide range of climatic parameters used in the statistical analysis, high humidity, rain and snow were found to have significant effects to the efficiencies of the two PV installations, which in some cases could annihilated any system output. This study has also revealed the geographical issue of birds in this coastal city as their droppings can create overheated spots on the PV panel and reduce its output.



## 1. Introduction

Operating efficiency is an important consideration when evaluating the application of PV technology. Standard testing of PV is normally carried out indoor under controlled test conditions (STC) of 25 °C and solar irradiance of 1000 W/m$^2$. However, solar spectrum through atmosphere varies depending on the locality and climatic conditions as well as agents in the air such as water vapour, $CO_2$ and dust particles [1].

Dust is a term applied to solid particles with various diameters ranging from 0.1 μm to 1000 μm. Generally, about 50% of dust particles have diameters less than 20 μm and they are classified according to their sizes as follows [2,3]:

- Deposited Particle Matter – any dust that falls out of suspension in the atmosphere
- Total Suspended Particles (TSP) – particles 50 μm in size or less
- $PM_{10}$ – particles 10 μm in size or less
- $PM_{2.5}$ – particles 2.5 μm in size or less

One of the early studies on dust and soil particles on the solar collectors was carried out in the middle of 1940, which investigated the effect of pollution and dust on the solar thermal cells and the mirror reflectance [4]. At that time, Hottel and Woertz were among

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the pioneers investigating the impact of dust on solar thermal flat-plate collectors [4]. They conducted performance tests for three month on collectors of a power plant at 30° inclination under rainy environmental condition and found that the effect of deposited particles on the collector's performance was surprisingly small of about 4.7% [4].

After 1970, research studies of dust effect on solar photovoltaic panels were conducted mainly in terms of system characteristics particularly the tilt angle and different type of glazing materials. Most of these studies were carried out in Saudi Arabia and Kuwait, which showed the surface degradation and solar intensity reduction were significant and rapidly occurred during the first 30 days of exposure. The results indicated that without cleanup the reduction in efficiency increased from 33.5% after one month to 65.8% after six months [5–7].

From 1990, comprehensive studies on dust deposition were carried out with improved accuracy in experimental measurements. They revealed many collectors had lower electrical and thermal performances after a short exposure period [8,9]. El-Shobokshy and Hussein were pioneers who performed comprehensive study on the impact of dust on PV cells in Saudi Arabia [10]. Their studies included the physical properties of the dust accumulation and deposition density on PV efficiency. The results showed the impact of cement particles to be the most significant, with a 73 $g/m^2$ deposition of cement dust resulting in an 80% drop in PV short circuit voltage [10].

Many of the recent papers have investigated the relationship between PV output and dust deposition density including comparisons of particle sizes through outdoor or indoor experiments. In 2006, Eliminar et al. in Egypt [11] evaluated the transmittance of glass at regular intervals over a period of seven months and after every thunderstorm occurring in the surrounding area. Their investigation, which used 100 glass samples positioned at different tilt angles and at eight orientations, involved a complete mineralogical analysis of the dust accumulated on the transparent covers of solar cells. The results showed that the reduction in glass transmittance depended strongly on the dust deposition density and it diminished from 52.54% to 12.38% when the dust deposition density increased from 4.48 $g/m^2$ to 15.84 $g/m^2$ [11].

In 2010 Kaldelis and Kapsali demonstrated the reduction of PV efficiency depended strongly on particle composition and the source of air pollutants [12]. In their experiments, the panels were covered uniformly with sprayed water containing sieved particles of a specific diameter range, from which the experimental data concerning the effect of three representative pollutants (air particles, red soil, lime stone and carbonaceous fly ash particles) on the energy performance of PV were analysed. The results showed the greatest deterioration was caused by the deposition of red soil with approximately 16 W decrease per hour, representing 19% reduction of the output when compared with a clean panel. However, the effect for limestone and ash samples was small; they were approximately 10% and 6% respectively [12]. They also identified the need to investigate the dust effect on the energy performance of photovoltaic by laboratory simulations and measurements [13,14].

Qasem et al. investigated the effect of dust concentration, wavelength and spectral transmittance on PV performance. Dust samples were collected from Kuwait and accumulated artificially on sample glass at different tilt angles. The measured data showed the highest rate of decrease in transmittance was at wavelength smaller than 570 nm when the tilt angle was less than 30°. This study also showed that with a dust cover of 8.5 $mg/cm^2$ the reductions in output for Si, C–Si and CIGS PVs were 33%, 28.6% and 28.5% respectively [15].

L. Dorobantu, revealed the effect of large local depositions and impurities such as bird droppings, water stains, traffic pollutants and agricultural dust on solar cell from real and simulated experimental data [16]. The images captured by the thermo-vision camera clearly showed a temperature increase of up to 10 °C, from the 27.8 °C on the clean surface to 37.5 °C with bird's dropping [16]. One example which illustrates the adverse effect of bird droppings on the surface of PV is an installation at Alcatraz (US, prison), a craggy island one and half miles off the coast of San Francisco, which has a 307 kW PV array. The challenging problem is how to clean the bird droppings from the arrays when rain is infrequent during the summer months while the bird are attracted to the warmth of the panels [17].

Some research indicated the performance of solar collection systems could also be affected by geographical and environmental parameters [18]. For example, some regions in the Middle East and Asia are suffering from air pollution due to sand movements and dust storms while in Europe the frequent rainy days and occasional snow – under these conditions the outputs of installed solar collection systems will be reduced.

Literature review has revealed that there is no existing knowledge on the effect of weather conditions on the efficiency of PV in the UK. The city of Brighton, which has the highest annual solar radiation in the southeast of the United Kingdom, has been chosen as the locality for this small scale study.

