Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 – 19 September 2014

Solar Resource Assessment over Kuwait: Validation of Satellite-derived Data and Reanalysis Modeling

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Abstract

The Kuwait Institute of Scientific Research (KISR) has been mandated to develop a first industrial complex of wind, PV and CSP systems at Shagaya, Kuwait. To that end, KISR is also engaged in a full-fledged resource assessment program, based on both ground-based observations and extensive modeling. In this study, ground observations of solar radiation at 5 sites are compared to modeled predictions from various sources. These include a 19-year time series of GHI and DNI obtained from GeoModel's SolarGIS satellite model, a 35-year GHI time series from NASA's MERRA reanalysis model, and a 23-year monthly climatology of GHI and DNI from NASA's SSE database. The long-term monthly mean GHI values obtained from MERRA and site-adapted SolarGIS show reasonable agreement. In contrast, the various predictions of GHI from the raw SolarGIS and the SSE GHI data, as well as most predictions of DNI, exhibit significant differences, likely because of diverging estimates of aerosol effects. The SolarGIS time series is significantly improved by its site adaptation. When derived from either MERRA or SolarGIS, both the GHI inter-annual variability and its long-term trend disagree substantially, which requires additional scrutiny.

Keywords: Solar resource assessment; SolarGIS; MERRA; aerosols; direct normal irradiance

1. Introduction

Kuwait is actively pursuing the development of renewable energy (RE) to help decrease its domestic consumption of oil. The Kuwait Institute of Scientific Research (KISR) has been mandated to develop a first phase of large RE systems and study their performance. This project, now in its execution phase, is planned to include 10 MW of wind, 10 MW of photovoltaic (PV), and 50 MW of concentrating solar power (CSP) systems. A reliable resource assessment and characterization are the first steps for a successful introduction of renewable energies and, in particular, solar energy applications. The best option is to have data from radiometric/weather stations covering at least 10 recent years (but optimally longer) of continuous measurements. In the vast majority of cases, no measured data or long-enough time series exist at proximity of the development sites under scrutiny. The usual practice is to install such a station at a project site as soon as that site is selected for development, collect local radiation and weather data, and use them for validation or adaptation of modeled data, etc. However, only very recent data can be collected this way, which is not enough to describe the long-term weather variability.

Because of these limitations, solar resource assessments need to rely on long historical records of modeled data. Various types of models are available, and can be classified as either numerical weather prediction (NWP) models or satellite models. Models of the first category are those that are primarily used to provide weather forecasts, but they can also be used retroactively in reanalysis mode to provide continuous modeled records of many weather variables. Examples of worldwide reanalysis data are those derived from the Modern-Era Retrospective Analysis for Research and Applications (MERRA), Climate Forecast System Reanalysis (CFSR), or ECMWF re-analysis (ERA) models, developed by NASA, NCEP/NOAA, and ECMWF, respectively. One of their numerous outputs is global horizontal irradiance (GHI), which is central to this study. NASA's Surface meteorology and Solar Energy (SSE) database uses other techniques to offer global gridded daily and monthly-mean GHI data, as well as monthly mean direct normal irradiance (DNI) data. Despite its coarse resolution (1x1°), this database is popular because it covers the world and is freely available. In contrast, satellite models used in resource assessment studies are typically developed on a commercial basis. They rely on satellite imagery to locate the position of clouds and evaluate their radiative impact (as well as that of other atmospheric elements) on GHI and DNI. Examples of such models are Heliosat and GeoModel's SolarGIS. Typically, reanalysis data have a longer record (dating back to 1979 or before) compared to satellite-derived data, but conversely have lower spatial and temporal resolution. The two types of data are used in this study in an attempt to reveal potential differences or synergies.

Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.08.01 Available at http://proceedings.ises.org

At sites where *long-term* radiometric measurements are not available, combining *short-term* measurements and data from meteorological models improves understanding of long-term weather and solar radiation characteristics, and can decrease the original model bias significantly (see, e.g., Gueymard et al., 2012). Over arid or desert areas with low cloudiness, this bias is most likely caused by the use of imprecise aerosol inputs (Cebecauer et al., 2011; Gueymard, 2011). Data providers refer to the model/measurement combination process just mentioned as “site adaptation” or “record extension”. One of the goals of this study is to evaluate the effectiveness of one of these techniques.

A first solar resource assessment was carried out by KISR in 2010 to generate solar irradiance and other related meteorological data. The reported data, although useful, was generally incomplete, not quality assured and had too large uncertainties to design solar power plants. In 2012, recognizing these problems, KISR engaged in a full-fledged RE resource assessment program, based on both ground-based observations and extensive satellite-based modeling. This report provides preliminary results about the solar resource in Kuwait, and discusses what can be expected from state-of-the-art satellite-derived irradiance predictions and reanalysis models in a region where a major source of variability is in the form of dust aerosols.

2. On-site measurements

2.1 Description of sites and instruments

The objective of the KISR measurement campaign is to acquire high-accuracy solar and weather data in a long-term commitment of reducing uncertainties in the solar resource at different sites, and also as a way to derive solar resource maps and cumulative data of verified accuracy. Five radiometric stations have been installed in Kuwait during 2012. These stations are uniformly distributed (Fig. 1a). As a desert country, Kuwait is characterized by intensely hot and dry summers (between May and October), with average highs ranging from 42°C to 49°C, and short winters (December to February), when air temperature often drops below 10°C. From June to September very low cloud cover is recorded, with small regional differences across the country, while strong winds and heavy dust storms frequently occur and may last for days.

