QATAR DYNAMIC SOLAR ATLAS AND SOLAR RESOURCE ASSESSMENT

Yasir Mohieldeen, Luis Pomares, Daniel Perez-Astudillo, Dunia Bachour, Saiyed Wahadj

Qatar Environment and Energy Research Institute(QEERI), HBKU, Qatar Foundation, Doha, (Qatar).

Abstract:

Solar resource assessment is key preliminary to any successful solar energy production project. This study presents the solar resource assessment and mapping efforts that are currently being carried out at the Qatar Environment and Energy Research Institute (QEERI) in Qatar, to create a dynamic solar atlas for Qatar, showing solar irradiation, across the country, every 15 minutes. These data are essential for the successful harnessing and utilization of solar energy.

Rigorous analysis of solar irradiation components measured through ground monitoring stations combined with data derived from satellite imagery has made it possible to generate the dynamic atlas. The developed maps will help identify areas and locations with high solar energy generation potentials. Direct Normal Irradiance (DNI), Diffused Horizontal Irradiation (DHI) and Global Horizontal Irradiation (GHI) will be calculated from the satellite images and calibrated and validated with their corresponding ground measured values. The time series of these valuable maps will enable solar energy short-term forecasting and will contribute to the successful operation of solar energy production facilities in the country. The generated datasets will be available through a solar geo-portal on the World Wide Web.

Keywords: Solar atlas, solar irradiation, network optimization, METEOSAT MSG, solar monitoring stations, solar modeling, neural network, Heliosat, and solar forecasting.

1. Introduction:

The primary objective of this paper is to present the solar atlas development programme at Qatar Environment and Energy Research Institute (QEERI), a member of Qatar Foundation. The study will present the framework and the plan to achieve these goals. Achievements so far and the status of the solar atlas as it stands now (at the time of presenting this paper) are also included, along with the next/future steps.

The paper is structured as follows: First, a brief overview is given about Qatar and its electricity demand in the background section. Second, the need for the solar atlas and its importance to Qatar's solar energy plan is highlighted. The framework for the atlas development is described in section 2. Section 3 presents some concluding comments.

1.1 Background

The State of Qatar wants to generate 20% of its electricity requirement from solar power by 2020. This policy aims to meet the increasing electricity demand induced by increasing population and the associated urbanization with its energy-hungry life-style while adopting at the same time environmental-friendly renewable energy. Qatar's population has increased almost five times from 0.37 million to 1.74 million between 1986 and 2010, and six times between 1986 and 2014, as shown in Fig. 1.

doi:10.18086/swc.2015.07.07 Available at http://proceedings.ises.org

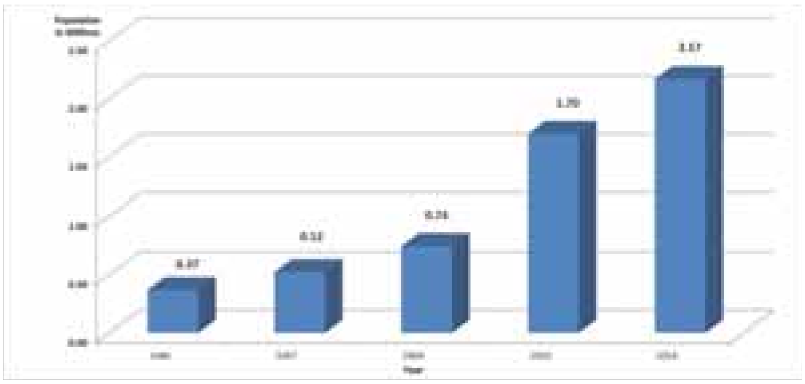


Fig. 1: Population growth in Qatar in millions

Source: (QSA, 2013; PC, 2006; TE, (2014)

The electricity and water company in Qatar KAHRAMAA has reported an increase in the maximum network load from 941 MW in 1988 to 3,990 MW in 2008 and reached 6255 MW in 2012 (KAHRAMAA, 2013). The number of customers increased from 132,429 in 1998 to 293,604 in 2013 (ibid, 2013)

This increase in demand is triggered also by changes in life-style, indicated by electricity per capita consumption figures. The per capita consumption grew from 12.963 KW in 1998 to 17.774 KW in 2007 (ibid, 2013).

To meet this increasing demand for electricity, and as a dry country with no hydro-power resources, Qatar has increased the number of gas-generated electricity plants in the 2000s from 3 to 8 plants. Electricity production over the last few years is shown in Fig. 2.

