Waveband analysis for understanding the soiling impact on PV systems

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CEAEMA
CENTRO DE ESTUDIOS AVANZADOS EN ENERGÍA Y MEDIO AMBIENTE

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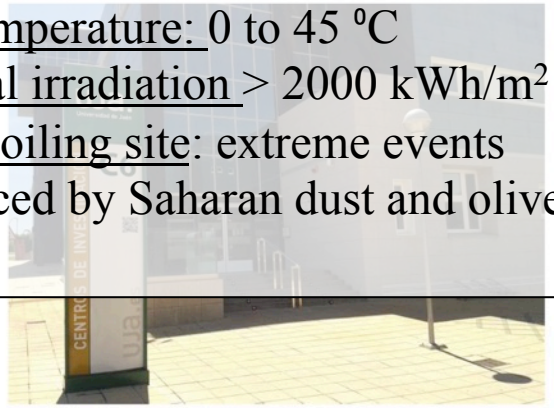
The Centre aims to **promote** and **lead research** and **high education** in Renewable Energies and Environment in EU

Jaén (37º46′ N;3º47′ W)
Climate: Continental-mediterranean
Air temperature: 0 to 45 ºC
Annual irradiation > 2000 kWh/m^2
Low-soiling site: extreme events produced by Saharan dust and olives trees

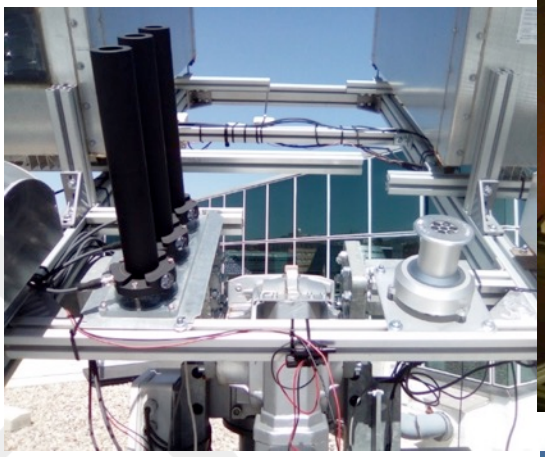


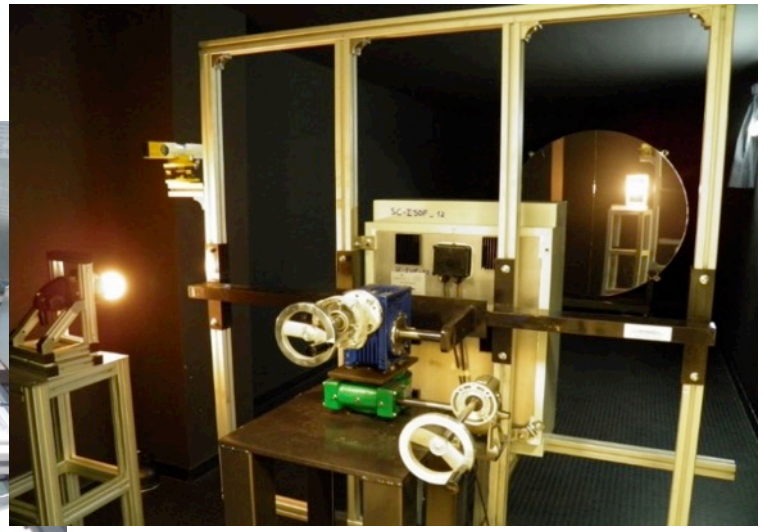
- Biomass Division
- Solar PV Division
- Meteorology Division
- Electric and Mechanical Engineering Division
- Ecology Division

Main research activity on PV

- Characterization, evaluation and Quality control of PV modules and plants
- Photovoltaic integration and rural electrification (self-consumption, micro-grids, smarts cities)
- Solar photovoltaic for development
- Developing of concentrator systems: optical design, thermal management, solar cells, etc.

