Investigation of Soiling Effects on Solar Glass Covers in the Climate of Muscat, Oman

Andreas Jurack[1], Jasim Al Mamari[2], Sausan Al-Riyami[2,3], Jörn Scheuren[1], Rutger Schlatmann[1,3]

[1] University of Applied Sciences, Berlin (Germany)

[2] Institute of Advanced Technology Integration (IATI) / The Research Council (TRC), Muscat (Oman)

[3] Helmholtz-Centre, PVComB, Berlin (Germany)

Abstract

Soiling and the accumulation of dust on transparent covers of solar thermal collectors have a negative effect on their solar transmittance. This results in a lower optical performance and can reduce the thermal efficiency of a solar plant. The Sultanate of Oman recently tends to implement solar technologies as an option of renewable energy, but experiences and studies in this field are still limited. Previous studies around the globe have shown that the rate of accumulation of dust and soil and the corresponding efficiency loss is highly dependent on the location and climate and vary significantly. This study aims to quantify the loss in solar transmittance over time for the location of the Innovation Park Muscat and identify options to compensate them. For that aim, eight samples of transparent collector covers were exposed in different configurations to determine the impact of the soiling on the solar transmittance. Besides several lessons learned during field operation in a hot desert climate region, the results of the data analyses show that the solar transmittance is being reduced due to soiling by ~0.3 % to ~0.5 % per day and the effect is highly dependent on the weather.

Keywords: solar transmittance, transparent cover, soiling

Corresponding author: jasim.almamari@trc.gov.om

1. Introduction

Within an international collaborative in the Sultanate of Oman between the German Research Centre For Geosciences Potsdam (GFZ), the Technical University in Berlin (TUB), the Helmholtz Centre Berlin (HZB), the University of Applied Sciences Berlin (HTW) and KBB Kollektorbau GmbH (KBB) - a manufacturer for solar thermal collectors - a non-residential building shall be cooled with an absorption chiller and a solar thermal plant throughout the whole year. The operating power for the chiller will be supplied by a solar collector field with an area of 2500 m² to 3500 m² depending on the degree of autarky, storage size and solar fraction (Cordes et. al., 2018). Dust and soiling is influencing the optical characteristics of the solar collector field. It mainly effects the solar transmittance of the glass cover. Literature shows that the negative effects are highly dependent on the location and climate of the solar plant (Duffie and Beckman, 2013; Sarver et. al., 2013). Some areas like Boston, MA show a decrease of only a few percent over a year (Hottel and Woertz, 1942), whereas other regions, especially on the Arab peninsula, show rates of up to 50% within a few months (Al-Hassan and Ghoneim, 2005).

For the design of the solar plant, it is necessary to obtain knowledge on how fast the transmittance and thus the energy yield decreases at the specific location. Moreover, how a cleaning schedule has to be designed to secure the safe operation of the cooling plant throughout the whole year. A lessened yield because of dust and soiling has to be compensated by a rigid cleaning schedule or a bigger aperture area of the solar field. For the city of Muscat in the Sultanate of Oman, there is to this day no data for the decrease of transmittance available that could be used for the economical design of large-scale solar thermal plants. Yet there has been some studies with photovoltaic modules, which show a significant loss due to a single dust event, but no comprehensive investigation over a long term (Sarver et. al., 2013).

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Fig. 1: Overview of the experiment site with eight different transparent covers in their frame, four different PV glass samples and a weather station with temperature and humidity sensor, wind direction and wind velocity sensor

2. Location and Climate

The site is located in the Innovation Park Muscat (IPM) in the western stretches of the capital of the Sultanate of Oman on the northeast of the Arab Peninsula as it is shown in Fig. 2. The location lies between the Gulf of Oman and the Al Hajar Mountain range. It is noteworthy, that the biggest sand desert on earth, the Rub-al-Khali desert, stretches to the foothills of the Al Hajar, which leads to the common formation of dust storm. Even though during our observations there was no such event.

Muscat has an arid climate and is located in a desert region. There is very little precipitation in winter and virtually no precipitation in summer. Even though during our experiment there was an unusually high amount of days with rain. A situation that has a significant effect on the accumulation of dust. The winter temperatures are pleasant around 21° C. In the summer month, the temperatures might rise as high as 50° C. Additionally, the southwest monsoon is influencing the climate and brings wet currents, which lead to very high humidity. This makes the heat even more oppressive and dangerous. In addition, it leads to the formation of dew on night cold surfaces even in the hot summer month. The north coast of Oman is also influenced by the Shamal winds from northwest, which is dry and often transports dust from Jordan and Syria to Iraq and over the Gulf of Oman to the Gulf States including Oman (El-Baz and Makharita, 1994).

