SHORT TERM SCIENTIFIC MISSION (STSM) – SCIENTIFIC REPORT

The STSM applicant submits this report for approval to the STSM coordinator

Action number: CA16202
STSM title: Forecasting dust impact on solar energy in Egypt (FINDING)
STSM start and end date: 04/09/2018 to 27/09/2018
Grantee name: Panagiotis Kosmopoulos (pkosmo@meteo.noa.gr)

PURPOSE OF THE STSM FINDING

The exploitation of renewables is a cornerstone for sustainable development, through efficient energy planning, towards the goal of gradual independence from fossil fuels, while ramping up renewables is essential to meet sustainable development goals (SDGs) without decelerating economic growth and reducing welfare. Given its geographical location, by far the most important potential source of renewable energy for Egypt is the sun. Simultaneously, as cloudy conditions in Egypt are rare, aerosols (mainly dust) is the most common source of solar irradiance attenuation (Perez et al., 2006), causing performance problems in renewables. The most widespread technologies for the use of the energy potential of sun privileged locations are the photovoltaic (PV) and the concentrated solar power (CSP) plants, on which dust episodic presence causes solar energy losses of the order of 80% and 50% for CSP and PV installations, respectively (e.g. Kosmopoulos et al., 2017). Numerical prediction of aerosol particle properties has become an important activity at many research and operational weather centers (Benedetti et al., 2014) due to the growing interest from the solar energy industry. As a result, the need for improved Earth observation (EO)-based solar energy potential assessment is increasing in order to fulfill the increasing integration of solar farms into the Egyptian electricity grid and load exchanges. In the framework of the COST's action "InDust" we proposed the short term scientific mission (STSM) entitled "Forecasting dust impact on solar energy in Egypt - FINDING". The main goal of FINDING project is the investigation of dust effects on solar energy estimations and forecasting. As the main study area is Egypt, aerosol from anthropogenic (city pollution and industry) and natural (dust) sources play an important role in solar radiation attenuation. In particular, the main source of aerosols is Saharan dust and more specifically the Khamaseen dust storms (it is a fifty days phenomenon; Khamaseen in Arabic means "fifty") that are frequent from mid/March through April (El-Askary et al., 2009).

DESCRIPTION OF WORK CARRIED OUT DURING THE STSM FINDING

Through FINDING project we identified and exploited aerosol monitoring observations from MODIS, dust forecast products like CAMS, and solar radiation assessments based on the solar energy nowcasting system (SENSE) developed in the framework of the Geo-Cradle project (http://geocradle.eu/en/). SENSE is based on the synergy of RTM simulations, speed-up technologies using machine learning and real-time atmospheric inputs from satellites and models (Kosmopoulos et al., 2018). In the framework of FINDING project, we integrated the aerosol forecast data from CAMS and MODIS to the SENSE irradiances (Global Horizontal and Direct Normal Irradiances; GHI and DNI, respectively).

The main goal of FINDING was the exploitation of dust monitoring from satellite observations. The outputs from the above platforms were customized to targeted end-users needs. These end-users are from the private and public sectors and are already existing collaborators from the Geo-Cradle project, and more specifically are the Ministry of Electricity and Renewable Energy of Egypt (MERE), the New and Renewable Energy Authority (NREA) and the Magdi Yacoub Heart Foundation (MYF) in Aswan. The above mentioned activity in Geo-Cradle has been led by PMOD/WRC. As a result we established a network involving research institutions (NOA and PMOD/WRC), service providers (CAMS and MODIS for aerosols and dust information and our team for solar energy applications) and end-users (MERE, NREA and MYF) of information on the impact of dust on solar radiation and energy potential in Egypt. This aspect contributed towards establishing a network with research institutions (PMOD/WRC) and possibly other inDust related and the mentioned end users. It is also contributed to a major inDust goal which is the enhancement of the cooperation with North Africa involving them to European based science.

From a societal point of view, the energy security is critical for the growth and prosperity of the local and regional economy. As solar power production increases it becomes more and more important to be able to predict production and hence the "impact" on the electricity system. The lack of forecasts or inaccurate forecasts results in an inefficient operation of the electricity system and can even endanger security of supply. Simultaneously, solar-energy-related installations have been increasing their share on the total energy demand as defined by the local distribution and transmission system operators (DSO and TSO, respectively). As a result, accurate solar energy and dust forecasts are crucial in the energy exchange marketplace in Egypt, where on-the-spot energy prices are defined by supply and demand equilibriums. If the local energy traders can have an accurate estimate for the solar energy supply, this provides them with a comprehensive advantage with clear economic benefits for their day-to-day market operations. So, FINDING project is able to assist the aforementioned socio-economic sectors, which are directly affected by the presence of airborne mineral dust and its impact on solar energy supply, by enhancing the availability of relevant solar energy and dust estimation products, services and solutions, in order to coordinate and evolve the current R&D energy transmission and distribution activities. Concerning the capacity building in the solar energy sector in Egypt, the MERE, NREA and MYF were familiar with our provided applications and hence, were able to further promote the use of dust products as a complementary approach to the already delivered solar energy applications in terms of solar atlas services, books, business plans and real-time nowcasting products.