Main Facilities





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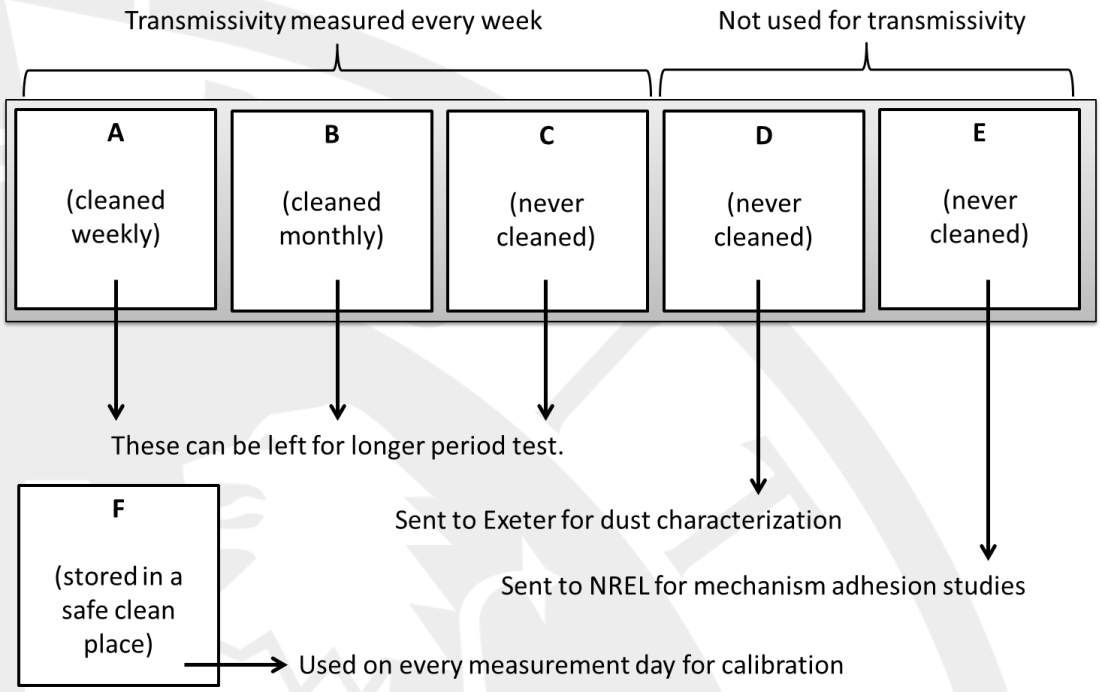
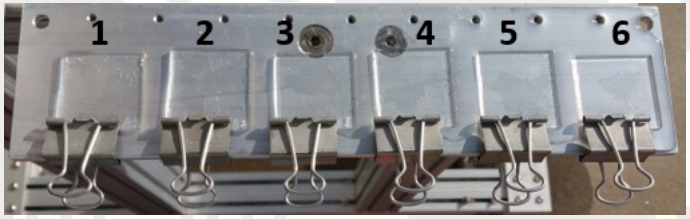
Experimental procedure





- Seven identical 4 cm × 4 cm sized and 3 mm-thick Diamant® low-iron glass from Saint-Gobain Glass were shipped to each location.
- Coupons A to E were installed outdoors, at zero tilt angle, using a supporting structure.
- Coupon F was kept in a safe, dust-free container and used to calibrate and compare the different spectrophotometers.
- Weekly transmission measurements were taken on coupons A, B and C at each site.
- Daily weather data and, where available, mean daily concentrations of particulate matter (PM) have been recorded.
- A dry cleaning is performed by using a microfiber cleaning cloth.

Experimental procedure

Figure 1. One of the coupons.

Figure 2. Supporting structure.

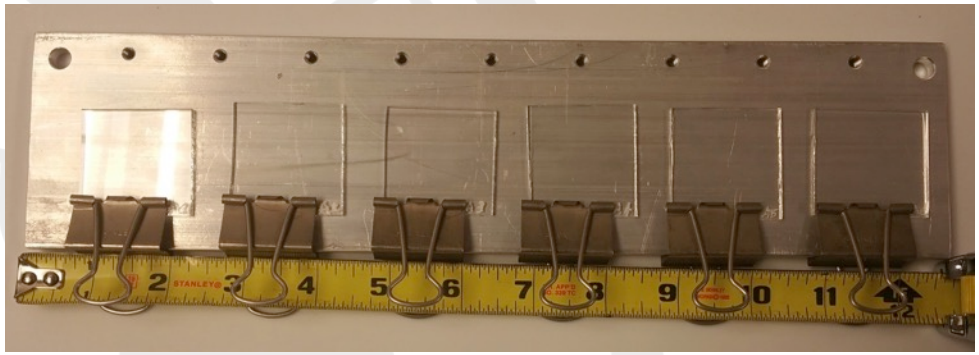
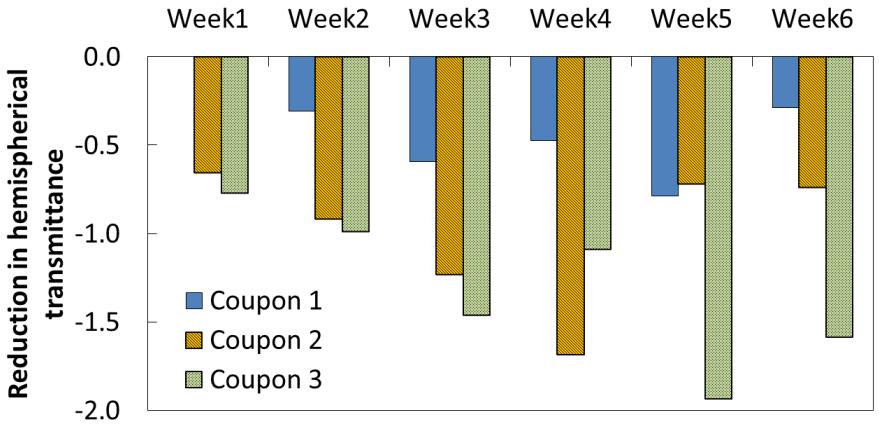


