QEERI SOLAR ATLAS

QATAR'S FIRST SOLAR ATLAS TO MAP RENEWABLE ENERGY POTENTIAL

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معهد قطر لبحوث البيئة والطاقة
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SOLAR ENERGY IN QATAR

▶▶ Simple calculations demonstrate the total amount of solar energy received on earth surpasses massively the total energy needs of mankind by several orders of magnitude - estimated to a ratio in the range of 4-5x10^3. If such large amounts of energy are directly available to all nations, there is obviously a geographical factor associated with the latitude, and from this perspective the State of Qatar is blessed with very high levels of irradiance at the ground level, making solar-powered processes the best option for the country in terms of sustainability and of climate change risk mitigation; the recently announced 800MW Al Kharsaah solar photovoltaic (PV) power plant is a major and remarkable move in this direction. It will meet 10% of the peak electricity demand in the country.

Converting solar energy into a usable energy vector such as electricity, requires a detailed and accurate estimation of the available resource in order to allow such conversion to be an economically viable industrial activity and the preferred choice in terms of electricity generation. As a member of Qatar Foundation and most active national research institute in this field, QEERI has initiated several years ago a program of estimating the solar resource at the ground level for the State of Qatar. This work results in an impressive amount of data accumulated with high time and space resolutions, and sophisticated algorithms to process and convert them in a powerful tool for our stakeholders. As QEERI Executive Director, I am particularly proud to see the official release of this report and the corresponding 2020 Qatar Solar Atlas, as one of our tangible contributions to the Sustainability Initiative of our Foundation. It represents several years of efforts in data collection and modeling for our ENERGY Center. I express my deepest gratitude to the teams of our ENERGY Center having contributed to and finalized this report.

- Dr. Marc Vermeersch,
Executive Director, QEERI

▶▶ The 2020 Solar Energy Atlas is the result of the cutting-edge professional efforts of leading experts in QEERI. The Atlas is a key element to support the solar based renewable national development of progressive policies, identify new profitable investments and markets which will drive the creation "green" jobs and a technological innovation ecosystem. This edition of the Solar atlas will further contribute to building a climate-resilient, prosperous and sustainable future where renewable energy has a significant penetration rate in the energy mix in a business efficient and reliable manner. Following editions will be based in the results presented in this document and will include the simulated energy yield of different solar technologies based on our estimated solar resource, a solar energy forecasting service at the sites of QEERI National Ground Radiometric Network, and for the whole Arabian Peninsula taking into account aerosols concentration and the soiling analysis to predict areas with highest and lowest soiling and seasonal variations.

- Dr. Veronica Bermudez,
Senior Research Director, Energy Center, QEERI

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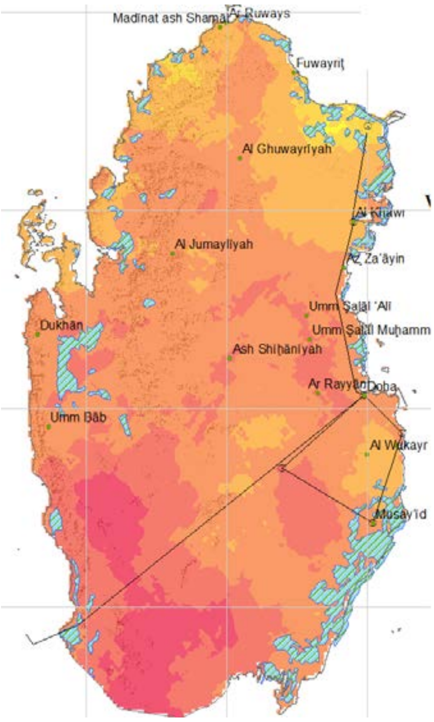

QATAR SOLAR ATLAS

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LIST OF ABBREVIATIONS

INTRCAMS	Copernicus Atmosphere Monitoring Service
CSP	Concentrating Solar Power
DHI	Diffuse Horizontal Irradiance (W/m2)
DNI	Direct Normal Irradiance (W/m2)
GHI	Global Horizontal Irradiance (W/m2)
GTI	Global Tilt Irradiance (W/m2)
MFG	Meteosat First Generation
MVIRI	Meteosat Visible and Infrared Imager
O&M	Operation & Maintenance
rMBE	Relative Mean Bias Error (%)
rRMSE	Relative Root Mean Squared Error

CONTENTS

EXECUTIVE SUMMARY

▸▸The deployment of solar energy projects in Qatar needs, as a first step, precise information on the availability of solar resources. An accurate understanding of the regional solar energy characteristics improves decision-making processes for the selection of the best technologies and solutions to be used, as well as the definition of targeted policies and investments.
This report presents results of the solar resource assessment and mapping activities in the Energy Center at the Qatar Environment and Energy Research Institute (QEERI). This Solar Atlas uses existing ground measured radiometric data that have been compared with available solar radiation data derived from satellite images in order to generate a model which, after proper validation, has been used to fit satellite data optimally to the local conditions of Qatar.

This Solar Atlas has two main objectives:

- To explain the methodologies and outcomes of the solar resource and solar power potential assessment and forecasting, based on the combined use of models, machine learning solutions and data. It documents the uncertainty of solar and meteorological data, which are key elements in the technical and financial evaluation of solar energy systems, and provides solutions to minimize the risks.

- To improve the awareness and knowledge of resources for solar energy technologies by producing a comprehensive countrywide dataset and maps based on the highly accurate QEERI developed models. The report evaluates key solar climatic features, and the geographic and time variability of solar power potential in the country and provide solutions to solar and power production forecasting.

The uncertainty of the solar resource data has been minimized by the regional model adaptation based in the ground measurements collected at the 15 solar meteorological stations across Qatar QEERI operated. The solar radiation measurements from these stations are then used in combination with 15-minute satellite-derived values to provide a complete, ground-calibrated precise map of solar resources in near real time, with a spatial resolution of 5 km throughout the country.

The corrected daily and hourly values have been used to generate the yearly GHI and DNI maps. Long-term yearly values and monthly means for GHI and DNI have been compiled in raster formats.

The maps show that, through most the Qatar, yearly sum of global horizontal irradiation is in the range of 2000 to 2200 kWh/m2. GHI is distributed more homogeneously throughout the country, while DNI exhibits higher variability as a consequence of the high aerosol loads; which have, also, a different seasonal behavior affecting the spatial distribution. The seasonal variability is very low, compared with other countries, which qualifies Qatar as a country with highly feasible potential for PV power generation.

The key achievements of this project is supplying solar country-wide data and maps, based on the extensive validation of the solar model by high accuracy solar measurements across Qatar. The data underlying this report are delivered as high-resolution maps, and are accessible as raster GIS data for the whole territory of Qatar, representing long-term monthly and yearly average values. This data layers are accompanied by geographical data layers in raster vector data formats.

To finalize, QEERI has developed a solar energy forecasting service using multi-variate machine learning methods with ground measurements from QEERI radiometric stations using a state-of-the-art patent protected algorithm. The capability to forecast the potential solar energy is key for the successful and optimized operations of solar power plants.

1. INTRODUCTION

▶▶ Oil and natural gas make up to 48% of Qatar's Gross Domestic Product (GDP) (Qatar Central Bank data in 2017). The country is lowering its dependency on fossil fuels and moving toward a knowledge-based economy. Due to the instability of oil prices, the Qatari government has developed the Qatar Second National Development Strategy (QNDS) 2018–2022 (following the success of the Qatar National Development 2011-2016) as an efficient strategy aiming at achieving the goals and aspirations of the Qatar National Vision 2030. Among the objectives to transform the economy of Qatar, we can find the development of alternative natural energy sources, which are sustainable, generate much less pollution than fossil fuels, create jobs, have greater self-reliance and could allow for an optimized use of national natural resources.

Solar energy is the main other option available to generate electricity on an industrial scale, while reducing air quality pollution and greenhouse gas emissions to the atmosphere. Qatar has set a goal of attaining 20% of its energy from solar power by 2030. The country is very well-positioned to capitalize on solar photovoltaic systems thanks to its typical daily average annual solar radiation value exceeding 6 kWh/m^2 (Pomares & Sanfilippo, 2017). The first utility-scale PV plant in Qatar started its construction in Summer 2020. As a first stage, 350 MWp will be tentatively connected to the grid in 2021, while a second phase targeted for 2022 will allow the country to reach 800 MWp in 2022, corresponding to 10% of the country's peak electricity demand.

The two main applications to convert solar energy into electricity and industrial heat are photovoltaic (PV) conversion and concentrated solar power (CSP). The yield production of the energy generated from these technologies depends mainly on the magnitude of the available solar resource, it's the quality and type, as well as the way it is captured by the solar devices. Global Horizontal Irradiance is of interest for flat-plate photovoltaic and thermal systems, while Direct Normal Irradiance is primarily used in concentrated solar power applications and buildings (e.g., building integrated PV, BIPV, and cooling load requirements). In the case of tracking solar PV or bifacial (solar PV modules able to capture the solar radiation with the front face of the module, and the albedo, or reflected radiation, with the back side), the modelling of other solar components is necessary to predict the yield of these technologies.

As a first step, the deployment of solar energy projects in Qatar (as in any other place in the world) needs accurate and precise information on the available long-term solar resource. The characteristics of the information needed, strongly depends on the business category of the data user. In the current study, the Qatar Solar Atlas provide essential information in terms of solar energy availability and its quality to identify the best areas for the development of utility-scale and off-grid solar power plants, as well as the best technology (PV or CSP). The main objectives behind this need are to decrease the cost of produced energy, optimize the utilization of the available land, analyze the variability due to environmental factors and integrate the production into the grid, analyzing how it fits with the demand profile during the day and the year.

Besides location, a precise knowledge of the solar resource improves the decision-making process to select the solar technologies to be used, as well as defining appropriate policies and investments.

The selection of an adequate location for a solar conversion energy system is critical to its success, while at the same time it can be challenging because of the varying nature of solar radiation. Weather fluctuations and seasonal sun position changes have significant effects on a solar system's performance. The characterization of the solar resource must include its magnitude, i.e., the amount of available solar energy at an area of interest over a long period, as well as its variability over time. Knowledge of this variability is essential for improving the design of a solar plant, as well as accurately estimating the long-term performance of the power plant; understanding and forecasting the production variations in time to better fit the demand and grid requirements. Furthermore, it is crucial to know the variability of the solar resource in space (it means, how it varies on its location), so that the regional differences of solar energy are taken into account to reduce operation, maintenance and energy transmission costs, while at the same time improving the reliability and long term performance.

The solar resource can be measured by on-ground meteorological stations or modeled by satellite imagery. Ground radiometric stations are the best way of providing high frequency and accurate data (when measuring equipment are well-maintained and have high accuracy) for a specific location. Satellite modeled data provide estimations with lower temporal rate compared to ground radiometric measurements, however they can characterize a long history over extensive territories. Satellite-based solar data are not capable of reproducing instantaneous values with the same accuracy as ground sensors, but it can provide robust aggregated values, i.e., hourly, daily, monthly, and yearly.

For the production of the 2020 Qatar Solar Atlas, we have developed a methodology that allows us to use existing ground measured radiometric data and compare them with available solar radiation data derived from satellite images to generate a model which, after proper validation, has been used to fit satellite data optimally to the specific local conditions of Qatar.

2. COMPONENTS OF SOLAR RADIATION

Incoming solar radiation enters the Earth's atmosphere, where it can be transmitted, absorbed, or scattered by the atmosphere in varying amounts depending on its wavelength, resulting in an effective attenuation when it reaches the ground. In this context, the most critical attenuating factors of solar radiation are aerosols (solid, liquid particles), water vapor, and clouds. The spatial and temporal distribution of these parameters determines the amount of visible broadband solar radiation that can be exploited, but also allows dividing the solar radiation into three fundamental components, according to the possible solar energy conversion technologies (Figure 1):

- **Direct Normal Irradiance (DNI)** (W/m^2) is the amount of solar radiation (power) received per unit area on a surface perpendicular (normal) to solar radiation that comes directly from the sun disc without having being scattered by the atmosphere. According to the WMO (World Meteorological Organization), the DNI is measured in a normal direction to the sun with a pyrheliometer, designed with about 5-degree field of view (FOV) full angle.

- **Global Horizontal Irradiance (GHI)** (W/m^2) is the amount of solar radiation (power) received per unit of area from a solid angle of 2π steradians on a horizontal surface. This component comprehends radiation received directly from the solid angle of the sun disc, as well as diffuse sky radiation that has been scattered in traversing the atmosphere. It is measured on the surface with a horizontally mounted pyranometer.

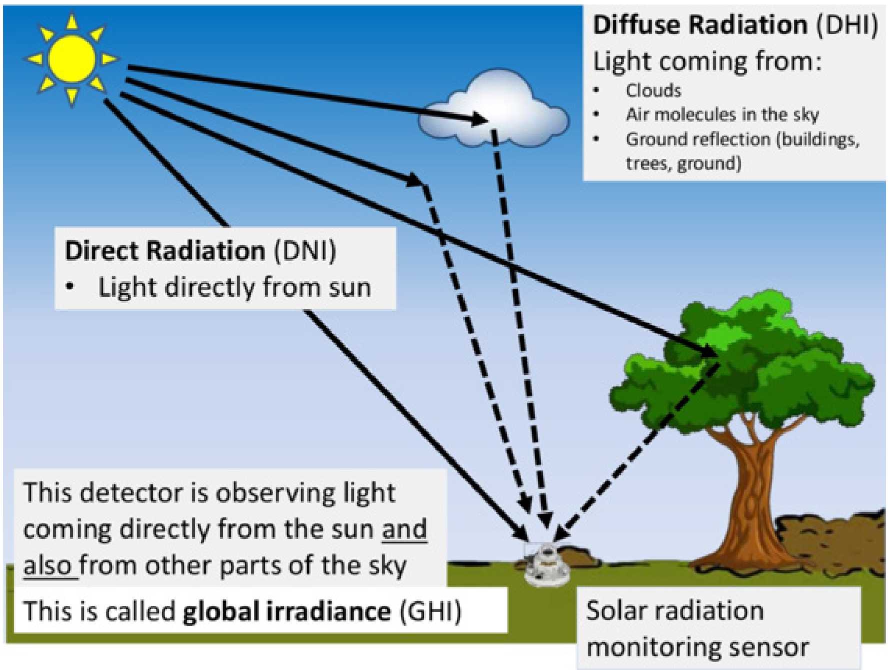


Fig 1: Fundamental components of the solar radiation

- **Diffuse Horizontal Irradiance (DHI)** (W/m^2) is the amount of solar radiation (power) received per unit area on a horizontal surface, after its direction has been changed due to scattering processes by the atmosphere. It is measured on the surface with a pyranometer placed horizontally and shaded with a shadow device to avoid the direct irradiance.

These three solar irradiance components are needed to know the quantity of energy that we will be able to convert with a specific solar conversion system. On any surface, direct plus diffuse irradiance equals global irradiance. For a horizontal surface, DNI can be converted to direct horizontal irradiance using the solar zenith angle (SZA) at the time of interest and geometrical calculations.

DNI reaches maximum values under clear-sky conditions, i.e., with no clouds, a clean and dry atmosphere (it means, low water vapor and aerosol concentrations). The presence of clouds makes the GHI and DNI decrease. In particular, the DNI can drop to almost zero under overcast conditions, which is critical for certain solar technologies. Clouds, high levels of water vapor and/or aerosols in the atmosphere make DHI increase against DNI, meaning that the scattered radiation is more abundant than the direct one. Hence, it is essential to have accurate parameterizations of cloud presence and aerosols, as well as water vapor concentrations, when modeling solar radiation.