### *1.1. Case study city – Brighton, UK*

Brighton, together with Hove, is a city in East Sussex, Southeast England. The summer temperatures by the sea can be five or so degrees lower than those two miles inland due to the oceanic sea breezes. Temperatures in July is around 20–21 °C during the day but rises to the low 30 °C during heat wave periods. The South Downs hills in the north usually shield the city from severe weather. Winters are usually mild with occasional snowfalls when the city sometimes badly affected [19] (see Table 1).

Fig. 1 shows average amount of solar irradiation over a period of 10 years.

The air quality monitoring report in 2012 shows this city has roadside levels of nitrogen dioxide above objective levels parallel with narrow or enclosed streets in either city or village environments. In recent decades legislation has led to source reduction in emissions of lead, benzene, polycyclic aromatic hydrocarbons (PAH) and carbon monoxide. In 2011, $PM_{10}$ monitored at roadside showed an eleventh monthly mean, from February to the end of December, of 27.4 $\mu g/m^3$. This is lower than the annual average limit value of 40 $\mu g/m^3$ with only 15 daily means greater than 50 $\mu g/m^3$. According to the report by the national monitoring network in 2011 [21], the annual mean $PM_{2.5}$ of about 12 $\mu g/m^3$ was half of the EU target of 25 $\mu g/m^3$. The review on Brighton's environment showed that its air is relatively clean and the level of air pollutants that may settle on the surface of PV panels is low.

## 2. Methodology

This study adopted a three-perspective approach to investigate the effect of weather conditions on the performance of PV panels. Firstly, the indoor laboratory based simulation, secondly the outdoor field measurements and thirdly statistical evaluation of weather parameters on system outputs from two existing PV installations.

### *2.1. Indoor experiments*

Based on the results from the analysis of particle size deposited on a PV sample in the Brighton area, laboratory experiments were carried out to simulate the effect of similar-sized ambient particles

**Table 1**
Climate data for Brighton, UK [19].

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average high °C (°F) | 8 (46) | 8 (46) | 9 (49) | 12 (53) | 16 (60) | 18 (64) | 20 (68) | 21 (69) | 18 (65) | 15 (59) | 11 (52) | 9 (48) | 14 (57) |
| Average low °C (°F) | 3 (38) | 3 (38) | 4 (40) | 6 (43) | 9 (48) | 12 (53) | 14 (58) | 14 (58) | 12 (54) | 9 (49) | 6 (43) | 4 (40) | 8 (47) |
| Precipitation mm (inches) | 88 (3.46) | 60 (2.36) | 51 (2.01) | 58 (2.28) | 56 (2.2) | 50 (1.97) | 54 (2.13) | 62 (2.44) | 67 (2.64) | 105 (4.13) | 103 (4.06) | 97 (3.82) | 851 (33.5) |

Source: Met Office.

on the transmittance reduction through glass surfaces. For this test, silica based particles in the range of 1–20 μm were used to create the effect of different quantities of artificial dust on the transmittance reduction. In this regard, a cubic sealed box was used whereby the dust particle were scattered inside from a height of 1 m and allowed to settle down on the glass surface with the aid of a slow speed fan blower. The results were considered as a benchmark for comparison with the results from outdoor experiments.

### 2.2. Outdoor experiments

For outdoor experiments 28 identical pieces of glass with the dimensions of 6 cm × 8 cm × 3 mm were used. They were placed on an acrylic frame on the roof of the Engineering Block of the University of Brighton at seven different tilt angles (0°, 15°,30°, 45°, 60°, 75° and 90°) as shown in Fig. 2. They were all south facing with four pieces of glass to be collected at time intervals between one and four weeks. Dust accumulation was monitored over a two months period between mid-February to mid-April 2013 with measurements and laboratory analysis at weekly intervals. At the same time weather parameters such as temperature, wind speed, wind direction and relative humidity were recorded.

Transmissivity measurements through the glass units were compared with a similar clean glass unit using a set of SP110 Apogee pyranometer under a fixed light source and connected to a digital current–voltage meter. Further procedures were carried out to establish the deposited dust particle on each glass unit by weighing the unit before and after cleaning using a GR200 weight balance with a high sensitivity of 0.1 mg. To establish the particles sizes distribution, a Malvern Mastersizer 2000 particle analyser was used. Comparing the clean and dusty sample's output the ratio of the amount of the transmittance percentage reduction was calculated. Furthermore, two sets of regression analysis have been carried out to relate the gather dust deposit data: one on the relationship with environmental variables such as temperature, humidity, wind speed and dust density, and the second on transmittance and dust density at different tilt angles. The analysis was based on the stepwise method of the multi-variable linear regression available in the SPSS20 software.

In order to determine the accuracy of the measured data, some dust samples have been retested by measuring the transmissivity through the Spectrophotometer available at the Pharmacy laboratory of University of Brighton. Results showed many similarities with a very tiny difference (approximately 0.001). Furthermore, Alfa-Cronbach coefficient function in SPSS has been applied to test the validity of measured data. Despite variable weather conditions in Brighton, Alfa coefficient showed an acceptable percentage range between 82% and 85%.

### 2.3. Environmental parameters and system output

This is a comprehensive statistical analysis to establish the relationships between parameters representing the weather conditions and the in-situ operational performance of installed PV panels. Two existing PV installations in the Brighton region were investigated. The relevant data were collected including nominal and measured electricity production figures, global irradiation received by the panels and comprehensive set of weather data. The relationship between the systems output and environmental variables were analysed using the SPSS20 software.