The FINDING project was mainly a radiative transfer study, so the selection of the hosting institution was based on this criterion. PMOD/WRC is a world expert institution on reference solar radiation measurements, RTM development and simulations, while Dr. S. Kazadzis and PMOD/WRC is the principal investigator (PI) of the GAW PFR aerosol network and the SENSE pilot through the Geo-Cradle project. As a result, the FINDING project benefited, and hence exploited, all the above knowledge and expertise in order to precisely estimate the dust impact on solar radiation and energy in a place with specific aerosol and dust climatological specifications (e.g. Khamaseen dust storms and activity). In order to study and forecasting the dust impact on solar energy in Egypt we evaluated the MODIS and CAMS aerosol databases in the following ways:

a) We calculated a 16 year aerosol optical depth (AOD) climatology from MODIS and we estimated the corresponding impact in terms of percentage attenuation for the GHI and DNI.
b) We used the MODIS daily AOD values for the last 3 years (2015-2017) in order to evaluate the CAMS AOD 1 day forecasts for the whole Egypt and for eight specific locations with high solar energy exploitation potential.
c) We evaluated 3 forecasting techniques, the CAMS 1 day forecasts, the MODIS persistence (PERS) based on the previous day values and the MODIS climatology (CLIM) by using the 16-year average values.

Finally we made a financial analysis for specific locations and for a hypothetical system scenario of 10 MW in order to quantify the impact of aerosol and dust presence on the energy production from PV and CSP systems and on the annual, monthly and daily revenues under climatological and extreme dust event conditions.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

The FINDING project estimated the impact of dust on surface solar radiation and energy in Egypt based on Earth Observation (EO) techniques. For this purpose, we exploited the synergy of monthly mean and daily post processed satellite remote sensing observations from the MODerate resolution Imaging Spectroradimeter (MODIS), radiative transfer model (RTM) simulations and already developed speed-up technologies based on machine learning, in conjunction with the 1-day forecasts from the Copernicus Atmosphere Monitoring Service (CAMS). As cloudy conditions in this region are rare, aerosols and in particular dust (e.g. the Khamaseen dust storms) are the most common sources of solar irradiance attenuation, causing performance issues in the photovoltaic (PV) and concentrated solar power (CSP) plant installations. The proposed EO-based methodology is the solar energy nowcasting system (SENSE) which was developed in the framework of the GEO-CRADLE project and was able to quantify the extent of dust impact on solar energy potential by using as a main input to the SENSE the aerosol optical depth (AOD) in terms of MODIS climatological values (15 year averages) and day to day monitoring and forecasting variability from MODIS persistent daily values and CAMS, respectively. The forecast accuracy was evaluated at various locations in Egypt (Alexandria, Cairo, Suez, Hurghada, Aswan, Luxor, Marsamatrouh and Asuit) with remarkable PV and CSP capacity installed and found to be within 5 - 12 % as compared to that obtained from the satellite observations, highlighting the ability of such modelling approaches for solar energy planning. The pure dust can result in Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) attenuation by as much as 64 - 107 for GHI and 192 - 329 kWh/m^2 for DNI annually, while this energy reduction is climatologically distributed between -0.7 to -12.9 % in GHI and -2.9 to -41 % in DNI with the maximum values observed in spring following the frequent and intense dust activity of Khamaseen. Under extreme dust conditions the AOD is able to exceed 3.5 resulting daily energy losses of more than 4 kWh/m^2 for a 10 MW system. Such reductions are able to cause financial losses that exceed the daily revenue values and hence highlight the usefulness in energy management and the day-to-day market operations. The overall methodology aims to promote the nowadays EO capabilities and techniques as to be incorporated and utilized through solar energy studies and applications in sun-privileged locations with permanent dust sources. The following Figures present the main results of the STSM FINDING:

Figure 1a shows the 16-year climatology of AOD from MODIS for the region of Egypt. It is a combination of the MODIS algorithms Dark Target and Deep Blue Level 2 which provides reliable aerosol optical properties for arid regions like Egypt at high spatial resolution (0.1 degree). Figures 1b and 1c depict the radiative transfer at the surface level in terms of percentage attenuation of the GHI and DNI as compared under clean and clear sky conditions. For the RTM calculations we used the SENSE system which produced almost 1.5 million simulations for the implementation of these results. Figure 2 describes the correlation of the CAMS forecasted AOD with the MODIS AOD observations, as well as the corresponding surface solar radiation levels by using as inputs the CAMS and MODIS AOD values. We note here that the comparison was performed for the MODIS overpass time positions. Table 1 shows 8 specific locations in Egypt with high solar energy potential and which were used as case studies for the performed analyses. Figure 3 presents three of the selected locations for which we performed additionally the financial analysis. These locations (Cairo, Asyut and Aswan) were selected because of their different latitude zones in order to represent conditions with various aerosol sources and solar energy potential levels. Figure 4 depicts the forecasting reliability of CAMS, MODIS persistence and MODIS climatology approaches as absolute energy losses for GHI and DNI for the eight locations in Egypt. The main scope for this comparison is to highlight the advantages of the high temporal resolution CAMS forecasts (1 per 3 hours) against the MODIS low temporal resolution observations (1 per day). The MODIS climatology is able to provide information about the aerosol background for each location but is unable to monitor the intraday aerosol variability and hence the impact on solar energy. The MODIS persistence makes the assumption that the AOD is persistent from the previous day observation. This is useful for accurate aerosol levels but under new dust event cannot follow the rapidly differentiating AOD values. The CAMS 1-day forecasts provides information about the total aerosol and the pure dust particle levels based on the MACC classification. In any case this comparison between the forecasting techniques is able to provide useful information to the energy managing authorities and investors about the nowadays solutions and to consider to opportunity cost from each aerosol, dust and energy forecasting approach.