The accurate knowledge of the value and characteristics of the different components of the solar radiation is key because different solar applications and technologies make an optimized use of different components of solar irradiance. For example, concentrating collectors require an accurate DNI estimations, while flat plate collectors require global tilted irradiance (GTI). GTI can be derived derived from the knowledge on DNI, DHI, GHI, and ground albedo (being the ground albedo the irradiation reflected by the ground surface). The DHI and DNI are also useful elements for daylight use applications, as well as for cooling load calculations in energy-efficient buildings. Therefore, it is crucial to estimate all three irradiance components, i.e. GHI, DNI, and DHI, plus GTI, to make the database suitable for a wide range of solar applications.

3. QEERI RADIOMETRIC STATION IN EDUCATION CITY

The QEERI's research and measurements of solar radiation activities started back in 2012. The first high-precision monitoring station, conforming to BSRN standards (http://bsrn.awi.de), was installed in Education City (25.33° N, 51.43° E) in November 2012. It was equipped with thermoelectric sensors measuring the solar radiation components separately. The sensors are mounted on a Kipp and Zonen SOLYS2 sun tracker, equipped with a sun sensor, in addition to the tracker's GPS receiver, for improved tracking accuracy, and also shading arm and ball assembly (Figure 2 and (Perez-Astudillo & Bachour, 2014)). One ISO 9060 first class pyrheliometer (CHP1, Kipp and Zonen) measures DNI, while two ISO 9060 secondary standard pyranometers (CMP11, Kipp and Zonen), one of them shaded, measure GHI and DHI. Additionally, a Kipp and Zonen CGR4 pyrgeometer is mounted on the tracker and shaded, providing longwave (LW) radiation measurements. All sensors are sampled at 1 Hz, and data are recorded as 1-minute averages.

Preventive maintenance for the station has been carried out mostly on a daily or semi-daily basis, with some limited periods of 1, 2 or 3 times per week. Inspections of tracker and sensor levelling (GHI, DHI, LW), shading (DHI and LW), tracking (DNI, sun sensor), as well as general operating conditions are included in this daily maintenance, as well as the cleaning of sensor domes/windows. Desiccants are checked in a regular base and replaced when required. The successful data collection and the visual inspections of the irradiance profiles is checked daily. Collected data are later flagged using BSRN-based quality checks, to obtain quality-filtered datasets of 1-minute and averaged values at various intervals (5, 10, 15, 30 minutes, hourly, daily, monthly, annual).

Other instruments were subsequently added to QEERI's facility for other solar, atmospheric, and meteorological measurements. For solar radiation, one rotating shadowband radiometer (RSR), to measure GHI, DHI, and DNI, and a Multi-Filter RSR for spectral measurements of the three irradiances, were deployed. For meteorological parameters, we added an Automatic Weather Station to measure temperature, humidity, pressure, wind speed and wind direction. In September 2017, the facility was decommissioned and relocated to QEERI's new site at the newly built HBKU Research Complex (25.32° N, 51.42° E) 750 m away from its initial location. The instruments started operation during the year 2018 after recommission (Figure 3).


Fig 2: QEERI radiometric station in Education City, Doha


Fig 3: QEERI solar radiation measurement facility at HBKU research complex rooftop.

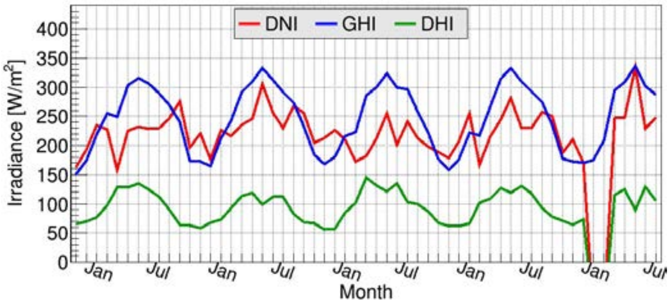


Fig 4: Monthly irradiances for all months of operation at the original QEERI site, from December 2012 to August 2017. In February and March 2017, DNI and DHI were not measured by the station.

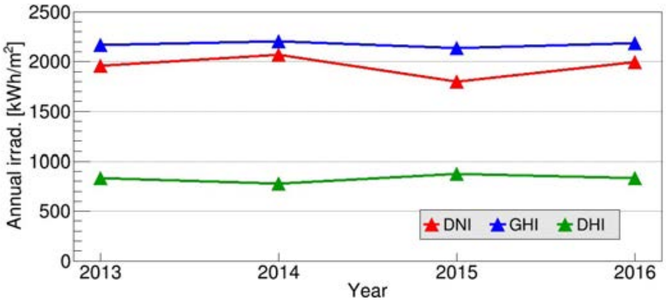


Fig 5: Annual irradiations. Although the station collected measurements up to mid-September 2017, only years with more than 85% of available data are shown in this graph.

4. QMD METEOROLOGICAL STATIONS

Global horizontal irradiance (GHI) has been measured by the Qatar Meteorological Department (QMD) (Martín-Pomares et al., 2017; Perez-Astudillo & Bachour, 2015) with automatic weather stations (AWS) since 2007, starting at a few sites and gradually expanding their capabilities to 12 locations around Qatar by 2011. At these sites, QMD used Kipp & Zonen pyranometers of type CM6B, compliant with all ISO 9060 specification criteria of an ISO First Class pyranometer, where several meteorological variables were measured: mainly, but not only, air temperature (T), atmospheric air pressure (P), relative humidity (RH), wind speed and wind direction. Routine maintenance for the solar sensors consisted of cleaning their domes at each site visit; however the cleaning frequency is not clear and it has not been able to determine it, as no written records are available. The QMD network of AWS has undergone an upgrade and expansion in recent years to include many more sites and using instruments that are more modern. Daily values from the initial network of stations were used to obtain the results shown in this document, i.e., calibration of solar radiation data derived from satellite images.

5. QEERI NATIONAL GROUND RADIOMETRIC NETWORK

From the beginning of its solar resource research, QEERI had the objective of developing a solar resource-mapping project for Qatar to assess the country's solar potential in collaboration with the Qatar Meteorological Department (QMD) (Martín-Pomares et al., 2017; Perez-Astudillo & Bachour, 2015). QEERI and the Qatar Civil Aviation Authority signed an initial Memorandum of Understanding (MoU) in 2013, and a more specific MoU was signed in 2015 with QMD, for the development of the Solar Atlas project.

For the Qatar Solar Atlas project, high-quality monitoring stations similar to the QEERI station at Education City (consisting of two pyranometers and one pyrheliometer, mounted on a sun tracker) have been deployed at 14 sites selected across Qatar, providing one-minute averages of the three irradiances, transmitted to QEERI and QMD servers every ten minutes.

Figure 6 shows some installations in three different sites around Qatar. Of the 14 locations, 9 are QMD sites, and 5 are QEERI's. All locations were chosen to provide comprehensive coverage of the country, creating a dense network in which the distance between stations is kept under 30 km (Figure 7 and Table 1).

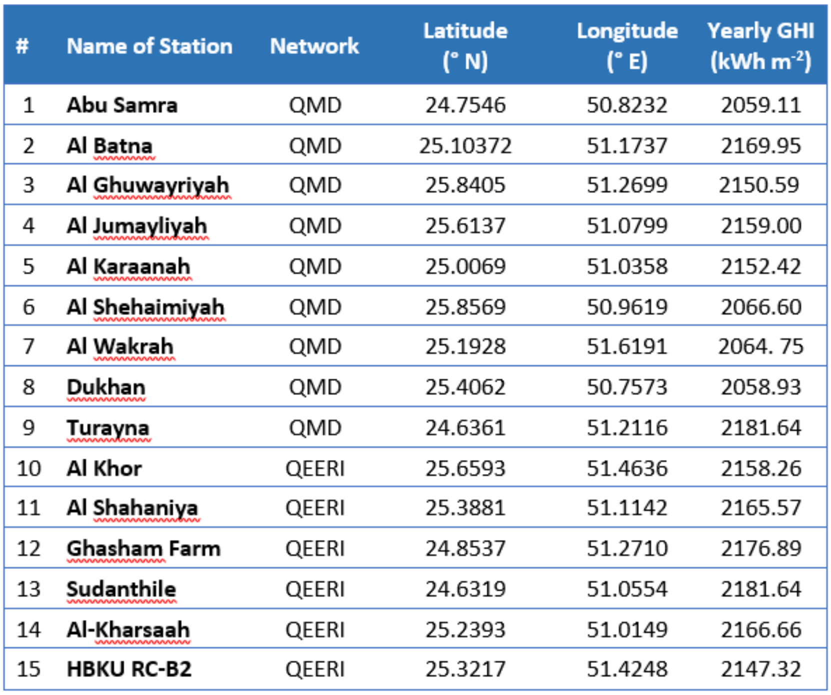
Fig 6: Different installations within the network

All stations measure GHI, DNI, and DHI (with QEERI equipment), as well as meteorological parameters (T, RH, P, wind speed, and wind direction, with QMD equipment). In addition, two of the QEERI sites also measure infrared and UV radiations. For the maintenance of the QEERI solar monitoring network, a team of technicians is assigned to carry out the preventive maintenance, in a predefined schedule where each and all stations are visited two times per week. The preventive maintenance includes the same inspections checks that have been discussed in section 3.

For data storing, QEERI hosts a server storing the data sent by the loggers in a local PostgreSQL database, which is then replicated in another QEERI server. For data display, a web application runs on the main server to display and visualize QEERI and QMD data in different forms such as maps, graphs, and tabular.

The solar radiation measurements from these stations are then used in combination with 15-minute satellite-derived values to provide a complete, ground-calibrated precise map of solar resources in near real time, with a spatial resolution of 5 km throughout the country.

Fig 7: The 13 sites (red dots) of Qatar's National Radiometric Network. QEERI's sites in this map are location at Al Shahaniya, Ghasham Farm and Sudanthile; the other 9 are QMD sites.



#	Name of Station	Network	Latitude (° N)	Longitude (° E)	Yearly GHI (kWh m^{-2})
1	**Abu Samra**	QMD	24.7546	50.8232	2059.11
2	**Al Batna**	QMD	25.10372	51.1737	2169.95
3	**Al Ghuwayriyah**	QMD	25.8405	51.2699	2150.59
4	**Al Jumayliyah**	QMD	25.6137	51.0799	2159.00
5	**Al Karaanah**	QMD	25.0069	51.0358	2152.42
6	**Al Shehaimiyah**	QMD	25.8569	50.9619	2066.60
7	**Al Wakrah**	QMD	25.1928	51.6191	2064. 75
8	**Dukhan**	QMD	25.4062	50.7573	2058.93
9	**Turayna**	QMD	24.6361	51.2116	2181.64
10	**Al Khor**	QEERI	25.6593	51.4636	2158.26
11	**Al Shahaniya**	QEERI	25.3881	51.1142	2165.57
12	**Ghasham Farm**	QEERI	24.8537	51.2710	2176.89
13	**Sudanthile**	QEERI	24.6319	51.0554	2181.64
14	**Al-Kharsaah**	QEERI	25.2393	51.0149	2166.66
15	**HBKU RC-B2**	QEERI	25.3217	51.4248	2147.32

Table 1. List of stations with coordinates and yearly GHI measured

6. SOLAR RADIATION DERIVED FROM SATELLITE IMAGES

⏩ Satellite imagery of Meteosat IODC (Indian Ocean Data Coverage) for the period 2003–2013 has been used to compute hourly values of GHI and DNI for all of Qatar. The satellite images window covers a geographical area located between latitude 24°–26.95°N and longitude 50°–51.95°E, with a spatial resolution of 0.05°×0.05° degrees. The methodology that we have used to calculate solar irradiance from satellite images has been previously detailed in (Pomares & Sanfilippo, 2017).

Solar irradiance under cloudless conditions has been estimated using the REST2 transmittance model (C. A.

As previously indicated, QMD had already been measuring GHI with an hourly resolution at various sites with different starting years. However, a complete assessment requires to measure the three broadband components (GHI, DNI, DHI) and at high temporal resolution, which led to the need of building a complementary network of stations.

Gueymard, 2008). The aerosol optical depth (AOD) at 550 nm, which is a needed parameter for the REST2 model, has been obtained from daily values of MACC retrievals (Eskes et al., 2015; Schroedter-Homscheidt, 2016).

Solar ground measurements have been used to improve satellite data estimations relative to the same areas covered by the solar ground stations, according to the methodology mentioned above, before processing the corresponding maps. The corrections were calculated for the locations of the QMD and QEERI stations, and applied to the whole geographic grid area under analysis (Polo et al., 2016). In the case of GHI measurements in the QMD and QEERI stations, data corrections have been applied daily. For DNI in the QEERI station, corrections were applied to hourly averages to produce monthly and yearly maps.

7. MEASUREMENTS UNCERTAINTY ANALYSIS

An improved assessment of satellite estimations was done using two types of uncertainty parameter of the measurements that are frequently used in the solar resource community (Espinar et al., 2009; C. a. Gueymard, 2014).

These are a parameter of uncertainty focused on the dispersion of data, and a parameter of uncertainty based on the differences in the distribution functions of the data.

The dispersion parameter uncertainty was calculated using relativized versions of the mean bias deviation (rMBD) and root mean square deviation (rRMSD), as shown in (1) and (2) below, where Y_{exp} and Y_{mod} are the measured and estimated values of the random variable, respectively, and N is the total number of points.

$$rMBD = 100\ \frac{1}{N}\sum_{i=1}^{N} \frac{(Y_{exp}-Y_{mod})}{\overline{Y_{exp}}} \qquad (1)$$

$$rRMSD = 100\ \frac{1}{\overline{Y_{exp}}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Y_{exp}-Y_{mod}\right)^{2}}\ ,(2)$$

On the other hand, the uncertainty parameter related with the cumulative distribution function (CDF), is derived from the Kolmogorov-Smirnov (KS) test (Espinar et al., 2009; C. a. Gueymard, 2014).

The rRMSD calculated is around 10% in all the sites, with a positive bias observed, indicating a general trend to underestimate the daily irradiation. A high coefficient of determination (around 0.9) was also found in the daily values of GHI.

Interestingly, when compared to the onsite ground measurements, satellite estimations overestimate DNI and underestimate GHI.

8. YEARLY GHI AND DNI MAPS OF QATAR

The previous methodology for solar radiation estimation from Meteosat imaging has been applied to generate hourly values of GHI and DNI over eleven years, corresponding to a Solar cycle, and with a spatial resolution of 0.05° for the region of interest. The estimations have been corrected according to the linear bias removal method resulting from the comparison with ground measurements. The final corrected data have been processed to aggregate daily values of GHI and DNI for the whole grid area under consideration, and for the period 2003-2013 using the QMD and QEERI daily data for GHI ,and only the QEERI hourly data for DNI.

The corrected daily and hourly values have been used to generate the yearly GHI and DNI maps, respectively. The domain used for the processing of the satellite images was 24-26.95° N and 50-51.95° E. Long-term yearly values and monthly means for GHI and DNI have been compiled in raster formats. Figure 8 and Figure 9 show, respectively, the maps of yearly average irradiation (i.e., average values of the annual sum of daily GHI and DNI). The monthly means of GHI and DNI are shown in the appendix.

