IMPACT OF SOILING ON TRANSPARENCY OF DIFFERENT GLASS TYPES: A COMPARATIVE STUDY

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To improve the optical properties of photovoltaic (PV) modules, many manufacturers use new glass surface structures that reduce glare. However, these modifications can increase susceptibility to soiling. This research presents a new method for assessing soiling by positioning glasses without solar cells on a reference PV module. With this method, the soiling of the glasses can be measured without the systematic measurement uncertainties from the power or irradiance measurement negatively affecting the measurement accuracy. To demonstrate the method, five glass types are tested at four tilt angles at three locations. In this paper, the preliminary results are presented together with the soiling data after two months at a selected site.

1 INTRODUCTION

Photovoltaic (PV) modules are a widely utilised method for converting solar energy into electricity, making solar energy a highly promising renewable energy source. However, the accumulation of dust and other pollutants on the surface of the glass is a major challenge for PV systems. This accumulation significantly reduces the transmissivity of the glass cover, resulting in a decrease in the amount of solar irradiation received by the solar cells. As a result, the power production performance of the solar PV modules is degraded, reducing their efficiency. Large differences in soiling effects are reported depending on the type of system and location. In some regions, depending on the local environmental conditions and the design of the PV module, this soiling can cause energy losses of up to 8.41% in its peak power output compared to a cleaned module [1]. This problem is particularly prevalent in dusty countries, where weather conditions can negatively affect the productivity of photovoltaic cells [2]. In desert areas, where airborne dust is prevalent, the productivity of PV modules is further reduced, despite their high irradiation and ample space for construction [1].

Several previous studies have investigated the effects of soiling on solar panels and the optimisation of solar panel performance in different environments. For example, the study conducted by Hassan Z. Al Garni [3] examined the impact of soiling on solar photovoltaic (PV) performance in Saudi Arabia. The study evaluated the performance of solar PV systems under soiling in different regions of Saudi Arabia, finding that PV performance can be reduced by 2% to 50%, and even up to 20% during a single sandstorm. The study highlighted several mitigation techniques, including regular cleaning, the use of bi-facial PV solar panels with solar trackers, and robotic cleaning systems. The study also characterised the size and composition of dust particles in different locations in Saudi Arabia and concluded that dust accumulation and cleaning costs are not significant barriers to large-scale, cost-effective solar PV deployments in Saudi Arabia, particularly in the central region.

Ramadan J. Mustafa et al [4] conducted a study to examine the impact of four environmental factors (dust accumulation, water droplets, birds' droppings, and partial shading) on the performance of photovoltaic (PV) systems. This is the first study to investigate all four factors simultaneously. The study found that water droplets had a positive impact on PV performance, reducing the temperature of the PV panel and improving power output by at least 5.6%. On the other hand, dust accumulation reduced power output by 8.80% and efficiency by 11.86%. The study highlights the importance of considering all environmental factors that can impact PV performance when designing and operating PV systems.

J.K. Kaldellis et al [5] conducted a study on the effect of air pollution on the performance of photovoltaic (PV) panels. They analysed the impact of three representative air pollutants - red soil, limestone, and carbonaceous fly-ash particles - on the energy performance of PV installations. They found that the deposition of solid particles on PV panels due to atmospheric air pollution resulted in a considerable reduction in PV energy performance, with the extent of reduction being dependent on the particles' composition and source. The study developed a theoretical model to predict the impact of regional air pollution on PV performance, which was validated using experimental results obtained in an urban environment with aggravated air pollution. The findings of this study highlight the need to consider air pollution as a factor that affects the performance and maintenance of PV systems, especially in urban areas.

