D6.1: Report on the environmental data with influence on performance of STE plants

WP 6: International Cooperation Activities

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1 Introduction

In order to perform a reasonable yield analysis for concentrating solar power (CSP) plants, it is of crucial importance to determine all the relevant parameters that are affecting the electrical energy generation. The effects of the environmental conditions in a desertic climate on the long-time efficiency of CSP components are not yet determined. Especially the high aeolian dust concentration is oftentimes of concern. On the one hand, it causes solar radiation extinction in the atmosphere due to scattering and absorption on aerosol particles. On the other hand, soiling is caused when aerosol particles settle on optical components like reflectors or absorber tubes for parabolic trough applications. A third effect is the mechanical damage caused by high energetic impacts of aerosol particles during sandstorm conditions. In order to better assess the three processes it is inevitable to conduct field experiments at representative sites.

2 Meteorological Stations

The five meteorological stations are well distributed over the Moroccan country (see Figure 1). They are situated in Oujda, Missour, Erfoud, Zagora and Tan-Tan and by that they are covering different representative environmental conditions from coastal to desertic. All stations have been equipped with temperature, relative humidity and pressure sensors. Wind speed and direction is measured at 10 m height. The basic meteorological data together with the exact location can be seen in Table 1. Furthermore irradiance is measured using a solar tracker equipped with pyrheliometers for direct normal irradiance (DNI), pyranometers for diffuse and global horizontal irradiance (DHI and GHI). In Erfoud and Zagora Rotating Shadowband Irradiometers (RSI) are used to derive GHI, DHI and DNI. Data is retrieved as 1 min and 10 min averages automatically at least daily and a quality control is applied.

Figure 1. Overview of the meteorological station network in Morocco.

Table 1: List of meteorological stations in Morocco with annual (Jan 2016 to Jan 2017) mean values. *data gap from 12.Jan-26.Jan and 5.Feb-20.Mar. **data gap from 1.Jun-6.Jun. ***total data gaps of around 46 days missing in the second half of the year. Irradiation data are taken from [1]

Site	Altitude	Lat. [°N]	Lon. [°E]	DNI [kWh/m²]	GHI [kWh/m²]	Temp. [°C]	Rel.Hum. [%]	Wind speed [m/s]
Oujda	617	34.650	-1.900	2048	1928	17.9	59	2.0
Missour*	1107	32.860	-4.107	2307	2070	19.9	47	3.4
Erfoud	859	31.491	-4.218	2229	2049	22.3	33	3.0
Zagora**	783	30.272	-5.852	2328	2172	23.6	26	3.5
Tan-Tan***	75	28.498	-11.32	1497	1872	18.8	81	4.4

The meteorological stations were also used for soiling and aging experiments of representative CSP materials. Furthermore soil investigations have been carried out in order to perform a more advanced site description. Also aeolian dust samples have been taken by various instruments and in-situ airborn dust concentration values are obtained in Zagora, Oujda and Missour.

It shall be pointed out that the installation and maintenance of the instruments used at the various sites wouldn't have been possible without the close collaboration of the partners DLR (Germany), IRESEN, University Oujda, MASEN and others (all Morocco). At every time there has been a strong and fruitful exchange about the possibilities of overcoming the physical and political boarders. When scientists from DLR travelled to the meteorological stations they have always been accompanied by scientific staff from the university of Oujda or IRESEN. During these joint station visits a lot of scientific knowledge was exchanged, but also personal relationships could be formed which significantly enhanced the quality of further collaboration. In 2016 DLR staff accepted the invitation to the Green Energy Park in Ben Guerir from IRESEN and got to know the facility plus a big part of the IRESEN group working there. Secondary projects after the STAGE-STE could be agreed on and scientific collaboration lead already to a few joint publications. In the following, two meteorological stations (Missour and Zagora) shall be described in more detail and in section three, an excerpt of the common research activities shall presented.

