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Abstract. For solar resource assessment of solar power plants and adjustment of satellite data, high accuracy measurement data of irradiance and ancillary meteorological data is needed. For the MENA region (Middle East and Northern Africa), which is of high importance for concentrating solar power applications, so far merely 2 publicly available ground measurement stations existed (BSRN network). This gap has been filled by ten stations in Morocco, Algeria, Tunisia, Egypt and Jordan. In this publication the data quality is analyzed by evaluating data completeness and the cleanliness of irradiance sensors in comparison for all of the stations. The pyrheliometers have an average cleanliness of 99.2 % for week-daily cleaning. This is a 5 times higher effort than for Rotating Shadowband Irradiometer (RSI) stations which even have a slightly higher average cleanliness of 99.3 % for weekly cleaning. Furthermore, RSI stations show a data completeness of 99.4 % compared to 93.6 % at the stations equipped with thermal sensors. The results of this analysis are used to derive conclusions concerning instrument choice and are hence also applicable to other solar radiation measurements outside the enerMENA network. It turns out that RSIs are the more reliable and robust choice in cases of high soiling, rare station visits for cleaning and maintenance, as usual in desert sites. Furthermore, annual direct normal and global horizontal irradiation as well as average meteorological parameters are calculated for all of the stations.

INTRODUCTION

Solar irradiance and ancillary meteorological data are needed for solar resource assessment of solar power plants. High accuracy measurement data are required for comparison and adjustment of long-term satellite data and derivation of the expected solar resource. Furthermore, reliable irradiance measurements are needed to validate Direct Normal Irradiance (DNI) forecasting methods. Starting in 2010, ten meteorological stations have been installed in the Middle East and Northern Africa (MENA) within the enerMENA project. This is an important extension of so far merely two publicly available ground measurement stations for DNI in this region that are of special interest for concentrating solar power (CSP) applications. So far solar resource assessment in this region has been based mainly on satellite data with an elevated and unsecure data uncertainty due to the sparse base of measurements for comparison. In this work we analyze especially maintenance and availability effects on the DNI data. The total and monthly completeness of DNI data is listed for all of the stations allowing an estimation of the data depending on the desired application.

FIGURE 1. Overview of the enerMENA stations situated in Morocco, Algeria, Tunisia, Egypt and Jordan.

OVERVIEW OF THE NETWORK

Most of the enerMENA stations, situated in Morocco, Algeria, Tunisia, Egypt and Jordan (Fig. 1) are equipped with pyrheliometers for DNI measurement and thermal pyranometers for diffuse and global horizontal irradiance (DHI and GHI). Two stations in Morocco use Rotating Shadowband Irradiometers (RSI) to derive GHI, DHI and DNI. Data control, documentation and quality assessment is carried out by CSP Services, DLR and ARMINES together with the local partners from CRTEn, CDER, IRESEN and the universities of Ma'an, Oujda and Cairo. Regular maintenance visits on site by CSP Services and DLR are combined with training courses. Table 1 shows all stations including site name, country, local project partner, station type (‘thermal sensors’ or ‘RSI’), altitude, latitude, longitude and date of activation. Here and in all of the following tables the ‘Thermal Sensors’ stations are separated by a green line from the ‘RSI’ stations. ‘Thermal sensors’ refers to a CHP1 pyrheliometer and ventilated and heated CMP21 pyranometers for DHI and GHI that are mounted on a Solys2 solar tracker with sun sensor.

TABLE 1. List of enerMENA stations sorted by their activation date. TS refers to ‘Thermal Sensors’ stations whereas RSI refers to ‘Rotating Shadowband Irradiometer’ stations.