Bouchra Laarabi et al [6] conducted a study on the characterisation of soiling on glass samples exposed to real conditions in the Rabat-Sale-Kenitra region in Morocco. The study found that soiling is a localised phenomenon, with deposition densities ranging from 0.37 g/m2/month to 2.86 g/m2/month. The effect of soiling on glass transmittance showed a reduction in the range of 1.05%/month to 10.04%/month, depending on the tilt angle and exposure period. There is a positive and linear correlation between the mass density of the deposit and the loss of transmittance, which is influenced by the period and location of exposure. The type of dust may also affect the degree of transmittance reduction. The particle size distribution was found to be prevailing in the range of 3-14 µm, with most particles having a regular shape. The study also observed enhanced cementation on the samples located near the ocean due to the presence of salt crystals on the surface.

The contemporary realm of photovoltaic research underscores a pressing imperative to delve deeper into the ramifications of soiling on solar panels across a spectrum of environmental paradigms, and more pertinently, the interplay between glass surface attributes and soiling dynamics. In the quest to optimise optical characteristics for Building Integrated PV (BIPV) and concurrently mitigate glare-associated challenges, numerous manufacturers are pioneering innovative glass surface architectures. However, the effects of these changes on soiling, particularly the accumulation of dust an on the glass facades and roofs, are still insufficiently understood.

To fill this gap, the present study aims to investigate the relationship between glass surface properties and the propensity for particle accumulation on PV modules. A series of five different glass variants have been positioned at different tilt angles in three different locations.

Subsequent evaluations include a assessment of the effectiveness of the PV glass, measured using a mini-module to assess glass transmittance. In soiling research, where two sites are located next to each other, it is common for researchers to name geographically distinct sites, each symbolic of unique climatic peculiarities [[7], [8], [9]].

2 OBJECTIVE

The results of the study are aimed in particular at specialists and companies who want to use new glass on photovoltaic modules and would like to know more about their tendency to soil. Two goals are set in the study:

1. A measurement procedure is to be developed, set up and tested with which the soiling of different types of glass can be tested under various conditions.
2. The first results shall quantify how much the tilt angle and the glass surface of a PV module influences the soiling.

The second objective is to be investigated on a larger scale in a later publication. This document only deals with the measurement system and first results as a proof of concept.

3 METHODOLOGY

3.1 Basic concept

The study process follows the following steps:

1. The transmission of all glass samples is initially measured (clean glasses)
2. The glasses are installed in different locations, inclinations and weathered.
3. The transmission is measured again periodically.
4. The degree of soiling (power reduction) is measured in percent from the loss of transmission.

The disadvantage of this concept is that the energy yield, which is proportional to the integral of soiling over time, cannot be determined. For this purpose, the decrease in transmission can be determined more precisely and attributed to the soiling with little error tolerance. Especially in the case of differently oriented glasses, it would not be possible to make an exact statement about soiling solely by monitoring the energy yield.

3.2 Transmission measurement

The measurement of irradiance (W/m^2) and irradiation (kWh/ m^2) is associated with large uncertainties even with high-quality measuring instruments. Similarly, the reduced yield or reduced power of a PV module cannot be clearly assigned to a cause using simple measurement and interpretation methods. For this reason, only relative measurements are used in this paper. A single PV mini-module is used as a sensor, which is covered with a cleaned reference glass for each measurement location and then operated for a short time (approx. 15 minutes) under stable and constant irradiation and temperature conditions. Thereby, spectral shifts due to weather conditions might influence the result, but the influence is proportional to the expected energy yield of a real PV module.

Between each individual power measurement of the mini-module with a glass sample, the power measurement of the mini-module with the reference glass is repeated. Thus, 7 x 4 + 1 = 29 reference measurements are obtained per measurement session. The irradiation-corrected variation of these basically identical measurements is considered as stochastic measurement error (measurement noise).

3.3 Preparation of measurements

In order to obtain measurement results that are as precise as possible, the following points are taken into account:

- The glass samples are aligned perpendicularly to the solar radiation for the measurement
- Measurements are only carried out with an irradiation of at least 900 W/m2.
- Measurements are only taken when the sky is cloudless.
- Measurements are only taken into account if the solar irradiation does not vary by more than +/- 20 W/m^2 during the entire measurement.
- The reference glass is cleaned on the front side before each measurement campaign. The back side is not cleaned or is cleaned as well for all sample glasses.