Figure 3. Coupons mounted on the support structure.

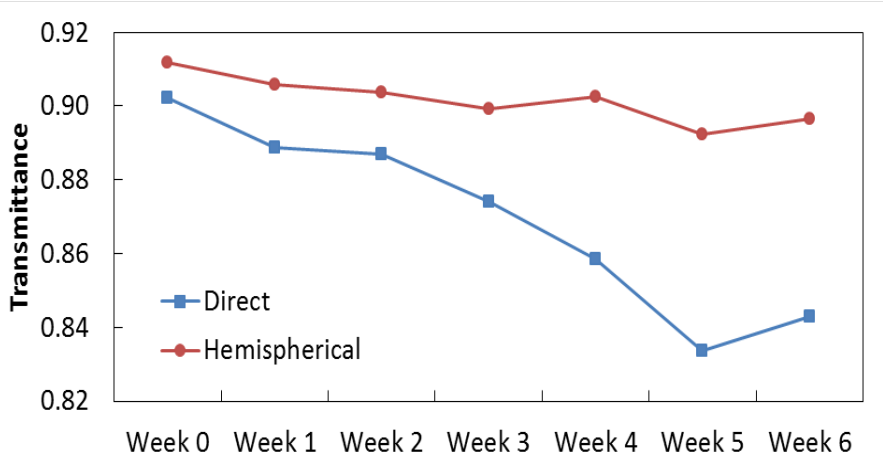
Experimental procedure

City, Country	*Coordinates*	*Climate classification*
Chennai, India	13.08, 80.27	Equatorial savannah with dry winter (Aw)
El Shorouk City, Egypt	30.12, 31.61	Desert climate (Bwh)
Golden (CO), USA	39.74, -105.18	Snow climate, fully humid (Dfb)
Jaén, Spain	37.79, -3.78	Warm temperate climate with dry summer (Csa)
Penryn, UK	50.17,-5.13	Warm temperate climate, fully humid (Cfb)
San José (CA), USA	37.29, -121.91	Warm temperate climate with dry summer (Csb)
Tezpur, India	26.70, 92.83	Warm temperate climate with dry winter (Cwa)

First results

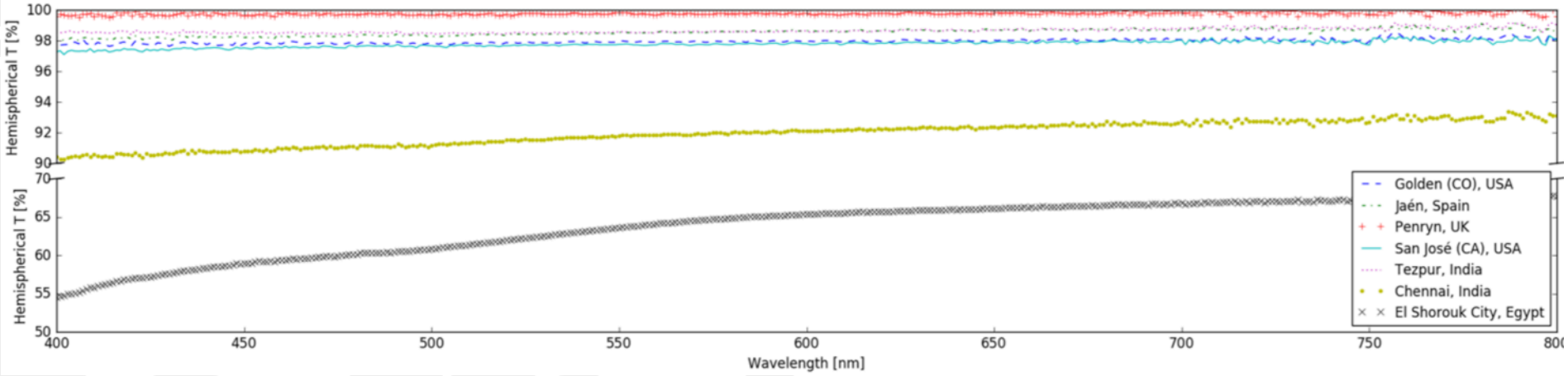


Progressive absolute drop in hemispherical transmittance, compared to the initial conditions, registered in Golden, CO. Transmittance is obtained by averaging the data recorded between 200 and 1100 nm, with a 1 nm step.