Site	Country	Local partner	Station type	Altitude[m]	Lat.[°N]	Lon.[°E]	Activation
Tataouine	Tunisia	CRTEn	TS	210	32.974	10.485	Dec. 13th, 2010
Ma'an	Jordan	University of Jordan	TS	1012	30.172	35.818	Jan. 11th, 2011
Oujda	Morocco	University of Oujda	TS	617	34.650	-1.900	Aug. 18th, 2011
Cairo	Egypt	Cairo University	TS	104	30.036	31.009	June 6th, 2012
Ghardaia	Algeria	CDER	TS	463	33.465	3.780	Sep. 30th, 2012
Adrar	Algeria	CDER	TS	262	27.880	-0.274	Sep. 27th, 2012
Missour	Morocco	IRESEN	TS	1107	32.860	-4.107	May 27th, 2013
Tan-Tan	Morocco	IRESEN	TS	75	28.498	-11.322	June 5th, 2013
Erfoud	Morocco	IRESEN	RSI	859	31.491	-4.218	May 30th, 2013
Zagora	Morocco	IRESEN	RSI	783	30.272	-5.852	May 31th, 2013

FIGURE 2. On the left the thermal sensor station of Missour, Morocco. On the right one can see the RSI in Erfoud, Morocco.

All stations are equipped with wind speed and direction measurements at 10 m height as well as temperature, relative humidity and pressure sensors. The Campbell Scientific CR1000 data logger is used for all stations. Data is retrieved as 1 min and 10 min averages automatically at least daily and quality controlled as described below. All sensors measuring irradiance are recalibrated at least every two years. The stations are continuously being upgraded with enhanced instrumentation for CSP relevant parameters. For soiling and ageing studies mirror samples have been exposed at different sites. Also cleanliness and soiling rates for reflectors have been measured in Missour and Oujda with the Tracked Cleanliness Sensor (TraCS) [1]. The TraCS measures DNI being reflected by a soiled mirror and the cleanliness is derived by comparison to the directly measured DNI. Circumsolar radiation will be measured from 2016 on with RSIs in Erfoud and Zagora (both Morocco) using the method from [2]. Atmospheric extinction data for application in solar tower plants is measured in Missour since spring 2015 and will be measured from 2016 on as well in Zagora with the ABC correction and the Vaisala FS11 as presented in [3]. Furthermore, a Grimm EDM 164 particle counter is used in Missour and another one will be installed in 2016 in Zagora. As an example, images from the stations in Missour and Erfoud (both Morocco) are shown in Fig. 2.

DATA QUALITY CONTROL

Meteorological data require being quality controlled, as lacking or erroneous ground data or data of unsecure quality are regrettably rather common at many sites but cannot be used for CSP yield analysis. Several error sources cause reduced data quality and completeness. The most common examples are broken sensors, sensor soiling, shading impacts caused by surrounding objects or animals and power outages. Most of those influences can be minimized by steady, frequent and thorough monitoring combined with regular site visits including maintenance and cleaning of the sensors. Some influences on the data can be treated–e.g. the signal reduction due to soiling can be corrected using a linear or more complex cleanliness reduction between two cleaning events, depending on the type of soiling. More difficult to treat are e.g. data gaps. These methods and corrections via interpolation or filling data from close stations or modelled data are required to determine the direct normal irradiation of an entire year. However, the accuracy of the filled or soiling corrected data is reduced and is therefore marked as described in [4]. Text comments, automatic flags from ENDORSE [5] and flags of data manipulation methods have been set for the documentation of data quality. For all stations data availability, annual direct normal irradiation, annual global horizontal irradiation and sensor soiling have been evaluated, to be found below.

Data Completeness

Before evaluating the physical parameters, the completeness and quality of the datasets collected by the ten enerMENA stations is illustrated. The monthly completeness of DNI data in percent for every station and every month is shown in Table 2 below, leaving fields of 100 % availability green without any number and white if no data has been collected. In the second column of the table the total completeness of every station is listed without considering the months of construction and commissioning of the station as they use to be incomplete. One can see that the more robust ‘RSI’ stations Erfoud and Zagora reach significantly higher completeness than the more complex stations with thermal sensors (average of 99.4 % for the RSIs instead of 93.6 % for the thermal sensors). Data completeness analyses from the further numerous RSI stations monitored by the company CSP Services yield a similar number than those derived here within the enerMENA project. Ma'an reaches 100 % completeness due to a neighboring station which can be used in cases of data loss. Therefore Ma'an has been excluded from the completeness analysis. The third column shows the total available data in months in which the stations of Ma'an and Tataouine reach the largest number of months due to their early construction date and long periods of continuous operation. It should be mentioned that data with tracking errors are marked in the data sets and excluded for the completeness analysis.