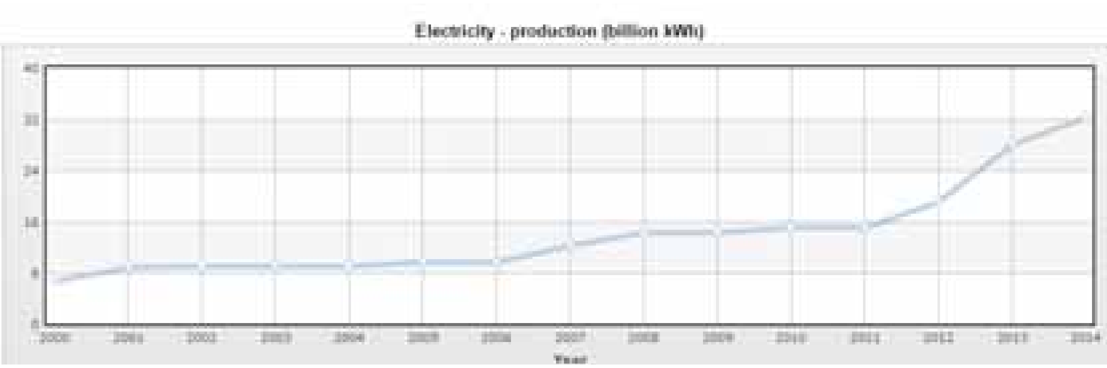


Fig. 2: Electricity Production in Qatar 2000-2014

Source: CIA World Factbook

Qatar is ranked as having the second-highest per capita ecological footprint among 150 countries, down from being the highest in 2012, according to the WWF's Living Planet Report (WWF, 2014). This report is published every two years. With these environmental concerns and the unstable oil prices in mind Qatar has decided to introduce clean renewable energy to produce electricity as opposed to non-renewable environmentally un-friendly natural gas.

Solar energy is arguably the most effective way to meet the increasing energy demand of Qatar and the region, for the following reasons: firstly, solar energy is renewable as opposed to the non-renewable gas and oil which are finite resources. Secondly, solar energy is clean and limits the emissions of Greenhouse Gases. Thirdly, using solar energy lengthens the life of oil and natural gas resources, and reserves them for future generations. .

A preliminary analysis of solar energy potentials carried out using historical data collected by Qatar Meteorological Department (QMD), reveals that there is a high potential of solar energy in Qatar. The ground-measured yearly average Global Horizontal Irradiation (GHI) for Qatar is 2113 kWh/m2/year (Bachour et al, 2013). GHI is suitable for the Photovoltaic (PV) method of converting solar energy into direct current electricity.

Another analysis carried out by QEERI (Perez-Astudillo *et al*, 2013) using data from a ground solar station installed at QEERI, collecting Direct Normal Irradiance (DNI), Diffused Horizontal Irradiance (DHI) and GHI, confirms the solar energy potentials in Doha.

1.2 Why the Dynamic Solar Atlas

The Solar Atlas and solar mapping is key to successful implementation of any solar energy production program in Qatar. The Atlas helps identify areas and locations with high solar energy generation potentials. It helps in the identification of the optimum locations for solar panels. Qatar is a small country but the spatial variability in solar irradiation is variable because of the existence of micro-climates related to different land-covers and effects of the sea on inland climate. The atlas helps a wide range of professionals to better understand the spatial and temporal distribution of the solar irradiation in the country.

The dynamic atlas provides near-real time solar maps every 15 minutes of solar data including DNI, DHI and GHI. These datasets are accessible online through the World Wide Web. The atlas also provides now-casting and forecasting of solar irradiation data that can be used for solar energy production management.

The maps are produced through rigorous analysis of solar irradiation components measured through ground monitoring stations combined with data derived from satellite imagery. Solar information produced from satellite images are calibrated and validated with their corresponding ground measured values.

2. Method & Framework:

This section describes the plan adopted to develop the dynamic solar atlas. The steps that were undertaken and future plans are also highlighted. These steps could be summarized as: data collection; and modeling of solar irradiation.

2.1 Data collection

The collection of high quality solar irradiation data is a key to the development of the atlas of solar resources of Qatar. It is necessary to install two kinds of equipment: a METEOSAT satellite ground receiving station and a number of solar monitoring stations.

2.1.1 Satellite data:

Data from METEOSAT satellite EUMETSAT program has been used in the study. A METEOSAT Second Generation (MSG) ground receiving station has been procured and installed at the QEERI premises in Doha. The MSG is a geostationary meteorological satellite collects weather information all over the globe. The sensor onboard the satellite, known formally as the Spinning Enhanced Visible and Infrared Imager (SEVIRI), observes the full disk of the Earth with a repeat cycle of 15 minutes. It captures images in 12 spectral wavelength regions or channels. Many parameters related to solar irradiation are recorded by these channels. The Water vapour, Infra-Red (IR), and the visible channels of the satellite are the main channels that are utilized here for modeling and mapping solar irradiation. Atmospheric Motion Vectors (AMV) products are received every hour. AMVs show cloud speed and direction and are used for atmospheric and solar irradiation forecasting. Fig. 3 below shows the satellite ground receiving station installed at the QEERI premises.

(a) **(b)**

Fig. 3: The METEOSAT MSG ground receiving station installed at QEERI in Doha. (a) The 2 meter antenna on the roof-top at QEERI's premises. (b) The receiving and processing servers of the MSG data in the GIS lab.

The raw data captured by the antenna (Fig. 3a) are processed and modeled/converted to solar irradiation values by combining them with ground measurements recorded at the ground Solar Monitoring Stations (SMS). These ground measurements and SMS are discussed in the following section.

2.1.2 Ground measurements:

High quality ground solar irradiation components measurements in selected locations are needed to model, verify and calibrate the satellite data to produce accurate estimates of solar radiation for the whole country. To determine the locations and the number of stations needed in Qatar, existing solar data collected by the Qatar Meteorological Department (QMD) was obtained and analyzed. The QMD network consists of 12 stations, designed to measure meteorological data. Global Horizontal Irradiation is the only solar component that is measured by QMD network.

A collaboration agreement with QMD has enabled QEERI to use QMD's network to install solar equipment on selected stations.