2.1. Missour meteo station

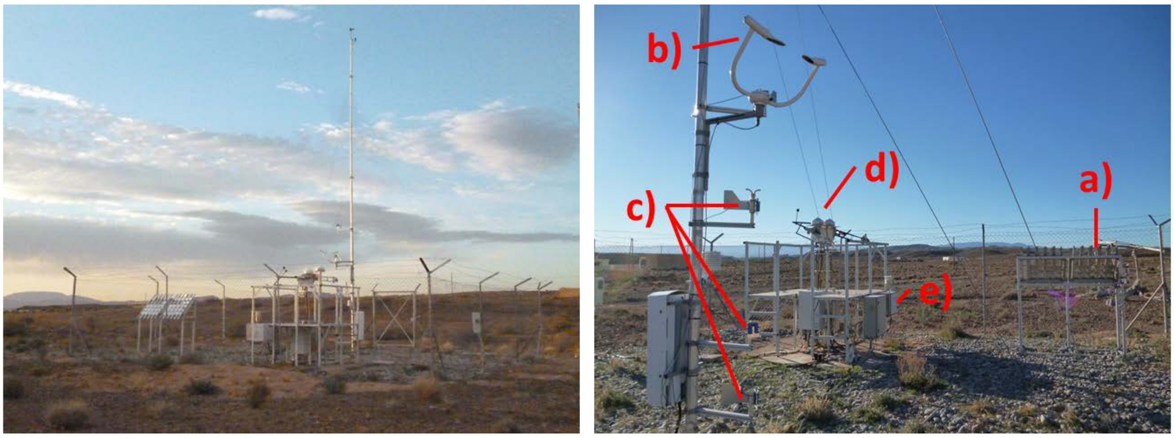

Figure 2. Missour meteo station from different view points. The setups indicated by letters are : a)reflector exposure rack; b) scatterometer FS11; c) optical light barrier sensors at different heights; d) TRACS; e) optical aerosol counter EDM164.

In addition to the general meteorological and irradiance equipment, the station in Missour has been equipped with several instruments in order to better understand and characterize the aeolian dust movement. The scattering and extinction losses in the lower atmosphere are a critical issue for solar power plants. To better assess the annual optical losses and make predictions on the economic consequences, the Vaisalla FS11 scatterometer has been installed. It is a well suited instrument for solar resource assessment as it measures the meteorological optical range (MOR) continuously and with low maintenance and electrical power effort [1]. Data acquisition is running since March 2015.

Also from March 2015 until December 2016, five optical light barrier sensors (type: YH03PCT8 from Wenglor) have been installed on a wind vane at different heights (0.6, 1, 2 and 3 m) above the ground. They are able to detect particles with diameters larger than 40 µm and give out a digital signal once a particle passes the laser beam. Measurements showed that the share of particles larger than 40 µm is insignificant at the investigated heights. Almost no signal could be measured even at the lowest height.

The Tracking Cleanliness Sensor (TraCS) is a measurement device for the soiling of solar mirrors. It has been installed in Missour and Oujda stations in 2013 and 2012, respectively. It consists of a second pyrheliometer on a solar tracker that is installed to measure the direct normal irradiance as reflected by a sample mirror. Comparing the reflected to the directly measured DNI is a measurement for the reflectivity of the sample mirror. The parameter cleanliness is calculated by comparing the reflectivity of a soiled mirror to its reflectivity in the clean state. In a next step, the soiling-rate is calculated. The soiling-rate is defined as the daily loss of cleanliness with time. Soiling of solar mirrors can be measured on site with high time resolution, enabling a correlation to other weather parameters.

In contrast to the light barriers from Wenglor, the EDM164 optical particle counter from GRIMM is designed to detect aeolian particles in a significantly lower diameter range. Particles between 0.25 µm and 32 µm are sorted in 31 size channels and their respective frequency is counted. Thereby conclusions on the dust concentration can be drawn which is useful for the modelling of extinction, soiling and erosion losses. Data collection is going on since March 2016.

A field exposure of representative reflector materials is taking place as well in order to correlate their performance change to the data of the aforementioned instruments. Aluminium and glass reflectors of various manufacturers are exposed since 2012 and are taken to the laboratory from time to time [2].

2.2. Zagora meteo station

Figure 3. Zagora meteo station from different view points. The setups indicated by letters are : a)reflector exposure rack; b) scatterometer FS11; c) high volume particle sampler; d) photovoltaic power; e) optical aerosol counter EDM164.

As all the other meteo stations, Zagora is equipped with the basic instruments and moreover exhibits some special equipment. Like in Missour there is a FS11 scatterometer, an EDM164 particle counter and the mirror exposure rack installed. Furthermore a high volume particle sampler has been installed at the site in March 2016. This device is a microcomputer based air volume sampler. It is designed to sample up to 100 cubic meter of air per hourand collect the dissolved particles on membrane filters. The filters are weighted before and after the sampling and mass concentrations is determined [3]. Because the station has been upgraded, a higher electrical energy demand originated. Since the station has no connection to the power grid, the installation of additional photovoltaic power and battery storage (under the solar panels) was necessary and has been done in March 2016.

2.3. Temara and Skoura meteo stations

A part of the collaborative project between MAScIR (Morocco) and CEA (France) deal with the soiling degradation of solar mirrors performances under Moroccan climate. Two different sites in Morocco are chosen to conduct the natural ageing tests in the collaboration CEA/MAScIR.

The first site is an Oceanside site located in Temara near to the Moroccan capital Rabat. The site is aboard the Atlantic Ocean (see Figure 4) and is characterised by its high degree of humidity and wind speed. The second site is a desert site located in Skoura near to Ouarzazate City in the south of Morocco (see Figure 4) which presents a high ambient temperature.