To use the solar resource in an optimal way, the proper locations of the projected power plants and weather stations must be carefully considered. In particular, the Shagaya location (Fig 1b) is of paramount importance here because it is where the RE installations will be first deployed. That location experiences short rainy seasons spread across winter months. The thunderstorm season (November) is followed by a period of cloudy weather and cold temperatures (as low as 0°C) until February or March. The autumn and spring seasons are distinguished by their brevity and intermittent weather patterns. Both Shagaya and Kabed are equipped with two separate monitoring systems: (i) three thermopile radiometers measuring GHI, DNI, and diffuse irradiance (DIF); and (ii) a rotating shadowband irradiometer (RSI) independently measuring the GHI and DIF components and deriving DNI by difference, using a silicon detector with proper temperature and spectral corrections. The three other sites are equipped with only a thermopile pyranometer for GHI and an RSI. Other weather variables (including temperature and wind) are also measured at all sites.

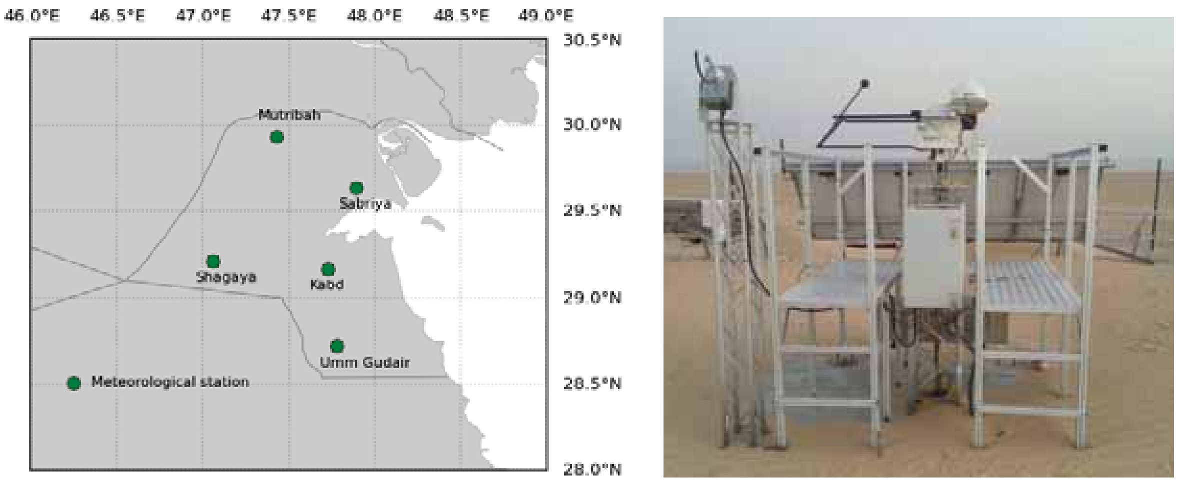

Fig. 1: (a) Map showing the position of the five radiometric stations; (b) Shagaya station: platform setup for one pyranometer, one pyranometer with shading ball, one pyrheliometer, one RSI, and standard weather sensors.

A high quality of the radiation data record is achieved by maintaining a stringent program of *daily* inspection and cleaning at the two primary stations (Shagaya and Kabed), and a relaxed weekly inspection and cleaning at the three other stations.

2.2 Quality Control

A first round of quality control (QC) was applied to the observations by the provider of the weather stations. GeoModel Solar applied a second round of QC prior to their undertaking of the site adaptation process. That round of QC was based on the methods assembled into the stringent SERI-QC procedures (NREL, 1993). The ground measurements were also inspected visually. Moreover the three components (DNI, DIF and GHI) obtained independently by the dual setups (thermopiles + RSI at Shagaya and Kabed) could be subjected to robust quality control based on redundancy tests. Data not passing QC were excluded from further analysis. The effect of the different steps of the QC process is summarized in Table 1. The solar irradiance and weather data are ultimately provided in both 10-minute and hourly time steps.

Tab. 1: Percent of measured pyrheliometer DNI, RSI DNI, and GHI data samples that did not pass various quality control tests.

Type of test	Shagaya			Kabed		
	RSI-DNI	Pyrheliometer	Pyranometer	RSI-DNI	Pyrheliometer	Pyranometer
Physical limits test	6.8%	4.9%	0.7%	7.7%	5.1%	0.7%
Visual test	0.2%	0.1%	0.1%	0.0%	0.2%	0.2%
Redundancy test	0.0%	0.5%	0.5%	0.0%	0.0%	0.0%
Total	7.0%	5.5%	1.3%	7.7%	5.3%	0.9%

The QC results indicate that only a very small fraction of data did not pass the physical limits test. Most of these occurrences represent data that had very small shifts in time recording, or that were measured around sunrise and sunset, when sensors are less accurate due to cosine error. The QC tests used in this study are as stringent as possible to avoid any ambiguity when comparing measured with satellite data.

2.3 Evaluation of stations

The comparison of quality-controlled DNI or GHI measurements from two independent instruments typically shows differences, which can be expected. In general the GHI data obtained from RSIs shows slightly lower values than that from pyranometers. In contrast, the RSI-derived DNI is similar to those from the pyrheliometer at Shagaya, but is slightly lower at Kabed (-2.3%). These differences are within the accuracy specifications of the RSI instrument. At all five sites, the comparison of GHI measurements shows lower readings from the RSI for high irradiances. This effect appears systematic, and reaches about 2.5–5% above 1000 W/m^2. As could be expected, the discrepancy is less for GHI than for DNI and varies between sites. The overall difference between RSI and pyranometer measurements of GHI ranges from -0.1 to -2.7%. The measurements from the Um Gudair and Kabed stations show slightly higher spread of values compared to the other three stations, which may indicate issues with, e.g., sensor soiling. Nevertheless, these differences are still within the accuracy specifications of the RSI instrument.

Tab. 2: Difference between RSI and pyranometer or pyrheliometer for five sites, in percent.