## 3. Process and results

### 3.1. Indoor experiments

Indoor laboratory experiments, which was unaffected by the unpredictable weather conditions in the UK, were setup as a preliminary investigation to establish the effect of different quantities of dust, of typical outdoor sizes, on the light transmittance through the glass surface. The selection of particle sizes was based on the data of outdoor dust collected from the surface of an installed PV panel. Silica based mineral sand consisted of primarily of silicon oxide was used and their particle size distribution lied between the limits shown in Table 2.

A small fan was used at the top of the chamber to simulate the turbulent dust movement as might occur in the outdoor environment. The dust particles were allowed to deposit in a free-fall manner from a height of 1 m onto a piece of glass placed horizontally. This test was repeated 31 times to meet the statistical

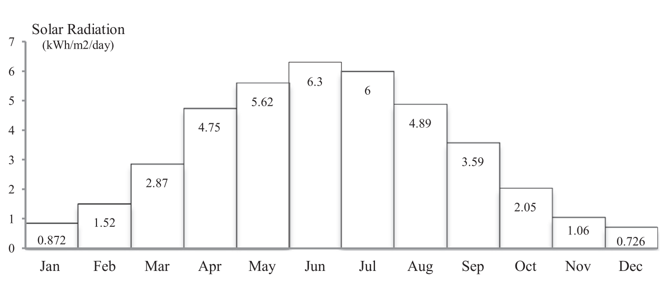



**Fig. 1.** Average amount of solar radiation (kWh/m$^2$/day) over 10 years [20].

**Fig. 2.** Outdoor glass samples.

**Table 2**
Particle size distribution of dust used in indoor tests.

| Particle size (microns) | Volume% smaller than |
|---|---|
| 1 | 1–3 |
| 2 | 9–13 |
| 3 | 21–27 |
| 4 | 36–44 |
| 5 | 56–64 |
| 7 | 83–88 |
| 10 | 97–100 |
| 20 | 100 |

**Table 3**
Outdoor number of samples and dust deposition.

| Deposit duration over 2 months | Number of samples | Dust deposition average (g) |
|---|---|---|
| Weekly | 56 | 0.0003 |
| Fortnightly | 28 | 0.00046 |
| Every three weeks | 14 | 0.00069 |
| Every four weeks | 14 | 0.00075 |

principles of 30 samplings as the minimum number of repetitions of an experiment. The relationship between dust deposition and its effect on the light transmittance through the glass is presented in Fig. 3.

The results show that as the dust accumulation increases from 0.001 g to 0.02 g the transmittance reduction through the glass increases from 1% to 10%. These figures are used as benchmarks to compare with the results obtained from the outdoor experiments.

### 3.2. Outdoor experiments

To investigate the effect of dust under real exposed conditions, a set of glass units configured at different tilt angles were set up on the roof of the Engineering Block at the University of Brighton from mid-February 2013 for a period of two months. A range of parameters have been analysed in details, they include: the amount of particles settled on the surface of glass in terms of weight (g) and density (g/cm$^2$), particle size distribution, and the transmissivity (%) through the glass unit. Table 3 summaries the number of samples and results of the dust depositions. After exposures between one to four weeks, the glass units were replaced and the collected units were analysed in the laboratory. Results in Table 3 show the amount of dust depositions for all the glass units over the experimental period range from 0.0003 g to 0.00075 g, which indicate low quantity of dust settlements on the glass units each with a surface area of 48 cm$^2$. This shows a potential transmittance reduction of at least 5% after 4 week exposure based on the results obtained from the indoor experiments.

Dust deposition is a complex phenomenon which is site and weather specific, hence daily weather variables such as average temperature (°C), humidity (%), visibility (km), wind speed (km/h) and precipitation (mm) were recorded, as shown in Fig. 4, for detailed study. Among these variables, visibility – a measure of the distance at which an object or light can be clearly discerned – is probably the most apparent indicator of air pollution and a representative parameter influencing the performance of PV panels due to the combined effects of absorption and scattering of light by

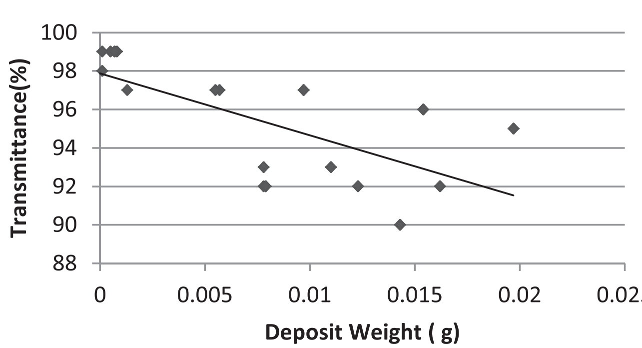



**Fig. 3.** Indoor dust deposition and transmittance (%).

gases, water vapour and dust particles, particularly effective in the range of 0.1–1.0 μm [21].

The dust and solid particles size distribution was analysed using the Malvern Mastersizer 2000 particle analyser in which the particles were characterized using laser diffraction based on the volume weighted distribution mean. This technique can provide a more accurate description of particle sizes thus enabling better understanding of their characteristics. The distributions of the dust collected on the glass units are shown in Fig. 5. The volume weighted mean varies within a wide range between 1 μm and 403.5 μm with an average of 153.2 μm. Most of the deposited particles on the surface of glass were very small, in the range of 0–20 μm, mainly due to vehicle pollution in the atmosphere. The larger particles were coarse particles mainly caused by bird droppings and water stains but their contribution was small.