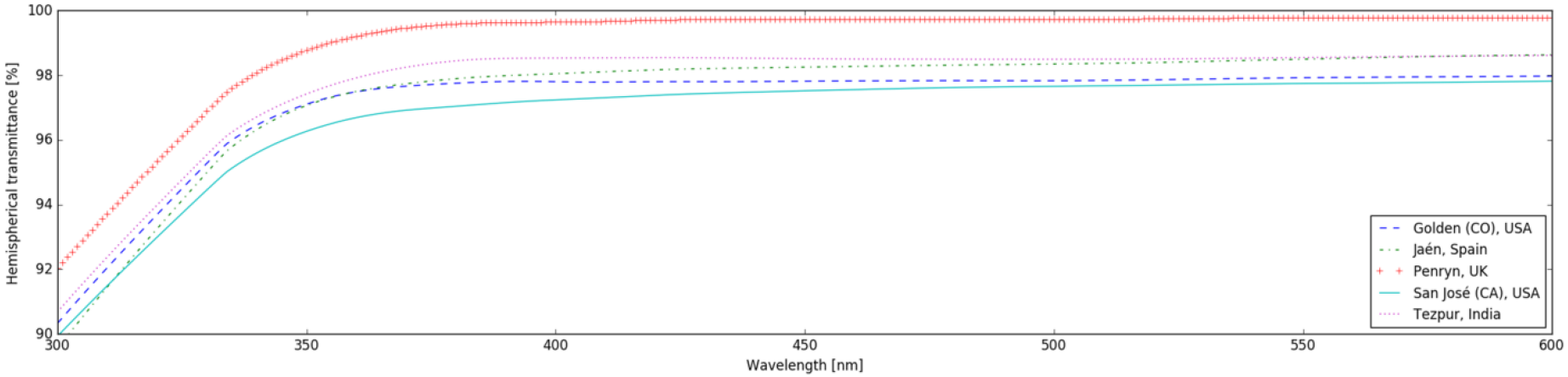
Direct and hemispherical transmittance of coupon 3 in Golden. Wavelengths between 500 and 1100 nm have been averaged.