Difference (%)	Shagaya	Kabed	Mutribah	Sabryia	Um Gudair
DNI (RSI – pyrheliometer)	-0.1	-2.3	—	—	—
GHI (RSI – pyranometer)	-0.1	-2.3	-1.5	-1.3	-2.7

The scatterplot of DNI values (Fig. 2) closely respects the expected diagonal in the vast majority of cases, with some clustering above the diagonal for Kabed. Only a small amount of data points (negligible compared to the whole dataset) shows a larger disagreement for low irradiances. For Shagaya, the DNI data streams measured by the two instruments over the whole period (Sep. 2012 to Aug. 2014) are remarkably similar. The monthly-mean difference between the global and direct irradiations measured at Shagaya with an RSI relative to those measured with thermopile radiometers is shown in Fig. 3. This difference is remarkably low during the 23-month period—especially for DNI, for which the difference is normally within ±1.5%. This can be attributed to the stringent calibration procedure that was undertaken prior to commissioning of the stations, and to the careful maintenance implemented since then. Notable exceptions occurred for DNI in November 2013 and April 2014, when the mean difference reached 12.4% and 3.2%, respectively. For a few days, the station had a problem with the backup batteries. This triggered the data-logger control software to reduce power consumption by shutting down the tracker of the pyrheliometer. The RSI could continue working normally because it does not consume much power. Thus, in such cases, more accurate DNI data are provided by the RSI. This perfectly illustrates the benefit of redundant measurements for the best possible quality-assured solar resource data, and also the importance of considering data breaks appropriately when evaluating monthly statistics (Roesch et al., 2011).

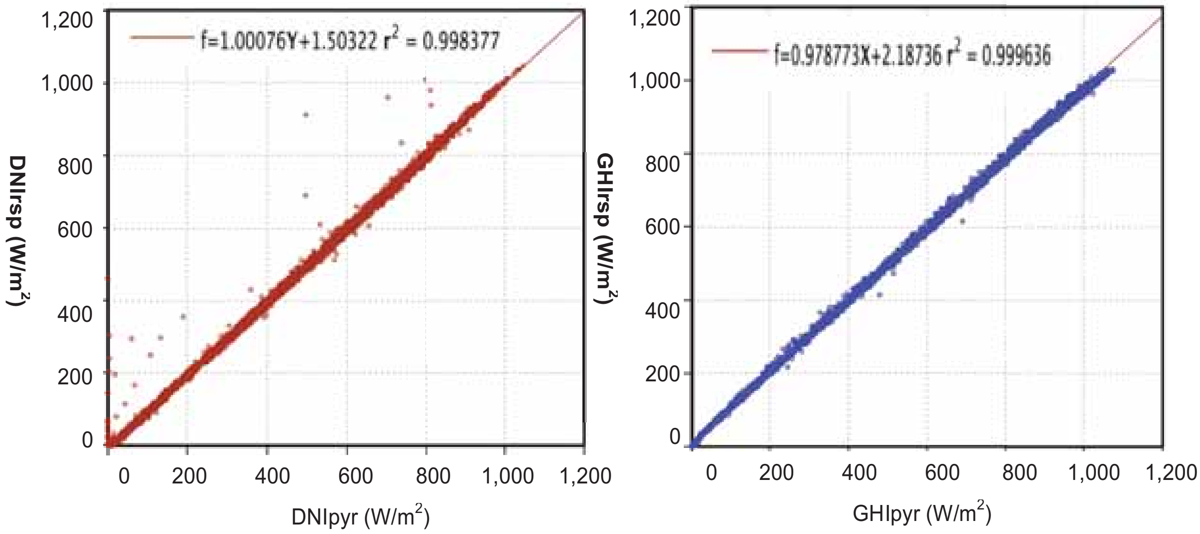

Fig. 2: Comparison of pyranometer/pyrheliometer and RSI measurements at Kabed. The X-axis is for measurements by pyrheliometer (DNI, left plot) or pyranometer (GHI, right plot). The Y-axis is for the RSI sensor.

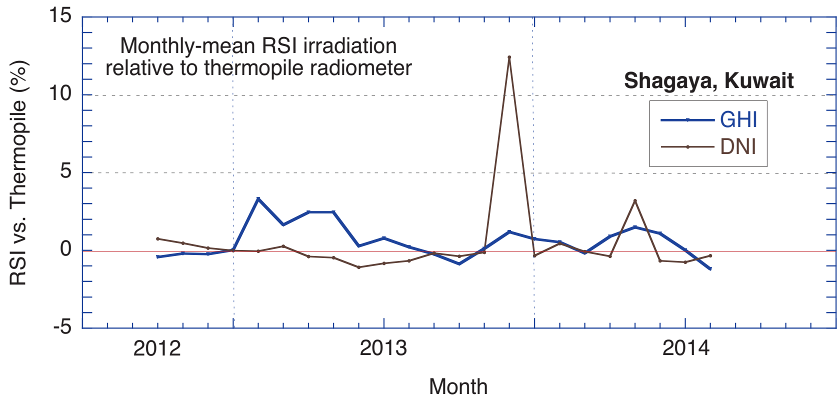

Fig. 3: Mean monthly percent difference between RSI and thermopile radiometer measurements for GHI and DNI at Shagaya.

The pyrheliometer (CHP1) and pyranometer (CMP21) used at all stations belong to the highest class of instruments available on the market. The RSI, which uses a silicon sensor, has a much narrower spectral response function compared to thermopile instruments. In Fig. 2, this may explain the disagreement between RSI and pyranometer at high irradiance, when the actual solar spectrum could differ from the specific spectral conditions that existed during calibration. Considering the daily cleaning frequency at Shagaya and Kabed, and the low failure rate in the redundancy tests (Table 1), the pyranometer/pyrheliometer setup is considered more accurate than the RSI, except obviously during periods of malfunction of the solar tracker. Thus data from the thermopile instruments were used for site adaptation. At Mutribah, Sabriya and Um Gudair, the relaxed weekly cleaning frequency may have a negative impact on the GHI pyranometer measurements, as this type of instrument is more sensitive to soiling than an RSI. Although the main soiling issues were detected by visual check, some small residual errors may be still present even after QC. For that reason, the site adaptation was based on RSI data for those stations.