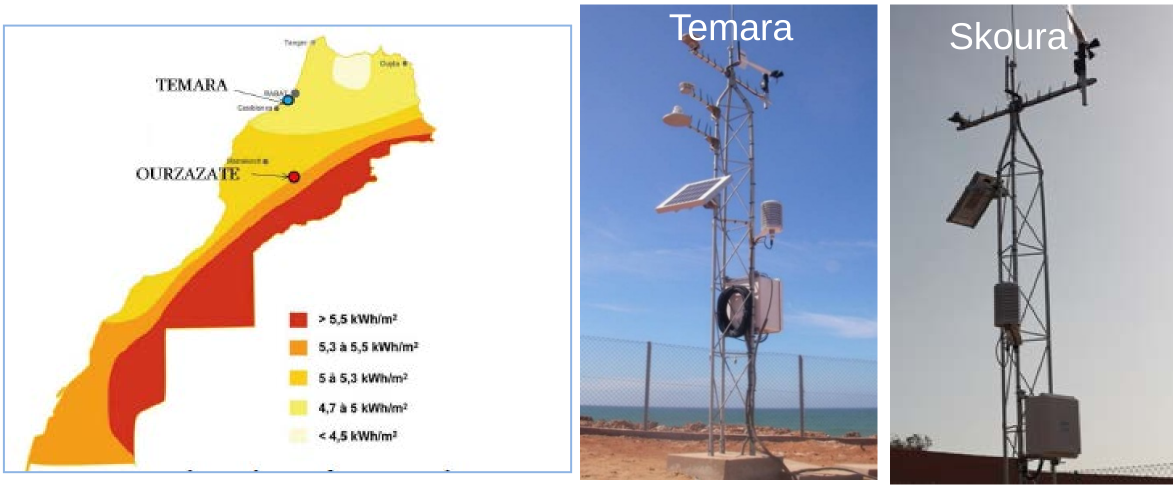

Figure 4 : 2 sites in Morocco: Temara and Skoura near Ouarzazate meteo stations

Climatic parameters of both sites are monitored with meteorological stations. The main measured parameters are wind speed and direction, ambient temperature, relative humidity, global irradiation and rainfall. The real-time data of each site are downloaded remotely through a 3G modem.

The recorded data from September 2012 to June 2014 in this project show that for the maximum wind speed values, the Oceanside site presents more than 25% of wind values higher than 5 m/s (see.Table.1). For the desert site, wind values above 5 m/s represent only 18% of the global recorded data. The high wind speeds values in the Oceanside site which reach a value of 22 m/s against 17 m/s for the desert site can be explained by the proximity of the site of the Ocean (see. Figure 4) above. This wind speed analysis is used to determine the wind velocities used for aging tests in controlled environment.

Table.2. Occurrence frequency of maximum wind speeds recorded by a mesh of 10 minutes in both exposure sites between September 2012 and June 2014 [6].

Wind speed (m/s)	Oceanside site (%)	Desert site (%)
V < 5	74.74	81
5 < V < 10	22.82	17.83
10 < V < 15	2.17	1.15
V > 15	0.28	0.01

The wind direction is interesting to estimate the main impact angle of sand particles on mirror's surface. The obtained results from the wind direction analysis in both sites will be used to choose the impact angles used for ageing tests in controlled environment. From the wind rose recorded from September 2012 to May 2014 (see. Figure 5), it was shown that the wind direction in the Oceanside site is characterised by a dominance of the south and south-west orientations, while in the desert site the wind direction is dominated by the east-north-east and west-south-west directions. Assuming that mirrors are exposed in both sites according to the south and with inclination equal to the site latitude, the potential incidence angle in Oceanside site will be closer to the normal impact angle that in the desert site.

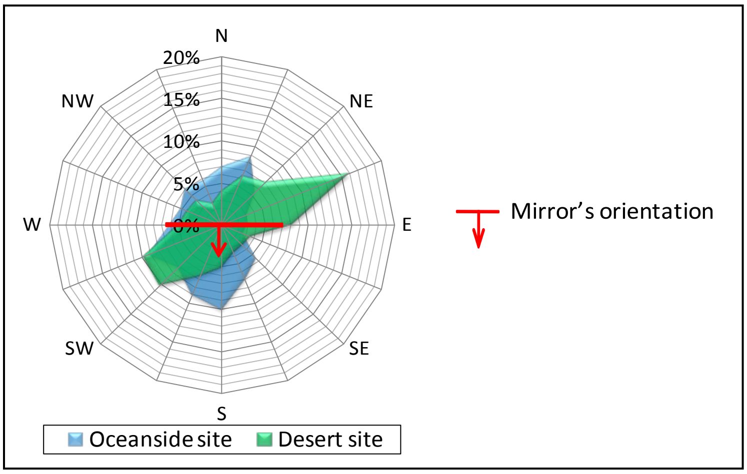

Figure 5 : Wind rose from the recorded data between September 2012 and June 2014.