To determine which stations in the QMD network to use for solar installation, a network optimization study was carried out on the network. The network optimization study also determines potential gaps in the network for solar measurements.

2.1.2.1 Solar Monitoring Stations (SMS) Network optimization:

Different techniques and methods have been developed by scientists and meteorologists to address the optimum site selection task (Singh et al, 2013; Mohajeri, 2010; Pardo-Igúzquiza, 1998).

The network was optimized first, by determining the maximum distance from a station that maintains acceptable relative variation in magnitude of solar irradiation. Second, by determining potential gaps in the network and cover them by new stations.

To determine the maximum distance with acceptable variability, the GHI data from the QMD network was analyzed. The QMD network of 12 stations is shown in Fig. 4 below.

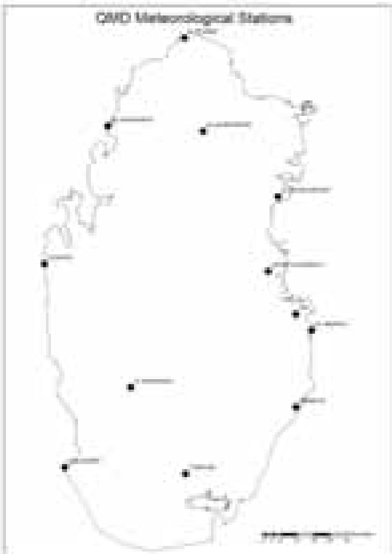


Fig. 4: Locations of the 12 solar monitoring stations operated by QMD.

GHI values were analyzed relative to the distances between the station sites. Daily and monthly GHI averages from QMD's stations were analyzed, along with corresponding GHI values derived from satellite images by Masdar Institute of Science and Technology (MIST)- the United Arab Emirates (MIST, 2015). Fig. 5 shows the relative variations, as a function of distance, of daily (red line) and monthly (blue) averages of GHI as measured at ground level by the 12 QMD stations. The (green) line is for monthly averages from satellite. The distances in the Figure are grouped in bins of 10 km, centered at 5, 15, 25 km intervals up to 160 km. For example the point at a distance of 65 km represents all pairs of stations with separation between 60 and 70 km. The relative variations of GHI are the averages for all pairs in each distance bin.

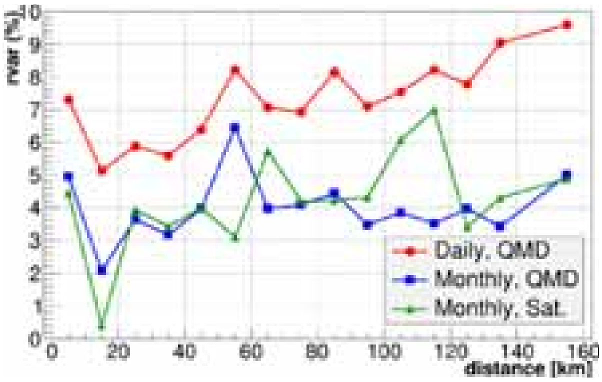


Fig. 5: Relative variations of GHI values as a function of distance between stations

Data Source: QMD, 2015

Fig. 5 shows that the selected stations less than 30km apart experienced 6% relative variation in their daily GHI measurements. Counter intuitively, a higher relative variation (7%) is found at the lesser distance of 5km, and this is attributed to stations being located in and around Doha City where various micro-climates are induced by variation in aerosol loads across the city. The authors consider 6% variation in daily GHI values of adjacent stations to be an acceptable variation.

In addition to the analysis of interstation solar radiation variability using QMD data, satellite imageries were also analyzed for network optimization. A 2010 average GHI image produced by Masdar Institute of Science and Technology derived from satellite data is analyzed using Moran's I index spatial statistics method.

The Moran's I index compares the differences between neighboring pixels and the mean to provide a measure of local homogeneity. The value range is between +1 and -1, where:

+1 = strong positive spatial autocorrelation, 0 = spatially uncorrelated, -1 = strong negative autocorrelation.

Results of the Moran's I index analysis are shown in Fig. 6.

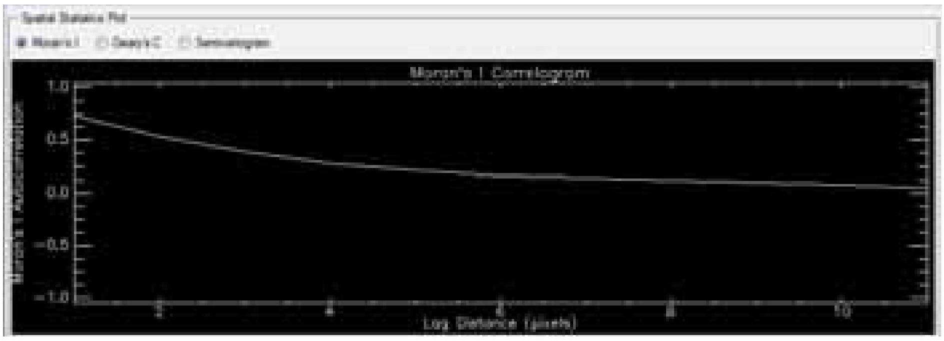


Fig. 6: Moran's I analysis on 2010 GHI pixel values.