TABLE 2. Completeness of the enerMENA stations DNI data in 10 min resolution. In the second column the total completeness over all years is listed whereas the third column shows the total available amount of DNI data in months. The value in brackets refers to data completeness after filling gaps with data from a neighboring station. Green fields mark complete months and white fields empty ones. A number in % is only set for incomplete months. The two stations at the bottom Erfoud and Zagora use RSIs, all other stations thermal sensors.

Site	Total data completeness	Total available data in months	2011 J	F	M	A	M	J	J	A	S	O	N	D
Tataouine	88.3%	47.7												
Ma'an	(100%)	53.6	58									98		
Oujda	87.2%	40.5								43		99		
Cairo	97.8%	35.4												
Ghardaia	94.0%	28.2												
Adrar	98.8%	32.7												
Missour	98.3%	24.6												
Tantan	90.8%	22.6												
Erfoud	98.7%	24.6												
Zagora	100.0%	24.9												

Site	2012 J	F	M	A	M	J	J	A	S	O	N	D
Tataouine												
Ma'an												
Oujda							99	89		87		
Cairo						24	80					89
Ghardaia									1			
Adrar									11			
Missour												
Tantan												
Erfoud												
Zagora												

Site	2013 J	F	M	A	M	J	J	A	S	O	N	D
Tataouine						51			96	85		
Ma'an												
Oujda											84	
Cairo		94		99	96		94	98	93			
Ghardaia			94			90		99	96			
Adrar		98	89							96		
Missour					2							
Tantan						83						
Erfoud						95						
Zagora						92						

Site	2014 J	F	M	A	M	J	J	A	S	O	N	D
Tataouine				53								91
Ma'an												
Oujda	95			99	90	49	91	59				
Cairo		96										94
Ghardaia						90	92	31	47	87		
Adrar	95									91		
Missour				81	80							99
Tantan		86	97	53	99							
Erfoud					69							
Zagora												

Site	2015 J	F	M	A	M	J
Tataouine	94	96				
Ma'an						
Oujda	83				86	
Cairo					92	95
Ghardaia						
Adrar					92	98
Missour						97
Tantan		91	75	10	75	93
Erfoud						
Zagora						

In order to get an overview of the site characteristics and the completeness and quality of the data, e.g. DNI data can be plotted in a carpet plot over a running day number (RDN) and Hour of Day (HOD) or over azimuth and elevation. As an example of long term measurements the data of Ma'an for the years 2011 to 2014 is shown in Fig. 3. On this site DNI is measured with a pyrheliometer mounted on a solar tracker. In the first plot one can see clear sky periods of several months during summer and autumn, visible as periods of mainly red color. Also data gaps can be detected easily as white stripes. Shading by obstacles can be detected in the RDN-HOD plot via blue stripes covering several days within regions with non-zero DNI values, see Fig. 4.