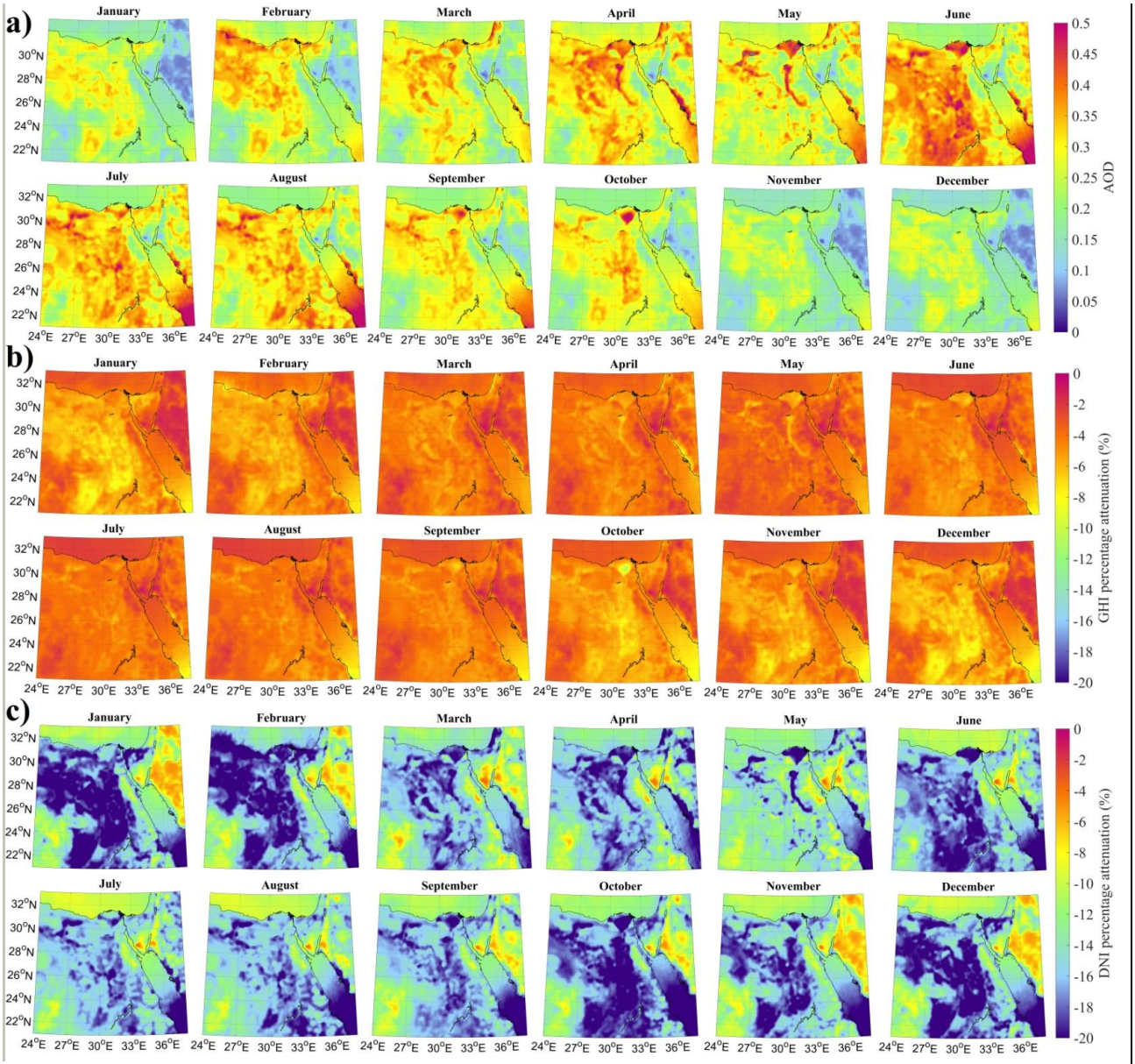

Figure 1: Monthly averages of (a) AOD at 550 nm in Egypt using the Dark Target and Deep Blue Combined Level 2 product of MODIS for the period 2002-2017, (b) GHI and (c) DNI solar energy percentage attenuations relative to the aerosol-free simulations under MODIS-based AODs.