3. Results and discussion

3.1 Ground data

The solar resource is found similar at the five radiometric stations, with a slight advantage at Shagaya and Um Gudair (Figs. 4 and 5). Seasonal variations in DNI are slightly skewed towards the second half of the year, due to higher aerosol loads during spring. A lower DNI is observed from October to May, with a maximum occurring in July–August. The effect of aerosols on GHI is not as strong, which induces a smoother seasonal variation, with minimum in November–February and maximum in June–August.

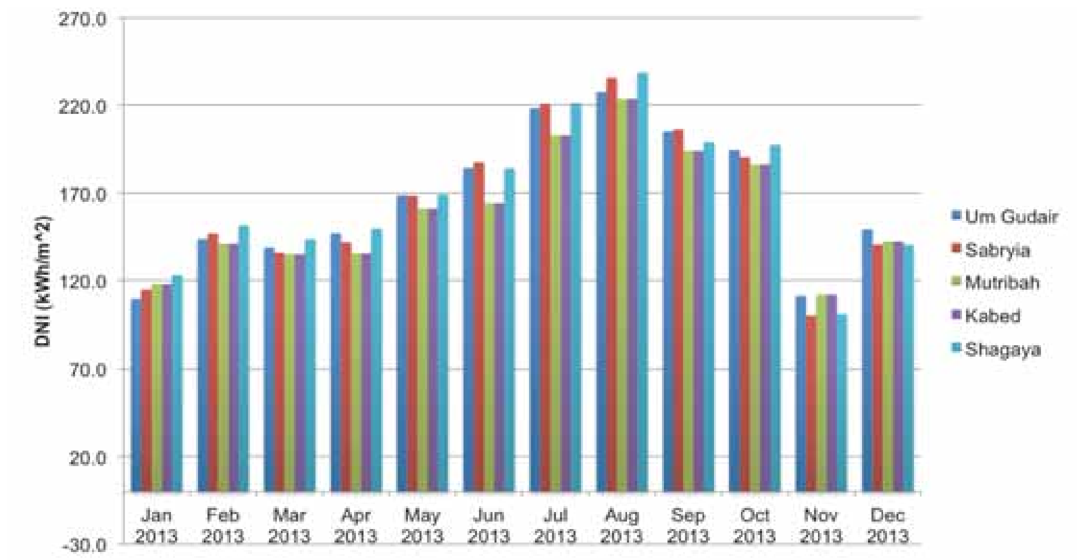

Fig. 4: Monthly DNI totals for the 5 ground stations in 2013

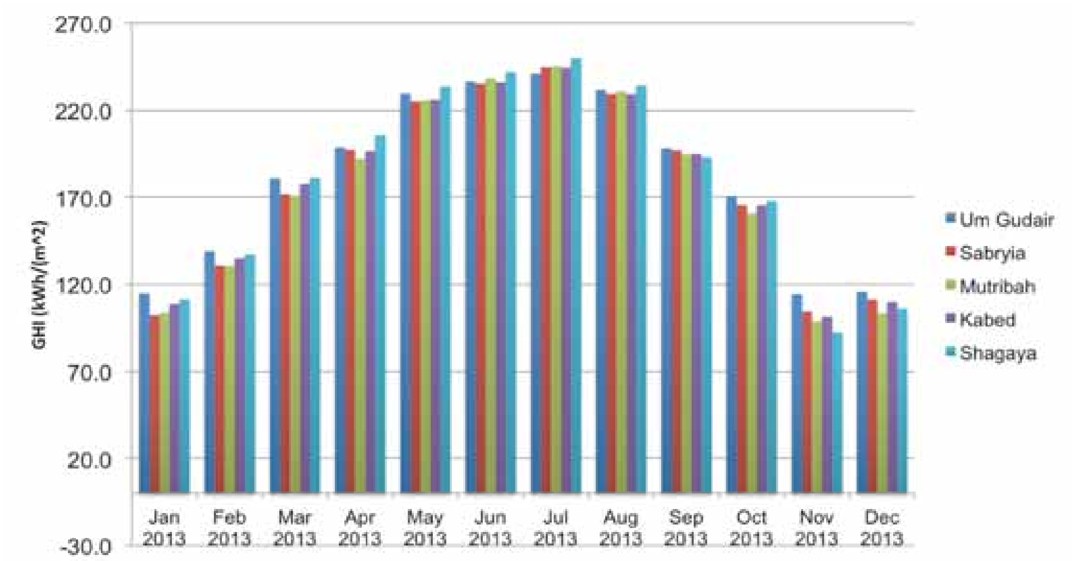

Fig. 5: Monthly GHI totals for the 5 ground stations in 2013.

The dust-impacted spring season is a challenge for maintaining the accuracy of radiation measurements due to rapid soiling and extreme operating conditions. In parallel, the prevalent high atmospheric turbidity increases uncertainty in solar modeling. Therefore the uncertainty in both measurements and modeled data is then higher than during other seasons, or than at other, less dusty sites. The uncertainty in long-term GHI and DNI estimates should be reduced after the ground-measurement campaign reaches a least five years, and by increasing the cleaning frequency of the RSI stations at Mutribah, Sabriya and Um Gudair to, e.g., twice a week. Further work will be devoted to a better knowledge of the temporal and spatial variability of the aerosol regime and its effect on GHI and DNI, e.g., using the sunphotometer now being deployed at Shagaya.