According to these maps, GHI is distributed more homogeneously throughout the country, while DNI exhibits higher variability as a consequence of the high aerosol loads; which have, also, a different seasonal behavior affecting the spatial distribution.

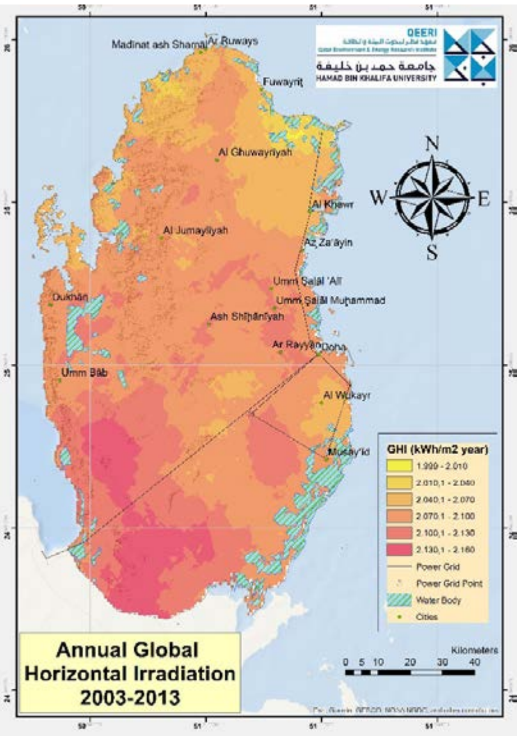


Fig 8: Yearly total sum of GHI (kWh/m2year) in Qatar for the period 2003-2013.

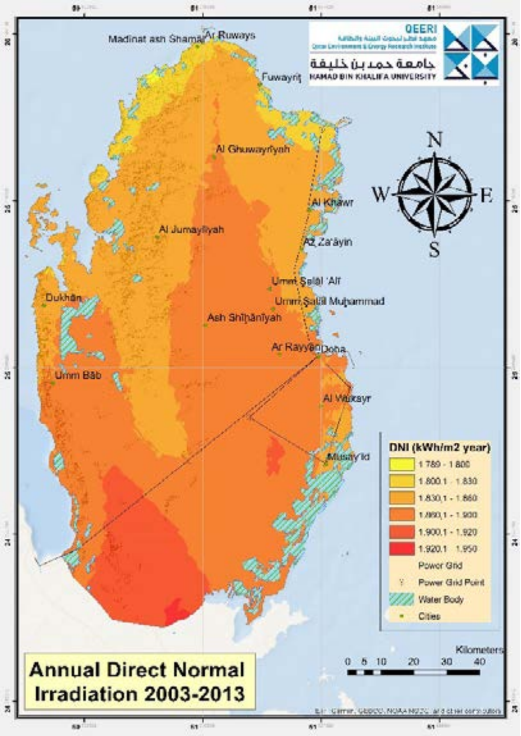


Fig 9: Yearly total sum of DNI (kWh/m2year) in Qatar for the period 2003-20132003-2013.

9. LONG-TERM INTER-ANNUAL AND INTRA-ANNUAL VARIABILITY

IInter- and intra-annual variability maps of solar radiation in Qatar has been produced using 33 years of satellite-derived data. The source of the satellite data is the Climate Monitoring – Satellite Application Facility (http://www.cmsaf.eu) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The 33 years-long (1983-2015) surface radiation climate data records are based on observations from the Meteosat First and Second-Generation satellites, and available in the second release of the Surface Solar Radiation Data – HELIOSAT (SARAH) data record Edition 2. These datasets have been used to derive the variables' deviations since it is one of the longest dataset available for solar radiation data.

The Climate Monitoring – Satellite Application Facility (CMSAF) model consists of two parts. The modified HELIOSAT method, which is used for the retrieval of the effective cloud albedo (CAL); and the MAGIC approach, which is used for the calculation of the all-sky surface radiation based on CAL. The combination of these methods is referred to as MAGICSOL. The MAGICSOL method provides the effective cloud albedo, the solar surface irradiance, and the direct surface solar irradiance and the spectrally-resolved surface solar irradiance.

Global Horizontal Irradiance Intra-Annual Variability

The intra-annual variability of GHI and DNI shown in Figure 10 and Figure 11 respectively, is calculated from the standard deviation of monthly GHI and DNI for the period from 1983 to 2015. The northern portion of the country, which is more exposed to the open sea, presents higher GHI intra-annual variability, while the overall average variability in Qatar ranges between 20 and 25%. This same location near the cost displays a higher DNI intra-annual variability related to the formation of clouds due to the generation of air convection from seawater and sea salt aerosols by wind gusts.

Global Horizontal Irradiance and Direct Normal Irradiance Inter-Annual Variability

The inter-annual variability of GHI and DNI is presented in Figure 12 and Figure 13, respectively. Inter-annual variability is calculated from the standard deviation of yearly GHI and DNI for the period from 1983 to 2015. The biggest variation is produced in areas near the coast due to changes in aerosols, although it could also be an artifact product of the SARAH Edition model, which does not make geometrical correction of the satellite images and thus the pixels of the satellite can slightly shift.

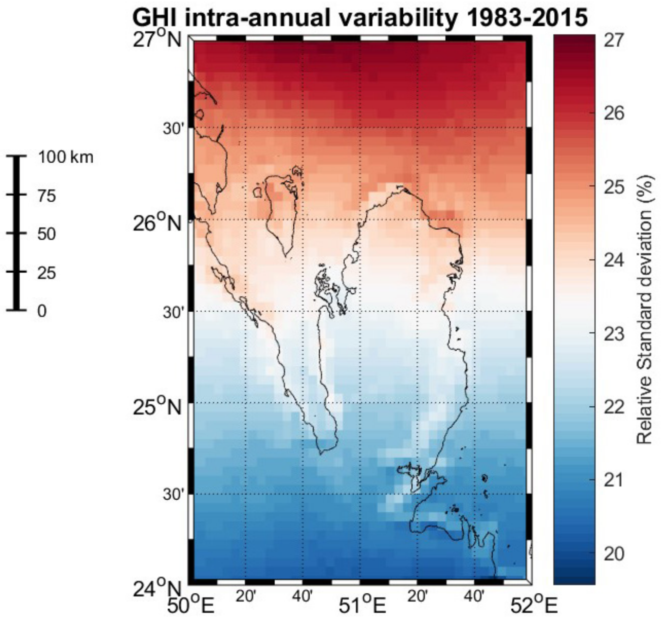


Fig 10: Intra-annual variability of GHI, in percentage, from SARAH Edition 2 database for the period from 1983 to 2015.

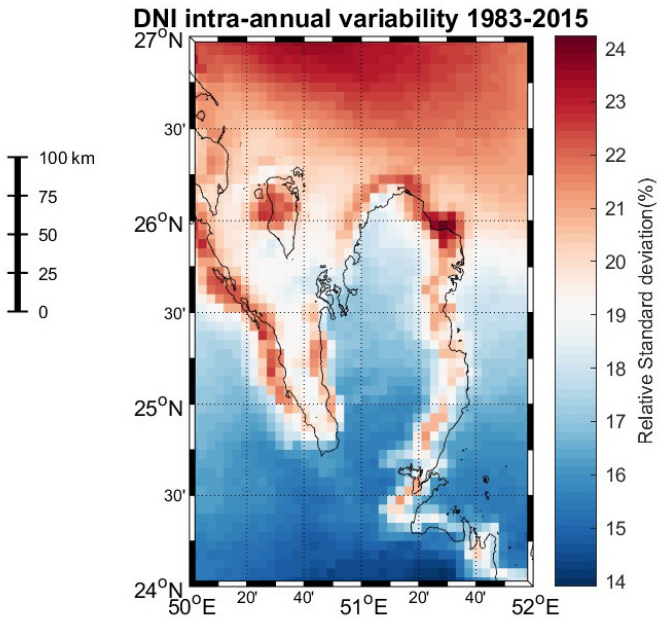


Fig 11: Intra-annual variability of DNI in percentage from SARAH Edition 2 database for the period from 1983 to 2015..

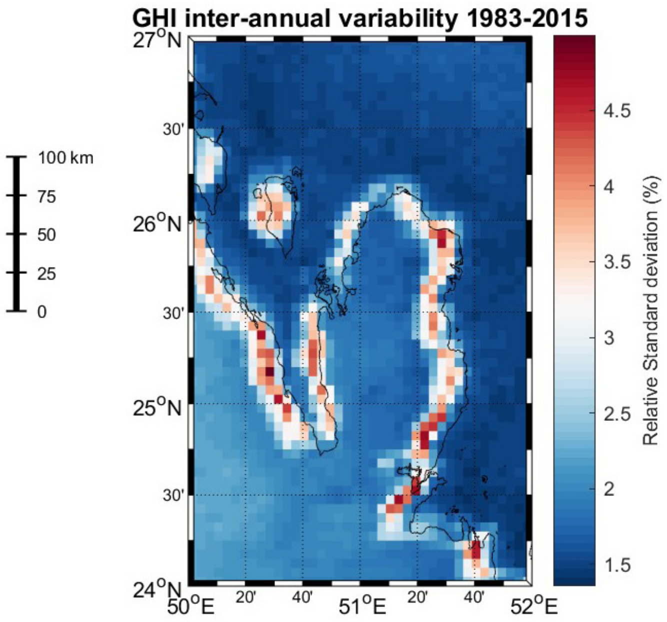


Fig 12: Intra-annual variability of DNI in percentage from SARAH Edition 2 database for the period from 1983 to 2015..

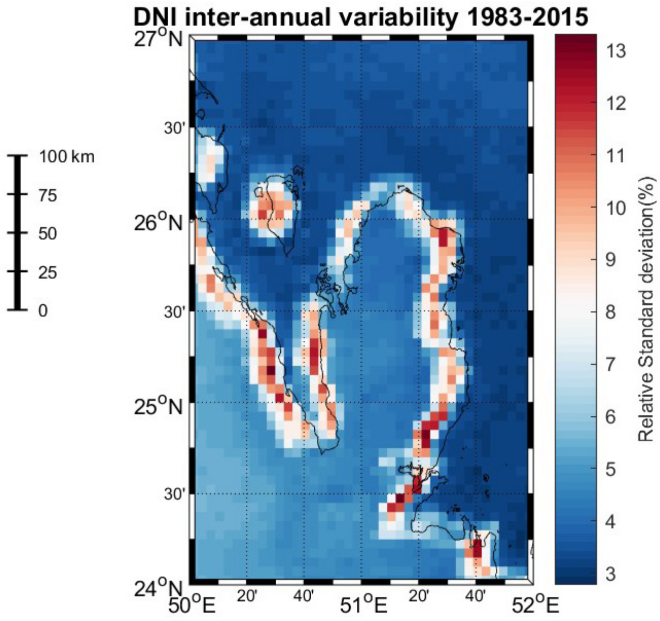


Fig 13: Inter-annual variability of DNI, in percentage, from SARAH Edition 2 database for the period from 1983 to 2015.

10. SOLAR ENERGY FORECASTING

⏩ Based on the previously described knowledge and capabilities for solar mapping, we have developed two solar energy forecasting services: one based on Machine Learning methods with measurements from QEERI radiometric stations, and the other based on Numerical Weather Prediction Models with the satellite-derived data. The combination of the two approaches has contributed to provide an improved accuracy to QEERI forecasting capabilities.

▶ Machine Learning Methods with Measurements from QEERI Radiometric Stations

QEERI has developed a solar energy forecasting service using multi-variate machine learning methods with ground measurements from QEERI radiometric stations using a state-of-the-art patent protected algorithm (Sanfilippo, Martín-Pomares, Mohandes, Perez-Astudillo, Bachour, 2016). This forecasting service can provide forecasts up to three days ahead in hourly increments for the 14 sites of the QEERI National Ground Radiometric Network previously detailed. An example of the forecasting details relative to Turayna station is reported in Figure 14.

Fig 14: Hourly forecasting details for the Turayna station site taken at 3pm on 9 April 2020.

In recent work (Scabbia, Sanfilippo, Fountoukis, Perez-Astudillo, Bachour, 2020), the machine learning approach has been combined with QEERI Numerical Weather Prediction methodology based on the WRF-Chem model (see next section) to provide 3-day ahead forecasts at hourly steps. It is worth mentioning that the capability to forecast the potential solar energy is key for the successful and optimized operations of solar power plants.

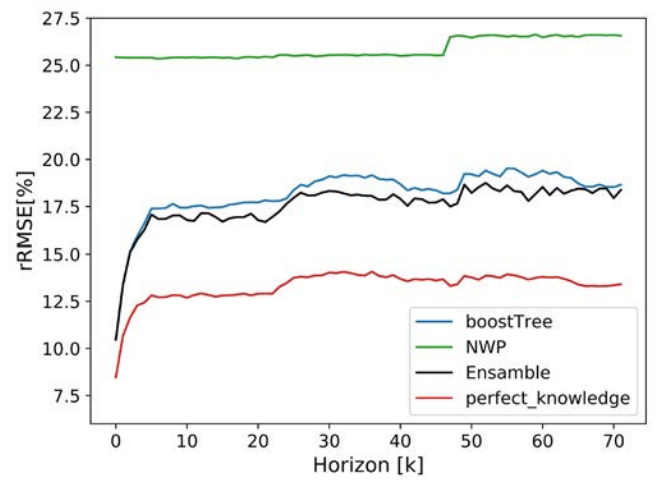


Fig 15: Annual average prediction rRMSE by hourly horizon for the machine learning (boostTree) and NWP models, and their ensemble.

The combination of machine learning with QEERI Numerical Weather Prediction the demonstrate a lower error rate (rRMSE), as showed by the Ensemble (black line) case in Figure 15, than either the machine learning (boostTree, blue line) or Numerical Weather Prediction model (NPW, green line). The Ensemble solution averages 89.5% accuracy during the first 6 hours of prediction, and 82.2% accuracy during the remaining 66 hours of prediction.

* https://www2.acom.ucar.edu/wrf-chem.

Numerical Weather Prediction Models with Satellite-Derived Data

Additionally, QEERI is running a solar radiation operational service based on WRF-Chem model (Fountoukis, Martín-Pomares, Perez-Astudillo, Bachour, & Gladich, 2018). GHI and DNI are forecasted over the Arabian Peninsula with a temporal horizon of 72 hours, a temporal time step of one hour, and spatial resolution of one kilometer. The next figures (19, 20 , 21, and 22) show examples of the forecasting output for DNI, GHI and Temperature at two meters above the ground for the domain of the Arabian Peninsula and Qatar.