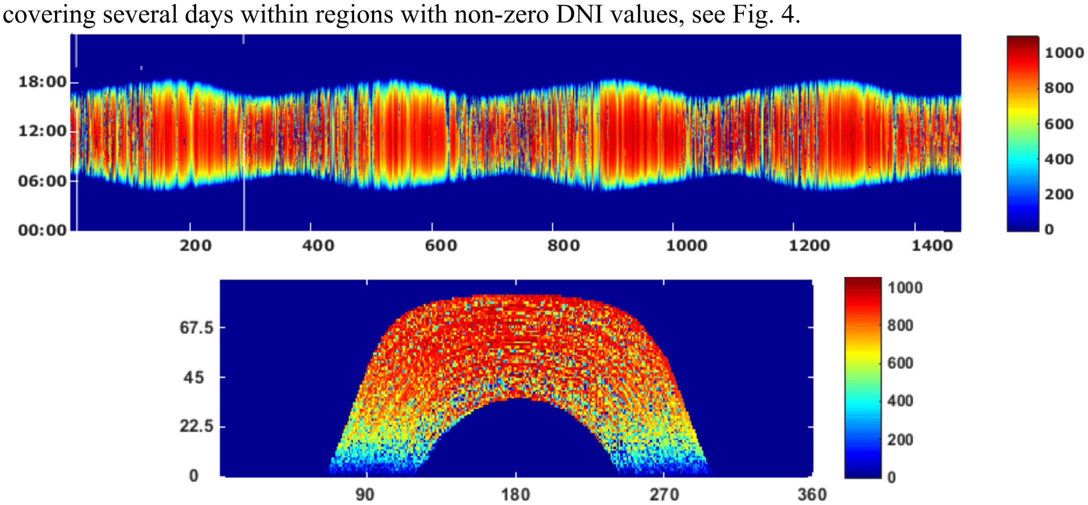

FIGURE 3. DNI measured by a pyrheliometer in Ma'an, Jordan (color bar in W/m²). Above plotted over a running day number (RDN) and Hour of Day (HOD) and below over solar azimuth and elevation angle. RDN = 0 is Jan. 1st, 2011.

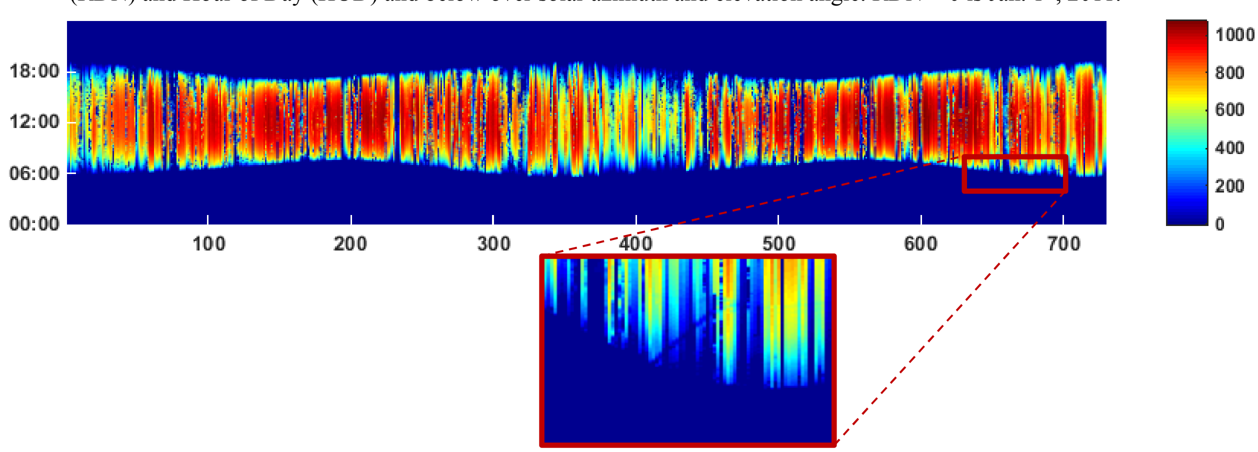

FIGURE 4. DNI overview graph as in the upper plot in Figure 3, but for Zagora, Morocco (color bar in W/m²) with July 1st, 2013 as RDN = 0. The detail plot in the lower part of the figure shows an obstacle visible as a diagonal blue line in the data.

For comparison the DNI data collected by a RSI of the meteorological station in Zagora, Morocco, is shown below starting from July 1st, 2013 and covering two complete years. In the first plot an artefact in the data due to shadowing by an obstacle can be seen, visible as a diagonal blue line. Such obstacles are usually detectable in a proper site evaluation; however it is regrettably not always possible due to security or practical reasons to find a site without any obstacles. Therefore a proper site description is important and gives way to detect and in consequence correct and eliminate such influences from the data set. In both plots (of the same type as above) it can be seen, that the highest DNI values are reached in winter for relatively low elevation angles. This is due to the lower sun earth distance in winter and even more due to the typically lower turbidity in winter that overcompensate the higher air mass [6]. Although in Zagora there are many days with high DNI no clear sky periods of several months can be seen. From this quick overview, one can also see the good completeness of this dataset.