3.4 Initial measurements

Before installing the glass samples, initial transmission measurements are carried out on the glasses. The subsequent soiling of the glass is determined based on these initial measurements.

To determine the transmission of a given glass sample S1 relative to the transmission of a reference glass Ref1, the following initial measurements are carried out:

- the power $P_{Ref1}(t-1)$ of the mini-module covered with the reference glass Ref1 are measured.
- The power $P_{S1}(t)$ of the mini-module covered with sample S1 are measured.
- The power $P_{Ref1}(t+1)$ of the mini-module covered with the reference glass Ref1 are measured again.

Where t denotes the time step or the number of measurements done.

Subsequently, the weighted mean value of the reference measurement is determined in order to compensate for any changes in irradiation between measurement 1 and measurement 2:

$$P_{Ref1}(t) = \left(\frac{1}{\Delta t_1} P_{Ref1}(t-1) + \frac{1}{\Delta t_2} P_{Ref1}(t+1)\right) \cdot \frac{1}{\frac{1}{\Delta t_1}+\frac{1}{\Delta t_2}}$$

Δt_1 and Δt_2 are the time difference between the $P_{Ref1}(t-1)$ and $P_{Ref1}(t+1)$ respectively and the $P_{S1}(t)$ measurement. They are used as weighting factors to take into account the fact that the reference measurement that is made closer in time to the sample measurement is closer to the conditions under which $P_{S1}(t)$ is measured. This means that changing irradiation conditions can be partially compensated for.

The relative transmission of the glass sample is then calculated as follows:

$$T_{S1}(t) = P_{S1}(t) \,/ P_{Ref1}(t)$$

With this measurement procedure, the relative transmission before installation compared to the reference glass is determined for each glass sample. For future soiling measurements, these transmission values will be used for comparison.

Because all 7x4 = 28 glass samples are measured directly one after the other, all reference measurements can be used for the glass sample measured immediately before as well as for the glass sample measured immediately after.

3.5 Soiling measurements

The procedure for measuring soiling is identical to the initial measurements. The only difference is that the reference glass Ref1 is cleaned before the measurements start. Because the reference glass is weathered like all other glass, any changes in the glass (e.g. turbidity) are not erroneously evaluated as soiling, but are compensated for with the help of the relative measurements.

By comparing the transmission of the samples measured in the soiling measurement with the initial transmission measurements $T_{S1}(t)$, the extent of soiling on each glass sample can be determined. The difference between the initial transmission values and the soiling measurements indicates the level of soiling caused by soiling on the glass samples.

3.6 Soiling calculation

Based on the measurements, the degree of soiling of the glass samples S_{S1} can be determined.

$$S_{S1} = 1 - T_{S1,soiled} / T_{S1,initial}$$

3.7 Estimation of measurement error

The uncertainty of the relative transmission ΔT_s is estimated by the standard deviation of repeated measurements of an identical glass. For this purpose, the reference glass $Ref1$ is used, since the most measurements are available for this glass. T_{ref}(t) is determined as:

$$T_{ref1}(\mathrm{t}) = \mathrm{P}_{ref1}(\mathrm{t})/\mathrm{P}'_{ref1}(\mathrm{t})$$

where P'_{ref1}(t) is the time-weighted average of $P_{ref1}(t-2)$ and $P_{ref1}(t+2)$. The difference of four-time steps ($t-2$ to $t+2$) is since the measurements in between $P_s(t-1)$ and $P_s(t+1)$ are sample measurements and not reference measurements. Due to the larger time intervals, it can be assumed that this procedure leads to a conservative estimation of the uncertainty.

A disadvantage of this error estimation is that it cannot be assumed that the obtained T_{ref1} values are normal distributed, since T_{ref1} is not a measured value but a calculated value. To be able to estimate to what extent T_{ref1} is normal distributed, the distribution is visualised in a QQ plot Figure 4.