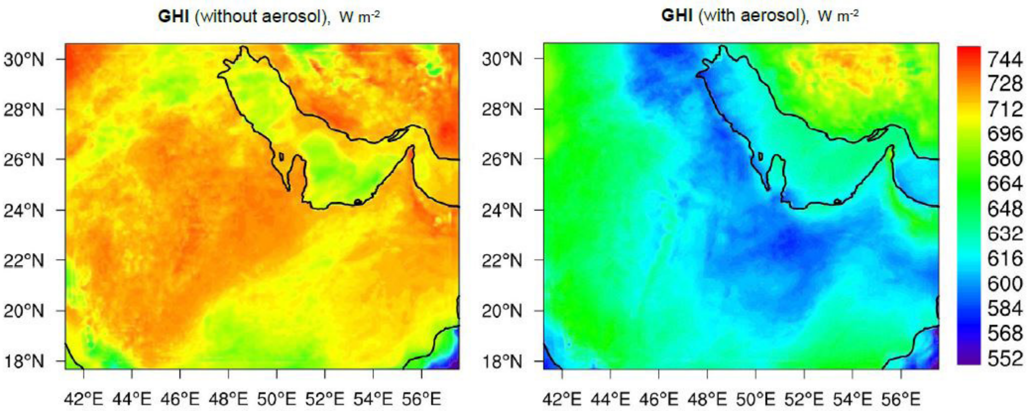


Fig 16 Average GHI (Wm^{-2}) predicted by WRF (without aerosols) and WRF/Chem-QEERI (with aerosols) during May 2019, over the Arabian Peninsula.

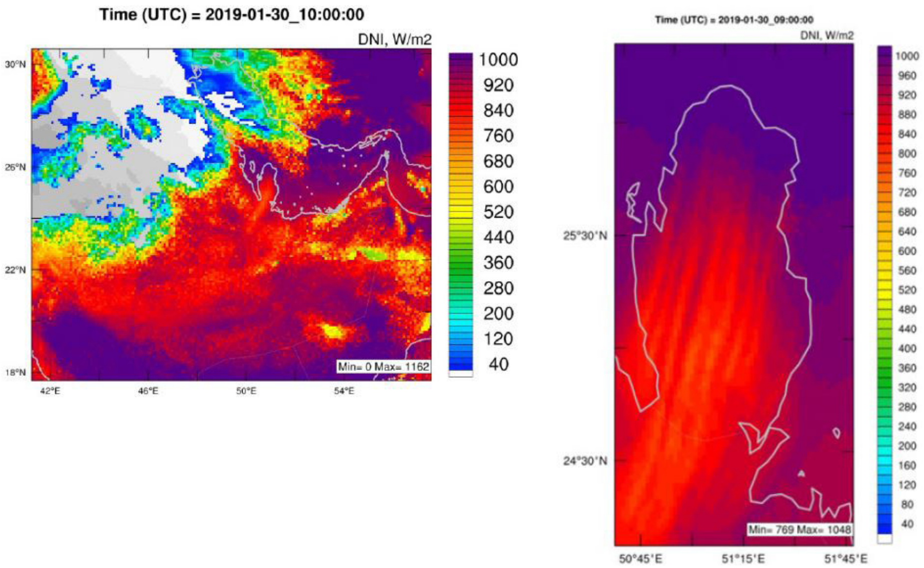


Fig 17: DNI Forecast (Wh/m^2) for Arabian Peninsula and Qatar domains for 30 January 2019.

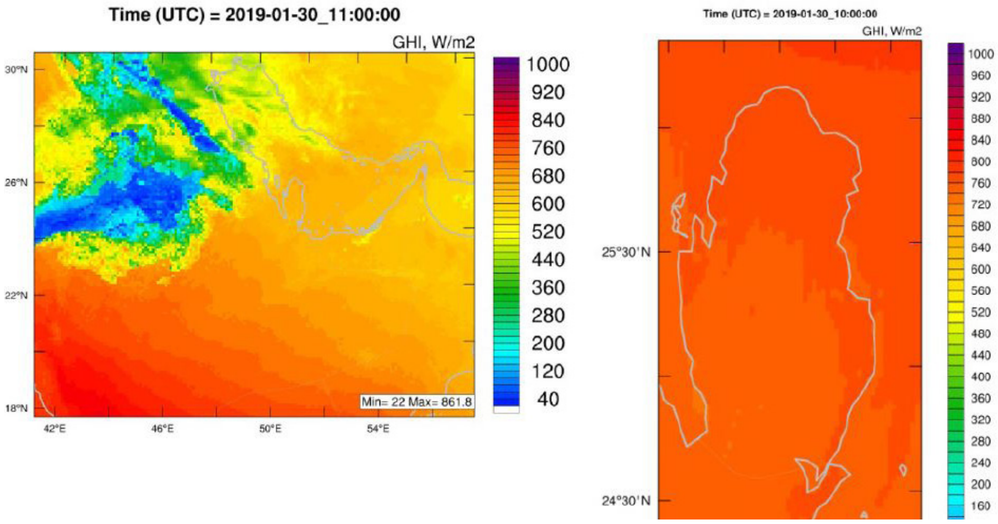


Fig 18: GHI forecast (Wh/m^2) for Arabian Peninsula and Qatar domains for 30 January 2019.

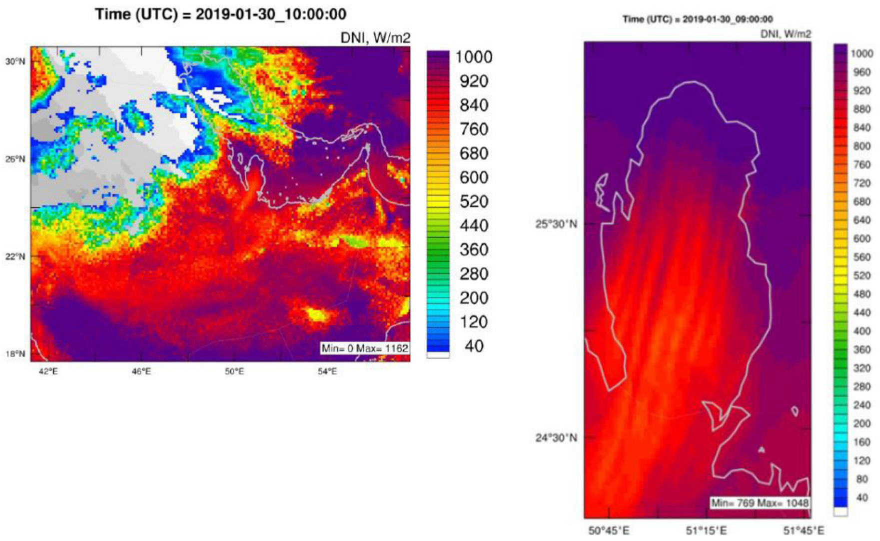


Fig 19: Temperature at 2 meters (Celsius Degrees) above ground forecast for Arabian Peninsula and Qatar domains for 30 January 2019.

11. SOILING ANALYSIS

The performance of PV panels is impacted by soiling and dust deposition and this is especially the case for the climatic conditions of the region and Qatar. Associated to the efforts in solar prediction and forecasting QEERI is currently developing an operational model to map the soiling appearance in the country and characterize its seasonality. The ultimate objective will be to optimizing cleaning schedules and method to optimize the use of mechanical force in the case of dry cleaning and water (externally supplied or as condensate on PV modules); and thus minimize of the cost of solar electricity produced in Qatar and maximize the return on investment on solar power plants. A preliminary example of QEERI soiling research project is shown in Figure 20, where it is shown the predicted monthly average spatial distribution of dust gravitational settling (in µg m^{-2} s^{-1}) as initially predicted using the WRF-Chem model at the ground level during (a) a summer and (b) a winter period in Qatar.

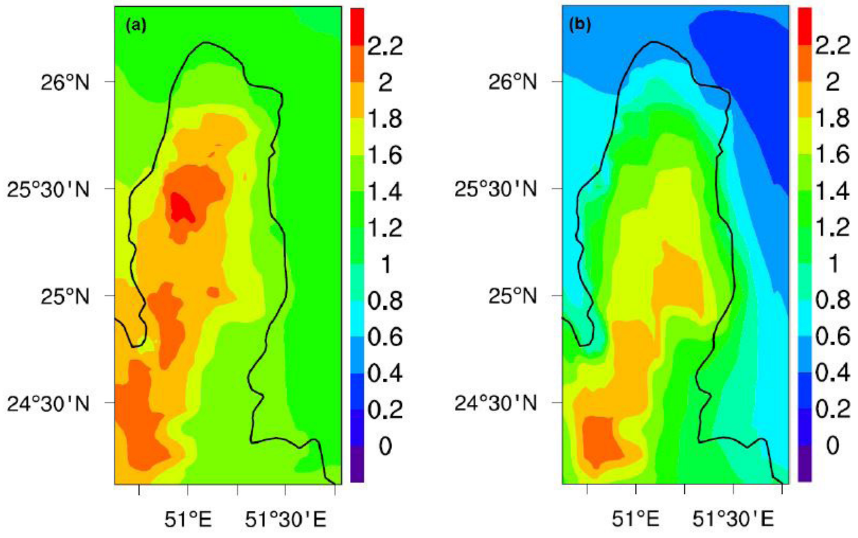


Fig 20: Monthly average spatial distribution of dust gravitational settling (in µg m^{-2} s^{-1}) as predicted by WRF-Chem at the ground level during (a) a summer and (b) a winter period in Qatar.

12. CONCLUSION

Select the right location and the adequate configuration of a solar conversion energy system is critical to its success and can be challenging due to the intrinsic variable nature of solar radiation. Weather fluctuations, location to location specificities and seasonal sun position changes have significant effects on a solar system's performance and thus in the economic return of investments in any solar power plant or facility. Based on high quality ground data (measured in the country since 2012), it is shown that the variability of the solar resource shows significant intra- and inter-annual variation. The observed deviation can strongly depend on the spatial location, with higher variability close to the shores, especially in the Northern and the Eastern areas of the Peninsula.

The availability of meteorological data from ground measurements in the last 8 years has proven to be a reliable and high-quality point of reference and means to calibration of satellite images enabling a higher spatial resolution (at the km-range).

Satellite images have also been studied as far as back 1983 to provide a long-term analysis of the evolution of the solar resource that can be linked with climate change. This knowledge will enable QEERI to continue estimating how the solar resource could evolve in the coming decades to enable the calculation of the expected return on investment for large utility solar PV plants and other solar technologies. The maps show that, through most the Qatar, yearly sum of global horizontal irradiation is in the range of 2000 to 2200 kWh/m^2. GHI is distributed more homogeneously throughout the country, while DNI exhibits higher variability as a consequence of the high aerosol loads; which have, also, a different seasonal behavior affecting the spatial distribution. The seasonal variability is very low, compared with other countries, which qualifies Qatar as a country with highly feasible potential for PV power generation.

Associated to the efforts in solar prediction and forecasting QEERI is currently developing an operational model to map the soiling appearance in the country and characterize its seasonality which will allow increase the energy yield and minimize the cost of solar electricity produced in Qatar and maximize the return on investment on solar power plants

The current report provides monthly maps of DNI and GHI for Qatar averaged over the period 2003 to 2013, covering a full sun cycle. Future reports will be issued by QEERI for more recent years, where the soiling mapping of the country will be included. This will include the simulated energy yield of different solar technologies based on our estimated solar resource, a solar energy forecasting service at the sites of QEERI National Ground Radiometric Network, and for the whole Arabian Peninsula taking into account aerosols concentration and the soiling analysis to predict areas with highest and lowest soiling and seasonal variations.

Interested stakeholders are encouraged to contact us: qeeri-communication@hbku.edu.qa

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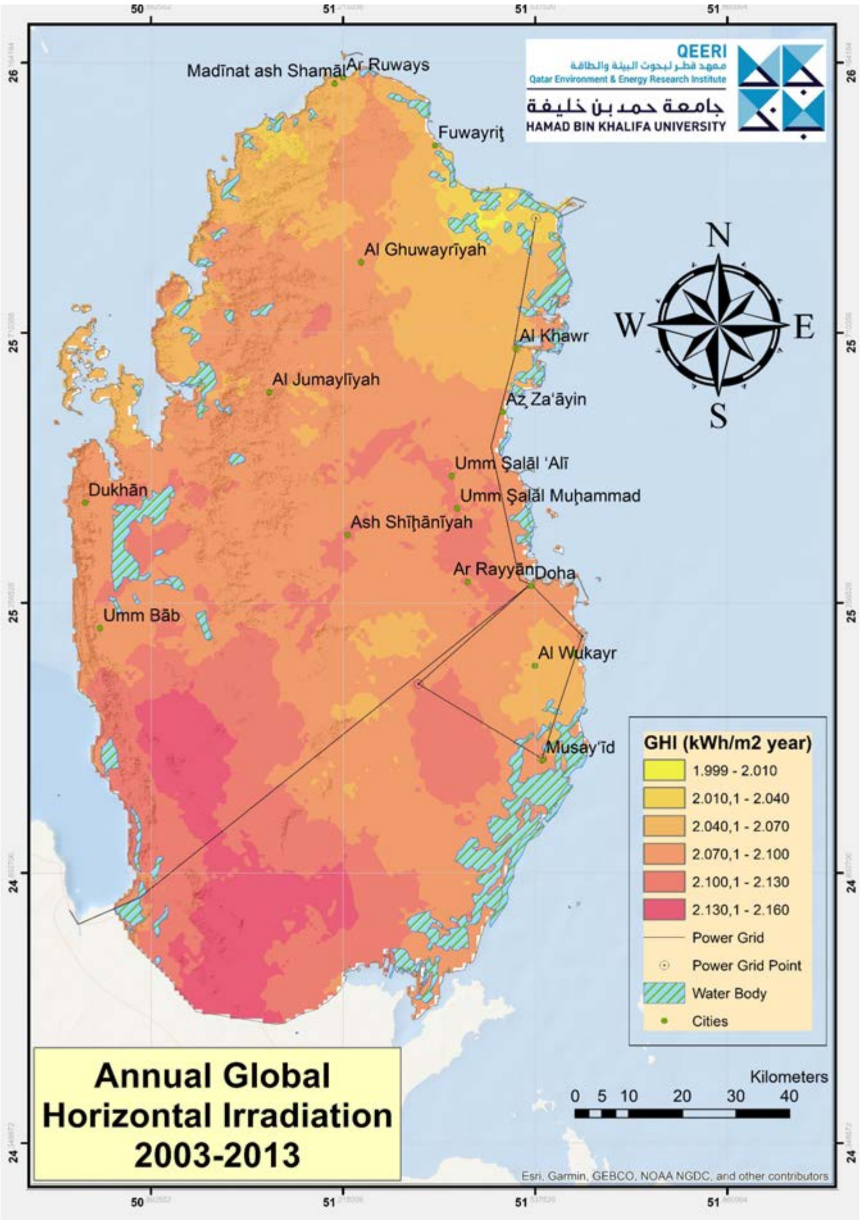
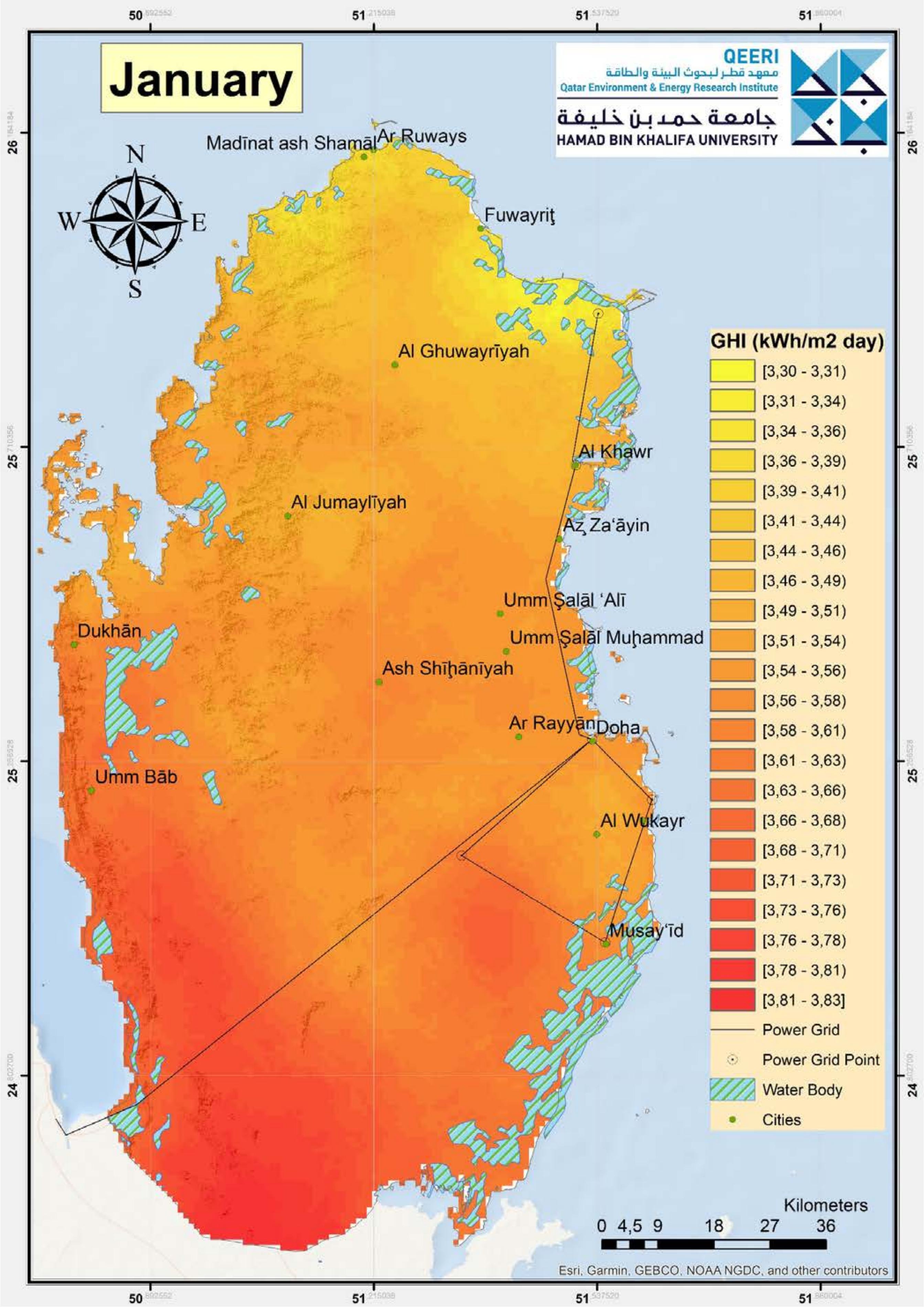
APPENDIX