The combination of dew-wet surfaces like glass covers at night and several natural sources of sand and dust in the region will probably lead to a high rate of dust and soiling. Additionally, the part of Muscat where the IPM is located is constantly growing, which means there is a continuous construction activity in close proximity to the site. The growing city also has a high volume of traffic, which is also a source of fine dust. Despite the constant modernization process there is still livestock farming in the area with herds of goats, which regularly raise dust as they pass the site.

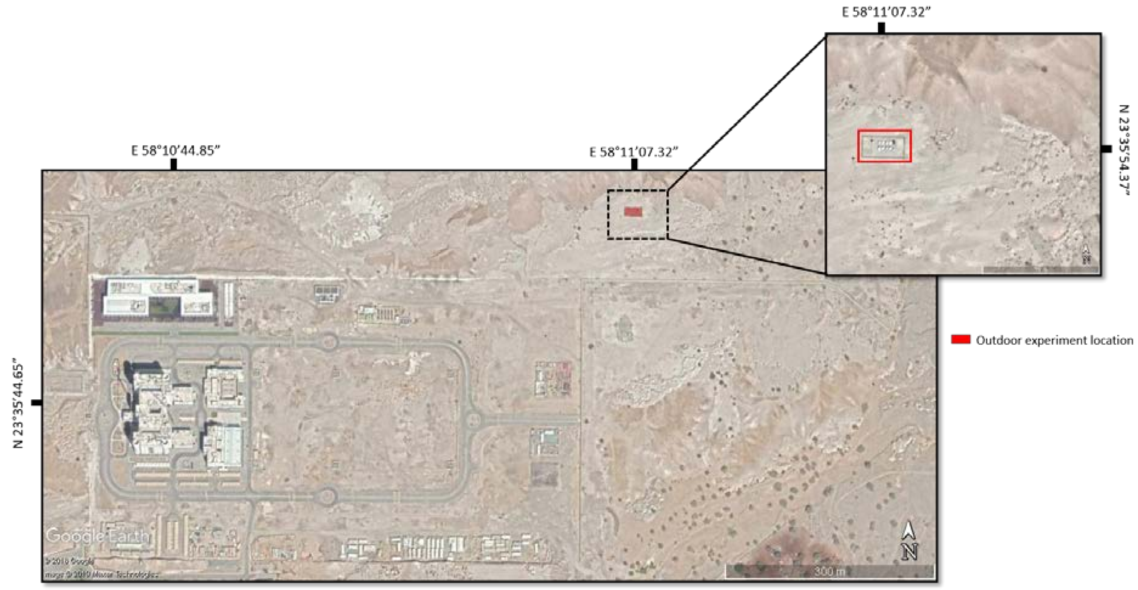

Fig. 2: Location of the experiment site at the Innovation Park Muscat [ref: Google Earth]

3. Experiment Design

For the investigation of the aforementioned topics, the following scientific questions have been incorporated in the studies objectives:

a) The change of the solar transmittance through soiling

The decrease of the collector efficiency in desert-like regions is expected to be mainly due to soiling on the glass, while the possible soiling of the absorber is expected to be negligible. Therefore, the focus of the investigation is on the solar transmittance of the transparent cover. In addition to the soiling, the transmittance might be also reduced due to a damaged glass surface and its coating, caused by sand storms or the cleaning process. By measuring the change of the solar transmittance of the covers, the main reasons for a decrease in the efficiency of solar thermal collectors can probably be determined.

b) The influence of the collector slope

The slope of the collector might also have an impact on the rate of accumulation of dust. It is possible, that an angle of 35° instead of 20° could lower the deposit of dust and thus the loss of efficiency caused through soiling. In this case the frequency of cleaning could be reduced. This effect will be investigated through the comparison of two identic samples with different slope angles.

c) The rate of soiling at different degrees of soiling

The sand and dust might behave different on a clean glass sample than on sample which is already covered with dust. This will be tested by cleaning one sample in a regular interval (e.g. monthly) and compare it with another identical sample which is only cleaned once a year.

d) The behavior and impact of different types of glazing

The surface of the glazing might have an impact on the soiling. A structured surface could support the deposit of dust and sand, while an even surface is easier to clean. The stress of sandstorms and the cleaning process could damage certain transparent covers more than others. To investigate this issue, samples with different transparent covers (structured, even, with and without anti-reflective coating).

e) Damage of the transparent cover

Sandstorms and the cleaning process, but also the high solar radiation and temperature could have an impact on the surface of the glazing. The exposed glass samples should be visually investigated and the solar transmission should be compared with unused samples after the experiment.