The uncertainty of soiling ΔS_{s1} is calculated based on the Gaussian error propagation:

$$\begin{aligned}
&\Delta S_{s1}^2 \\
&= \frac{\partial S_{s1}(T_{s1,\mathrm{soiled}}, T_{s1,\mathrm{initial}})}{\partial T_{s1,\mathrm{soiled}}}^2 \Delta T_{s1,\mathrm{soiled}}^2 \\
&+ \frac{\partial S_{s}(T_{s1,\mathrm{soiled}}, T_{s1,\mathrm{initial}})}{\partial T_{s1,\mathrm{initial}}}^2 \Delta T_{s1,\mathrm{initial}}^2 \\
&= \left(-\frac{1}{T_{\mathrm{S1,initial}}}\right)^2 \Delta T_{s1,\mathrm{soiled}}^2 + \left(\frac{T_{\mathrm{S1,soiled}}}{T_{\mathrm{s1,initial}}^2}\right)^2 \Delta T_{s1,\mathrm{initial}}^2
\end{aligned}$$

This error propagation calculation is used to compute the error bars of the soiling losses in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

3.8 Used glass samples

In this study, a total of five glass types or glass surfaces are to be examined. Table I shows the different glass types.

Table I: Glass types used

Glass type (Abbreviation)	**Description**
Standard Solar Glass (SSG1, SSG2, SSG3)	Standard solar glass is used in most PV modules. The reflection has some beam spread. The glass is highly transparent and has a relatively smooth surface. For reference and comparison reasons, 3 samples of this glass type are used.
Reference Glass (Ref1)	The reference glass is a SSG which is cleaned before each measurement session.
Float Glass (FG)	Float glass looks like window glass. The surface is perfectly flat. The reflection does not show any beam spread.
Satinated Glass (SatG)	This glass has a matt surface that strongly diffuses the reflected light. It is used especially in BIPV to achieve a matt surface.
Sandblasted Glass (SBG1, SBG2)	Float glass was sandblasted with two different grain types (glass pearls and Korund Biloxit) in the PV laboratory of the BFH. The surface of the glass is roughened and becomes matt.
Coated Glass (CG)	In this work, glass with a special anti-glare coating is to be used. However, at the time of going to press, the coated glass could not yet be installed.

While sandblasted glass is hardly used in practice, the use of standard solar glass, float glass and satinated glass in particular is common today. Figure 1 shows four example modules with similar glass as used in the study.

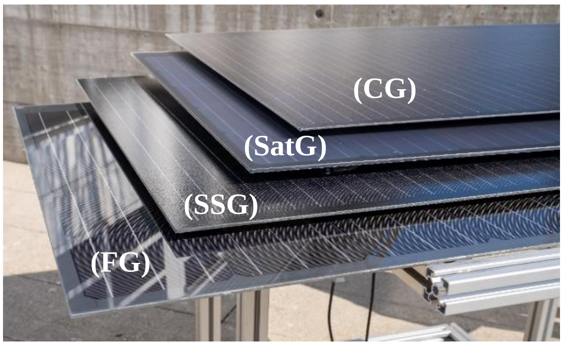

Figure 1: Examples of PV modules using similar glass

3.9 Mounting system

The glass samples used in the study were mounted on a specially designed fixture that ensured that the samples were tilted at the optimal angles of 1.5°, 10°, 30° and 75° for the tests. The mounting structure also prevented water from flowing from one glass sample to the other, which could potentially lead to additional cleaning of the lower glass samples.

To ensure the stability of the fixture and reliable results throughout the testing process, the fixture was installed on a stable foundation that consisted of either garden slabs or concrete slabs, depending on the location. This foundation provided a secure base for the experiment and prevented potential disturbances that could affect the testing process.