GLOBAL HORIZONTAL IRRADIATION (GHI)

- Yearly total sum of daily global horizontal irradiance (1 map).
- Monthly average of the daily sum for global horizontal irradiance (12 maps, one per month of the year).





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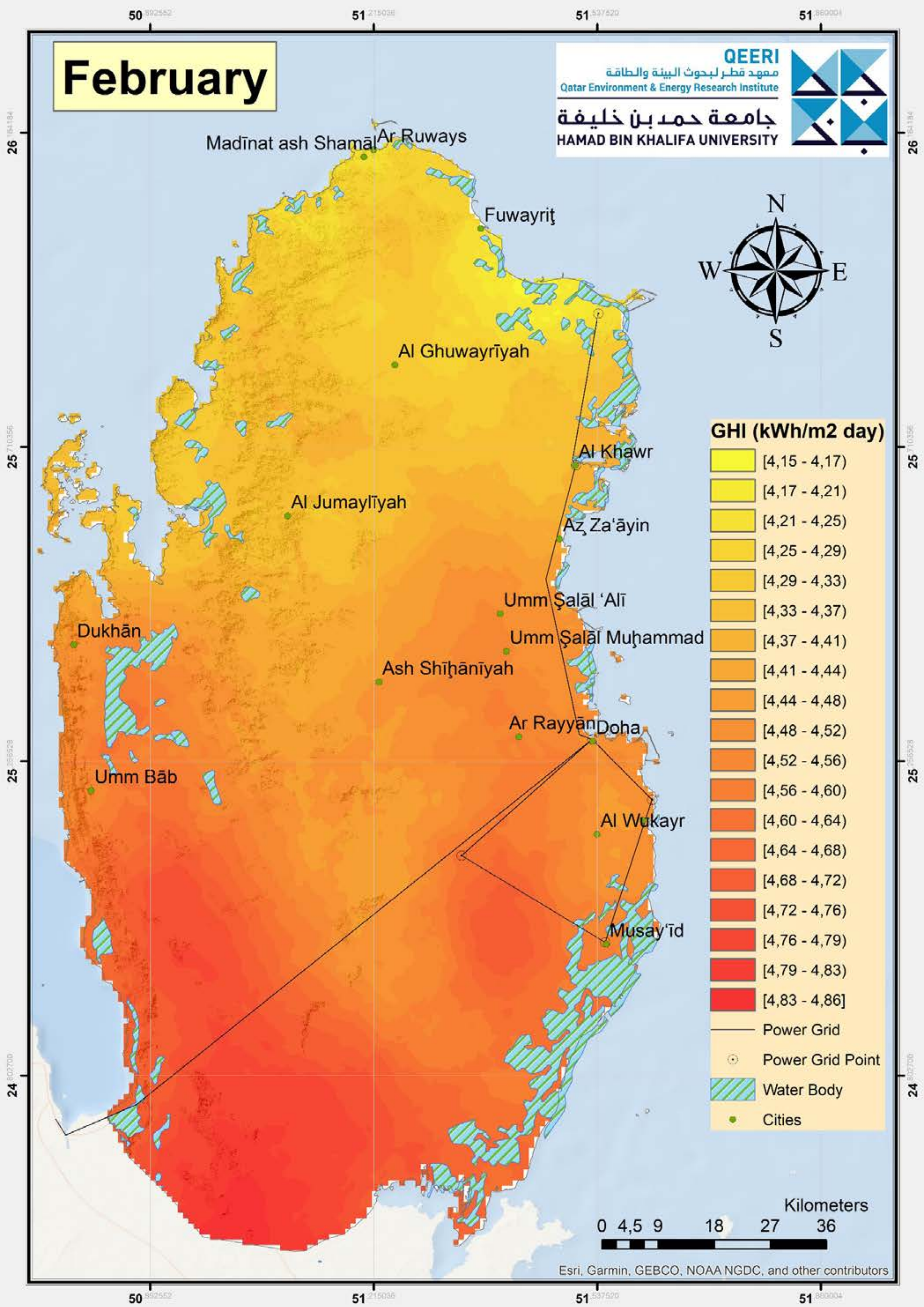
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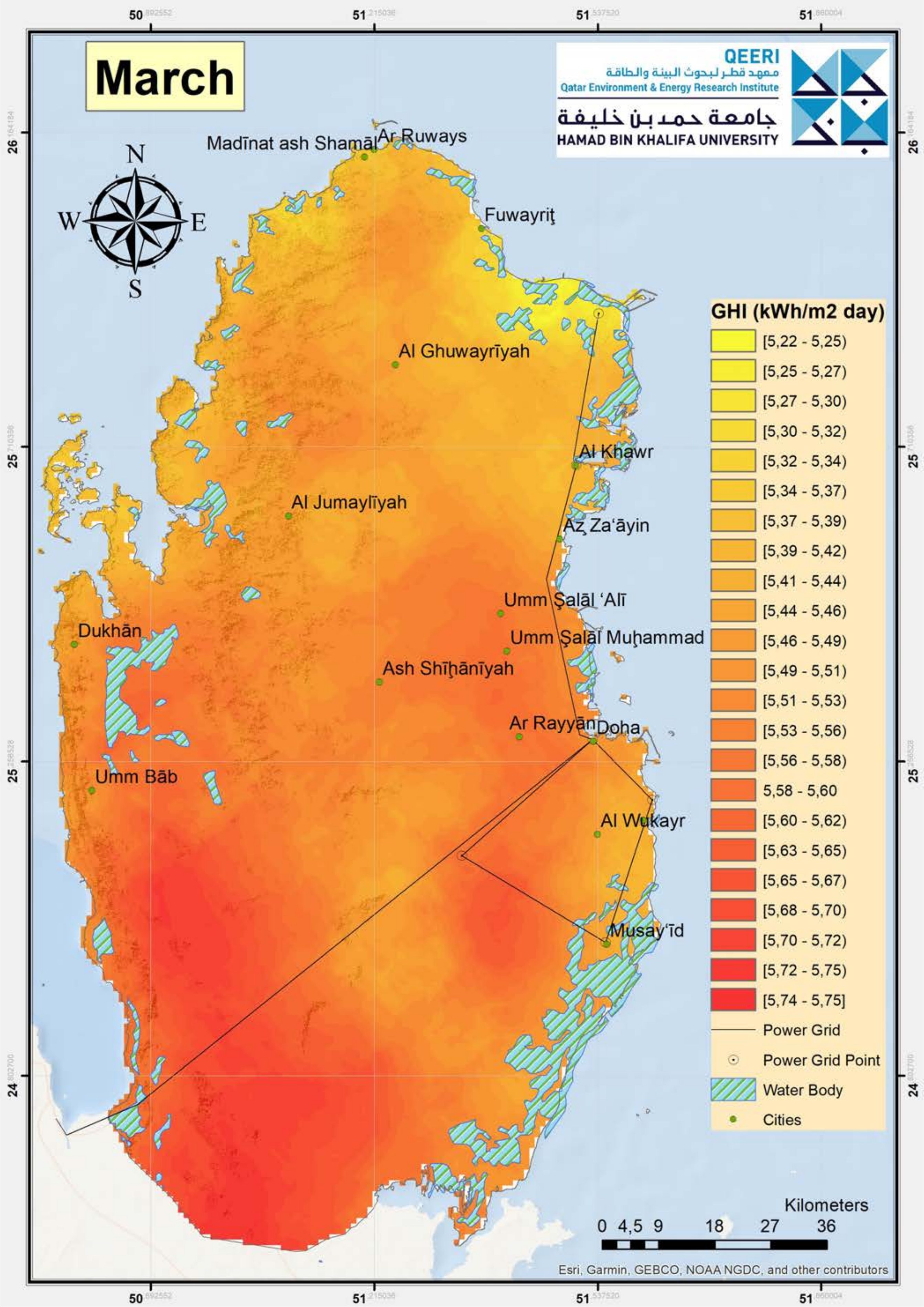
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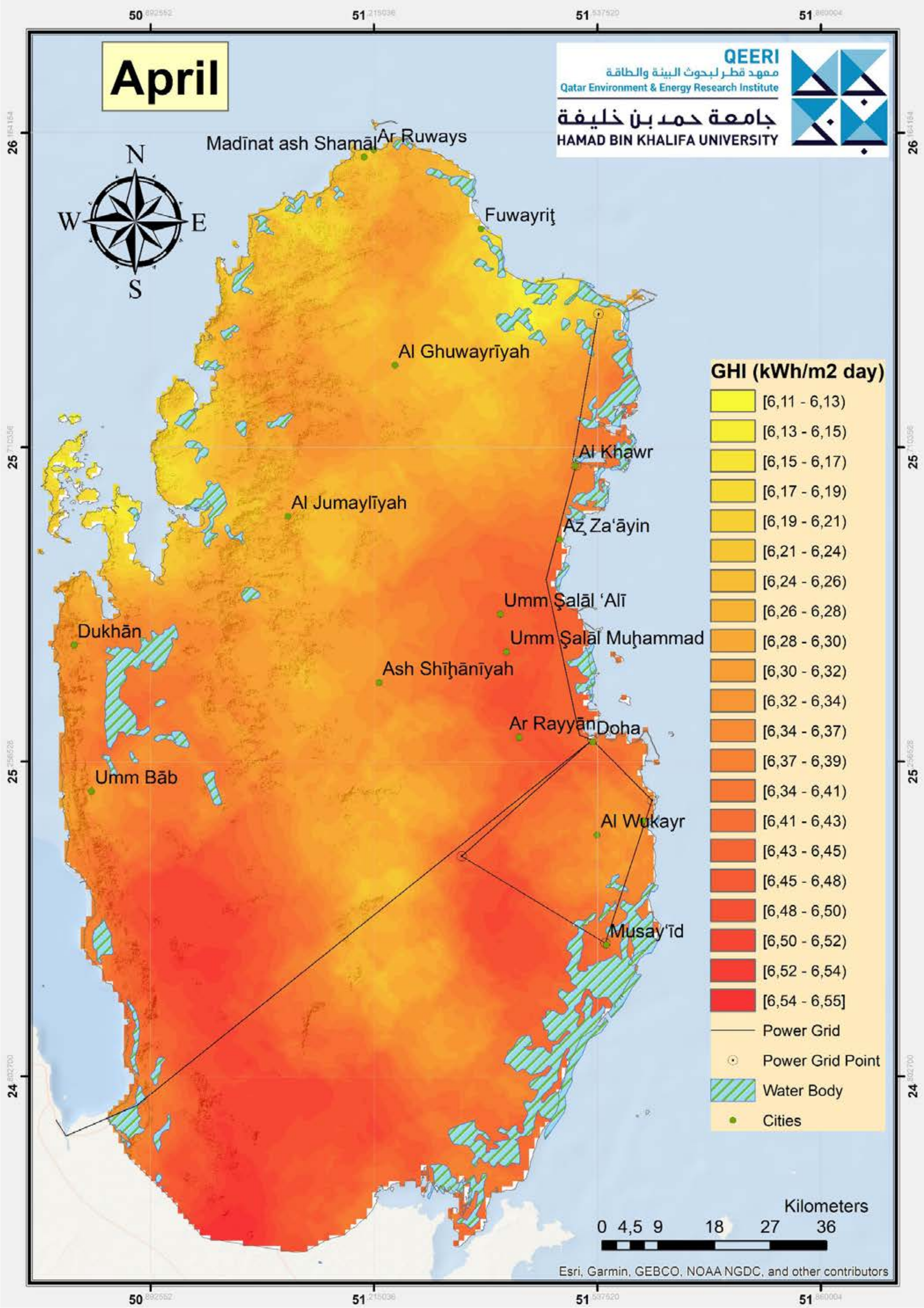
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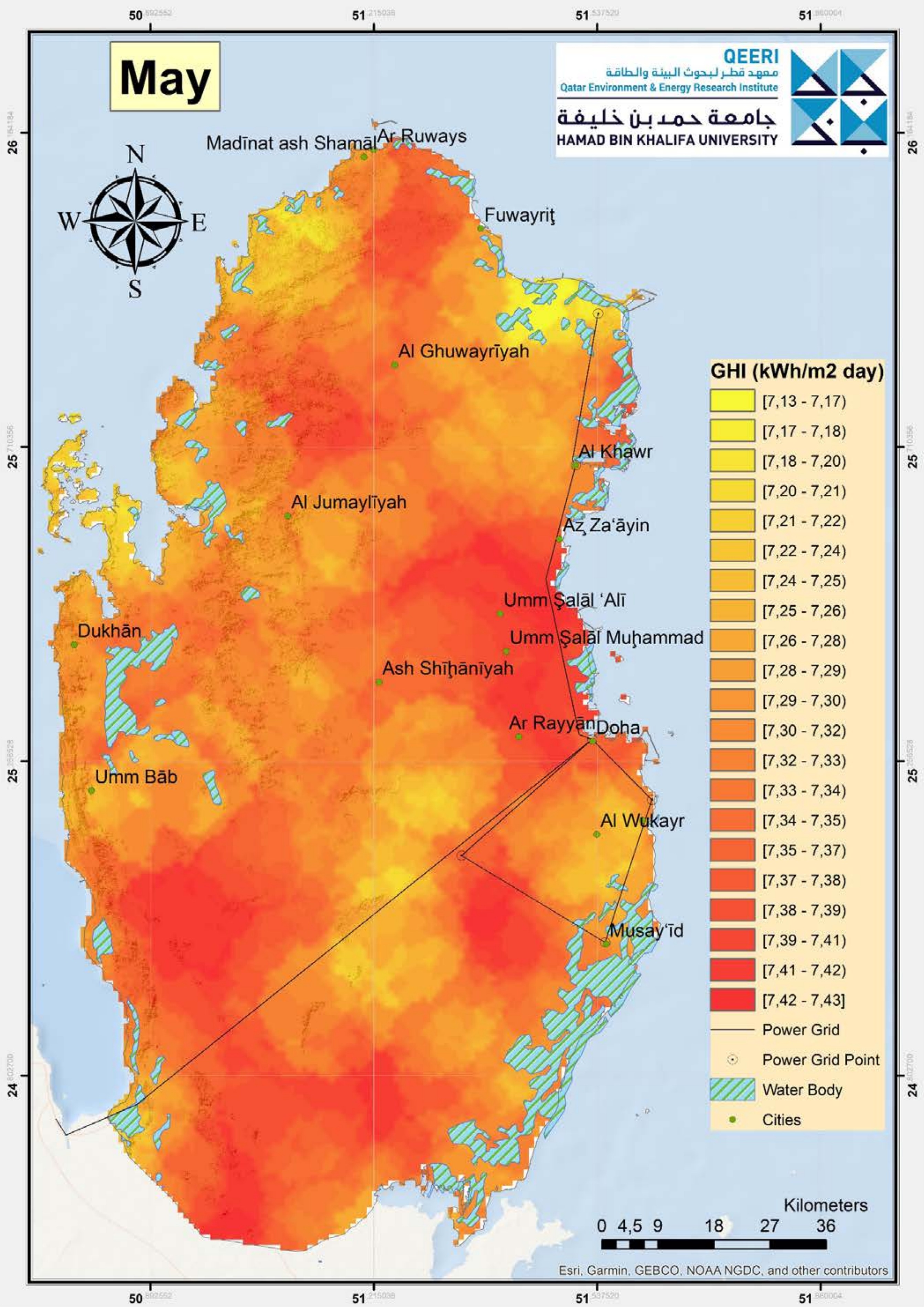
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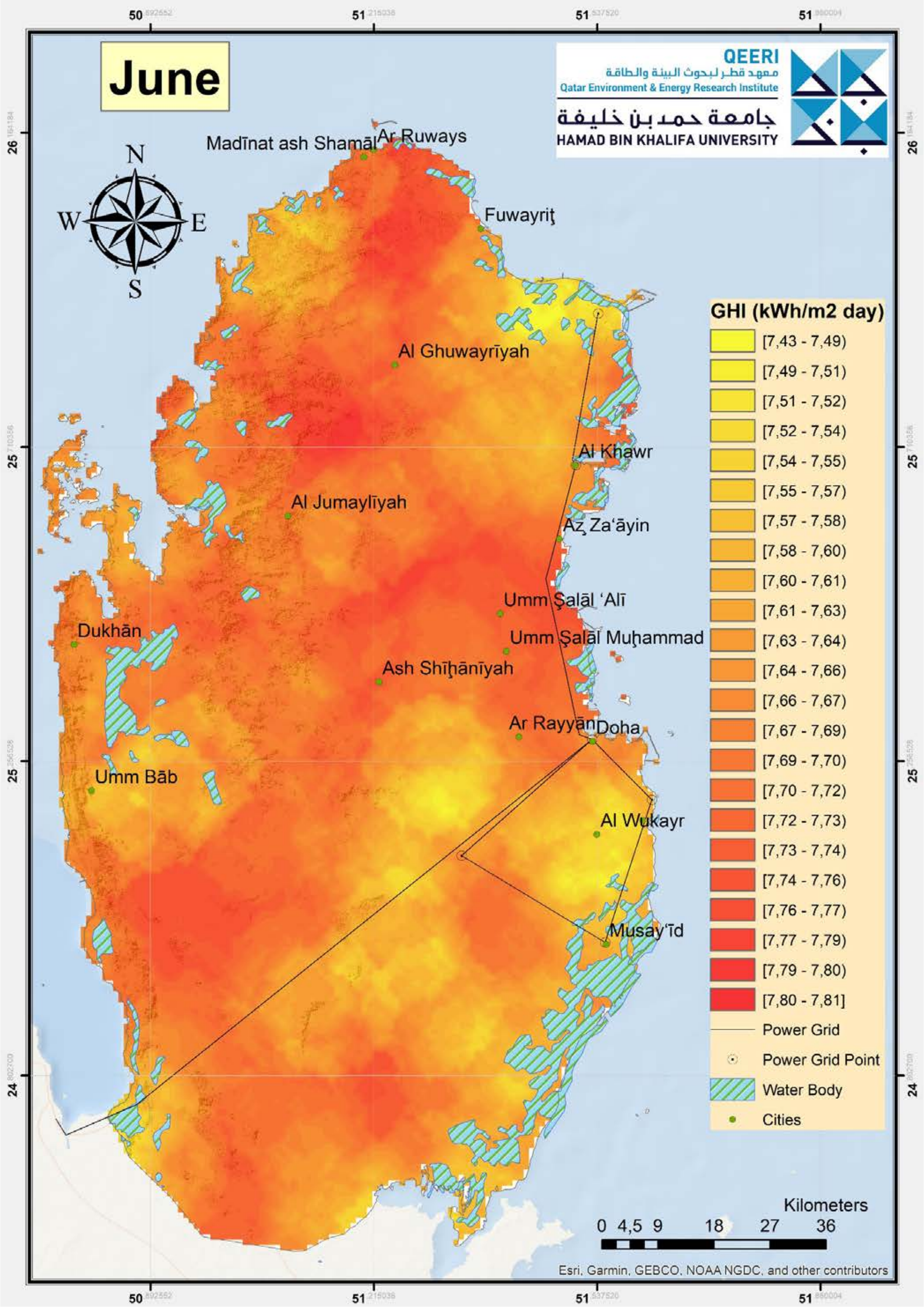
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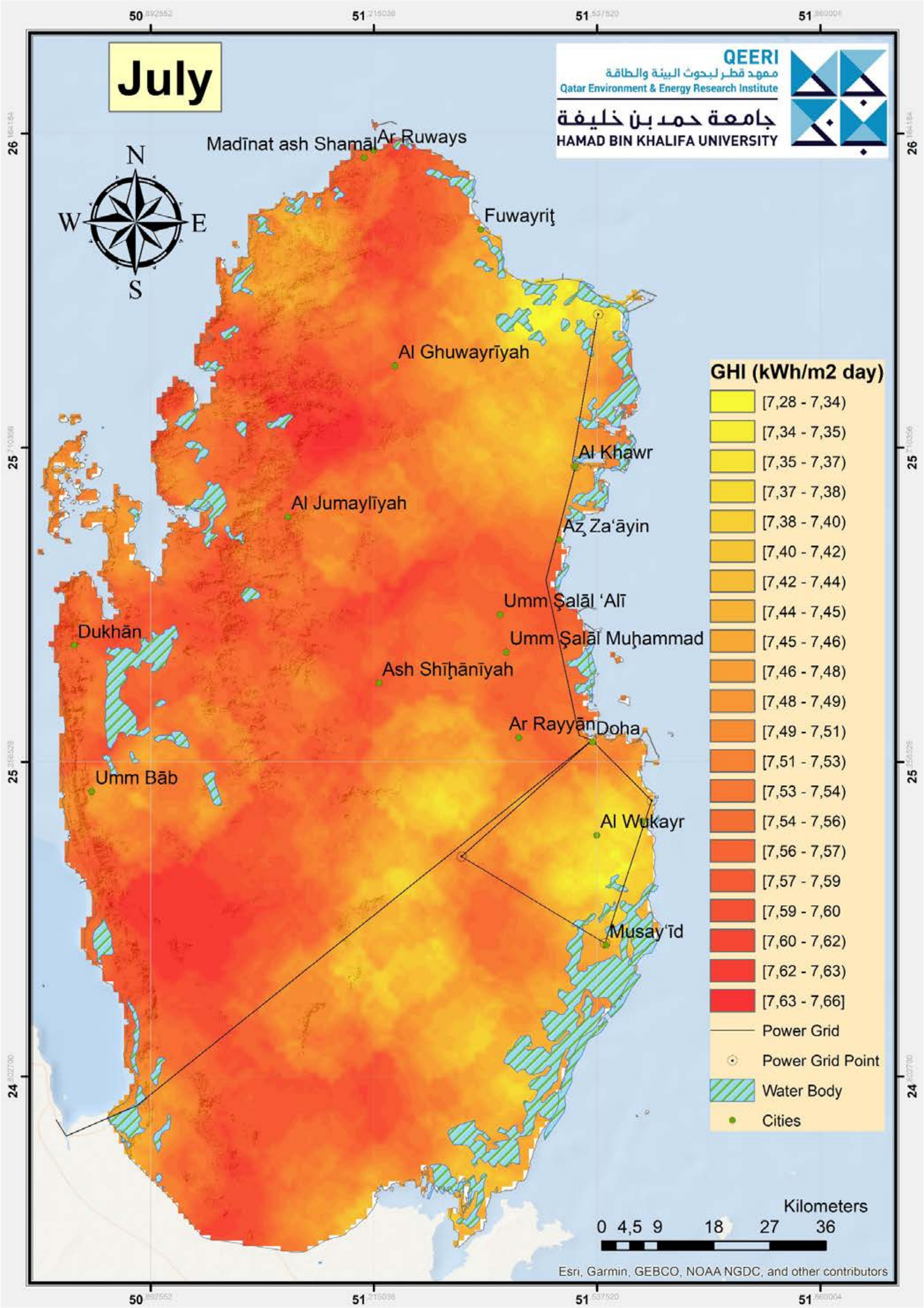
July