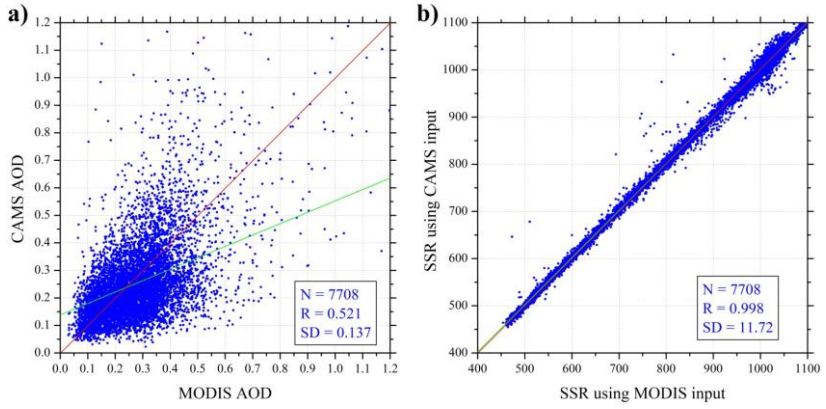

Figure 2: Scatterplots of (a) the CAMS forecasted AOD as compared to the MODIS observed values and (b) the SENSE simulated surface solar radiation (SSR) using as input the CAMS forecasted AOD as compared to the SENSE SSR using as input the MODIS AOD in Egypt for the period 2015-2017.

Table 1: Coordinates (degrees), population (in millions of people) and average height (meters above sea level) of the specific locations in Egypt.

Location	Population (m.o.p)	C ode	Latitude (^{o}N)	Longitude (^{o}E)	Height (m.a.s.l.)
Alexandria	5.172	**ALE**	31.2001	29.9187	12
Cairo	9.153	**CAI**	30.0444	31.2357	75
Suez	0.744	**SUE**	29.9668	32.5498	5
Hurghada	0.288	**HUR**	27.2579	33.8116	14
Aswan	0.290	**ASW**	24.0889	32.8998	194
Luxor	0.507	**LUX**	25.6872	32.6396	76
Marsamatrouh	0.448	**MAR**	31.3543	27.2373	30
Asyut	4.123	**ASY**	27.1783	31.1859	70

Figure 3: Study region and the specific locations of Cairo, Asyut and Aswan where the financial analysis was performed.

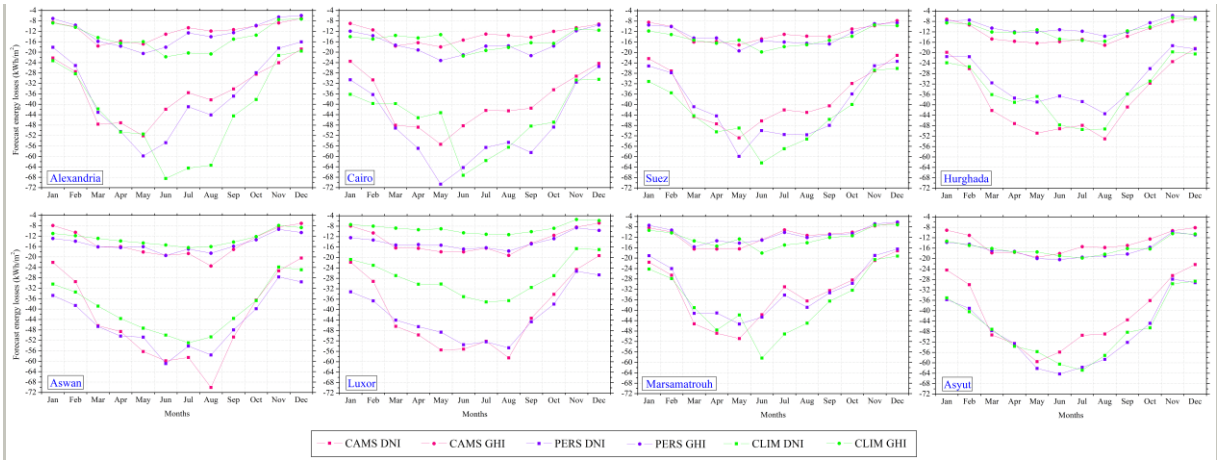

Figure 4: Monthly mean forecast solar energy losses in kWh/m^2 for the regions of Alexandria, Cairo, Suez, Hurghada, Aswan, Luxor, Marsamatrouh and Asyut. The AOD forecasting techniques of CAMS, MODIS persistence (PERS) and MODIS climatology (CLIM) were applied as inputs to the SENSE producing the solar energy potential in terms of GHI (circles) and DNI (squares). The CAMS produces 1-day forecasts with 3 hour temporal resolution, the PERS uses the MODIS AOD values of the previous day for the 1-day forecast as persistent aerosol conditions and the CLIM uses the monthly mean MODIS AOD values as steady aerosol conditions for every single time step of the whole month.