Fig. 6 shows the results of measured transmittance at different tilt angles, which vary between 94.5 and 98.5% over the experiment period. The lowest transmittance occurred when the glass unit was placed horizontally. Very little differences were noted for the glass units with different tilt angles exposed for only one week. For longer exposures of two, three and four weeks, there were some small but noticeable differences in the transmissivities. Due to the rainy weather conditions over the experiment period, reductions in transmittance at different tilt angles were small. However, some existing studies found wide variations in transmissivity such as reductions between 64% and 17% for tilted angles between 0° and 60° after exposure of 38 days in Kuwait [7].

Fig. 7a shows transmittances are reduced by approximately 1.5–3.5%, 2–4.5%, 2.5–5% and 4–5.5%, corresponding to exposures of one week, two weeks, three weeks and four weeks respectively. The maximum amount of transmittance reduction is about 5% after four weeks of exposure. Fig. 7b is an extrapolation for the period of 4 months without cleaning in Brighton. It shows that the reduction of transmittance is about 6%.

In order to analyse the effect of weather condition on dust deposition, a multi-variable linear regression using the stepwise method has been adopted and executed in the SPSS software. This method, based on the use of parameter's priority that takes into consideration the real and normalized figures, provides a means to examine the relationships between the dust density (g/cm$^2$) and the three weather parameters: temperature, wind speed, and humidity.

Results in Table 4 show that relative humidity is an influential variable on the dust deposition. Further analysis confirmed a strong relationship (with 95% confidence level) between relative humidity and dust density as represented by the following equation where $Y$ and $X$ indicate dust density (g/cm$^2$) and humidity percentage (%) respectively.

$$Y = (1.207E - 7)X - 4.689E - 6 \tag{1}$$

Further stepwise linear regression model was developed to examine the relationship between different tilt angles and dust densities (g/cm$^2$) with reference to the percentage reduction in transmittance. The results are shown in Table 5 from which a