First results: *Coupon E (two months of outdoor exposure)*



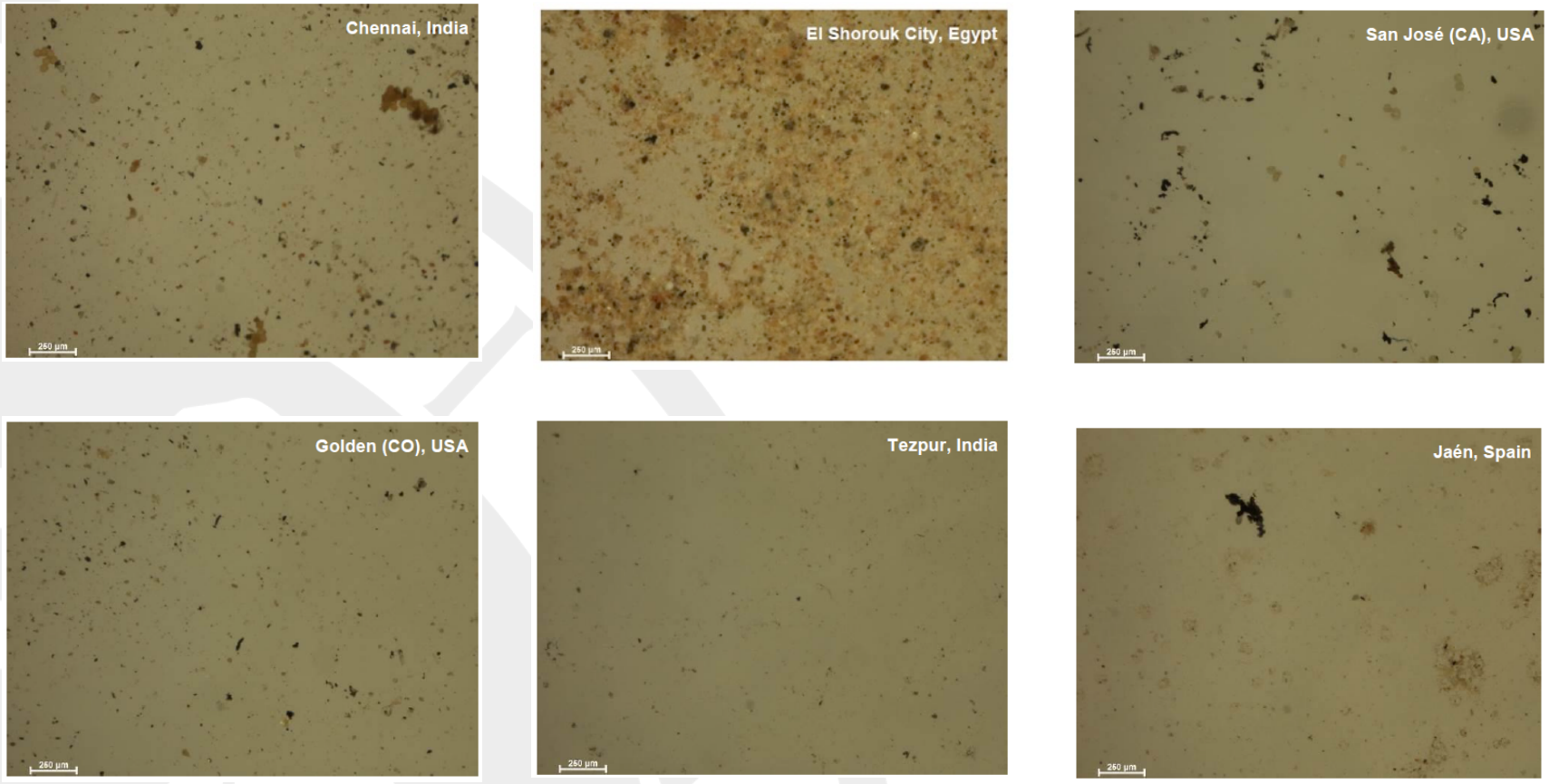
Hemispherical transmittance in the visible range of coupon E, referenced to the transmittance of coupon F. The spectra were measured using a PerkinElmer Lambda 1050 UV/Vis spectrophotometer with a 150 mm integrating sphere at NREL.

First results: *Coupon E (two months of outdoor exposure)*



Hemispherical transmittance in the visible and NIR range of coupon E for five low soiling sites, referenced to the transmittance of coupon F. The spectra were measured using a PerkinElmer Lambda 1050 UV/Vis spectrophotometer with a 150 mm integrating sphere at NREL and processed using a local regression technique to remove noise.

First results: *Coupon E (two months of outdoor exposure)*



Microscope pictures of six coupons at the end of the data collection. Pictures have been taken using a Nikon SMZ 1500 stereomicroscope at a magnitude of 5×: the scale bar on the bottom left represents a length of 250 µm.

First results: *Coupon E (two months of outdoor exposure)*

City, Country	Hemispherical transmittance [%]	Average particle area [μm^2]	Area coverage [%]
Chennai, India	84.2%	132-168	5.1-8.3
El Shorouk City, Egypt	63.1%	110-194	21.3-22.8
Golden (CO), USA	88.8%	55-100	1.7-2.4
Jaén, Spain	89.3%	33-92	1.3-1.4
Penryn, UK	90.1%	N.A.	N.A.
San José (CA), USA	88.5%	206-220	1.9
Tezpur, India	89.6%	47-60	0.3-0.4

Broadband hemispherical transmittance (300-2500 micrometers), average particle area, and percentage of the surface covered by particles, measured at the end of the data collection. unsoiled glass transmittance is 90.4%

- A **linear correlation**, with R^2 higher than 0.99, is found by comparing the percentage area covered by particles to the hemispherical transmission
- The **broadband hemispherical transmission** could be directly obtained from the covered area, independently of dust type and composition