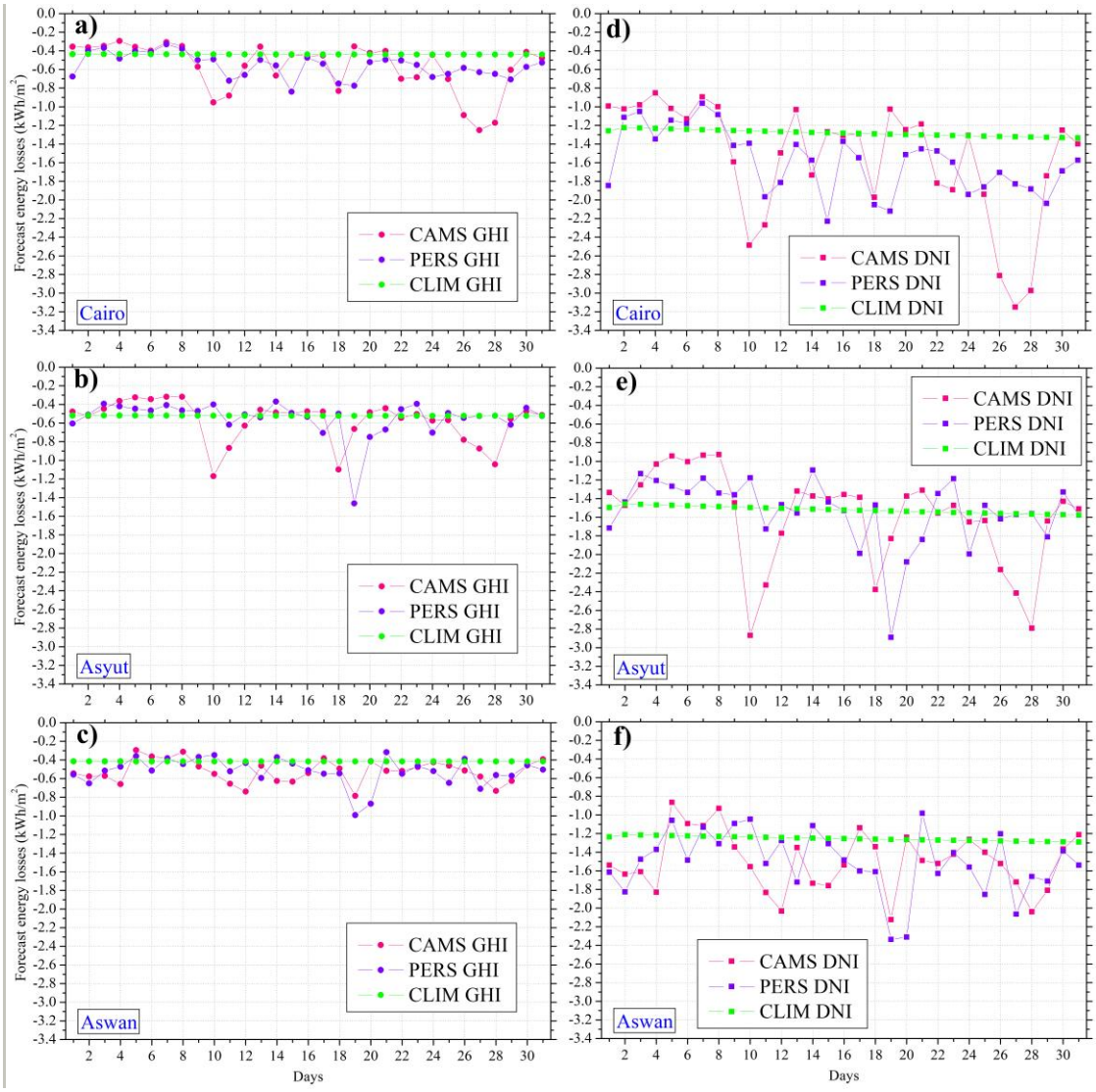

Figure 5: Daily mean forecast solar energy losses in kWh/m^2 for the regions of Cairo (a, d), Asyut (b, e) and Aswan (c, f). The AOD forecasting techniques of CAMS, MODIS persistence (PERS) and MODIS climatology (CLIM) were applied as inputs to the SENSE producing the solar energy potential in terms of GHI (a, b, c) and DNI (d, e, f).

Figure 5 shows the daily forecast solar energy losses as a zoom in to Figure 4 as to observe the differences as GHI and DNI of the 3 forecasting approaches at three representative locations. Figure 6 presents time series of simulated GHI and DNI using CAMS AOD inputs in the form of contour plots for the past 3 years as well as direct comparison against the MODIS persistent and MODIS climatology approaches. The assessment of such differences can be a useful tool for future scientific or solar sector oriented business plan studies, as it will directly contribute to the dust related uncertainties introduced to solar radiation and energy calculations and/or forecasts. Figure 7 represents the financial analysis of forecasting solar energy under extreme dust event conditions. To this direction we studied the dust event of the 18th of March 2017 at the region of Asyut as well as the previous and next day in order to identify the differences and the overall energy and financial impact. Indicatively, for the previous and next day, the daily energy production for PV systems was 7.47 kWh/m^2 and 7.29 respectively, while on the peak of the dust event the energy production was 5.3 kWh/m^2. For the CSP scenario, the daily energy losses as compared to the previous and next day were almost 4 kWh/m^2, meaning that for a 10 MW system the daily financial losses are able to exceed the daily revenue values.