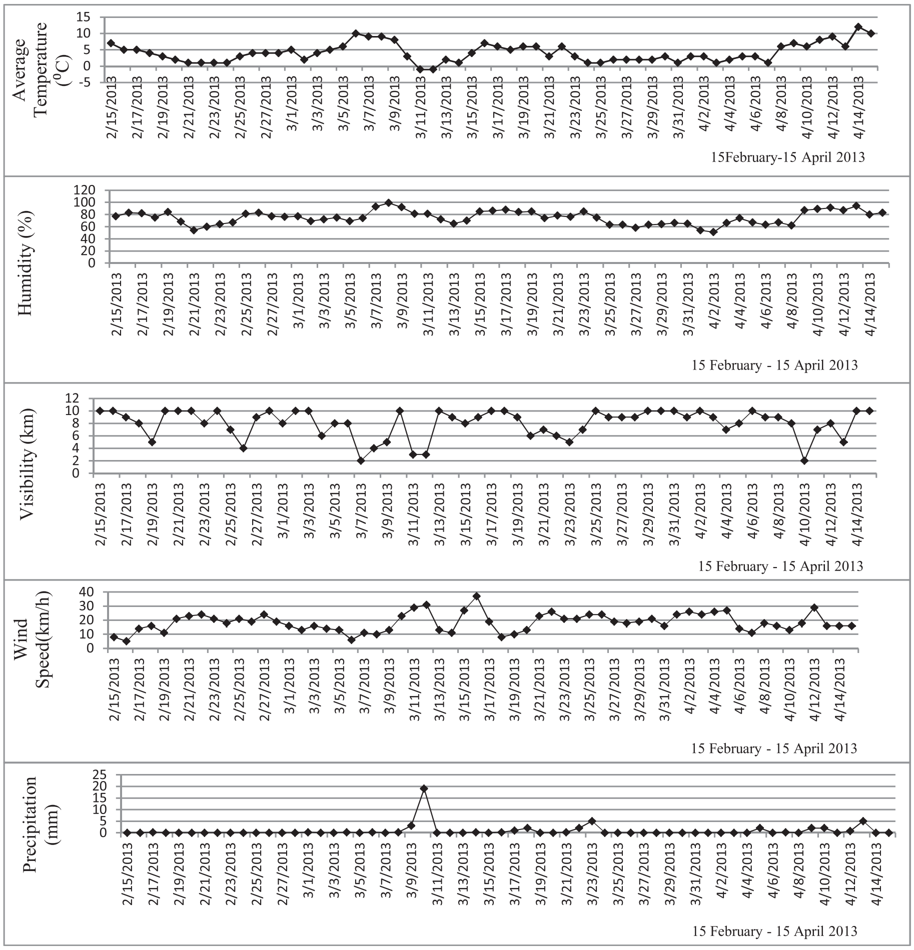



**Fig. 4.** Weather conditions during outdoor test, 15 February 2013 to 15 April 2013 [22].

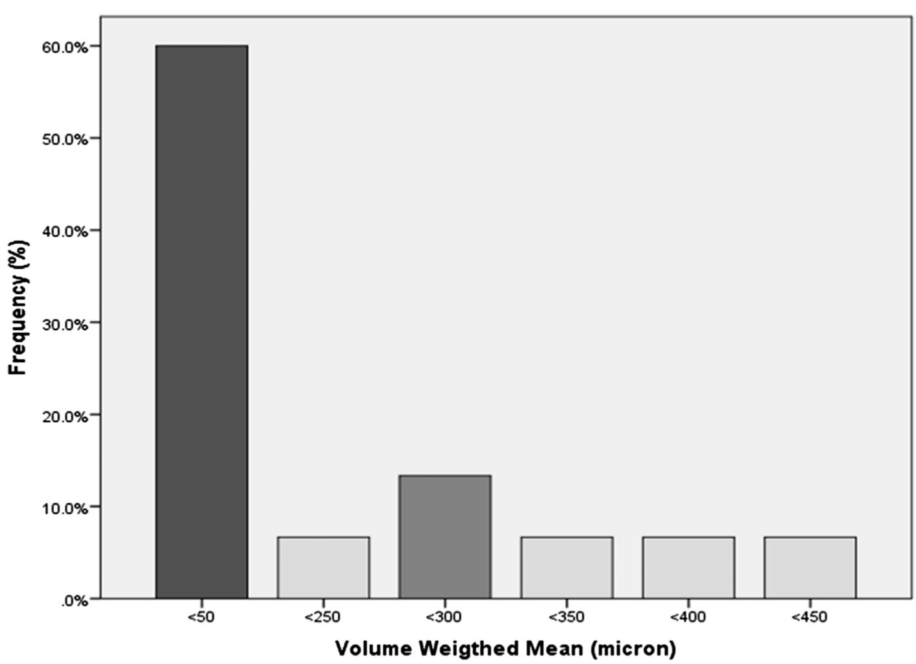



**Fig. 5.** Dust particle distribution due to volume weighted mean.

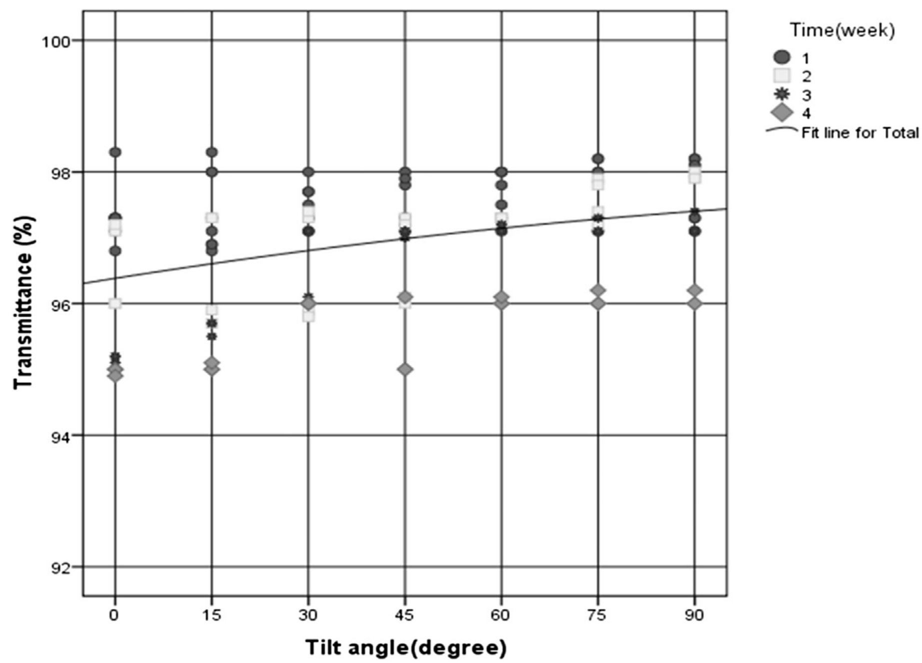



**Fig. 6.** Transmittance (%) for different tilt angles, March–May 2013.

relationship between dust density (g/cm$^2$) and the transmittance was established and represented by Eq. (2) where $Y$ and $X$ represent the transmittance reduction (%) and dust density (g/cm$^2$) respectively.

$$Y = 173542.78X + 1.965 \tag{2}$$

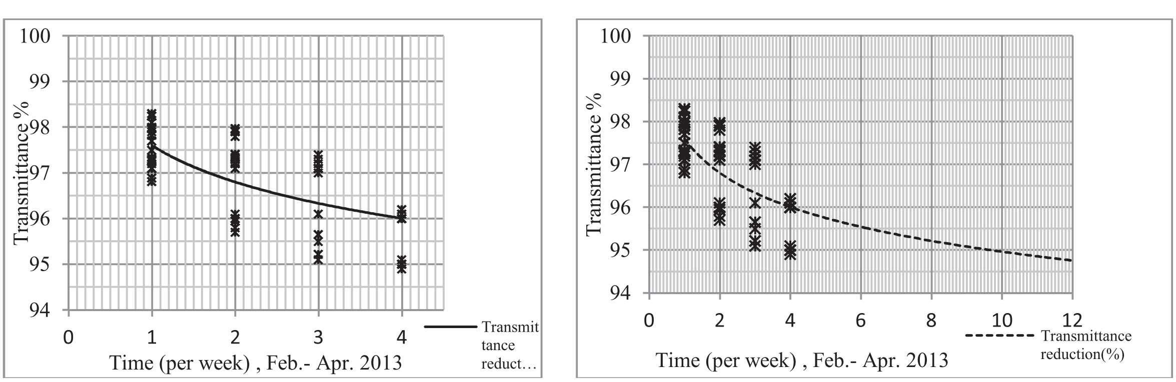
### 3.3. Installed PV systems

Results obtained from the outdoor experiments in Section 3.2 indicated the variable humidity (%) has the most significant influence on the deposition of solid particles on glass surfaces. A linear regression analysis was therefore employed to establish the relationship between humidity and PV output based on the performance of two live PV systems installed on the roofs of the Cockcroft Building and One Brighton Development.

#### 3.3.1. Cockcroft Building, University of Brighton

The solar PV plant is located on the roof of Cockcroft Building, University of Brighton. It consists of 132 PV panels each with dimensions of 1.55 m by 1.46 m. All panels are at 18° tilt angle facing southwest. The system has three inverters and rated to generate 43,000 kWh/year. Anodized water is used to clean the PV panels twice yearly that consumes approximately 25 L of water per panel. Fig. 8 shows the rain and bird droppings, after 6 months without cleaning, have created a significant area of dirt deposit on the surface that can cause efficiency losses due to localized overheating and shading. Among the three PV photographs, the left one shows only the front panel has been cleaned. The middle photograph is a close-up of one panel covered with dust, while the right hand photograph shows bird dropping on the panel that has not been cleaned for four months.