Results of Moran's I analysis shows that the spatial correlation of the 2010 GHI values was strong within neighboring pixels. The index value did not start from the value of 1 as one would expect since neighboring pixel values should have exhibited high autocorrelation. This discrepancy was due to micro-climate and satellite model errors. The spatial autocorrelation decreases as the distance between the measurements increases, and is nearly lost (that is close to 0 Moran's index) when it reaches 8 pixels apart. Since the pixel size is 3 km, this distance is equivalent to 24 km. The analysis further confirms the results obtained from QMD data analysis. Generally, 30 km distance between ground stations is considered as appropriate for good spatial coverage (Perez et al., 1997).

The results above imply that GHI measurements taken at one location could be considered as representative of up to 25-30 km away from that location. That is to say, a solar station measurement could be considered representative of the local irradiation status within a 25km radius from that station. For the sake of accuracy and achieving an adequate research quality data a 20km radius is used here. Fig. 7 below shows a 20km radius buffer that is covered by individual station in the QMD network of SMS. The red circles represent gaps that need to be covered.

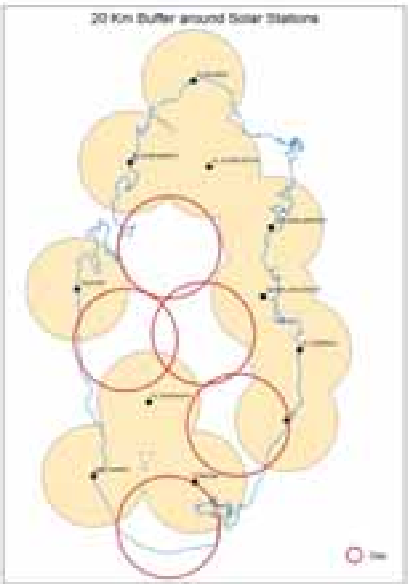


Fig. 7: Map of the coverage achieved with buffer zones of 20 km radius around QMD stations. The red circles show the locations of additional stations needed to cover the gaps.

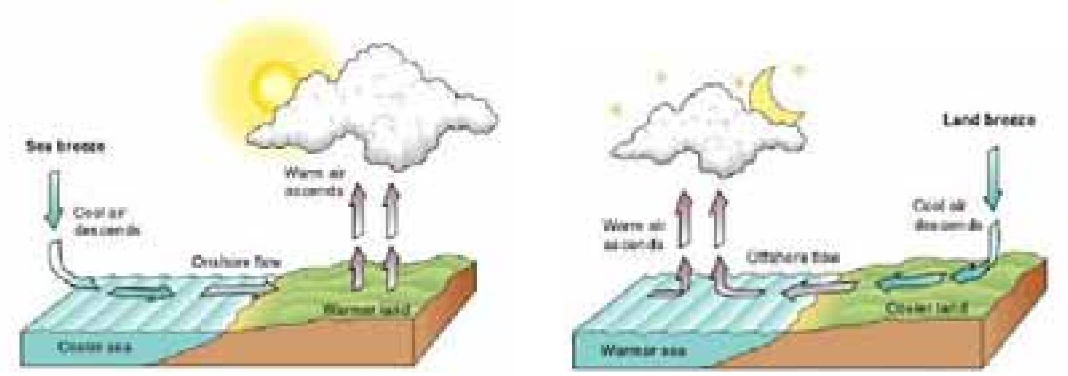
Site visits were conducted to all existing and proposed stations for sites verification. Fig. 8 below shows a photo of one QMD stations during a site visit.

Fig. 8: Location of one of the QMD stations, south west of Doha.

2.1.2.2 Land see-breeze effect:

In order to ensure representative sampling of the solar irradiation, many factors that influence the spatial distribution of solar irradiation have to be taken into account in the site selection for stations. As Qatar is a peninsula, it was necessary to study the influence of the sea on Qatar solar resources. The two main sea phenomena that might have influence on solar radiation and are considered here are land-sea breeze phenomenon, and the mixed land-sea satellite pixel.

The influence of land-sea breeze on aerosols concentration and transportation in the atmosphere along coastal areas has been investigated by numerous studies (Tsai et al, 2011; Kolev et al, 1998). The land-sea breeze (Fig. 9) arises because of differential temperature between land and water surfaces. During the day winds develop over water near land due to differences in air pressure created by their different heat capacities, as solar radiation heats the land more quickly than the water, causing sea breeze (Fig. 9a). At night, water's high heat capacity prevents rapid loss in water temperature and therefore remains warmer than land causing the winds to reverse direction (from land to sea, causing land breeze (Fig. 9b).



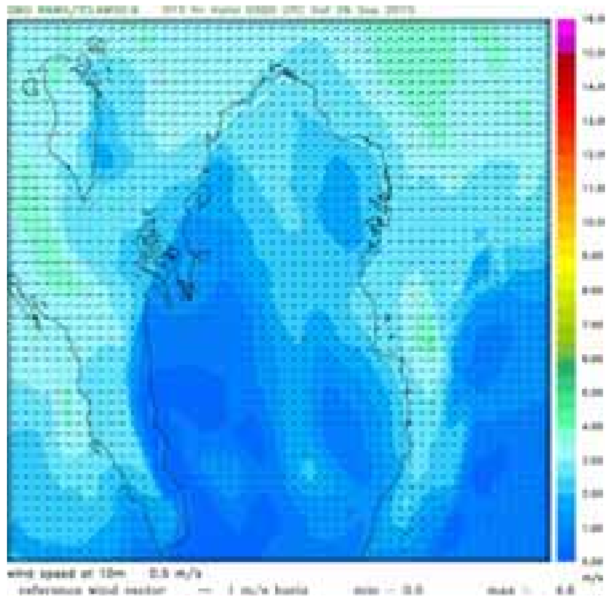
(a) Sea breeze **(b) Land breeze**

Fig. 9: Land-sea breeze phenomena.