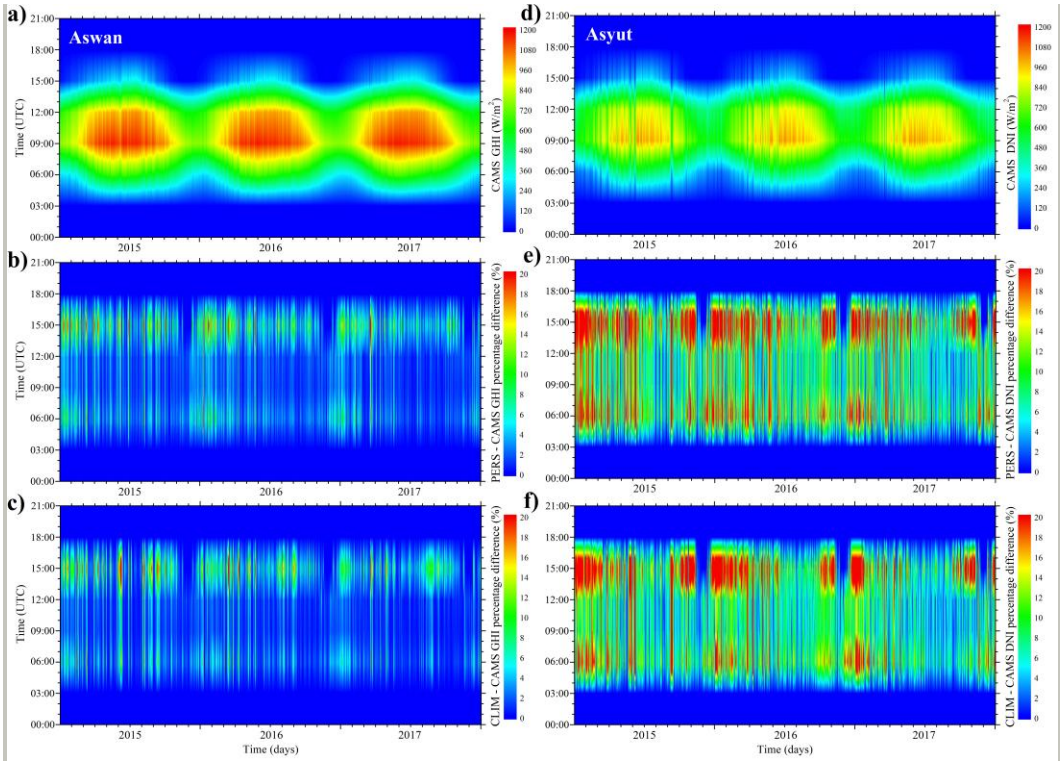

Figure 6: Contour plots of the GHI in Aswan (a, b, c) and DNI in Asyut (d, e, f) as simulated by SENSE using as AOD input the CAMS 1-day forecasts (a, d) and the percentage differences for GHI (b, c) and DNI (e, f) respectively as compared to the MODIS persistence (PERS) and MODIS climatology (CLIM) forecasting approaches for the period 2015 - 2017.

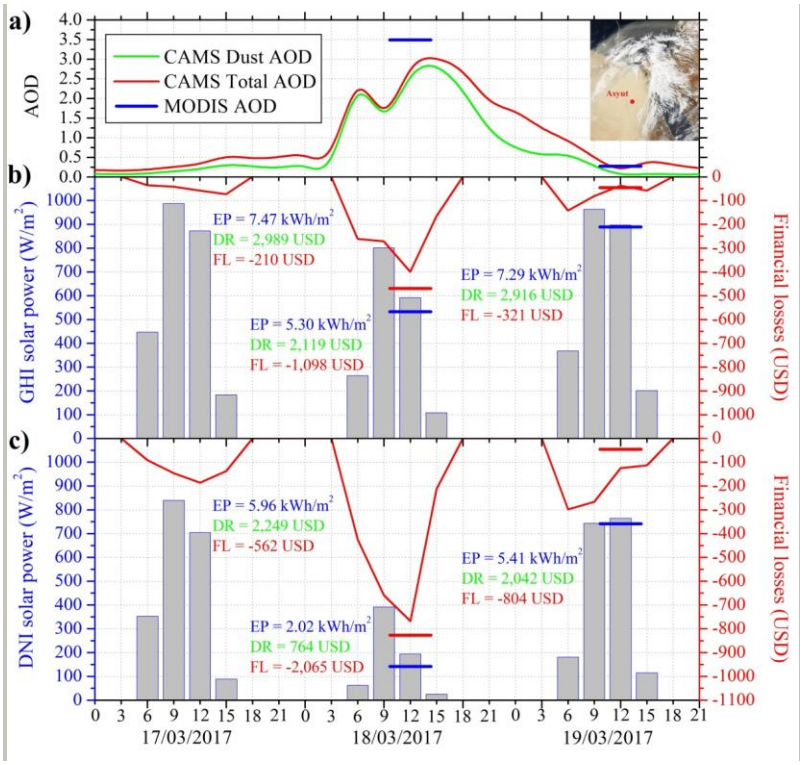

Figure 7: Temporal evolution and financial analysis of an extreme dust event impact (18 March 2017) on the AOD values (a) and on the produced solar energy from PV (b) and CSP (c) installations with nominal power of 10MW in the region of Asyut. The impact was quantified in terms of energy production (EP), daily revenue (DR) and total financial losses (FL). The blue and red insets show the corresponding solar power and financial losses respectively, using as input the MODIS observations.