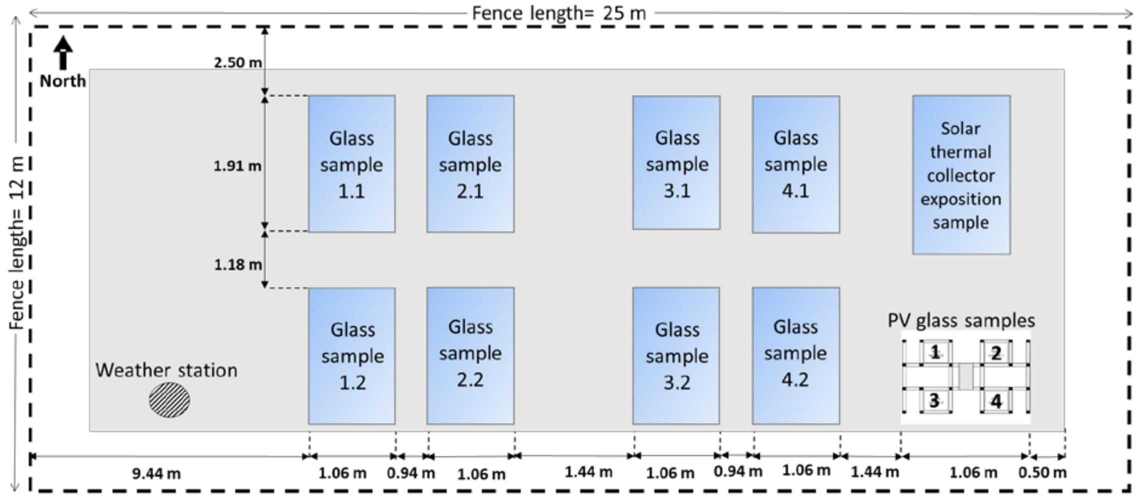

Figure 3 schematic view of the experiment site at IPM.

For that purpose KBB sponsored 8 glass covers for solar thermal collectors mounted on typical collector frames as it is shown in Fig 1. Figure 3 shows the setup of the experiment at IPM . The glass samples are being exposed in an area that has a concrete fundament and is surrounded by a fence. A weather station is also part of the setup and it contains sensor to measure temperature, humidity, wind speed and wind direction. The slope angles and general properties of the samples are listed in Tab. 1.

Tab. 1: overview of solar glass samples and their properties, the grey highlighted samples are included in the data analysis

Sample	slope	surface	coating	cleaning
1.1	20°	clear	none	yearly
1.2	35°	clear	none	yearly
2.1	20°	structured	none	yearly
2.2	20°	structured	none	monthly
3.1	20°	clear	Anti-reflective	yearly
3.2	20°	clear	Anti-reflective	monthly
4.1	20°	structured	Anti-reflective	yearly
4.2	20°	structured	Anti-reflective	monthly

4. Data acquisition

Since solar thermal applications use a broader spectrum of the electromagnetic radiation than photovoltaics (PV) the setup consists of two pyranometers CMP11 from Kipp&Zonen, which measure the global radiation in the spectrum from 285 nm to 2800 nm. A PV cell sensor could have simplified the measurement process, but would have also limited the spectrum that is measured. Both pyranometers are tested and calibrated. To ensure that both pyranometers are tilted correctly into the plane of the samples, they are mounted on an arm. This arm slides into a fixture construction on the side of each collector frame. That way it is ensured that both pyranometers are positioned correctly and in the same way in each measurement. The measurements are taken manually, since an automated solution was not applicable to the variety of samples and due to limited funding.

On a typical measurement day the first measurement is taken to determine the relative error between the two pieces of equipment. They are mounted onto the arm and positioned horizontally. The relative deviation between them is being logged and applied in the data analysis (see next chapter). Each glass sample has three positions for the arm that holds the pyranometers: the upper position a little bit above the middle of the glass as it is shown in Fig. 4, the middle position and the lower position is below the middle. The value for the solar transmittance for a specific glass samples is represented by the mean value of the three positions.