Average figures of actual electricity productions per month (kWh), solar irradiation (kWh) and humidity (%) were gathered.




a, Transmittance (%) in interval test time

b, Extrapolation of transmittance reduction% after 4 months in Brighton area

**Fig. 7.** Transmittance reduction (%) between test intervals.

**Table 4**
Results from stepwise method of linear regression analysis.

| Coefficients | | | | | | |
|---|---|---|---|---|---|---|
| Model | | Unstandardized coefficients | | Standardized coefficients | $t$ | Sig. |
| | | B | Std. error | Beta | | |
| 1 | (Constant) | −4.689E−6 | .000 | | −1.071 | .289 |
| | Humidity percentage | 1.207E−7 | .000 | .278 | 2.125 | .038 |

Dependent Variable: Density(g/cm$^2$).

**Table 5**
Results from stepwise regression model due to transmittance reduction, tilt angle and dust density.

| Coefficients | | | | | | |
|---|---|---|---|---|---|---|
| Model | | Unstandardized coefficients | | Standardized coefficients | $t$ | Sig. |
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 1.965 | .138 | | 14.206 | .000 |
| | Density (g/cm$^2$) | 173,542.78 | 26,675.122 | .663 | 6.506 | .000 |

Dependent Variable: Transmittance reduction(%).

The system efficiency was calculated with respect to the average sum of global irradiation per square meter received by the entire system (kWh/m$^2$) as shown in Table 6.

The correlation coefficient between humidity (%) and PV output has been calculated using SPSS software. Results showed that there is a negative relationship between these two variables with correlation coefficient of 0.322 which can be used as a means of validation for the equations in Section 3.2. Fig. 9 shows the relationship between humidity and PV output during March 2012 to January 2013, which clearly displays a negative relationship between these variables.

Fig. 10 shows the system efficiencies of the actual energy production of this PV installation. It can be seen that highest efficiency loss occurred in January 2013 (97%) which was mainly due to the rainy days in this month and low amount of solar radiation. With very small amount of suspended particles in the air, however, the effect of particle settlement on the panel is insignificant.

*3.3.2. One Brighton development*

One Brighton next to the Brighton train station is a development comprises of 172 apartments – from eco-studios to 3-bedroom units plus offices and community space. An on-site biomass boiler and PV panels provide approximately 50% of energy requirements with the remainder bulk purchased for residents as guaranteed green electricity through One Brighton Energy Services Company [25].

**Table 6**
Electricity production by solar power plant, University of Brighton (March 2012 to Jan 2013) [23,24].

| Fixed system: inclination = 18° | | Orientation = southwest | |
|---|---|---|---|
| Month | Humidity (%) | Em | Hm |
| Mar, 2012 | 77.93 | 2789.52 | 30,469.032 |
| Apr, 2012 | 78.26 | 5381.49 | 46,002.264 |
| May, 2012 | 78.51 | 6156.65 | 53,470.164 |
| Jun, 2012 | 82.5 | 5509.85 | 56,756.04 |
| Jul, 2012 | 81 | 3846.61 | 56,158.608 |
| Aug, 2012 | 78.6 | 5786.46 | 47,794.56 |
| Sep, 2012 | 72.3 | 4502.50 | 36,144.636 |
| Oct, 2012 | 81.5 | 2448.56 | 22,732.2876 |
| Nov, 2012 | 81.8 | 1581.82 | 12,546.072 |
| Dec, 2012 | 83.8 | 1184.75 | 9110.838 |
| Jan, 2013 | 84.7 | 343.96 | 10,723.9044 |

Em = Average monthly electricity production from given system (kWh).
Hm = Average sum of global irradiation in entire surface area (298.7) square meter received by the modules of the given system (kWh).
Solar radiation database used: PVGIS-CMSAF.

The PV system installation is 10 kWp consists of 40 units of 250 W mono-crystalline PV modules facing south. The system contributes to the daytime electricity consumption of the office building. The panels, shown in Fig. 11 are cleaned by using buckets of warm soapy water once a year.

A comprehensive review has been carried out to study the system output over a period of one year. Fig. 12 shows the monthly system energy production over the period of April 2012 to March 2013 based on records of the data monitored every 10 min.

Analysis of the weather variables and PV outputs has identified the influence of weather parameters including high humidity (more than 80%), precipitation (higher than 12 mm), and wind speed (smaller than 30 km/h) that led to the poor efficiency and low output from the PV panels. It also revealed almost zero PV output occurred when the weather conditions were either rainy or snowing.

With the knowledge from the outdoor experiments that there would be very small dust effect (5%) on the performance of PV panels, the system outputs were further examined, over the test period between mid-February and mid-April 2013, to identify if there were any other influencing weather factors. Results show the output of the PV system declined to less than the nominal 10 kWh output when there was high level of humidity, frequent rain and occasional snow. Results of statistical analysis in Table 7 show strong relationship (equal to −0.724) of the weather parameters to the PV output with rain, dust and solid particles in the descending order of influence.