3.2 Satellite Derived-Data

The surface solar irradiance in SolarGIS is obtained from satellite-derived observations and a series of parameterized models describing cloud transmittance, state of the atmosphere, and terrain conditions. The methodology is described in Cebecauer et al. (2010, 2012) and Perez et al. (2013). In particular, the clear-sky irradiance is evaluated by the Ineichen (2008) model, which, however, has been recently found to heavily overestimate DNI under high-turbidity conditions typical of desert environments (Gueymard, 2014). The natural variability in clear-sky atmospheric conditions is determined by changing concentrations of atmospheric constituents, namely aerosols, water vapor and ozone. The cloud index is calculated from routine radiance observations of meteorological geostationary satellites. The Meteosat satellite data used by SolarGIS has a spatial resolution of ≈3–4 km over Kuwait and a temporal resolution of 30 minutes. High-resolution SolarGIS time series of irradiance have been purchased from GeoModel to help the KISR resource assessment program.

MERRA reanalyses use data from global observations covering the "satellite era" (1979 to present) and assimilated into a global circulation model (NASA's GEOS-5). Similarly to other reanalysis projects, the analysis is designed to be as consistent as possible over time and thus uses a fixed assimilation system. The MERRA data considers the orography and roughness of the terrain. The time step is one hour and the spatial resolution is 2/3° long. x 1/2° lat. Unfortunately, MERRA does not provide modeled values of DNI.

The SSE database is derived from satellite observations of clouds for the most part. In the current SSE Release 6.0, the solar and meteorological data span 22 years from July 1983 to June 2005, and GHI (available on a daily basis) is derived from appropriate radiative transfer modeling using cloud-retrieved input data. DNI is empirically derived from GHI, and is only available on a monthly-average basis.

Mean monthly values of GHI and DNI, as obtained from different sources, are compared in Fig. 6. For GHI, the MERRA and "site-adapted" SolarGIS estimates agree relatively well on both their annual averages and seasonal variations. In contrast, the original, or "raw" SolarGIS predictions slightly underestimate during summer, whereas SSE more significantly underestimates GHI during all seasons, compared to the other modeled determinations. This behavior completely reverses with regard to DNI, which makes SSE's long-term annual average DNI 16.5% higher than that of the site-adapted SolarGIS. The latter results are substantially corrected upward during summer compared to the raw SolarGIS data.

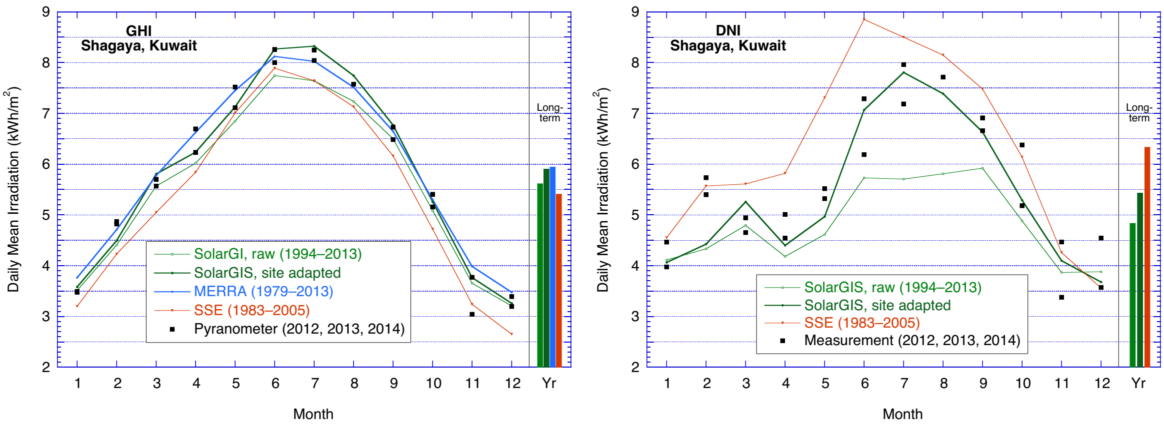

Fig. 6: Modeled and measured monthly-average data at Shagaya for GHI (left) and DNI (right).

As of this writing, the period of measured data is only 23 months, so that their long-term average cannot be calculated yet. The monthly-mean observations are rather displayed in Fig. 6 for each specific year of available data, which provides a preliminary visual appreciation of the interannual variability. Despite the short data period, the current ground observations support the conclusion that, for GHI, MERRA and the adapted SolarGIS provide unbiased monthly estimates, except maybe in November when they might both overestimate.

The situation is more complex for DNI. The raw SolarGIS largely underestimates in summer and February, whereas SSE largely overestimates, except in winter. The SolarGIS site adaptation procedure results in a strong correction during summer. Since summer is virtually cloud-free, this means the adaptation essentially consists in a substantial aerosol correction, thus confirming previous findings regarding significant biases in DNI datasets in regions heavily affected by dust aerosols (Gueymard, 2011; Gueymard et al., 2012).

Over dusty regions, like Kuwait, the site-adaptation procedure appears an essential component of an overall solar resource assessment, by guaranteeing relatively unbiased long-term solar resource time series, and ultimately better bankability of solar projects. In turn, the success of this site adaptation process completely depends on the availability of high-quality and unbiased ground observations during a sufficient period.