3 Selection of joint scientific results

3.1. Particle mass concentration

For Missour and Zagora dust concentration measurements with the EDM164 from GRIMM have been carried out for over one year. The raw data have been converted in total suspended particle concentrations (TSP). The frequency distribution of the TSP at both sites is in shown in Figure 4. The mean TSP values lie around 57 and 191 µg/m³ for Missour and Zagora, respectively. The median values ware at around 16 and 51 µg/m³, respectively. The events with TSP levels higher than 1000 µg/m³ have been measured with a 5 fold frequency in Zagora in comparison with Missour. The highest measured TSP value was 716760 and 41903 µg/m³ for Zagora and Missour, respectively.

These differences in TSP values are expected to have effects on the soiling and extinction behaviour as well as on the erosive destruction on the exposed materials on the respective sites.

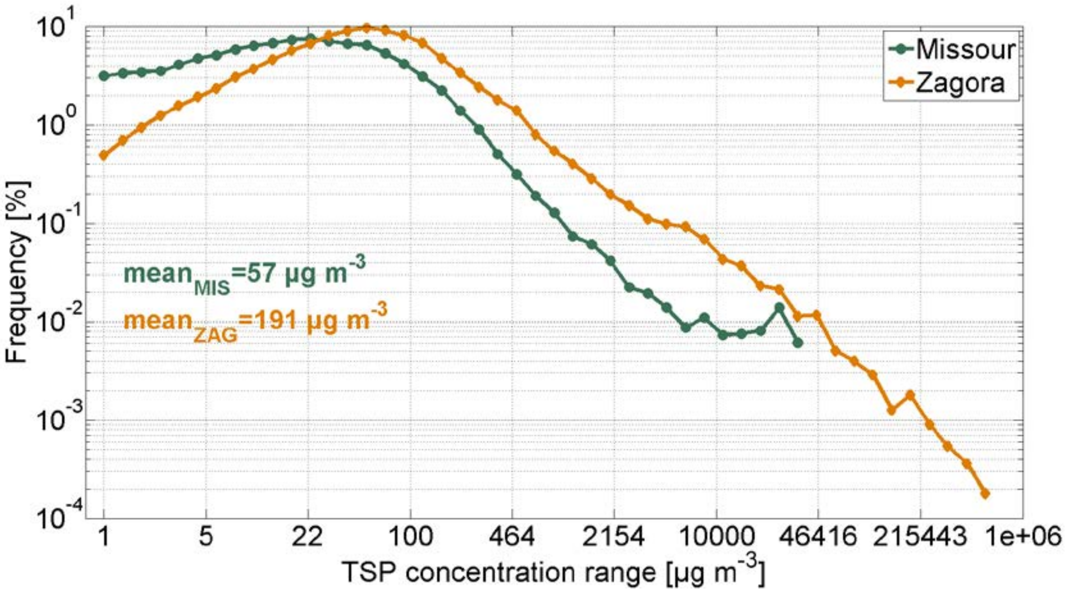

Figure 6: Frequency distribution of TSP values from the EDM164 particle counter between April 1, 2016 and May 1, 2017 in Missour and Zagora.

3.2. Soiling rate

Figure 5 shows a histogram of the daily soiling rate as measured with the TraCS instrument at two sites, Missour and PSA. Values below -0.03/day are summed up in the left bin. The histogram shows more occurrences of high SRs in MIS compared to PSA. The SR data has been analyzed in the time between January and December 2014. The mean SR in this time interval for MIS is -0.0071/day compared to -0.0051/day at PSA. The median values are -0.0034/day and -0.0032/day, respectively. The minimum SR is -0.093/day in MIS and -0.042/day at PSA, the standard deviation is -0.011/day in MIS and -0.006/day at PSA. The share of SR values greater than -0.005/day is 66 % at the PSA and 57 % in MIS. Thus there are a higher number of more severe soiling events in MIS compared to PSA. The mean value over the lower 50 % of the values is -0.013/day in MIS and -0.0085/day at PSA which confirms that soiling events are more severe on average in MIS than at PSA once they surpass the median of the datasets.

The result shows that the relative proximity of the Missour site to the Saharan desert increases the risk of severe soiling events such as a sand storm. We could detect more than 6 yearly sand storm events at Missour whereas at PSA the fewer severe soiling events are caused mainly by red rain, i.e. light rain with a very high dust load that is deposited on all exposed surfaces.