EVALUATION OF THE DATA AND MEASUREMENTS

Sensor Soiling

The measurement of irradiance and especially of DNI is generally sensitive to sensor soiling. However, it makes a difference if a measurement equipment is operated at a manned place and regularly maintained like e.g. at a University or if it is collocated at a remote site where frequent maintenance is hardly feasible. Moreover, regional differences in soiling probabilities have been observed [7]. At some sites a daily signal reduction of up to 1 % or more can occur. In order to assure high data quality regular sensor cleaning is crucial, especially for the dustier sites. Nevertheless even with proper cleaning steps in the signal occur at the moment of cleaning. Those cleaning events can be documented listing the cleaning times and signal rise allowing for a DNI soiling correction. This correction assumes a linearly soiling between two cleaning events; however also different approaches are possible and detectable for experts. Fig. 5 shows how the erroneous data points are corrected and flagged.

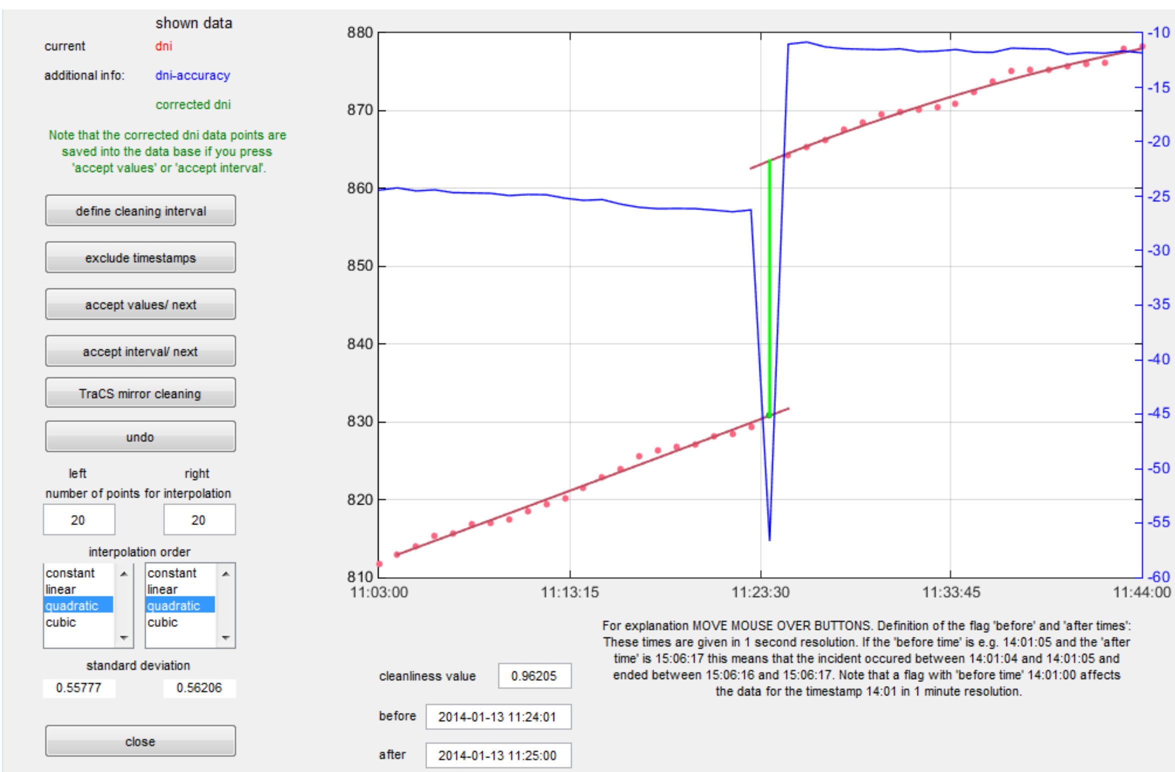

FIGURE 5. The evaluation of a cleaning event in Adrar, Algeria, on January 13th, 2014 in the DNI[W/m^2] data. In this particular case only one data point at 11:24 o'clock is interpolated and being flagged. The green line shows the assumed signal step of about 32 W/m² and at its lower end lies the interpolated data point. The MDMS software [4] permits interpolation of different order and number of interpolation points in order to perform every correction as good as possible.