Figure 2 shows the planned setup of the glass samples mounted on the specially designed structure and illustrates how the structure was installed to maintain the angle of inclination and prevent water from flowing between the samples. These measures were taken to ensure the accuracy of the study results and minimise potential errors that could result from unstable or improperly mounted samples. Figure 3 shows the first installation made in Hindelbank.

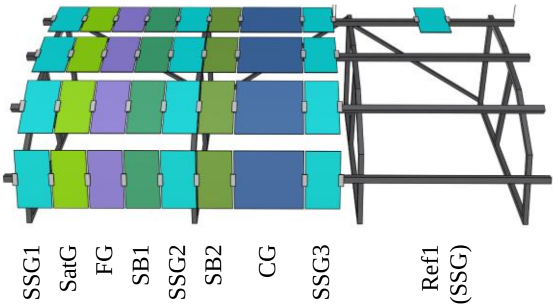

Figure 2: Mounting structure design

Figure 3: Test bench installed in Hindelbank

3.10 Locations

The installations are made at three different locations in Switzerland. In Table II, the different locations are described and classified.

Table II: Locations for the test bench installation

Location	Description
Burgdorf, Gsteig	Burgdorf is a small town in a rural setting. The test stand is located at around 570 m above sea level on the flat roof of a building belonging to the Bern University of Applied Sciences. The soiling level is estimated to be rather low. 
Hindelbank	The test stand is installed at 540 m above sea level on a farm in a rural area. The soiling level is very high due to the farming operation. 
Thun, Gwatt	The test stand is installed on an industrial building at 580 m above sea level in Thun. The soiling level is considered to be low. 

4 RESULTS

4.1 Uncertainty

The measurement uncertainty is determined by examining the deviation between measurements of the identical glass Ref1. Figure 4 shows the QQ plot for the initial measurements and the first soiling measurements in Hindelbank.

It can be seen from the QQ plots that the calculated deviations largely follow a standard normal distribution. However, very large and very small deviations are no longer exactly in the expected normally distributed range. Also, the measurement error for the soiling measurements in Hindelbank are larger than the measurement errors for the initial values.

From this it can be deduced that the error calculation is fundamentally correct for most values, but for large and small measurement values, calculated soiling becomes inaccurate. In particular, the outlier in Figure 7 cannot be explained by the calculated and shown error range. For illustration purposes, the individual calculated values are also listed in Figure 5.

The measurement uncertainty calculated on the basis of the values shown in the QQ plots are shown in Table III. The large difference in measurement uncertainty between the two measurements can be explained by the less constant weather conditions in Hindelbank.

Table III: Measurement uncertainty

Measurements	Measurement uncertainty
All initial measurements, all sites	σ = 0.00269 2σ =0.005392
Soiling measurements, Hindelbank only	σ = 0.00864 2σ =0.01728

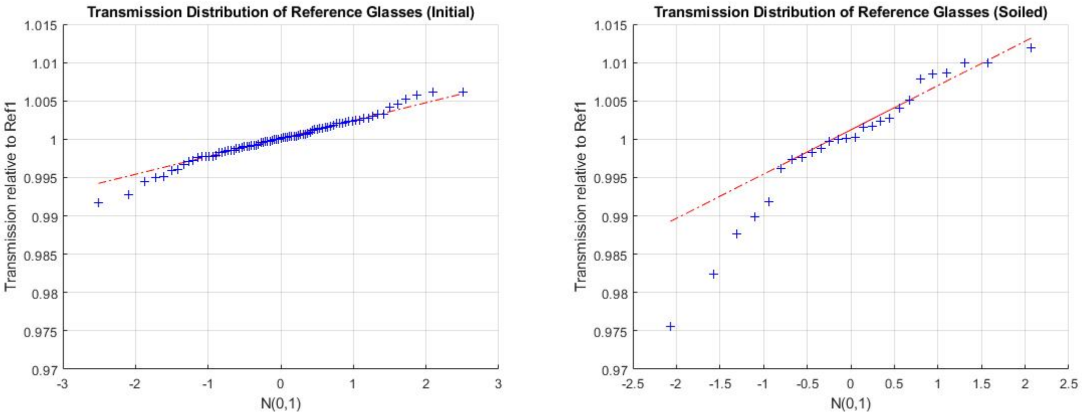

Figure 4: QQ plots for initial measurements (left) and soiling measurements in Hindelbank (right).