Results

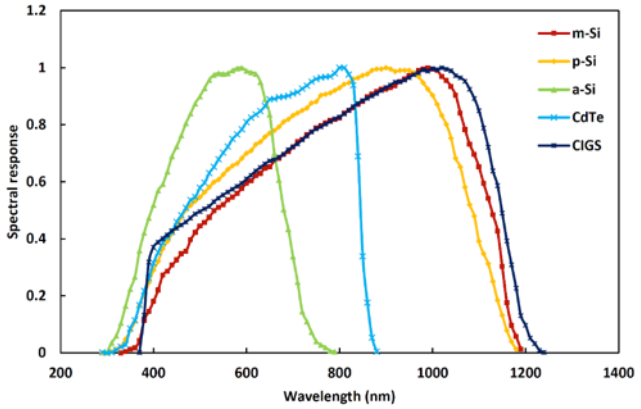
Location	T_{UV} (%) (300–400nm)	T_{Vis} (%) (400–700nm)	T_{NIR} (%) (700–1300nm)	SAPE (eV) (300-1100nm)	T (%) (300–1300nm)
Chennai, India	87.6	91.7	93.0	1.761	92.1
El Shorouk City, Egypt	46.3	62.7	69.6	1.711	65.2
Golden (CO), USA	96.1	97.9	98.3	1.767	98.0
Jaén, Spain	96.0	98.5	98.9	1.766	98.5
Penryn, UK	97.9	99.8	99.9	1.768	99.7
San José (CA), USA	95.4	97.7	98.1	1.766	97.7
Tezpur, India	96.6	98.6	99.1	1.766	98.7

- Soiling produces a higher attenuation at shorter wavelengths
- Soiling produces a red-shift of the spectral irradiance

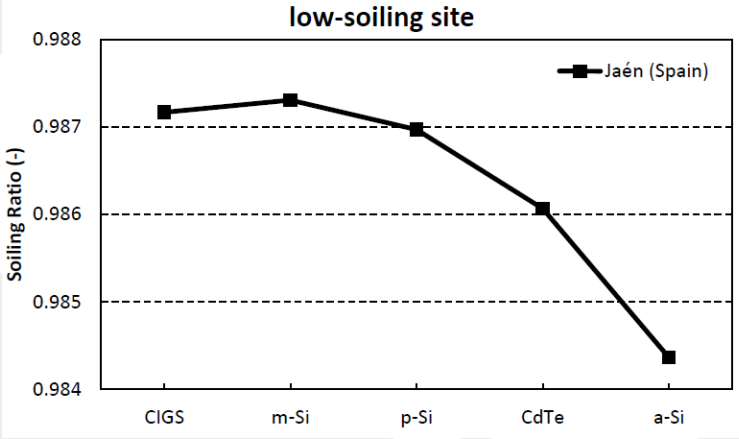
Soiling Average Photon Energy (SAPE, in eV):

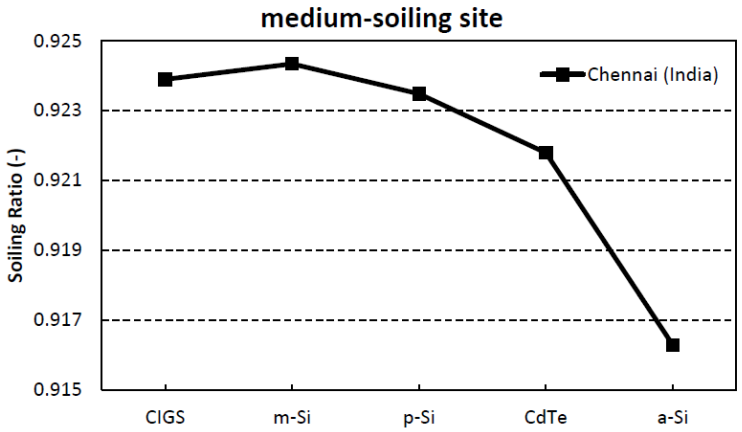
$$\mathrm{SAPE} = \frac{hc}{q}\frac{\int_{\lambda_{min}}^{\lambda_{max}} E_{ref}(\lambda)\tau_{soiling}(\lambda)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} E_{ref}(\lambda)\tau_{soiling}(\lambda)\lambda d\lambda}$$

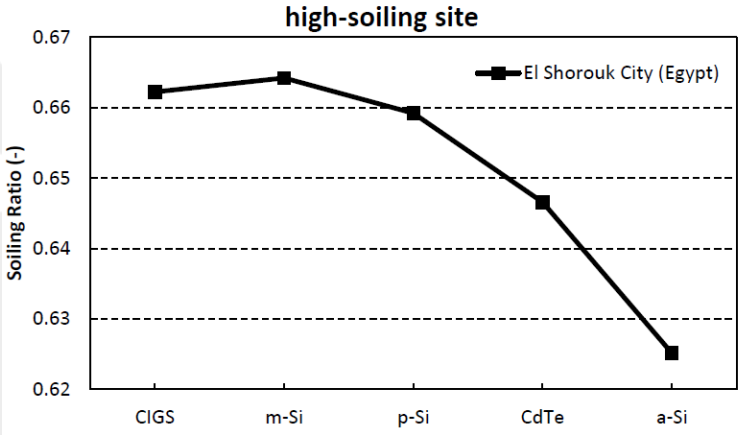
- **APE = 1.88eV for the AM1.5G reference spectrum (λ_{min}= 290nm and λ_{max} = 1100nm)**