Collecting all the cleaning events, also those of constant irradiance at the cleaning event due to clean sensors before cleaning, one can calculate the average *cleanliness* of the sensors. The *cleanliness* is defined as

$$cleanliness = DNI_{soiled} \; / \; DNI_{clean} \quad (1)$$

with the DNI measurement with a soiled sensor DNI_{soiled} and the DNI measured for the same conditions with a clean sensor DNI_{clean}. The *cleanliness* is a measure that includes the effects of both the soiling rate due to dusty air and the frequency of sensor cleaning. The latter can be improved by daily cleaning which is of high importance. This is necessary particularly at sites with pyrheliometers measuring the DNI as they are more sensitive for soiling than RSIs due to their clear optics and scattering losses in the instrument [7-9]. The DNI sensor soiling has been evaluated trying to cover one complete year starting in July 2014. In cases of missing cleaning documentation those intervals have been excluded and anterior intervals have been evaluated. The exact intervals with the number of evaluated cleaning events are listed in Table 3. In Fig. 6 one can find the *cleanliness* for all stations, showing Ma'an and Cairo as comparably soiled sites whereas the DNI data from Tataouine and Oujda is less affected by soiling. In any case one needs to mention that those numbers only give a rough idea of the site soiling as cleaning events cannot always be evaluated, e.g. when no signal step can be retrieved from the DNI data due to clouds. In this case the coincidence between the measured DNI and the DNI calculated from the measured GHI and DHI has been used, which assumes approximately clean GHI and DHI sensors. Therefore the calculated values shown in the bar diagram in Fig. 6 can only give a lower boundary of the real soiling. To complete the information used for the calculation of the average *cleanliness* the first and last date of evaluation as well as the number of evaluated cleaning events is provided in Tab 3.

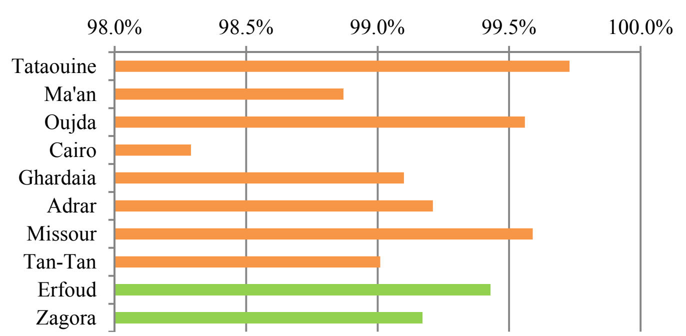

FIGURE 6. DNI sensor average *cleanliness* over one year shown for every enerMENA station. For details of the evaluated data see Tab. 3.

TABLE 3. Average cleanliness for every station and intervals as well as number of cleaning events used for its calculation

Site	Average cleanliness	First date	Last date	Number of evaluated cleaning events
Tataouine	99.7 %	September 8, 2014	July 11, 2015	155
Ma'an	98.9 %	July 16, 2014	July 12, 2015	119
Oujda	99.6 %	January 6, 2015	July 7, 2015	135
Cairo	98.3 %	July 15, 2014	July 12, 2015	164
Ghardaia	99.1 %	January 16, 2014	July 6, 2014	41
Adrar	99.2 %	October 9, 2014	July 12, 2015	185
Missour	99.6 %	August 5, 2014	July 8, 2015	197
Tan-Tan	99.0 %	July 26, 2014	June 1, 2015	84
Erfoud	99.4 %	August 26, 2013	May 6, 2015	28
Zagora	99.2 %	July 14, 2014	June 30, 2015	31