Fig. 4: the two pyranometers are mounted onto an arm that is held by a fixture construction to ensure that the measurements are always at the same position

Taking into account, that there are 8 glass samples with 3 positions each. Because water is a scarce resource in Oman, the regular cleaning was done dry. A soft cloth is used to wipe off dust and dirt by hand from top to bottom. To limit the physical stress for the person taking the measurement, the routine is shortened to only one position for each sample after Ramadan. During Ramadan the measurements are suspended.

To avoid being in the direct sun for too long during midday, the measurements start early in the morning. This results naturally in low positions of the sun - or high angle of incidences (AOI) in the plane of the glass samples. High AOI result in low incidence angle modifiers (IAM), because a significant part of the radiation is reflected or absorbed by the glass. Because of these effects, that where not foreseen during the experiment design process, the analysis had to be reduced to the samples that are measured at last in each measurement day: 3.1, 3.2, 4.1 and 4.2. The reduction made sure that the measurements were all taken under an AOI lower than 50°, resulting in an IAM of at least 0.9 for each sample, reducing the error.

5. Data Analyses

The global radiation which is measured under the glass sample is noted with G_{glas} The global radiation in plane of the glass sample, measured next to the glass sample, is noted with G_{ref} For each position the pyranometers are being exposed for 3 minutes, which results in around 450 single values for each position, that are used to calculate a mean value. Mean values are noted with an overline: $\bar{G}_{glas}$

Since the instruments are handled manually, there is always a small relative deviation between them. A correction factor k is determined with the first measurement of each day:

$$k = \frac{\bar{G}_{ref}}{\bar{G}_{glas}} \quad \text{(eq. 1)}$$

The next step in the analysis is to account for the angle of incidence by the calculation of the incidence angle modifier (IAM). Since we exposed only the glass covers with a frame, the Ambrosetti-equation is not applicable. For the calculation of the physical IAM the authors used the function physicaliam(), which is part of the PVLib library for Python (Holmgren and Hansen, 2013). It uses Fresnel's Law and Bouguer's Law to calculate the angle-dependent IAM factor $K_{\tau\alpha}$ (De Soto et. al., 2006). The physical properties of the glasses that were used are summarized in Tab. 2.

Tab. 2: Physical properties for the reduced set of solar samples. For the unstructured samples 3.1 and 3.2 the value are taken from (Wesselack et. al., 2017) and for the structured samples 4.1 and 4.2 the values are taken from test certificates (SPF, 2019) and information from KBB Kollektorbau GmbH

Sample	surface	coating	T	n	K	D
3.1 / 3.2	clear	anti-reflective	96 % ± 0.5 %	1.35	4	3.2 mm
4.1 / 4.2	structured	anti-reflective	96 % ± 0.5 %	1.35	4	3.2 mm

With the correction factor k and the the IAM factor $K_{\tau\alpha}$ the solar transmittance of each position i can be calculated by

$$\tau_{sol,i} = \frac{1}{k} \frac{1}{K_{\tau\alpha}} \frac{\bar{G}_{glas,i}}{\bar{G}_{ref,i}} \qquad \text{(eq. 2)}$$

The solar transmittance for one day and for one specific glass sample is the mean value of all the positions that were measured on that day: three position before Ramadan and only the middle position after Ramadan. All the measured and calculated values and the physical properties used in the calculation are prone to errors and uncertainties. The authors would like to highlight some of them:

- uncertainties in the physical properties:
  - the physical properties (Tab. 2) were not measured in a laboratory
  - they are only valid for clean glass. Dust and soil will most likely raise the refraction index and absorb a higher fraction of the solar radiation
  - the uncertainty is higher, the higher the AOI is
- error margin:
  - the lower the radiation, the higher the error in the measurements of G
  - the higher the angle of incidence, the higher the error in the IAM

6. Findings

6.1 Effects of dew on the accumulation of dust

Owing to high humidity in this region, dew is a common climate effect. At night, the temperature of the glass surface drops below the dew point, which leads to the formation of dew on the cold surface of the solar glass. This has two opposing effects on the accumulation of dust:

First, the dew-wet surface attracts dust particles, which are held at the surface through adhesion. Instead of just being blown over the surface, the dust is attracted by the water and accumulates over time. When the sun rises, the dew evaporates, leaving the accumulated dust on the surface. This effect has a negative influence, because it speeds up the accumulation of dust at night.