Results: *Soiling Ratio for the AM1.5G reference spectrum*



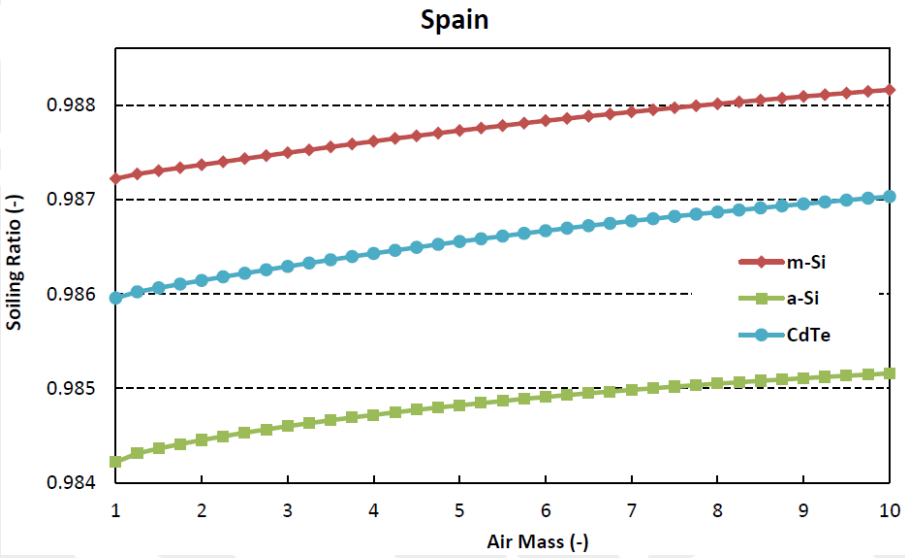


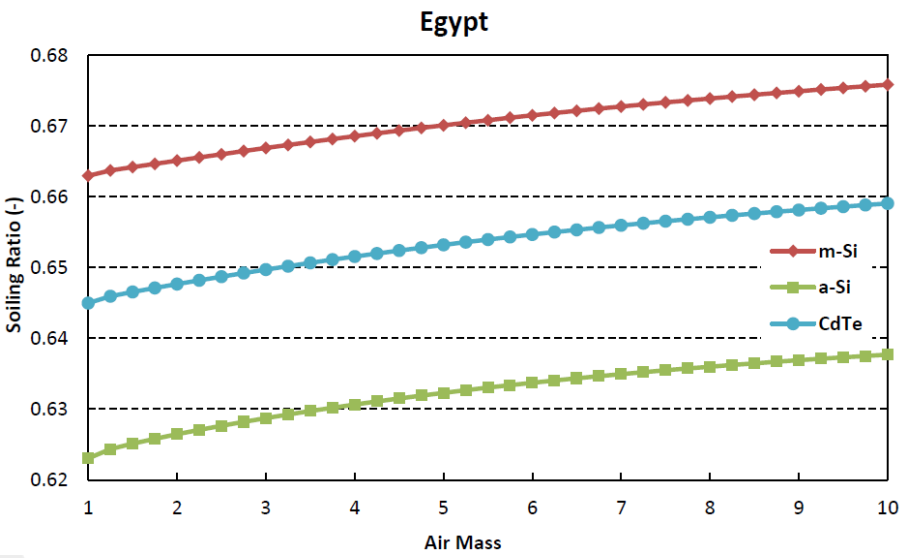


$$Soiling\ Ratio\ (-) = \frac{\int_{\lambda 1}^{\lambda 2} E_G(\lambda)\tau_{soiling}(\lambda)SR(\lambda)d\lambda}{\int_{\lambda 1}^{\lambda 2} E_G(\lambda)SR(\lambda)d\lambda}$$

a) The impact of soiling is higher on materials with high energy gap
b) The difference is higher as the soiling losses increase

Results: *Soiling Ratio as a function of air mass*





a) The soiling losses are effected by spectral changes, mainly by AM.
b) The soiling losses decrease with AM (higher at midday than in the sunset and sunrise).
c) The aerosols and water vapour seem not to play an important role at non-extreme weather locations.