The mean cleanliness averaged over all 'thermal sensors' stations is 99.2 % being slightly smaller than the cleanliness of 99.3 % averaged over the two RSI stations. This result is remarkable because it is detected from the measurement signals that the RSIs are in average cleaner than the thermal sensors. However this result needs to be analyzed more detailed: the RSIs are cleaned approximately 5 times less than the thermal sensors. The result is not that soiling with both types of instruments is the same but that the same order of cleanliness is achievable with both types of instruments; however with 5 times higher effort and costs for the thermal sensors. This is a huge advantage for the maintenance efforts and costs of stations equipped with RSIs, especially when located remote. The recommendations are to clean thermal sensors daily or at least every working day and to clean RSIs once every week (usually once a week is sufficient here).

Annual Irradiation and Further Meteorological Parameters

As the meteorological measurements already cover at least two years for every station, parameters like the average annual direct normal irradiation (AADNI) and the average annual global horizontal irradiation (AAGHI), average temperature, relative humidity and wind speed can be calculated. For every station the maximum number of available years has been evaluated. Occurring data gaps have been filled following the rules by Hoyer Klick [10]. Simplified they can be stated as:

- Gaps of up to 3 hours should be interpolated.
- Gaps from 3 h to 4 days should be filled by copying the missing hours from neighboring days.
- Gaps with more than 4 days should be filled by copying the data of the same day of year from another year.

The values of the enerMENA datasets after application of those rules are listed below in Table 4.

TABLE 4. Average annual irradiation and mean values of selected meteorological parameters of the enerMENA stations. The 'first date' and 'last date' indicate the evaluated interval for each station.

Site	**Evaluation interval**	**AAGHI[kWh/m^2]**	**AADNI[kWh/m^2]**	**Temp. [°C]**	**Rel. Hum. [%]**	**Wind speed [m/s]**
Tataouine	June 1, 2011 - May 31, 2015	2097	2291	20.3	52	3.3
Ma'an	June 1, 2011 - May 31, 2015	2327	2798	17.9	39	3.8
Oujda	June 1, 2012 - May 31, 2015	1928	2048	17.5	60	2.1
Cairo	June 1, 2012 - May 31, 2015	2090	2054	23.5	53	2.6
Ghardaia	June 1, 2013 - May 31, 2015	2161	2355	21.1	35	2.3
Adrar	June 1, 2013 - May 31, 2015	2296	2326	25.2	22	3.1
Missour	June 1, 2013 - May 31, 2015	2070	2307	18.1	48	3.7
Tan-Tan	June 1, 2013 - May 31, 2015	1872	1497	19.0	83	4.3
Erfoud	June 1, 2013 - May 31, 2015	2049	2229	21.9	33	3.1
Zagora	June 1, 2013 - May 31, 2015	2172	2328	23.5	29	3.8

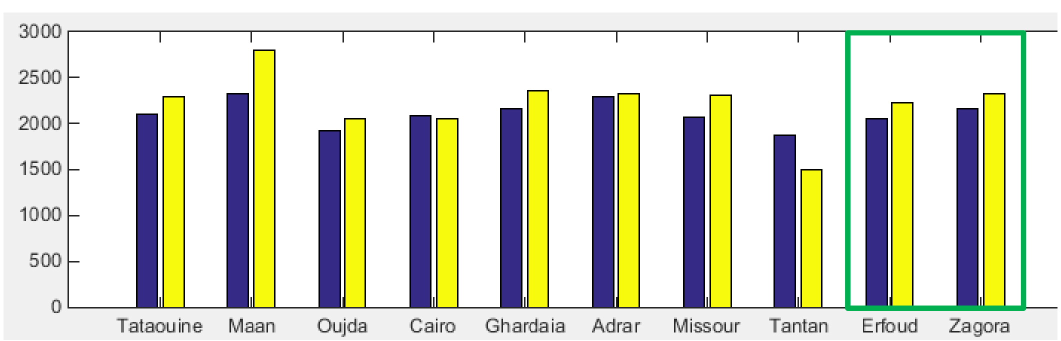

FIGURE 6. Average annual global horizontal (AAGHI, blue) and direct normal (AADNI, yellow) irradiation in kWh/m^2 of the enerMENA stations.