However, in some nights, the formation of dew is so strong, that water drops are forming on the glass. As Fig. 4 shows these drops will get bigger until they flow down the surface. On their way down the glass cover, they pick up dust and carry it down to the lower edge of the collector frame as it shown in Fig.5. This can be described as a self-cleaning process and has a positive influence on the transmittance.

Fig. 5: When dew is forming it can generate droplets that flow down the glass cover. This creates visible flow patterns

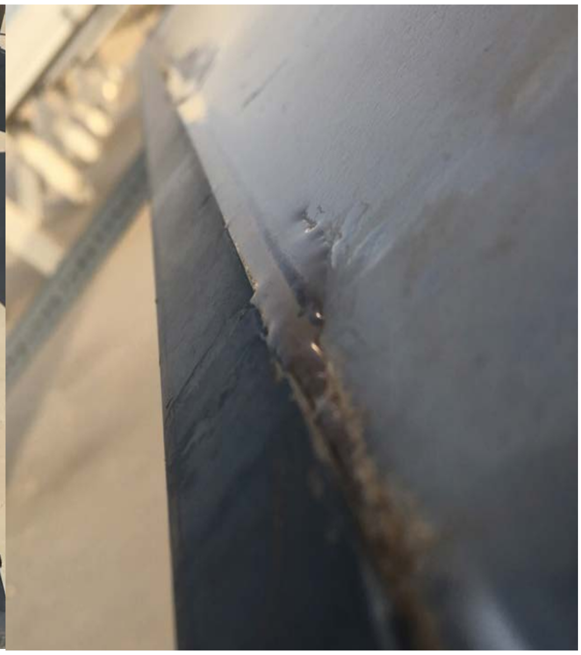

Fig.6: When dew flows down the glass surface it will reach the lower edge of the frame. Dust that has been picked up by the dew will accumulate there.

6.2 Effects of dust on the transmittance of glass covers

The experiment started with a thorough wet clean, using purified water: this is marked with (1) in Fig 7. The corresponding values are summed up in Tab 3. The first measurement of the clean glass covers shows the values that the manufacturer promotes (compare with Tab 2). This ensured that the method we chose is suitable to evaluate the changes in transmittance. Within the first few weeks of exposure the glass samples start to accumulate dust and dirt and the transmittance is being reduced. After 38 days of exposure the samples 3.2 and 4.2 were dry cleaned with a cloth ("(2) - dry"). The solar transmittance from the wet clean could not be fully recovered. Instead the samples lost 1.45 % (3.2) and 1.39 % (4.2) compared to a wet clean.

Unusual for the location and the time of year, there were a couple of rain days. They are marked with a black diamond in Fig. 7. The first heavy rain event was between April, 11th and April, 14th with 4 consecutive days with rain, which cleaned the samples very effectively. The second heavy rain event was during Ramadan on May, 19th and May, 20th. There is no measurement data for that event, but an on-site observation of the samples suggested, that all of them where cleaned after the two days with rain, restoring the transmittance like the first event in April.

Within the 3 month (89 days) after the first dry clean, the experiment was continued and the solar transmittance of the glasses decreased continuously. During Ramadan no measurements were taken. Over the whole period between the two cleanings the glass cover 3.1 lost 16.8 % or 0.19 % per day in solar transmittance. The structured sample 4.1 lost only 13.81 % or 0.16 % per day. This is a very conservative statement, since we know that the samples were cleaned due to heavy rain during Ramadan. If we assume that the rain was effective in cleaning the glass and restoring the transmittance we get a different result: The samples 3.1 and 4.1 lost 33 % of their transmittance in a period of 77 days (from the rain to the last measurement on August, 5th). This is an average rate of loss of transmittance of 0.42 % per day. And it is even worse in the period between the first dry clean and the last measurement before Ramadan: The samples lost 7.5 % of their transmittance within 14 days – a rate of loss of transmittance of 0.53 % per day.

The samples that were dry cleaned again on July, 8th lost a significant amount of solar transmittance compared to a thorough wet clean: the clear glass sample 3.2 lost 4.46 % compared to day 1. The structured sample 4.2 lost 2 % compared to a wet clean.