Results: *6-months of outdoor exposure at Jáen*

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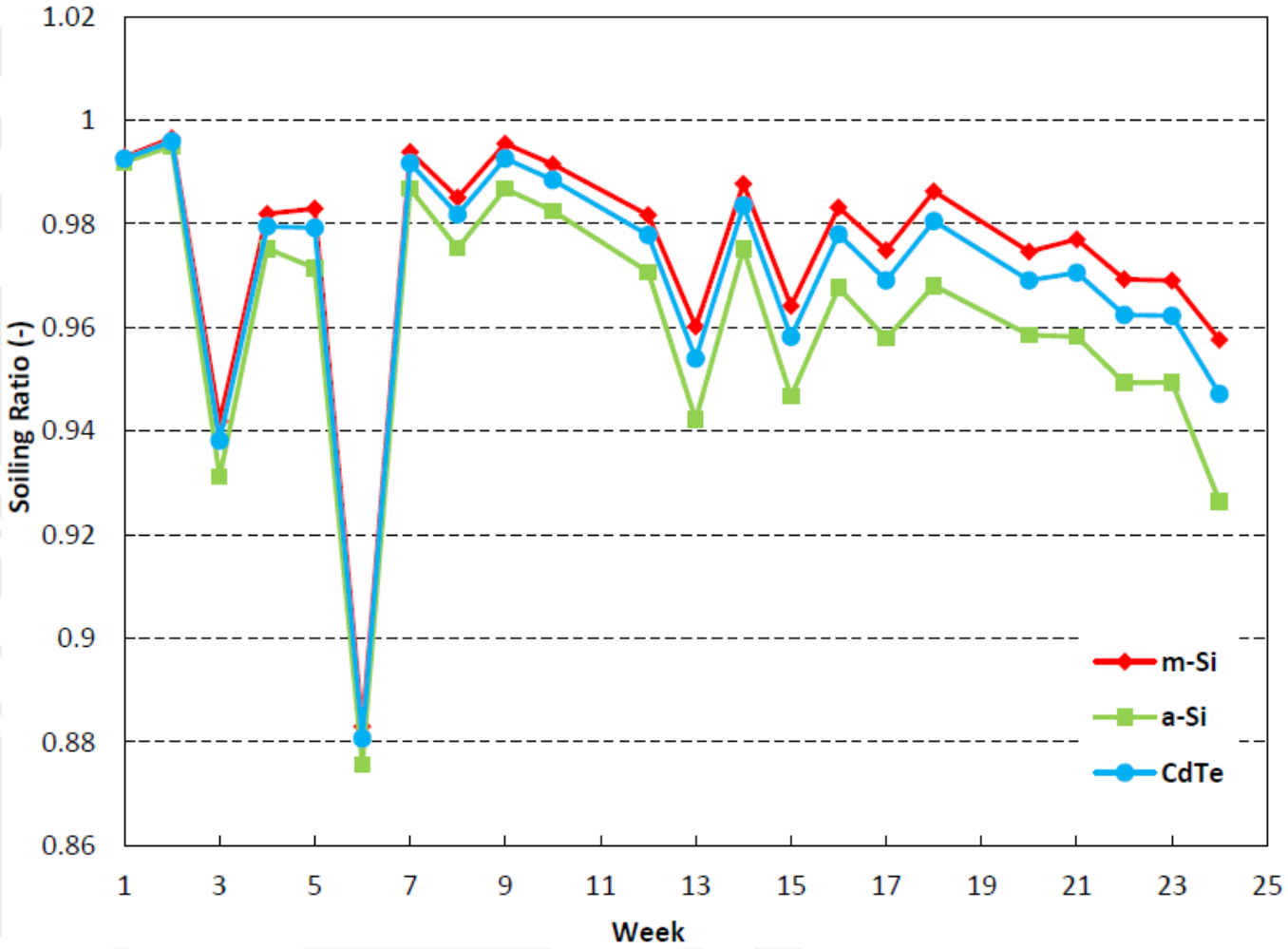

Weekly evolution of Soiling Ratio index estimated for three PV materials.

Preliminary conclusions

- Direct transmission is more affected than hemispherical.
- There is a linear correlation between the area covered by particles and the broadband hemispherical transmittance.
- Soiling produces a higher attenuation at shorter wavelengths, and therefore, a red-shift of the spectral irradiance.
- The impact of soiling is higher on materials with high energy gap, and this increases as the average transmittance decreases.
- Soiling losses are affected by the time-varying spectrum, i.e. higher at midday than ant sunrise and sunset.

Acknowledgments

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THANK YOU FOR YOUR ATTENTION!

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