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معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
50 .892552
51 .215036
51 .537520
51 .860004
26 .164184
25 .710356
25 .256528
24 .802700
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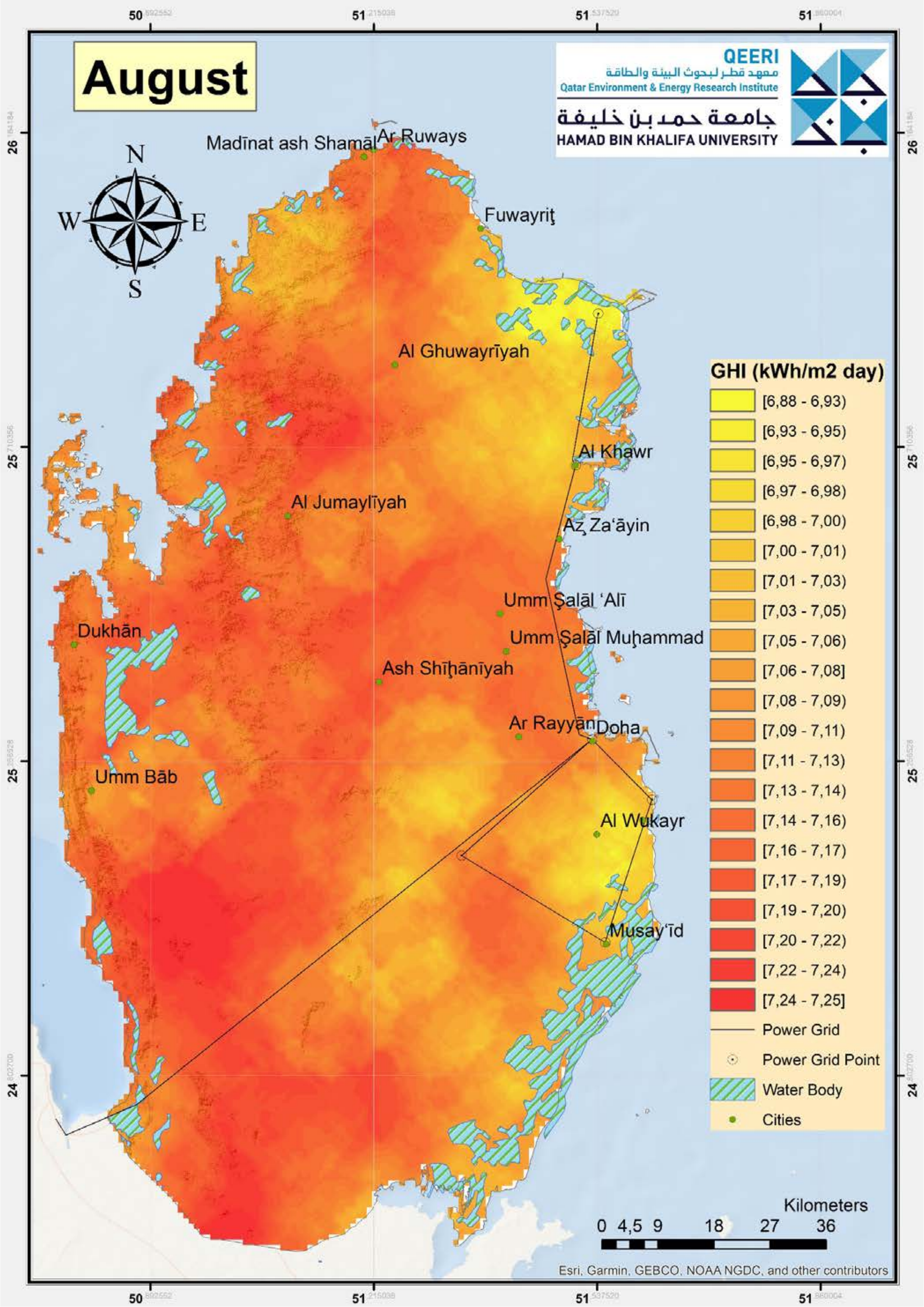
Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az̧ Za‘āyin
Umm Şalāl ‘Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay‘īd
GHI (kWh/m2 day)
[7,28 - 7,34)
[7,34 - 7,35)
[7,35 - 7,37)
[7,37 - 7,38)
[7,38 - 7,40)
[7,40 - 7,42)
[7,42 - 7,44)
[7,44 - 7,45)
[7,45 - 7,46)
[7,46 - 7,48)
[7,48 - 7,49)
[7,49 - 7,51)
[7,51 - 7,53)
[7,53 - 7,54)
[7,54 - 7,56)
[7,56 - 7,57)
[7,57 - 7,59
[7,59 - 7,60
[7,60 - 7,62)
[7,62 - 7,63)
[7,63 - 7,66]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