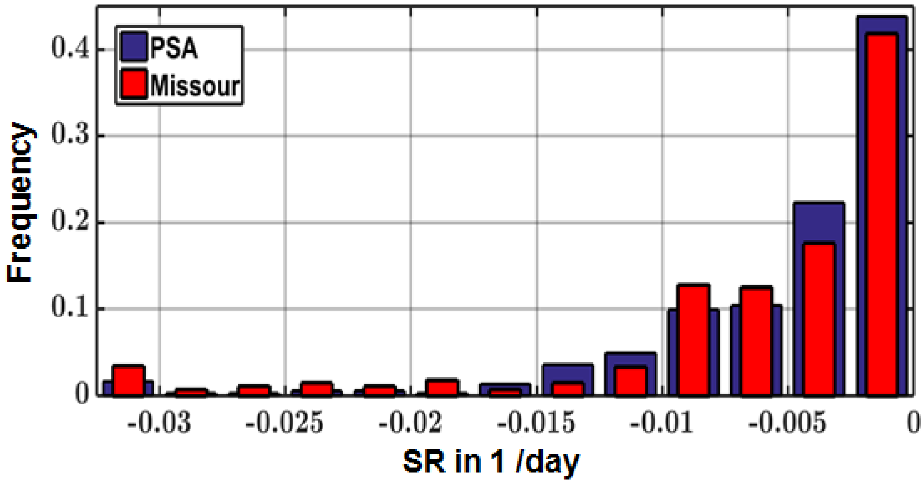

Figure 7: Histogram of soiling rates measured between 1, January 2014 and 1, January 2015 at the PSA and in Missour.

In order to analyse the variation of soiling rate based on these parameters, a study was conducted on mirrors samples exposed in the two sites through Morocco. In both natural sites, mirrors are exposed in racks :

- One type with an inclination equal to the site's latitude and oriented towards the south.
- Another type of erosion racks oriented through four different orientations according to the predominant wind orientations, e.g. east-north-east, and four different inclinations.

Figure 8 : (a): Temara Oceanside site racks; (b): Skoura desert site racks.

Surface soiling deposition rate is a function of several parameters related to the nature of the surface, deposits and environmental conditions in the installation sites (wind speed and direction, rains) and mirrors exposure conditions (inclination angle, orientation, height).

Figure 9 shows two examples of mirrors exposed at different inclination angles (0° and 90°) that present different aspect and density of soiling.

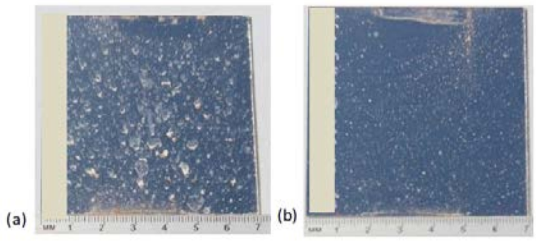

Figure 9 : mirrors exposed at different inclination angles, (a) : 0°, (b) : 90°.

Figure 10 shows cumulated loss of specular reflectivity for different orientations (ENE, SSE, OSO, NNO) of mirrors exposed at 0° (Figure 10).

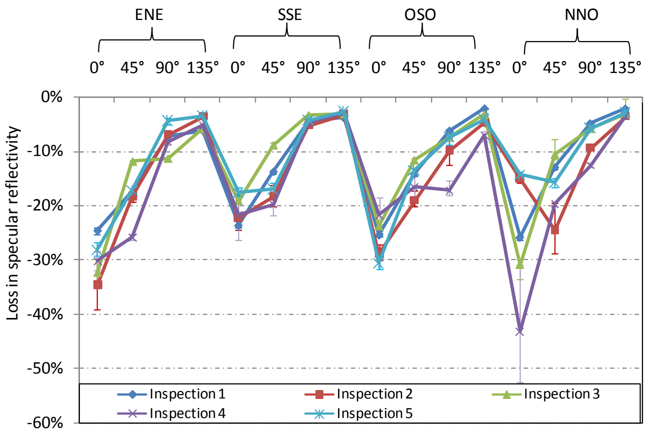

Figure 10 : Loss in specular reflectivity due to soiling deposition of samples exposed according to different configurations.

The effect of soiling deposition on cleaned samples and on the soiled samples on the specular reflectivity of mirrors were also studied (see Figure 11).