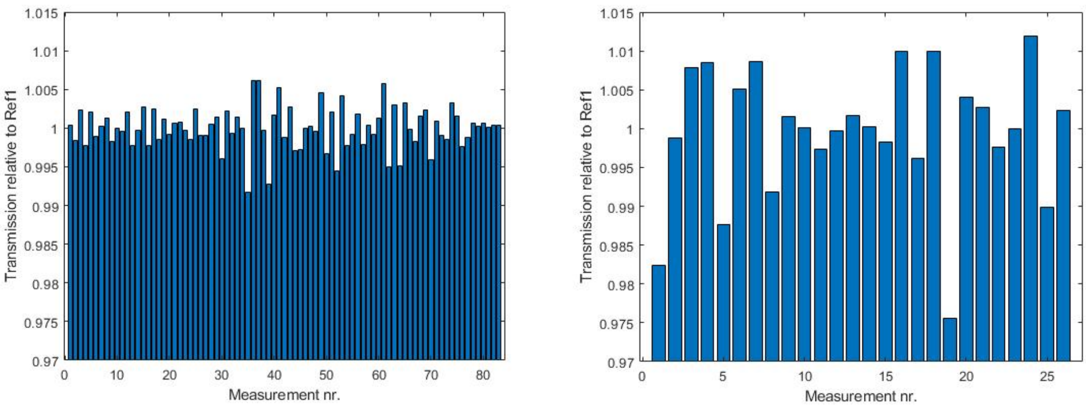

Figure 5: Calculated transmission values of the first measurements (left) and the first measurements in Hindelbank (right). The baseline values include the reference module measurements from all three locations, whereas the Hindelbank measurements only include the measurements from the glasses installed in Hindelbank.

4.2 Initial measurements

The initial measurements show the differences in the transmission of the tested glasses when new (Figure 6 and Table IV). The specified range refers to the spread of the measured values. The measurement uncertainty can be stated as 2σ =0.005392 according to Table III. The following findings can be made

- The standard solar glass SSG has the highest transmission when new. The SSG is given as a reference lens with a value of 1.0.
- The frosted SatG glass is just behind the reference glass with a transmission of 0.978. The variation between the frosted glasses is small.
- The float glass FG has an even lower transmission of 0.949.
- The transmission of the sandblasted glasses is significantly lower than that of the other glasses at 0.876 and 0.855. In addition, the dispersion between the individual sandblasted glasses is two to four times as high as the dispersion of the reference glass.

Table IV: Initial relative transmission measurement results (measurement precision: 2σ =0.005392)

Glass type	Transmission relative to SSG
SSG	1.000 ± 0.005
SatG	0.978 ± 0.007
FG	0.949 ± 0.008
SB1	0.876 ± 0.014
SB2	0.855 ± 0.024

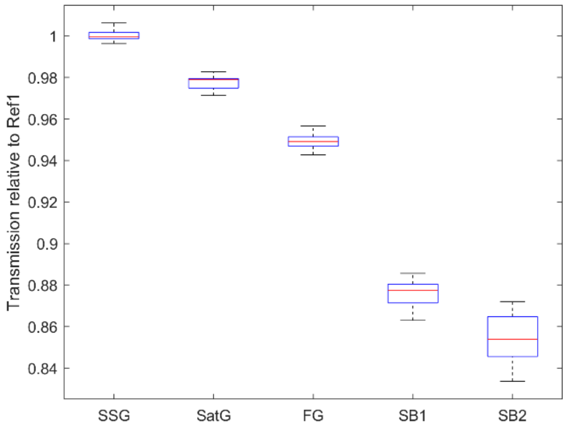

Figure 6: Initial relative transmission measurement results (measurement precision: 2σ =0.005392, not indicated in the box plot).