As the average annual global horizontal and direct normal irradiation are of special interest they are shown in Fig. 6. It has to be stated that the cited values refer to the average of two, three or four annual irradiation values, depending on the number of available years for each station. Hence, the given annual irradiation values may deviate notably from the expectable long-term values. A site of extraordinary high annual AADNI of 2798 kWh/m^2 is Ma'an in Jordan, which is situated at a relatively high altitude of 1012 m above mean sea level. It is visible that the AAGHI do not vary much between the different sites and are below the values of the AADNI except for the station in Cairo and Tan-Tan. In Cairo the slightly higher AAGHI might be explained by the comparably high turbidity at that site. The comparably low AADNI of 1497 kWh/m^2 for Tan-Tan is due to clouds and frequently reported fog, which is also linked to a high relative humidity of 83 % averaged over all the year. The effect of clouds was analyzed further using satellite data. Meteosat Second Generation (MSG) with its Spinning Enhanced Visible and Infrared Radiometer (SEVIRI) instrument scans the Earth within 15 minutes and provides satellite imagery with several km spatial resolution (3 km at nadir). The AVHRR Processing scheme Over cLouds Land and Ocean (APOLLO) has been adapted to the MSG SEVIRI instrument. It discretizes all pixels into four different groups called cloud-free, fully cloudy, partially cloudy (i.e. neither cloud-free nor fully cloudy) and snow/ice-contaminated, before deriving physical properties ([11-14]). Each fully cloudy pixel is checked to see whether it is thick or thin cloud, depending on its 11 µm and 12 µm brightness temperatures and, during daytime, its channel 0.6 µm and 0.8 µm reflectances. Optically thin clouds (with no thick clouds underneath) are taken as ice clouds, i.e. cirrus, whereas thick clouds are treated as water clouds. Having time series of such cloud information at the location of interest and their surroundings, we define area-specific cloud situations by following ideas of [15] in the following manner:

- clear = at least 90 % cloud free pixels in a local surrounding; a clear pixel is defined as having max 10 % cloud coverage.
- bright overcast = more than 50 % of the local surroundings are cloudy pixels, but at least 20 % of them are thin ice clouds only
- dark overcast = more than 50 % of the local surroundings are cloudy pixels, and more than 80 % of them are not thin ice clouds
- partly cloudy = the rest

For Tan-Tan, the amount of clear area cases is very low with 35 % of all daytime cases only. Also, the cloudy area situations are typically classified as dark overcast or partly cloudy, showing also for the partly cloudy cases a much higher value than other enerMENA stations. Those two classes typically result in very low DNI values, while bright overcast situations are typically thin ice clouds, which at least result in medium DNI values.

CONCLUSION AND ACKNOWLEDGEMENTS

Within the enerMENA project a valuable network of stations has been setup in the MENA region. It fills the geographical gap left by other radiation measurement networks. The data is now available for validation of satellite and model derived data, validations of nowcastings and project planning. We furthermore investigated the typical sensor cleanliness for the different sites and could corroborate the recommendation that daily cleaning is crucial for the measurement quality of pyrheliometers. The cleanliness of DNI measurements taken by RSIs and pyrheliometers has been evaluated. It turns out that the RSI stations with a cleaning frequency of about 1 per week results in an even higher cleanliness as for pyrheliometers which are cleaned week-daily. Therefore high accuracy measurements by comparably expensive thermal sensors make sense only if they are accompanied by frequent cleaning and maintenance. The latter also assures a good data completeness as malfunction of sensors is detected early. Average completeness of 93.6 % for the stations with thermal sensor and 99.4 % for the RSI stations have been found showing an advantage of the RSIs. In order to gain long term radiation data and further relevant meteorological parameters for CSP, it is desired to continue the operation of the stations and to enhance them with advanced instrumentation.

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