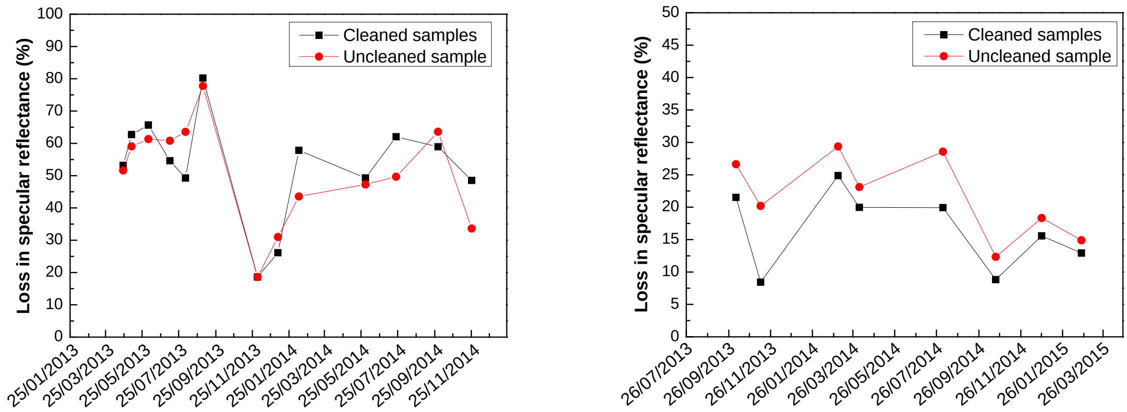

Figure 11 : Comparison of the reflectivity loss of cleaned and soiled mirrors exposed in the seaside a) and the desert b) sites [5]

In addition, it was also evaluated the effect of wind speed on soiling accumulation upon mirrors surfaces. Results in Figure 11 and Figure 12 show that this parameter presents different effects according to the wind direction and the presence of rains during the exposure period. It was found that soiling deposition can be released in case of high wind speed according to the exposure direction.

Moreover, by analysing the variation of the maximum wind speed at the two exposure sites, it should be noted that depending on the season there are slight differences in wind speed values in both sites (Figure 12). By evaluating the effect of rainfall on the soiling rate, it has been found that, depending on the sample exposure direction, rain can have a natural cleaning effect at high wind speeds.

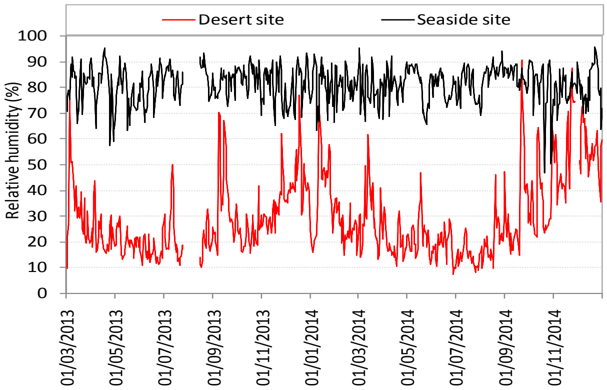

Figure 12 :Average relative humidity recorded in both sites [5]

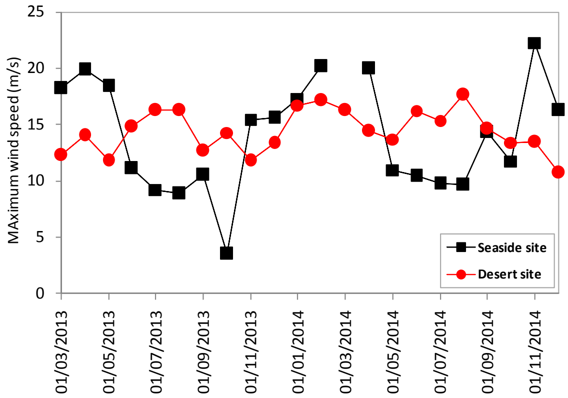

Figure 13 :Variation of the maximum wind speed in both sites [5]

The dust samples collected from both sites were characterised by realising various analyses. Microscopic observations have been performed on dust particles left after drying drops of dirty water deposited on a glass wafer in order to characterise dust size and morphology. X-ray diffraction and FTIR analyses were performed with this dust to identify its mineralogical components. Finally, the dirty water salinity was monitored using a conductivity meter VWR EC300.

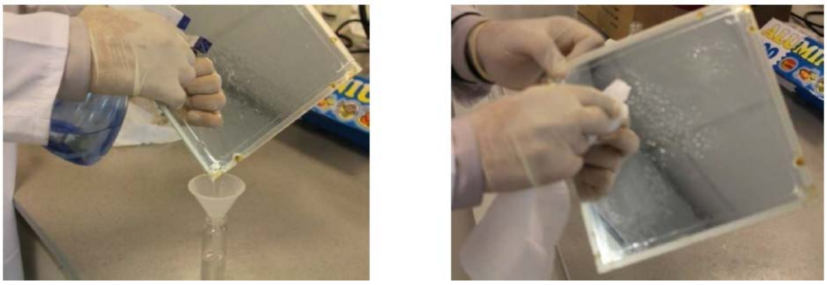

Figure 14: Method for washing mirrors and collecting dust deposited [5]

The obtained results show that soiling depositions on mirror samples exposed in the seaside site contains salt and sand particles while those collected from samples of desert site contain only sand particles.

The size of collected particles was also characterised during the sampling period.