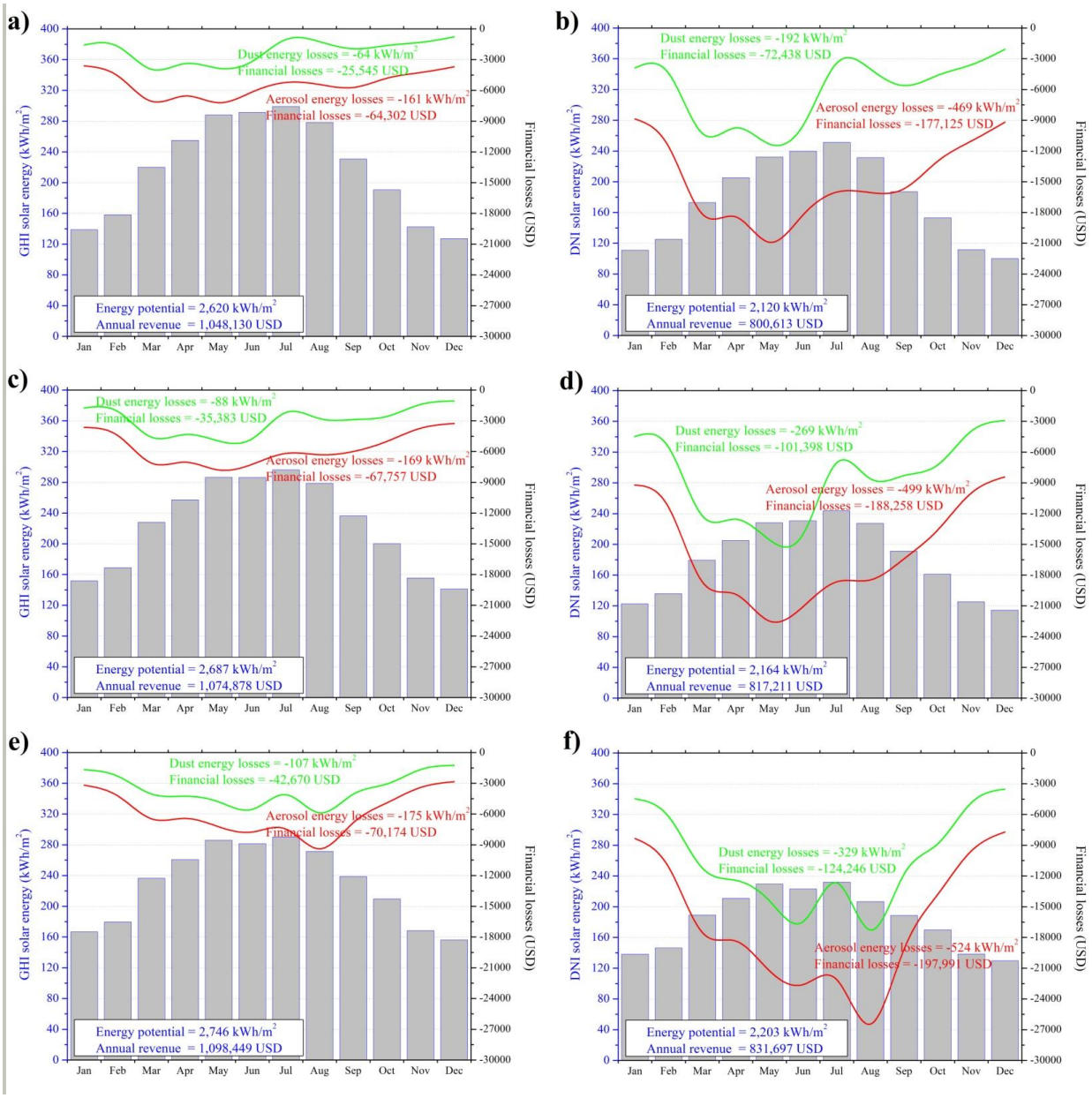

Figure 8: Financial analysis of the aerosol and dust impact on the produced solar energy from PV (a, c, e) and CSP (b, d, f) installations with nominal power of 10MW in the regions of Cairo (a, b), Asyut (c, d) and Aswan (e, f). The impact was quantified in terms of monthly mean and total financial losses and solar energy potential.

Finally, Figure 8 presents the financial analysis for the specific locations focusing on a hypothetical scenario of a system with nominal power of 10MW at the regions of Cairo, Asyut and Aswan. The system specifications were classified into the exploitation of GHI from PV technologies and DNI from CSP plants. The financial results were cross validated with similar and existing solar farms in Morocco, China, US, and Germany, while the exact feed-in tariffs were provided by the NREA in order to estimate realistic financial and system energy output results.