The long-term temporal variability in GHI and DNI is an important factor to consider when evaluating the financial risks of large solar power projects, which must maintain their performance in the future, during at least two decades. The GHI anomaly, or interannual variation in GHI of a specific year compared to its long-term average, is shown in Fig. 7. The long-term 1994–2013 mean annual value from the adapted SolarGIS database is chosen here as reference for the MERRA, SSE and SolarGIS anomalies. Interestingly, the adapted SolarGIS and MERRA data agree quite well during the period 1995–2003. Then, however, their predictions develop trends in opposite directions, which is a source of concern. Over the long term, an upward trend (or "brightening") in the resource is apparent when considering the MERRA results, but a reverse trend ("dimming") appears when rather using the SolarGIS data—mostly driven by decreasing GHI since 2003. SolarGIS also has larger interannual variations than MERRA. In contrast, SSE displays an upward trend since the Pinatubo years, with however a remarkable ≈10% reduction in magnitude compared to MERRA. In 1991, the Pinatubo effect impacted SSE by a loss of ≈19% in GHI compared to the previous year, in strong contrast with MERRA, for which the loss was only ≈2%. These findings were not anticipated and call for further scrutiny, since it is essential to correctly evaluate the long-term trend in solar resource.

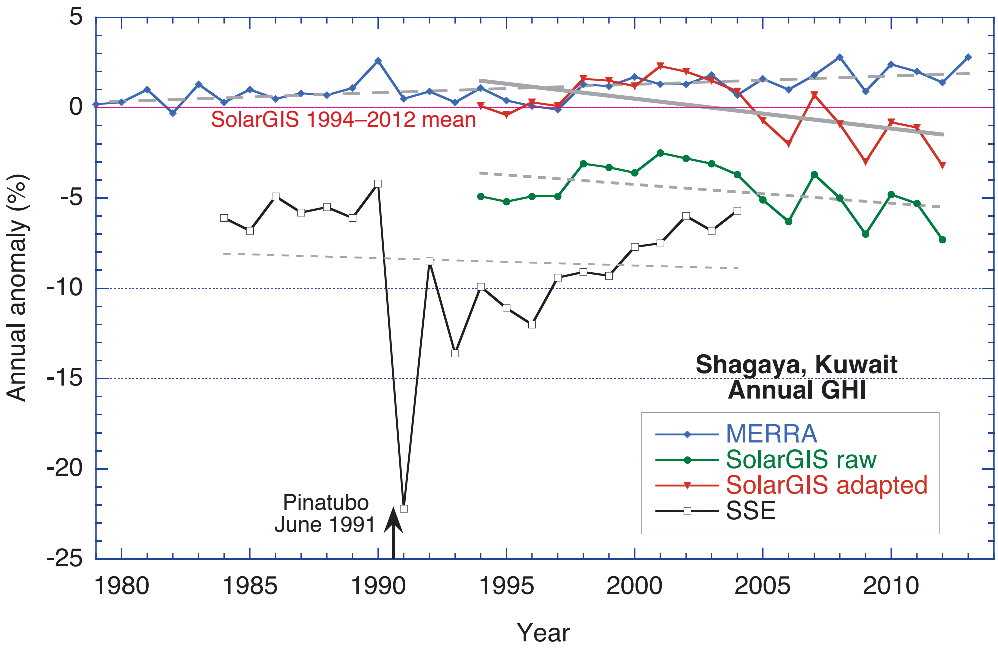

Fig. 7: Annual anomaly in the GHI solar resource and long-term trends at Shagaya obtained from MERRA, SSE and SolarGIS, all relative to the 19-year mean adapted SolarGIS data.

A very important input to radiation models is the Aerosol Optical Depth (AOD). For that quantity, the data source used by SolarGIS is the chemical transport model known as MACC (Monitoring Atmospheric Composition and Climate), which is developed by the European Center of Medium Range Weather (ECMWF), based on the work of Morcrette et al. (2009). In Kuwait the daily variability in AOD can be very high, which confirms previous findings (Gueymard, 2012). An example of daily MACC-derived AOD variability is presented in Fig. 8 for the Shagaya station, after site adaptation corrections.

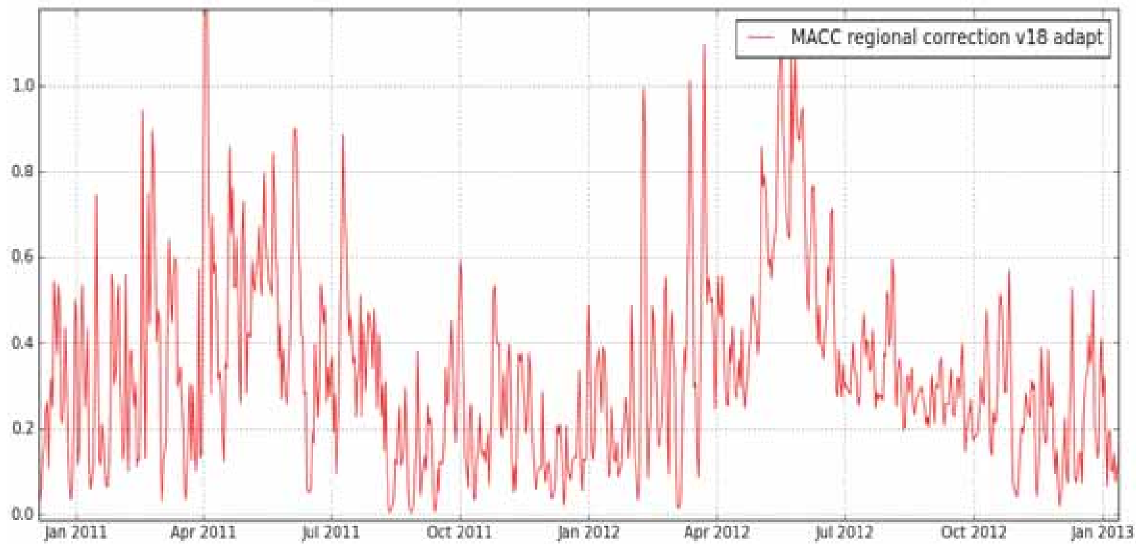

Fig. 8: Daily values of regionally adapted AOD at 670 nm used in SolarGIS for Shagaya, 2011–2013.