## 4. Discussion and conclusion

In this paper, the effects of dust and other solid particles deposited on glass covers to the performance of PV panels have

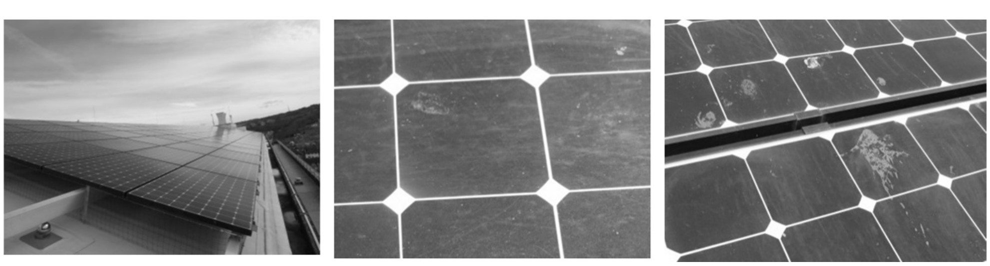


**Fig. 8.** PV panels on the roof of Cockcroft Building.

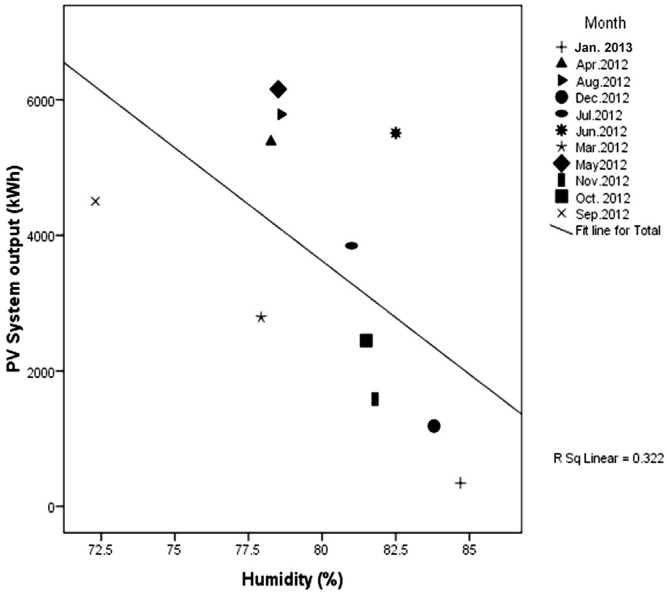



**Fig. 9.** Correlation between humidity and PV output.

been investigated through indoor and outdoor experiments under the south-eastern UK climatic conditions.

Existing studies by other researchers have been mainly focussed on particle size distribution in the range of 1–1000 microns, which is not applicable to regional weather conditions in the UK such as Brighton. This research therefore commenced by exploring the size and density of dust and solid particles in the air. From the results of the analysis of data gathered from an existing PV panel, particles sizes with the range smaller than 20 microns in size were identified as appropriate and hence adopted in the indoor experiments. The objective of indoor experiment to establish the effect of different quantity of dust deposit on the light transmittance was achieved through simulating the dust deposit on glass cover comparable to conditions occur during drier weather. On the other hand, the transmittance reduction over the winter/spring period was successfully determined through outdoor experiments which measured and analysed the dust size, distribution, quantity and weight. Results from outdoor experiments indicated only 5% reduction of transmittance with particle sizes typically between 1 and 500 microns, but the majority of particles, as revealed prior to the indoor experiment, were smaller than 20 microns. This outcome reflects the amount of outdoor dust accumulation under the winter rainy climate is small hence results of variations in transmittance at different tilt angles have not been reported.

However, the correlation study on the relationship between dust deposition and weather parameters, such as temperature, wind speed and relative humidity, has revealed that the level of relative humidity is strongly significant to the transmittance reduction. Strong relationships also exist, for both indoor and outdoor experiments, between particle density and transmittance reduction as represented by Eq. (2).

Results from the outdoor experiments show that particle sizes deposited on the glass units lie within 1–50 microns, which can easily stick to the flat surfaces when there is no rain. This condition will be exacerbated during the hot summer weather if high relative humidity exists to create a cementing effect on the surfaces. Even a small amount of such fine particles can reduce transmittance by as much as 11% as derived from the indoor experiment results.

The effect of weather conditions on the performance of PV panels was demonstrated through analysing the system outputs of two existing solar PV installations. Results from both studies revealed that weather conditions, particularly rain and snow, have the most negative effect on the performance of installed PV panels