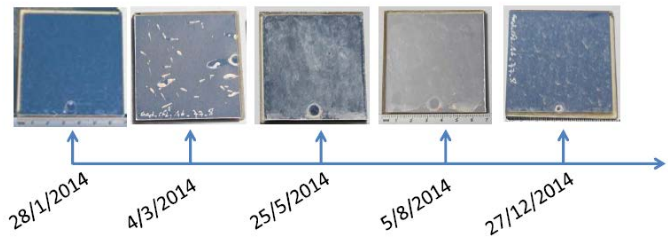

Figure 15: Soiling deposits on glass mirrors during different exposure times [**5**]

It was shown that the variation of soiling rate is highly affected by environmental conditions as it is directly related to the exhibition season. In addition, it was shown that the rainfall is a natural cleaning agent when it is associated with high wind speed, whereas the rate of soiling is higher in the case of low wind speed.

3.3. Erosion on Reflector materials

Glass and Aluminum Reflectors have been exposed at the various sites and sent back to DLR, or have been recollected during maintenance trips. From optical reflectance measurements and microscope analysis the damage modes on the reflectors could be evaluated. There have been clear differences in the degradation modes for the various sites, especially for the aluminium reflectors [2]. But also the silvered-glass mirrors exhibit degradation characteristics. For example in Zagora significant surface defects could be detected which are supposed to be caused by strong sandstorm activity at that site [4]. This can also be stated for Erfoud even though in a more attenuated way. On the other sites almost no defects nor significant reflectance losses could be measured for silvered-glass mirrors. A publication on the site assessment for solar energy plants concerning sandstorm is going to be submitted to “Solar Energy Journal” this summer.

The exposure of reflector materials gives valuable insights in the characteristics of erosion effects (defect dimensions and frequency). The optical analysis of the outdoor exposed samples facilitates the tailoring of the erosion parameters used for artificial erosion setups in WP8. In Figure 15, the microscope image of the front surface of a silverd-glass mirror is shown after natural erosion a) and after artificial erosion b). It can be seen, that the damage mode can be simulated to a quite realistic extent. The absolute number of the defects can easily be increased by linearly increasing the testing time/test dust mass density.

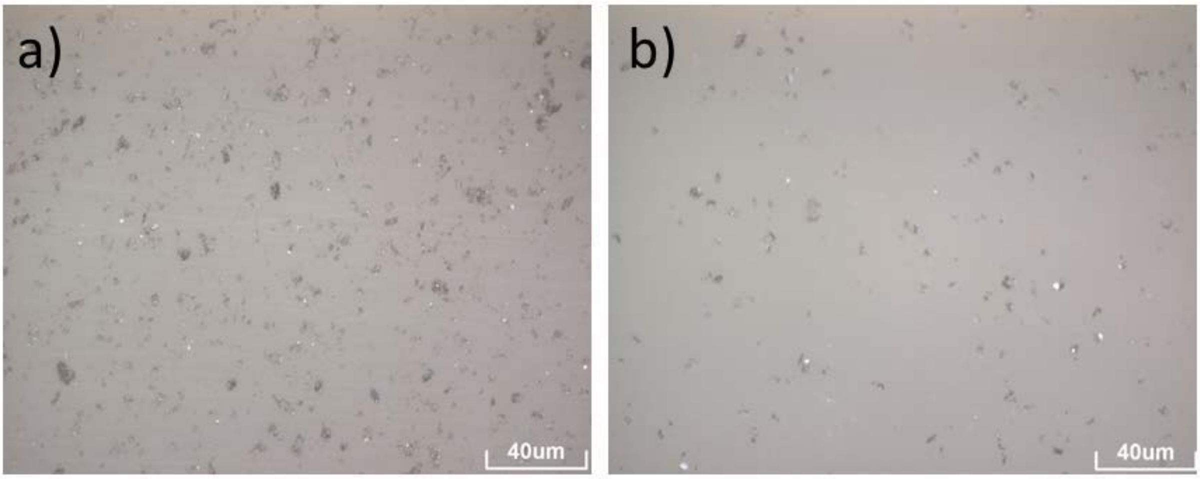

Figure 15. Glass sample after erosion. a) exposed to Zagora for 3.5 years showing a reflectance loss of 4.9%; b) simulated erosion with 0.4 g/cm² at 20 m/s showing a reflectance loss of 1.6%.

A task of the collaborative project between MAScIR and CEA deals with the degradation of solar mirror performances under Moroccan climate. The influencing parameters, climatic (wind speed and direction), geological (sand properties), on surface erosion were monitored and analyzed in two different sites in Morocco [6]. Mirrors samples are exposed in the Oceanside site from August 2013 and from May 2013 in the desert site.

During this period, no degradation other than surface erosion was identified on the exposed mirrors. Therefore, the decrease measured in specular reflectance can be directly related to the effect of surface erosion.