Table 3 provides the regionally adapted AOD values obtained by GeoModel after correction of the raw MACC data, based on one year of radiometric measurements at Shagaya. Figure 9 shows calculations of the daily clearness indices K_t and K_b for GHI and DNI, respectively, from 1994 to 2012. The MACC data is available on a 6-hourly basis, but only since 2003. For the years before 2003 (i.e., 1994–2002 in the present case) SolarGIS only uses a monthly climatology obtained from the post-2003 daily data, which introduces a discontinuity. As could be expected, DNI (Fig. 9b) is more affected than GHI (Fig. 9a), since it is ≈3–4 times more sensitive to AOD than the latter (Gueymard, 2012). Separate trend lines for each of the two periods clearly show a brightening effect before 2003 and a dimming effect thereafter. This discontinuity may be related to the change in aerosol data just explained, and/or to an increasing trend in regional AOD since then. The latter explanation would be consistent with the recent dimming period observed in Iran (Rahimzadeh et al., 2014). The discontinuity can also explain the diverging trends observed in Fig. 7 between MERRA and SolarGIS after 2003. This serious issue obviously calls for a more detailed investigation.

Tab. 3: Atmospheric optical depth (AOD) seasonality, as derived from regionally adapted MACC model. Monthly averages of AOD at 670 nm for 2003–2012.

Station	Jan	Feb	Mar	Apr	Jun	Jul	Aug	Oct	Nov	Dec
Shagaya	0.27	0.33	0.33	0.45	0.50	0.39	0.31	0.29	0.24	0.26
Mutribah	0.29	0.35	0.34	0.48	0.51	0.36	0.30	0.29	0.25	0.26
Kabed	0.28	0.35	0.35	0.48	0.52	0.38	0.31	0.27	0.24	0.26
Sabryia	0.28	0.35	0.35	0.48	0.51	0.35	0.29	0.26	0.24	0.26
Gudair	0.28	0.34	0.34	0.46	0.51	0.38	0.30	0.26	0.22	0.25

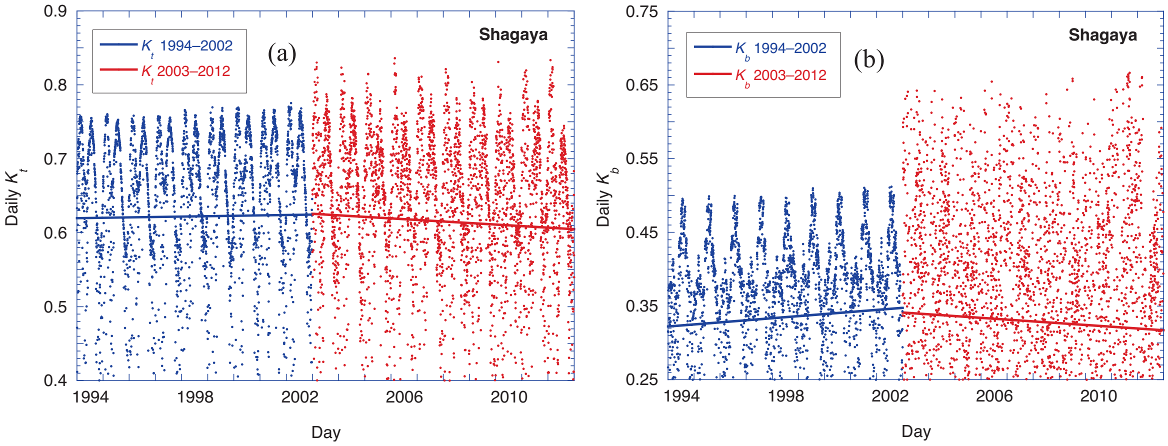

Fig. 9: Adapted SolarGIS daily clearness index and trend lines at Shagaya for 1994–2012; (a) GHI; (b) DNI.

Further analysis on the effect of aerosol on daily irradiation can be seen in Fig. 10a for GHI and Fig. 10b for DNI. For DNI during the period 1994–2002, the daily K_b is much less variable than during 2003–2012 because of the use of long-term monthly-mean AOD data, which tends to heavily compress the daily variance. Although summer months are essentially cloud-free, Fig. 10b shows a high and wide variability in the clearness index from day to day. In Fig. 10, K_t and K_b also display an interesting bi-modal pattern during the year, with two lows in spring (April) and winter (November). This phenomenon is assumed to be typical of desert areas of the region, such as Shagaya. In April, a low-level jet wind stream starts to blow and thus elevates dust, which in turn increases AOD. During winter, dust clouds originating from Syria and Iraq are transported with high-level jet streams and move over Kuwait. This elevated turbidity in November can explain the slight overestimation of modeled GHI and DNI observed in Fig. 6. As could be expected, these seasonal patterns appear more clearly in the case of K_t (Fig. 10a).