August
QEERI
معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
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Umm Şalāl ‘Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay‘īd
GHI (kWh/m2 day)
[6,88 - 6,93)
[6,93 - 6,95)
[6,95 - 6,97)
[6,97 - 6,98)
[6,98 - 7,00)
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[7,01 - 7,03)
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[7,19 - 7,20)
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[7,22 - 7,24)
[7,24 - 7,25]
Power Grid
Power Grid Point
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Cities
Kilometers
0 4,5 9 18 27 36
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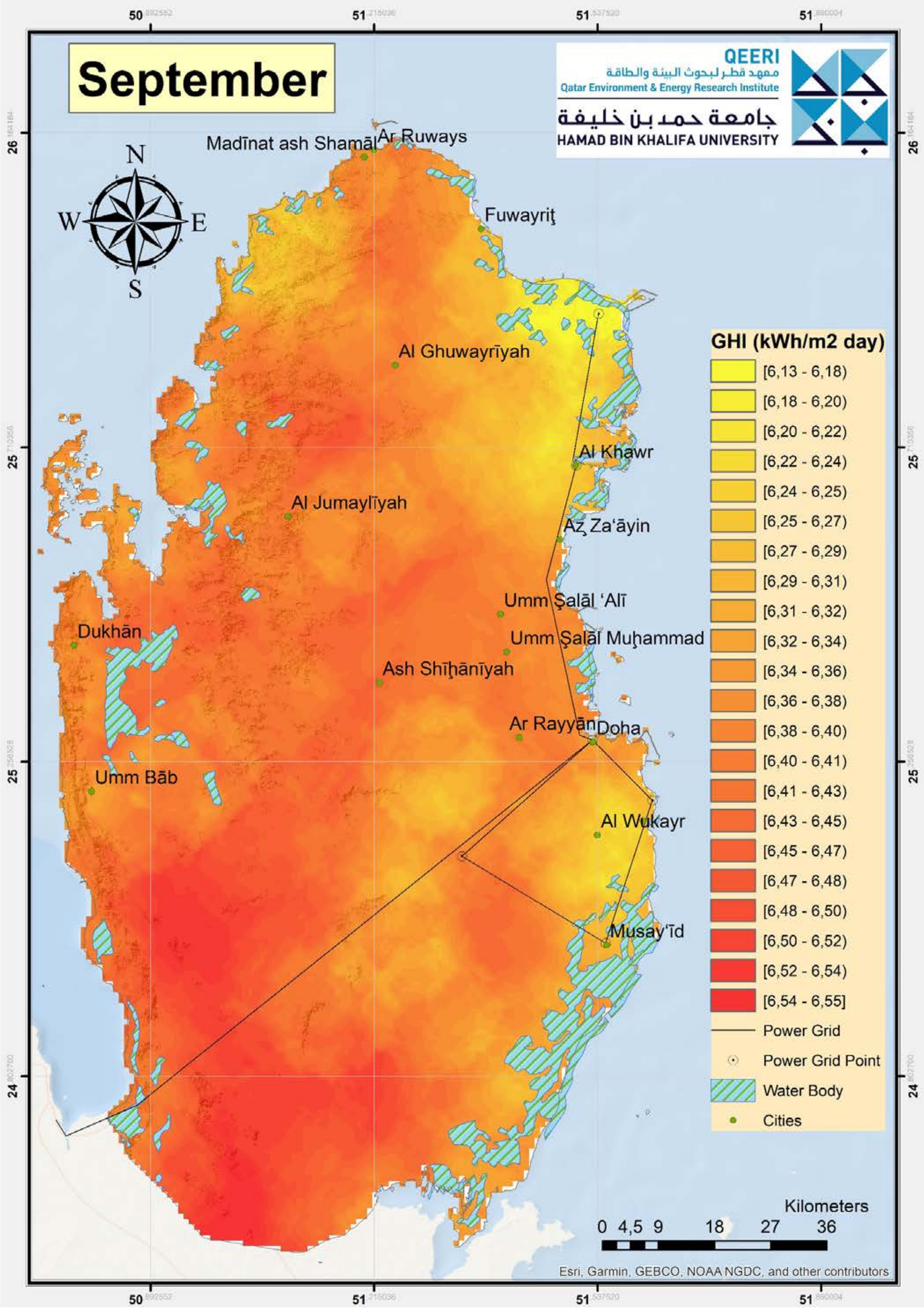
25.710356
25.256528
24.802700


September
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Qatar Environment & Energy Research Institute
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Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
GHI (kWh/m2 day)
[6,13 - 6,18)
[6,18 - 6,20)
[6,20 - 6,22)
[6,22 - 6,24)
[6,24 - 6,25)
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Power Grid
Power Grid Point
Water Body
Cities
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Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
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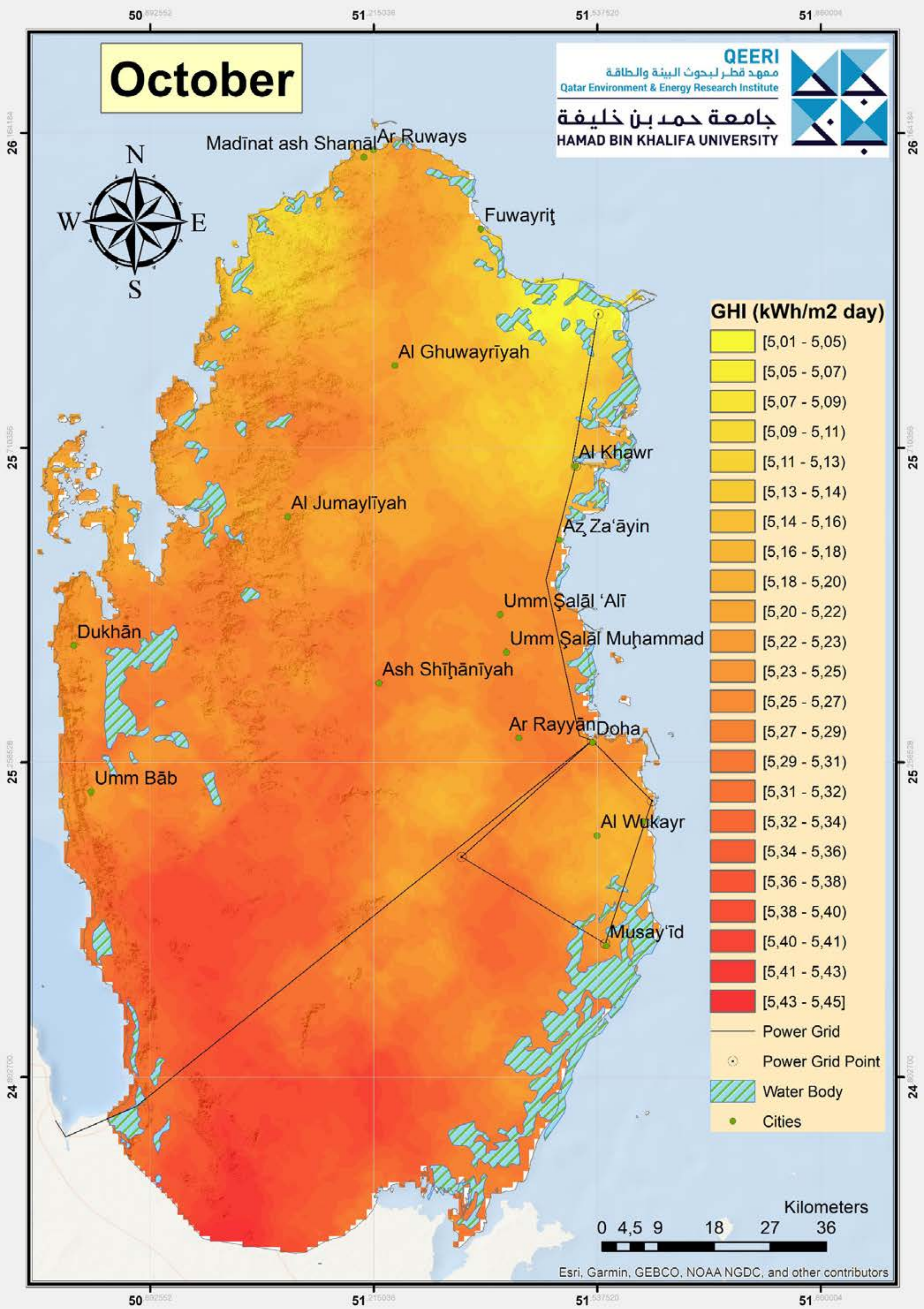
October
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Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
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Umm Şalāl 'Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
GHI (kWh/m2 day)
[5,01 - 5,05)
[5,05 - 5,07)
[5,07 - 5,09)
[5,09 - 5,11)
[5,11 - 5,13)
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[5,38 - 5,40)
[5,40 - 5,41)
[5,41 - 5,43)
[5,43 - 5,45]
Power Grid
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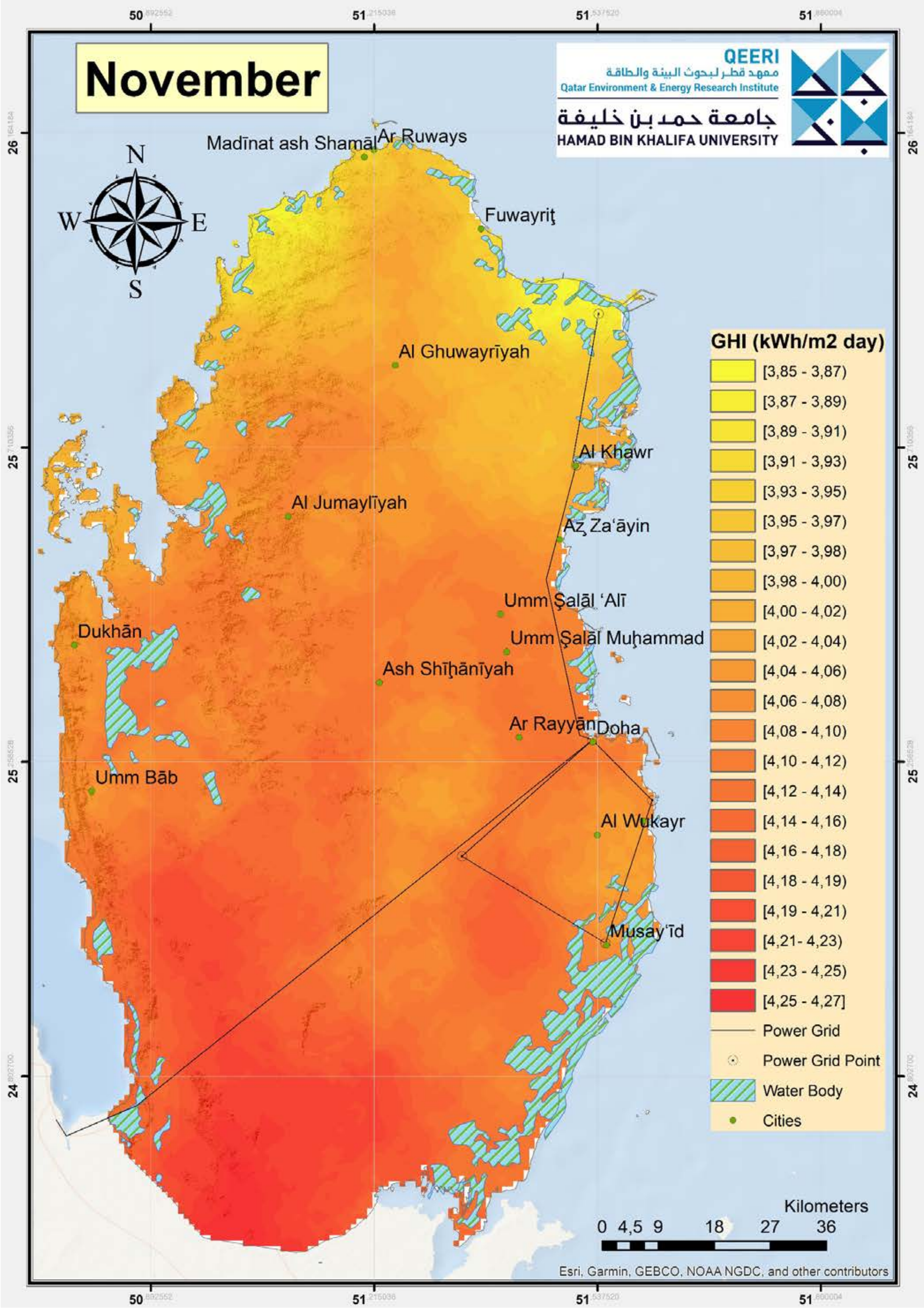
November
QEERI
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Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
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Umm Şalāl 'Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
GHI (kWh/m2 day)
[3,85 - 3,87)
[3,87 - 3,89)
[3,89 - 3,91)
[3,91 - 3,93)
[3,93 - 3,95)
[3,95 - 3,97)
[3,97 - 3,98)
[3,98 - 4,00)
[4,00 - 4,02)
[4,02 - 4,04)
[4,04 - 4,06)
[4,06 - 4,08)
[4,08 - 4,10)
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[4,12 - 4,14)
[4,14 - 4,16)
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[4,18 - 4,19)
[4,19 - 4,21)
[4,21- 4,23)
[4,23 - 4,25)
[4,25 - 4,27]
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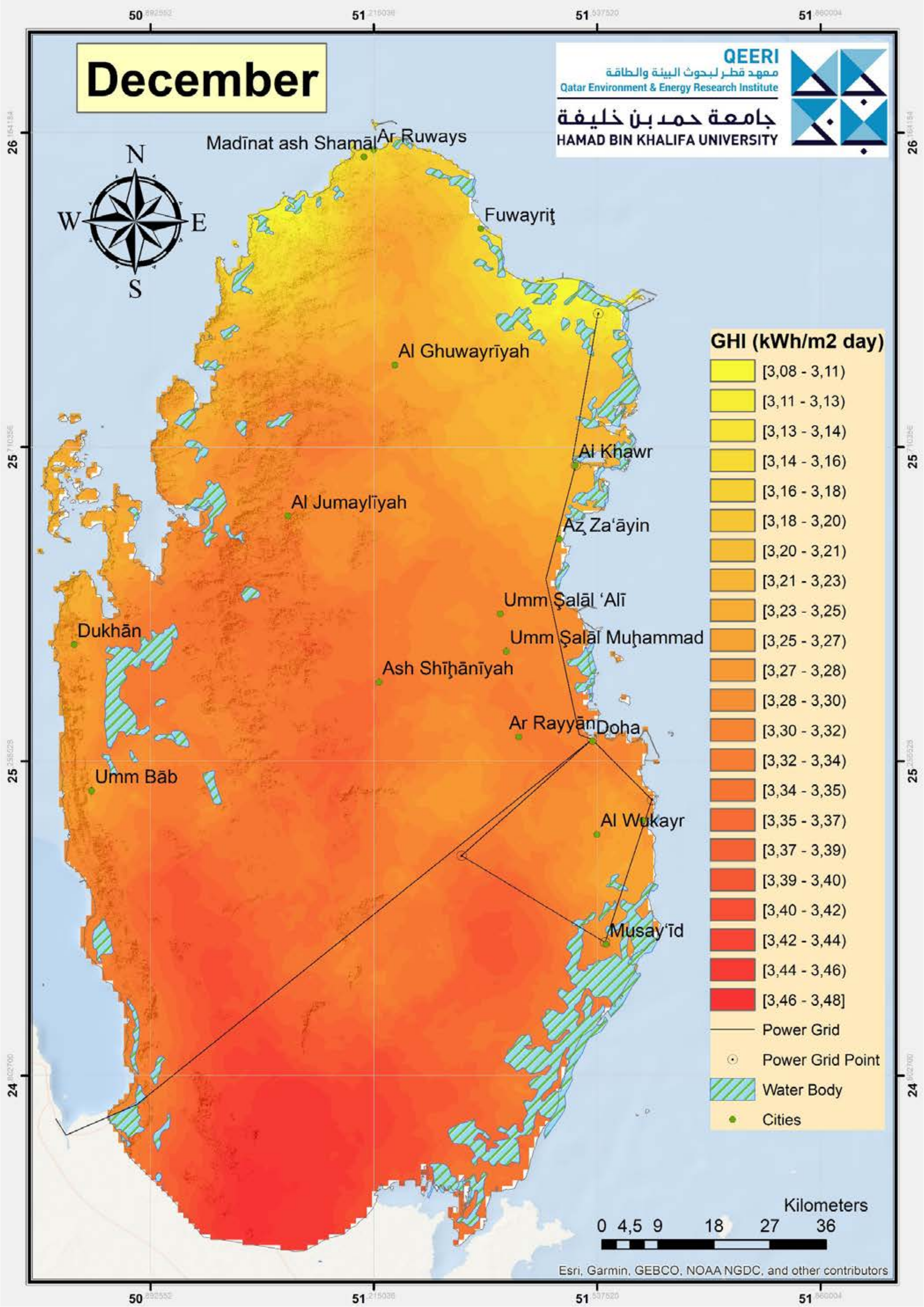
December
QEERI
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Qatar Environment & Energy Research Institute
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HAMAD BIN KHALIFA UNIVERSITY
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51 215036
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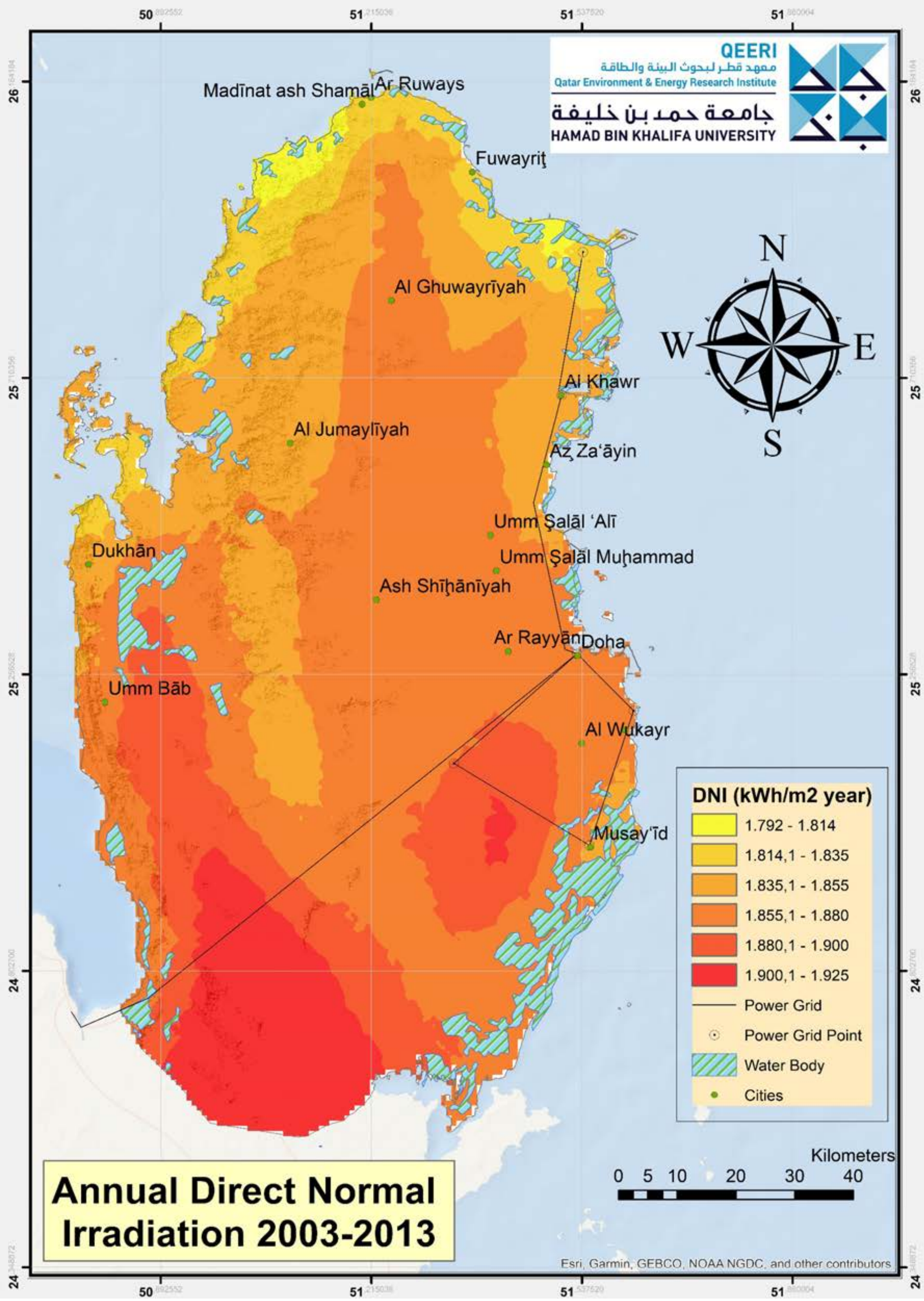
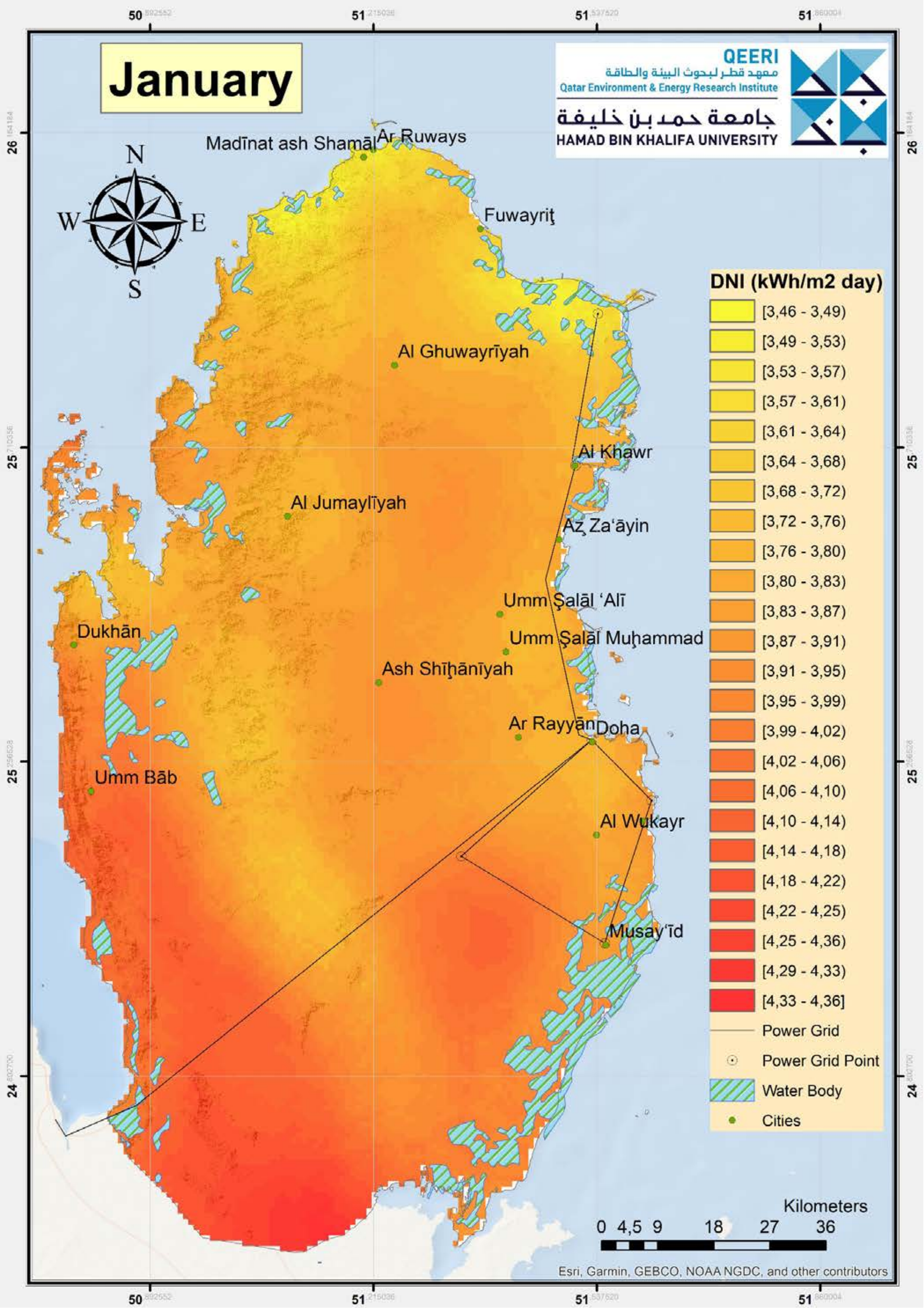
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
GHI (kWh/m2 day)
[3,08 - 3,11)
[3,11 - 3,13)
[3,13 - 3,14)
[3,14 - 3,16)
[3,16 - 3,18)
[3,18 - 3,20)
[3,20 - 3,21)
[3,21 - 3,23)
[3,23 - 3,25)
[3,25 - 3,27)
[3,27 - 3,28)
[3,28 - 3,30)
[3,30 - 3,32)
[3,32 - 3,34)
[3,34 - 3,35)
[3,35 - 3,37)
[3,37 - 3,39)
[3,39 - 3,40)
[3,40 - 3,42)
[3,42 - 3,44)
[3,44 - 3,46)
[3,46 - 3,48]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