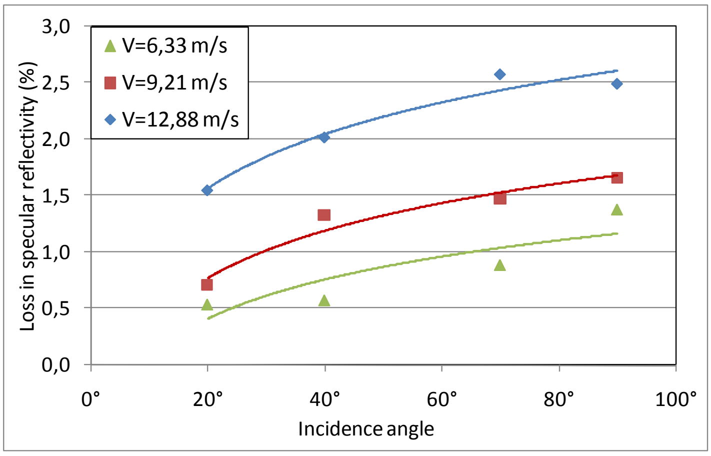

Figure 16. Effect of incidence angle and wind speed on the specular reflectivity losses. [7]

In conclusion, the site of TEMARA is very aggressive, all the exhibited samples show degradation by corrosion at the end of the project, which represents approximately 2 years of exposure. On the other hand, we observe almost no corrosion on the mirrors exposed in Skoura.

3.4. Extinction

The measured raw MOR values from the FS11 scatterometer in Missour have been compared with values from the PSA.

Figure 17 displays the according histograms for MOR data from August 1, 2015 until September 15, 2016 for PSA and Missour. It can be seen that the mean MOR at PSA lies around 50.7 km while the mean MOR in Missour is around 37 km. These results fit quite well to the results shown in Sect. 3.2. It can be assumed that higher mean soiling rates are also connected to higher particle loads in the lower atmosphere which causes an increased attenuation of solar radiation and therefore lower MORs.

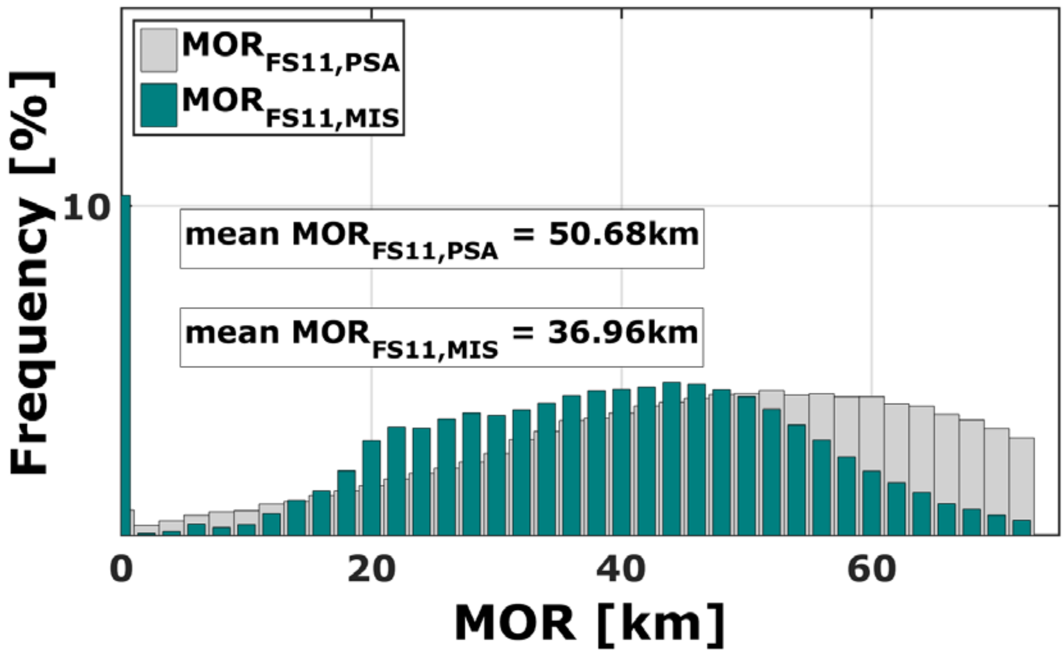

Figure 17 : Frequency distribution of raw MOR measured by Vaisala FS11 scatterometer between August 1, 2015 and September 15, 2016 in Missour and PSA.

Results of the joint research among IRESEN and DLR on the topic of the determination of atmospheric extinction for solar tower plants will also be presented at the SolarPACES 2017 in Chile where a validation of a transmittance model for the sites of PSA, Missour and Zagora will be presented.

4 Appendix

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