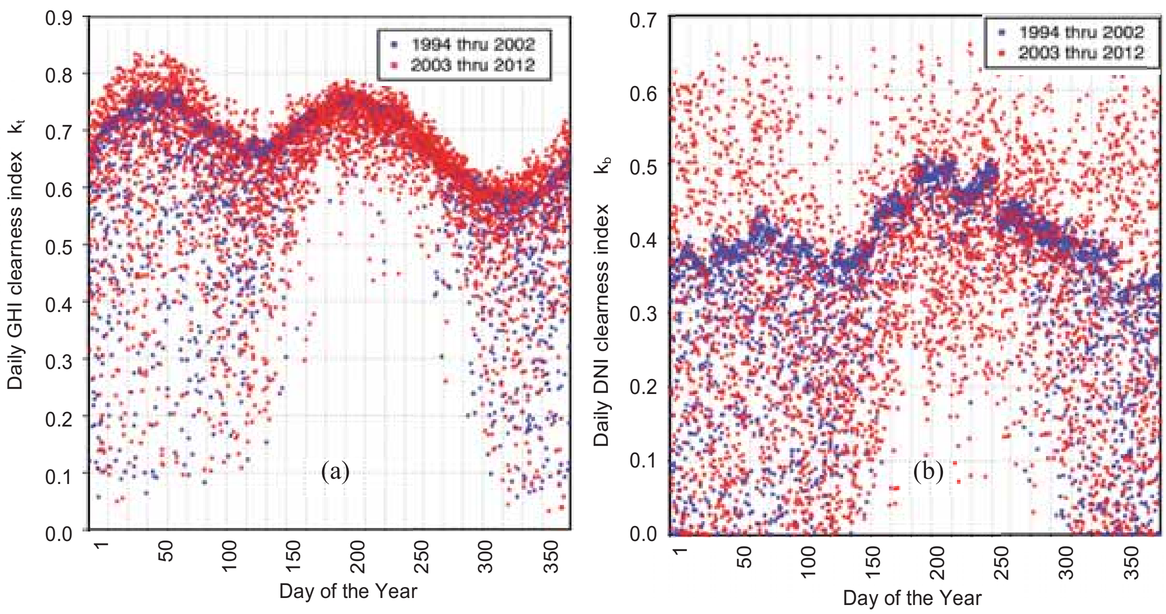

Fig. 10: SolarGIS daily clearness index vs. day of the year for 1994–2012 at Shagaya; (a) GHI; (b) DNI.

As was shown above in Fig. 7, the annual GHI results of the MERRA and SolarGIS models correlate well before 2003. A good correlation is also generally observed on a monthly basis (Fig. 11), although significant deviations between the two models start to develop after 2003, for the possible reasons discussed above.

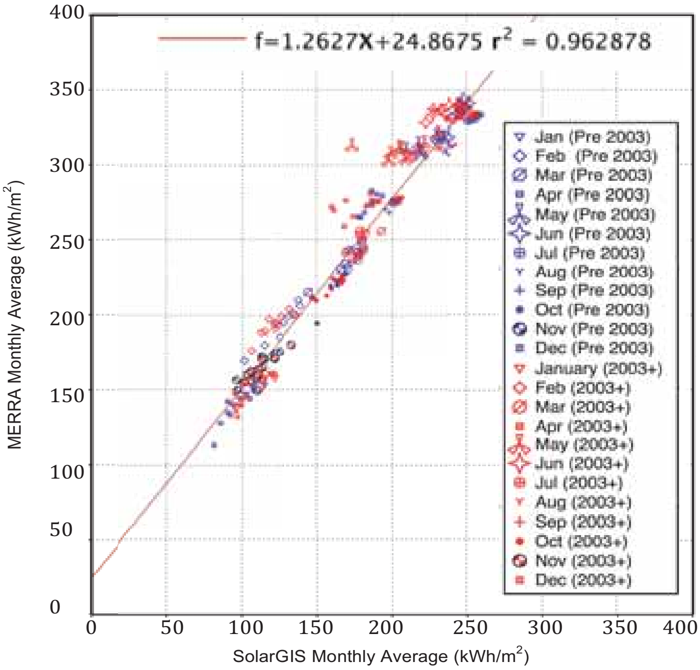

Fig. 11: MERRA vs. SolarGIS monthly-average GHI for the periods 1994–2002 and 2003–2012 at Shagaya.

4. Conclusion

The resource assessment campaign undertaken by KISR since 2012 has been successful. Based on both well-maintained ground measurements at five stations and state-of-the-art satellite-derived data, it has provided the desired high-quality database and solar resource maps for Kuwait. This is the result of an accurate choice of sites for the weather stations, the installation of high-precision instruments (with redundancy at two sites), frequent site visits for maintenance and cleaning, and a serious quality control procedure. A very high fraction of valid data points is thus achieved, which is commendable considering the harsh desert environment.

This campaign is expected to continue for at least five more years to reduce the uncertainty in the current solar resource statistics, since they are affected by significant interannual variability in aerosols and cloudiness. After completing the installation of a sunphotometer at the Shagaya station, it is expected that a full characterization of the aerosol optical properties will be achieved during the campaign.

Although the use of solar/meteorological models is necessary to derive the surface irradiance and study its interannual variability, the selection of the most appropriate type of model is still a complex issue. A satellite-based model, such as SolarGIS, can provide accurate determinations of DNI for the last ≈20 years, but only after site adaptation. Moreover, its handling of aerosol data at different time scales during that period may introduce artificial trends, comparatively to more temporarily stable reanalysis data, for instance.

Site adaptation of the satellite-based solar irradiance time series with short-term high-quality ground measurements appears essential to reduce the substantial systematic deviations present in these time series at sites affected by large and variable aerosol loads. In the case of Kuwait, this site adaptation completely transforms the conclusions that would be drawn from an incomplete resource assessment based solely on modeled irradiance data. For Shagaya, for instance, the annual-average DNI is increased 13% by the adaptation process, transforming the local resource from moderate (before adaptation) to sufficient for viable concentrating power applications. High-quality aerosol data must be available to accurately model DNI and GHI. The large underestimation of the raw satellite-derived DNI found during the (cloudless) summer season indicates that the modeled AOD estimates are then highly overestimated. Improvements and/or corrections to the MACC model are thus desirable. These should benefit from local ground observations of AOD, to be started soon.

The present findings finally suggest that, over Kuwait, the NASA-SSE database has significant bias in both GHI and DNI, and higher uncertainty overall, compared to the MERRA and SolarGIS models.

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