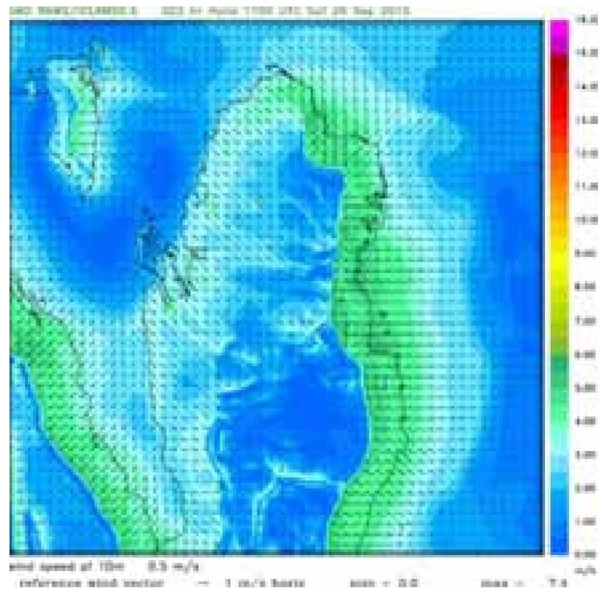
These studies of land-sea breeze have shown that these phenomena lead to high concentration of aerosols in coastal areas and result in aerosol circulation (between land and water) along the coastal line This high concentration is due to the accumulation and the forward and backward movements of the aerosols between land and water, leading to aerosol entrapment around the coast. All pollution sent from land to the sea at night and early morning, returns back to the coast during the day. The high aerosol concentration leads to high diffusion of solar irradiation.

As for Qatar, the land-sea phenomena could be observed by the RAMS/ICLAMS model applied by the QMD for wind monitoring as shown in Fig. 10, on the 26th Sept 2015. Land breeze is shown in Fig. 10a (at 03:00

AM UTC time) early in the morning when the sea is warmer than the land, whereas see breeze is shown in Fig. 10b (at 11:00 AM UTC time) when the land started to heat up a clear reverse of wind direction took place from the Arabian Gulf into the eastern coast of Qatar.



(a) Land breeze



(b) Sea breeze

Fig. 10: A normal day Land-Sea Breeze sequence in Qatar, 26th Sep 2015.

Source: QMD, 2015

It should be noted that nine out of twelve of QMD stations are coastal stations, and located in areas most affected by the land-sea breeze phenomena and hence by aerosols. This means that the existing sampling structure/regime is biased and is not necessarily optimum for solar mapping.

To optimize the sampling of the solar monitoring stations network, more inland stations have been introduced by shifting some coastal stations to inland sites (Al Rwais, Qatar University, Doha Airport & Umsaid); and by introducing/proposing new inland station sites (Ghasham Farm, Jumailiah, Um Wishah, Suda-nithail, Camel Racing court). The final optimized SMS network is shown in Fig. 11 below.

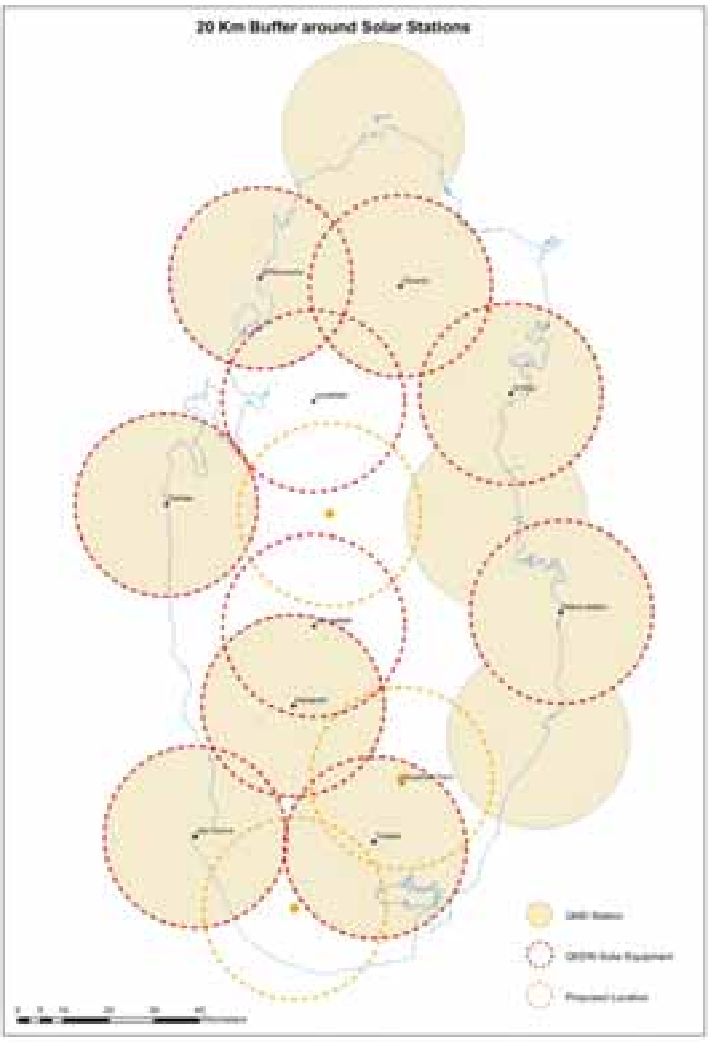


Fig. 11: Optimized Solar Monitoring Stations Network, with existing and proposed stations indicated.