Overall it is apparent that the clear, unstructured glass samples perform worse that the structured glass covers. That could have several reasons. The covers are still on site, so these reasons are only possibilities and have not been validated:

- dust is accumulating faster on the clear glass
- the surface of the structured glass is bigger, so it transmits a larger fraction of the radiation while accumulating the same amount of dust
- the structured surface might capture more diffuse light due to its bigger surface

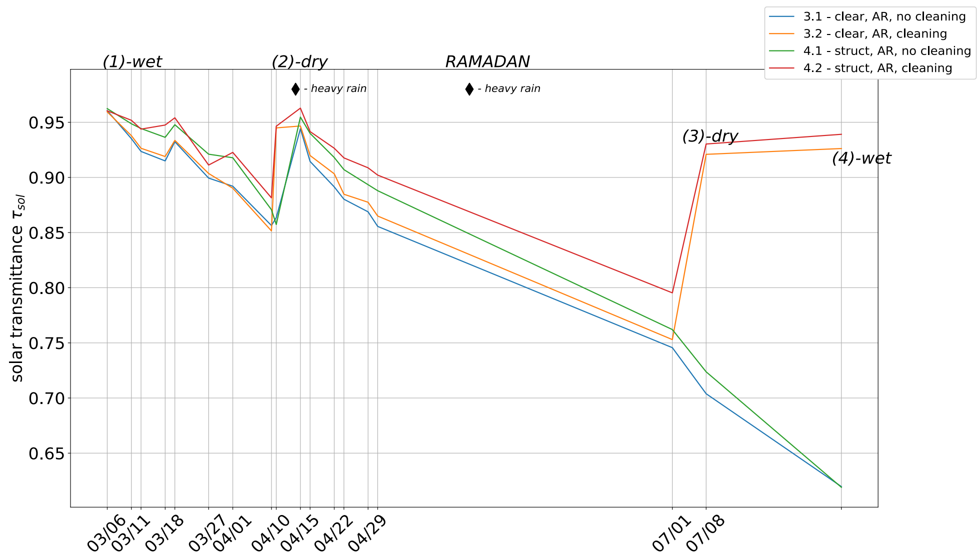

Fig. 6: Solar transmittance of the four samples with AR coating and different surface structures over time. The experiment started in March with a wet clean (1). The samples were then cleaned 3 times. 2 times with a dry cleaning method (2), (3) and ended with another wet clean (4). Two heavy rain events marked with a diamond had a strong cleaning effect.

Tab. 3: overview of the solar transmittance on the days of cleaning. The values for cleaned samples (3.2, 4.2) are given in pairs: (before clean) / (after clean)

Sample	(1) wet clean	(2) dry clean	(3) dry clean	(4) wet clean
3.1	96.06 %	85.64 % / -	74.57 % / -	61.97 % / -
3.2	95.94 %	85.15 % / 94.49 %	75.30 % / 92.09 %	86.40 % / 92.62 %
4.1	96.24 %	87.07 % / -	76.20 % / -	61.91 % / -
4.2	96.04 %	88.15 % / 94.64 %	79.53 % / 93.03 %	85.18 % / 93.91 %

7. Summary

The solar transmittance of the exposed transparent glass covers has been reduced by ~10 % in one month and ~15 % in the next 3 months. We could see, that the effect is highly dependent on the weather and during our experiment we saw unusually often rain events, which cleaned off some of the dust having a positive effect on the transmittance. It is also expected that dust storms will have a significant negative effect, but none could be observed. This means that the measured loss in transmittance is on the lower end of what is possible in this region.

The dry cleaning method that was used did not fully recover the original transmittance of the solar glasses. The loss after one month without cleaning is ~1 % and after 2 month without cleaning ~4 % for the clear glass and 2 % for the structured glass after dry cleaning. It is noteworthy that a strong rain event is as effective in restoring the transmittance as the dry cleaning method being used in this experiment.

In general the negative effect of the accumulation of dust is stronger for the clear glass than for the structured glass. Thus, the authors recommend using the structured glass for the investigated location. The loss in transmittance due to a dry cleaning regime has to be compensated with a larger collector area to still meet the energy demand for the specific cooling project. Alternatively, the authors advise a wet clean regime or an improved dry cleaning technique.

The next phase of the experiment has to show which solution is economically most efficient. The data for the exposed PV glass samples will be published separately in the near future. The whole experiment will continue to clarify some of the stated research objectives, which could not be included in this paper.

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