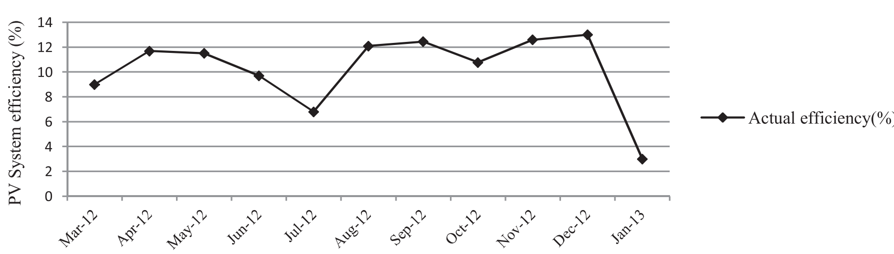



**Fig. 10.** PV system efficiency (%) based on actual amount of energy production.


**Fig. 11.** PV panels installed on the roof of One Brighton.

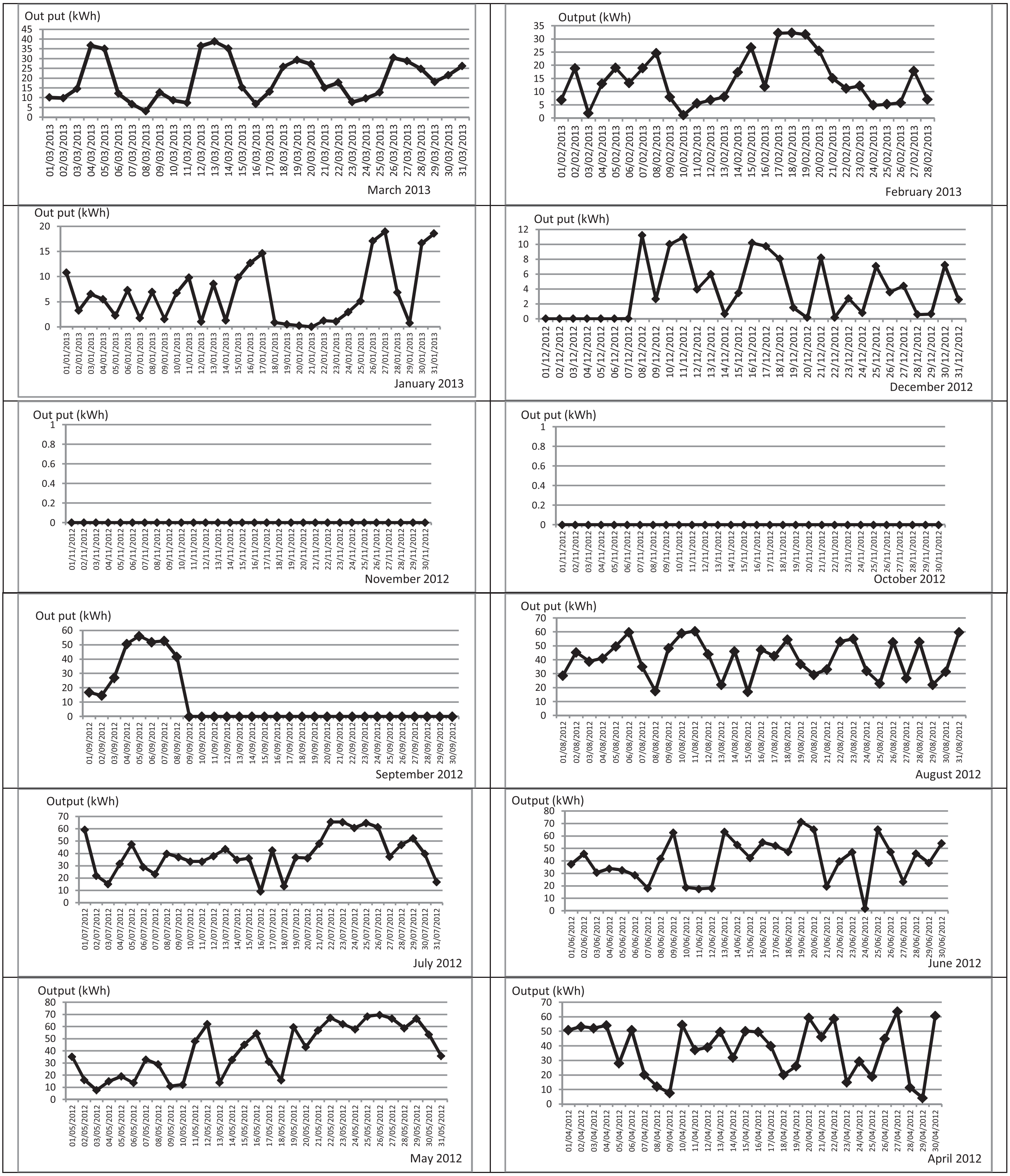



**Fig. 12.** PV system output, One Brighton Development, April 2012 to March 2013.

in the case study area. Moreover, over a period of one year there were instances of output close to zero because of high humidity (higher than 80%) and rainy conditions.

The effect of dust deposit on the PV panels was found to be small due to the regional weather and level of air pollution in Brighton, however, the performance was more affected by the local issue of bird droppings, which could cause hot spots on the panel resulting in drop of efficiency. This highlights the fact that laboratory based specifications or performance data are often inadequate to represent the actual operating conditions and the in-situ performance.

**Table 7**
Correlation coefficient between PV output and weather variables.

| Correlations | | PV Output (kWh) | Temperature (C) | Humidity (%) | Visibility (km) | Wind speed (km/h) | Precipitation (mm) | Weather event |
|---|---|---|---|---|---|---|---|---|
| PV output (kWh) | Pearson correlation | 1 | −.154 | −.255 | .084 | −.239 | −.149 | −.724* |
| | Sig. (2-tailed) | | .392 | .152 | .640 | .181 | .408 | .003 |
| | *N* | 33 | 33 | 33 | 33 | 33 | 33 | 14 |

* Correlation is significant at the 0.01 level (2-tailed).

In recent years, innovations have been applied to the glass coating of the PV panel to minimise the effect of weather conditions. Self-cleaning and hydrophilic coating are some of the commonly available methods, which should be considered for any new installations. However, the problem is not completely eliminated in particular for many existing PV systems installed in desert climates such as in the Middle East.

To address this problem, comprehensive studies on the issues of transmittance reduction due to weather conditions, including geographical issues such as bird droppings, are recommended. Such studies should encompass:

- Computer modelling and studies of environmental and climatic conditions, including pollution, precipitation, wind velocity, relative humidity, ambient temperature and other parameters, specific and relevant to the locality of the PV installation;
- Development of regional database of dust properties including dust type, chemical, biological, electrostatics characteristics, property, size, shape and weight;
- Methodology enabling accurate assessment of the annual performance of solar PV systems, taking into consideration any significant environmental, climatic and geographical factors currently excluded;
- Monitoring and evaluation of the effect of weather conditions on the performance of installed PV systems to establish a relational performance database for more reliable reference for prediction and validation.

This study has shown that there are significant discrepancies between the predicted and actual outputs from PV systems due to the lack of understanding and consideration of climatic parameters and their corresponding impact. With the expected escalation in the installation of solar PV systems in the UK, it is imperative to establish design methodology and database representative of the true performance that are essential for accurate financial and environmental evaluations.

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