Another reason for minimizing the number of coastal stations is to reduce the impact of the satellite "mixed-pixel" issue in the analysis when combining ground measurements with METEOSAT satellite images in the modeling. As the pixel size of these images is 3km, coastal station measurements might be analyzed with a pixel that partially covers land and water (mixed), and that could introduce in-accuracies to the model.

Based on the above optimized network, thirteen solar monitoring stations have been procured and are in the process of being installed in their respective sites. The next section discusses the processing of the data captured by the METEOSAT receiving station (Section 2.1.1) and the optimized SMS network (Section 2.1.2).

2.2. Data processing and solar modeling

This section describes how the satellite data collected by satellite ground receiving station and the ground measurements collected by the 13 monitoring stations are combined to create the atlas.

The SEVIRI satellite data are converted to solar irradiation estimates. Two methods are adopted to compare results. The first is to use existing empirical/physical models, in this case Heliosat model, and use local ground measurements data to adjust the model to Qatar climatic conditions.

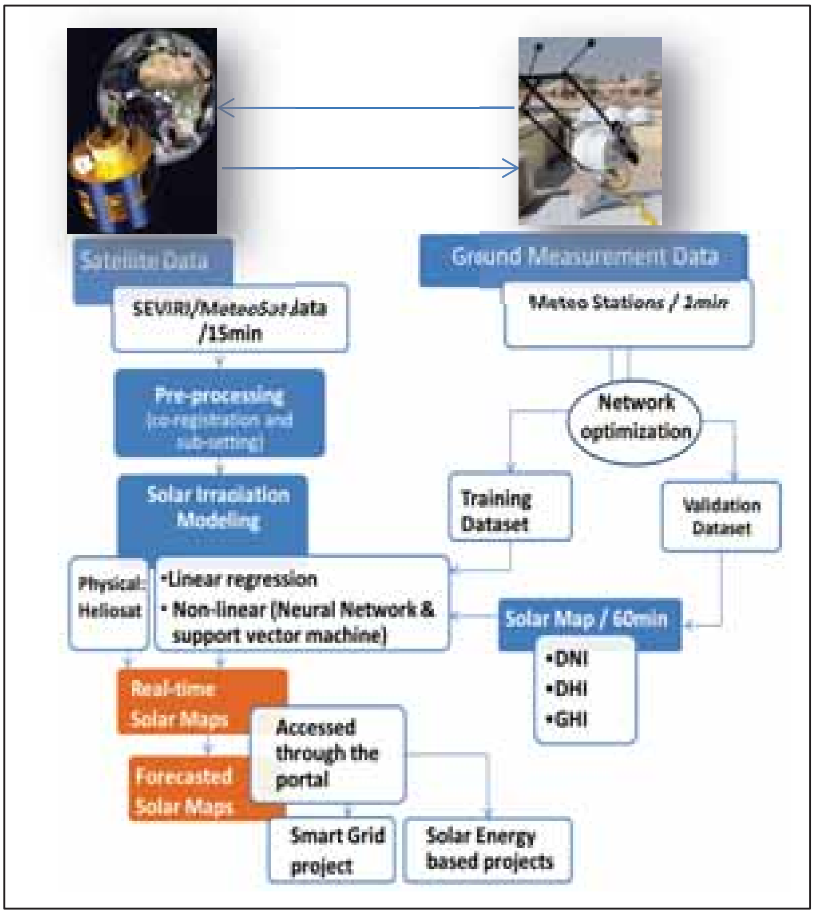


Fig. 12: The dynamic solar atlas framework

The main principle of the Heliosat method is the construction of a Cloud Index (CI) by comparing what is observed in the pixel by the sensor to what should be observed over that pixel if the sky were clear, which is related to the "clearness" of the atmosphere (Rigollier *et al*, 2002).

The CI is derived from the Meteosat 15 minutes satellite images. The CI is then used to calculate the atmospheric Clearness Index (Kc) values. First the Clear Sky solar radiation component is derived using Linke Turbidity values obtained from MACC II. Then the Kc is combined with CS solar radiation to produce all-sky solar radiation estimates from the satellite. The schematic diagram of this physical model is shown in Fig. 13 below.