4.3 Soiling measurements

The aim of this project is to carry out regular soiling measurements at all three locations. The results presented here refer only to the first, initial soiling measurements at the Hindelbank site. Because the soiling pressure is very high due to the agricultural operation, soiling levels of up to 6% can be measured after around two months of exposure.

Figure 7 and Table VI show the results of the soiling measurements. Table V summarises all values of a specific inclination angle. The value at 1.5° inclination of the SSG3 glass was not taken into account because it is an outlier that arose due to a measurement error. Table VI shows the average soiling across all angles of inclination for each glass type.

The following observations can be made:

- The steeper the glasses are installed, the less soiling there is.
- The differences are particularly high between standard solar glass and frosted glass.
- Sandblasted glass, but also float glass, shows less dependence on the angle of inclination when it comes to soiling than other glasses.
- The error range is large relative to the soiling. There is therefore hardly any trend to be identified, particularly for float glass and sandblasted glasses.

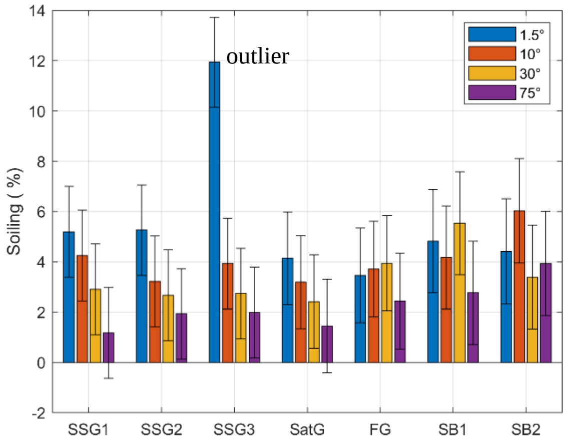

Figure 7: Soiling measurements in Hindelbank (measurement precision of transmission measurements: 2σ =0.0185—0.0209, calculated for the soiling ratio and indicated in the error bars)

Table V: Soiling measurements in Hindelbank by tilt angle (measurement precision: 2σ =0.01728)

Tilt angle	Mean soiling (%)
1.5°	4.55 ± 0.78 (without SSG3,)
10°	4.08 ± 0.72
30°	3.37± 0.72
75°	2.24 ± 0.72

Table VI: Soiling measurements in Hindelbank by glass type (measurement precision: 2σ =0.01728)

Glass type	Mean soiling (%)
SSG	3.37 ± 0.55 (without SSG3, 1.5°)
SatG	2.80 ± 0.93
FG	3.39 ± 0.95
SB1	4.33 ±1.02
SB2	4.44 ± 1.04

The errors shown in Table V and Table VI is calculated using the Gaussian error propagation.

5 CONCLUSION

In this study, a method for the systematic evaluation of the soiling tendency of different solar glass types was presented and demonstrated. Although the method is based on relative measurements, it should be noted that the measurement uncertainties, which range from 1.85 % to 2.09 %, exceed the soiling values in some cases. Despite this limitation, the data show a clear trend. In particular, it was found that after two months of soiling, glasses with a strong tilt accumulate up to three times less dirt than glasses with a slight tilt. This effect is more pronounced for glasses with a smooth surface than for those with a matt surface. For glasses with a matt surface, the soiling tendency seems to be less influenced by the inclination angle and corresponds more to the soiling behaviour of glasses with a less smooth surface.

6 OUTLOOK

This project is scheduled to continue in 2024. The focus is then on repeatedly measuring the degree of soiling of the glasses. The preliminary results shown here should be validated and generalised.

7 ACKNOWLEDGEMENT

This publication was written as part of the AURORA project funded by Innosuisse and with the support of the Swiss Government Excellence Scholarships program ESKAS. The authors thank you for the support.

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