FUTURE PLANS AND OUTPUTS

The results of FINDING project will contribute actively in the formation of energy related policies and the subsequent market uptake by setting up and disseminating a roadmap for short-future implementations. Indicatively, the already existing cooperation with the Egyptian MERE, NREA and MYF will make the

integration of dust and solar energy potential forecasts to the operational planning of both public and commercial TSOs and DSOs more effective through market mechanisms and the prospect of knowing the future performance of energy-based cargo sales. Since the driving force of decision makers is the direct profit to the real economy and society, the prospect of controllability the energy supply will form the demand accordingly, following the path of natural economic and political behavior. As a result, the FINDING project will lay out and highlight the actions for the long-term response to major energy challenges and will evolve the readiness and maturity of such an energy operating framework. The dissemination of FINDING results to public and national bodies in Egypt could forward the release of funds and make FINDING project, through InDust action and beyond COST programme, a starting point for short future investments related to solar energy products and activities and visioning innovative high-end applications and technologies.

The following bullets describe our next steps from the STSM FINDING:

- We will present the FINDING results to the related end users in the Egyptian region.
- We will include end-user aspects in the final publication paper.
- We will submit a scientific paper up to 3 months after the end of the FINDING project (31/12/2018).
- We will present the FINDING results in the COST meeting and related solar energy conferences/workshops (anytime within 2019).

The outcome of FINDING project will be a targeted scientific paper that will deal with the quantification and forecasting of dust impact on the Egyptian solar energy production. To this direction we will take into account the dust platform of CAMS and satellite dust observations from MODIS, while, for the solar energy potential assessments we will use the SENSE system which is based on methodologies and techniques described in Kosmopoulos et al. (2017; 2018). Until now we submitted the FINDING results as an abstract at the AGU conference and will be presented at 10-14 December 2018 at Washington, USA.
Kosmopoulos, P.G., Kazadzis, S., El-Askary, H., and El-Khayat, M.M.: Forecasting dust impact on solar energy in Egypt. AGU Fall Meeting 2018, 10-14 December, Washington, USA, Final Paper Number A13N-1487, 2018.

The forthcoming scientific paper is now under preparation and will have the following title and co-authors:
Kosmopoulos, P.G., El-Askary, H., Kazadzis, S., Taylor, M., Gkikas, A., Proestakis, E., and El-Khayat, M.M.: Earth observation based estimation of the dust impact on solar energy in Egypt. To be submitted at the special issue "Solar Radiation, Modelling and Remote Sensing" of the Remote Sensing journal (ISSN 2072-4292).

REFERENCES

- El-Askary, H., Farouk, R., Ichoku, C., and Kafatos, M.: Transport of dust and anthropogenic aerosols across Alexandria, Egypt. Annales Geophysicae 27, pp 2869-2879, 2009.
- Benedetti, A., Baldasano, J.M., Basart, S., Benincasa, F., Boucher, O., Brooks, M.E., Chen, J.P., Colarco, P.R., Gong, S., Huneeus, N., Jones, L., Lu, S., Menut, L., Morcrette, J.J., Mulcahy, J., Nickovic, S., Perez, C., Reid, J.S., Sekiyama, T.T., Tanaka, T.Y., Terradellas, E., Westphal, D.L., Zhang, X.Y., and Zhou, C.H.: Operational dust prediction. In Mineral Dust: A key Player in the Earth System. Knippertz, P., and Stuud, J.B.W., Eds. Springer, DOI: 10.1007/978-94-017-8978-3_10, pp 223-265, 2014.
- Kosmopoulos, P.G., Kazadzis, S., Taylor, M., Athanasopoulou, E., Speyer, O., Raptis, P.I., Marinou, E., Proestakis, E., Solomos, S., Gerasopoulos, E., Amiridis, V., Bais, A., and Kontoes, C.: Dust impact on surface solar irradiance assessed with model simulations, satellite observations and ground-based measurements. Atmos. Meas. Tech., 10, DOI: 10.5194/amt-10-2435, pp 2435-2453, 2017.
- Kosmopoulos, P.G., Kazadzis, S., Taylor, M., Raptis, P.I., Keramitsoglou, I., Kiranoudis, C., and Bais, A.F.: Assessment of the surface solar irradiance derived from real-time modelling techniques and verification with ground-based measurements. Atmos. Meas. Tech., 11, pp 907-924, DOI: 10.5194/amt-11-907-2018, 2018.
- Perez, C., Nickovic, S., Baldasano, J.M., Sicard, M., Rocadenbosh, F., Cachorro, V.E.: A long Saharan dust event over the western Mediterranean: Lidar, sun photometer observations and regional dust modeling. Journal of Geophysical Research 111, D15214, 2006.

LETTER FROM THE HOST INSTITUTION

Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center

Davos, Switzerland, 08.10.2018

To: InDust STSM committee

Dear Sir/Madam,

On behalf of the host institution Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC), of the inDust Shirt term Scientific Mission with title "Forecasting Dust Impact on Solar Energy in Egypt - FINDING" I confirm that the applicant Panagiotis Kosmopoulos, who is a postdoctoral researcher at the National Observatory of Athens (Greece), has successfully completed his stay (4 - 27 September, 2018) at PMOD/WRC.

Sincerely,

S. Kazadzis

Davos, Switzerland