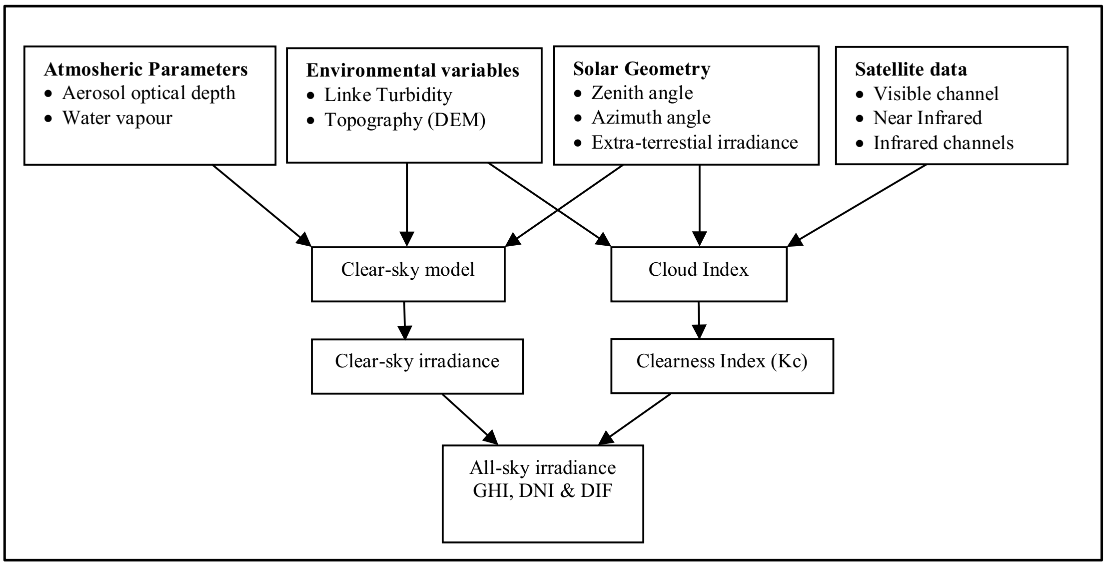


Fig. 13: Schematic diagram of the adopted Heliosat semi-physical all-sky solar radiation model

The satellite data used in the model and derived inputs to the model is listed in Table 1 below:

Model Input	Data source	Coverage period	Time step	Spatial Resolution
Cloud Index	Meteosat MSG Visible, NIR & IR channels	2005 to present	15 minutes	5 km
Atmospheric Optical Depth (AOD)	MACC II	2003 to present	Daily	125 km
Linke Turbidity	MACC II	2003 to present	Daily	125 km
Clearness Index	ESRA model	2005 to present	15 minutes	5 km
Water vapour	MACC II	2003 to present	Daily	125 km
Topography (DEM)	SRTM	Present	-	1km

Table 1: Input data to the satellite model

Ground measurements of daily GHI from nine QMD stations, with available measurements between2003-2013, were used to validate the satellite model results. The validation results and the uncertainty parameters of these daily GHI estimates are shown in Table 2 below. The mean relative RMSD for the stations was 11.5%. A relatively high coefficient of determination R^2 of 0.92 was depicted.

Station	MBD (Wh/m^2 day)	RMSD (Wh/m^2 day)	KSI	rMBD (%)	rRMSD (%)	KSI (%)	R^2
Dukhan	449.43	776.12	431.62	7.97	13.77	123.36	0.92
Turayna	63.96	601.34	17.88	1.09	10.21	5.11	0.92

AlShehaimiya	10.60	481.65	68.84	0.18	7.96	19.68	0.96
Ummsaid	235.28	708.94	336.36	4.12	12.41	96.13	0.91
Qatar University	204.33	595.18	269.30	3.50	10.20	76.97	0.94
AlKhor	95.75	697.08	195.80	1.62	11.80	55.96	0.91
AlKaranaah	238.81	690.89	283.94	4.06	11.75	81.15	0.91
AbuSamra	169.88	745.44	155.11	2.91	12.78	44.33	0.88
AlWakrah	126.68	727.61	132.80	2.17	12.48	37.96	0.89
Mean	**177.19**	**669.36**	**210.18**	**3.07**	**11.48**	**60.07**	**0.92**

Table 2: Validation results and the uncertainty parameters for the satellite-derived daily GHI

The resulted annual average GHI map for Qatar for the period 2003 to 2013, from the model, is shown in Fig. 14 below.

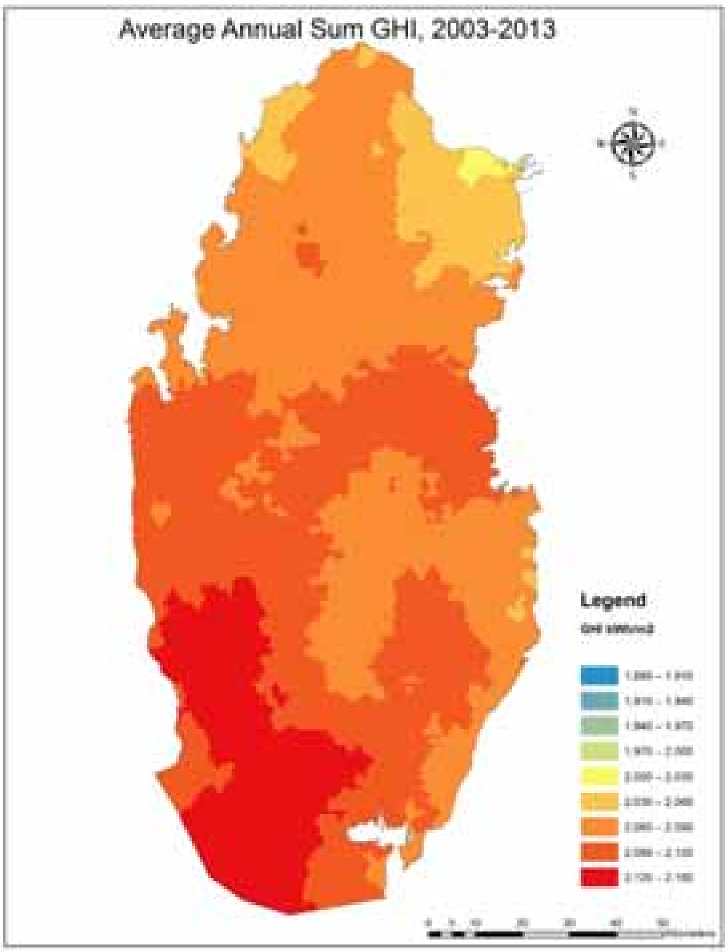


Fig. 14: Average Annual Sum GHI (kWh/m^2) for Qatar, 2003-2013

The second modeling method, that will be implemented, is a statistical model, regression analysis (linear, and non-linear such as neural network). In this method the satellite data will be regressed with the ground measurement from the 13 monitoring stations to derive accurate estimates of solar irradiation from the satellite imageries. The data processing methods are shown in Fig. 12 above.

Output from the models and the data processing and analysis are near-real time (every 15 minutes) solar maps show the spatial distribution of the solar irradiation parameters in the country. These results are used for solar forecasting and now-casting of irradiation, as shown in Fig. 12 above. Statistical models and weather prediction models will be used for forecasting. The generated datasets would be used for instance for smart grid management and any other solar-energy based projects. These datasets are stored and organized in a data-portal and disseminated online through the World Wide Web. The data-portal is highlighted in the next section.

2.3 *Results dissemination and data-portal:*

The solar datasets produced by the modeling are organized by a data-portal. The portal is a database and an application that enable the dissemination and querying of geospatial data. The data-portal application is built on ESRI ArcGis Server, Java scripting, and python programing. A snapshot of the on-line Qatar solar atlas is shown in Fig. 13. Point, line and polygons geometries could be used to query the solar maps and to extract statistics and values from them.

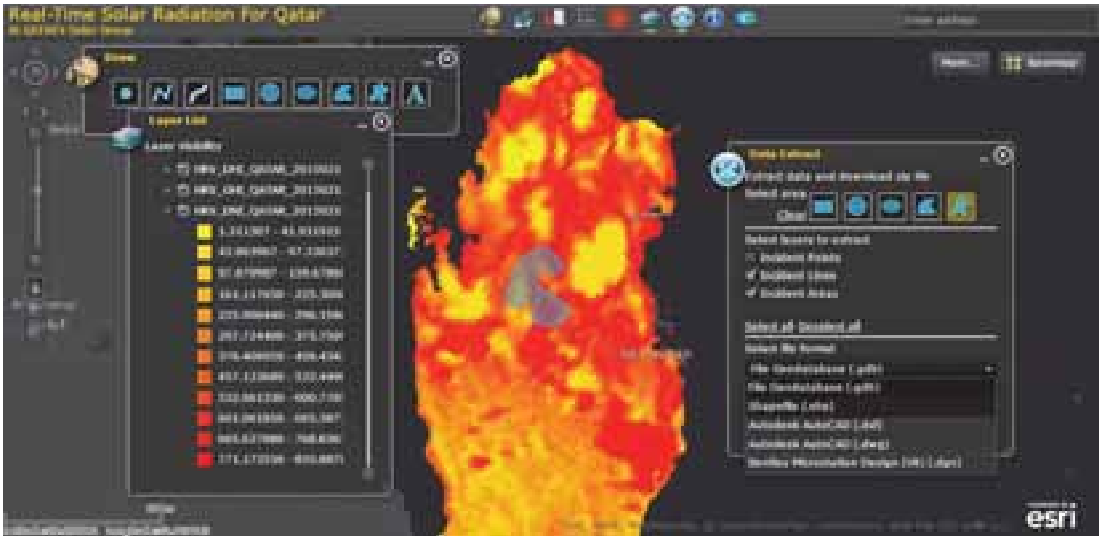


Fig. 13: A snapshot of the solar atlas geo-portal

3. Conclusion

The State of Qatar aims to generate 20% of its electricity requirement from solar power by 2020. This is to meet the increasing electricity demand caused by increasing population and to reduce the high ecological footprint resulted from dependency on oil and gas in generating electricity. Mapping the solar resources in Qatar and creating a solar atlas is key preliminary to the successful implementation of any solar energy project in the country.

This paper presented the solar resource assessment and mapping efforts that are currently being carried out at the Qatar Environment and Energy Research Institute (QEERI) in Qatar. A solar atlas for Qatar will be generated which will show solar irradiation, across the country, every 15 minutes. These data are essential for the effective harnessing and utilization of solar energy in the country.

Data collected by METEOSAT MSG satellite and by ground measurements have been combined and analyzed. The network of the ground measurement stations has been optimized in order to capture high quality data. The optimization was carried out based on rigorous analysis of daily GHI data collected by 12

QMD meteorological stations. The sea-breeze effect on solar energy, and the land-water mixed pixel issue were also taken into account in the optimization, by shifting some coastal stations to inland sites. The resulted average annual sum GHI map, derived from the Heliosat model, shows high potentials of solar energy generation using PV technologies. The time series of the 15 minutes GHI maps will also enable solar energy short-term forecasting and will contribute to the successful operation of solar energy production facilities in the country. The generated datasets will be made available and accessible through a solar geo-portal on the World Wide Web.

Acknowledgement:

The authors would like to thank Qatar Meteorological Department (QMD) for their collaboration and continuous support and for sharing their solar databases.

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