DIRECT NORMAL IRRADIANCE (DNI)

- Daily average of the daily sum for the solar variable (1 map).
- Monthly average of the daily sum for the solar variable (12 maps, one per month of the year).




January
QEERI
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Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[3,46 - 3,49)
[3,49 - 3,53)
[3,53 - 3,57)
[3,57 - 3,61)
[3,61 - 3,64)
[3,64 - 3,68)
[3,68 - 3,72)
[3,72 - 3,76)
[3,76 - 3,80)
[3,80 - 3,83)
[3,83 - 3,87)
[3,87 - 3,91)
[3,91 - 3,95)
[3,95 - 3,99)
[3,99 - 4,02)
[4,02 - 4,06)
[4,06 - 4,10)
[4,10 - 4,14)
[4,14 - 4,18)
[4,18 - 4,22)
[4,22 - 4,25)
[4,25 - 4,36)
[4,29 - 4,33)
[4,33 - 4,36]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
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50 892552
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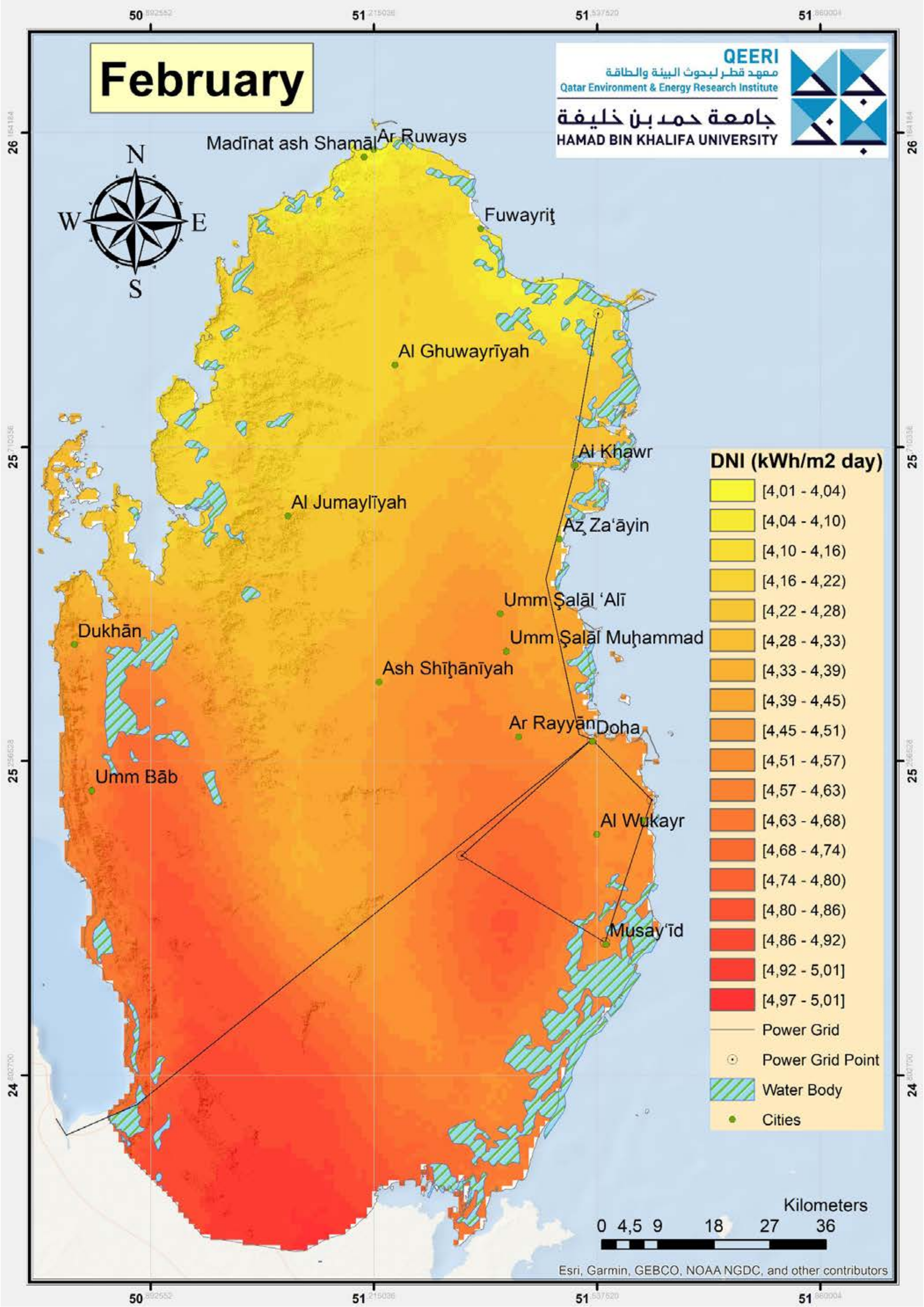
51 537520
51 860004
26 154184
25 710356
25 256528
24 802700


February
QEERI
معهد قطر لبحوث البيئة والطاقة
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Al Khawr
Al Jumaylīyah
Az̧ Za'āyin
Umm Şalāl 'Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[4,01 - 4,04)
[4,04 - 4,10)
[4,10 - 4,16)
[4,16 - 4,22)
[4,22 - 4,28)
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[4,33 - 4,39)
[4,39 - 4,45)
[4,45 - 4,51)
[4,51 - 4,57)
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[4,63 - 4,68)
[4,68 - 4,74)
[4,74 - 4,80)
[4,80 - 4,86)
[4,86 - 4,92)
[4,92 - 5,01)
[4,97 - 5,01]
Power Grid
Power Grid Point
Water Body
Cities
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Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
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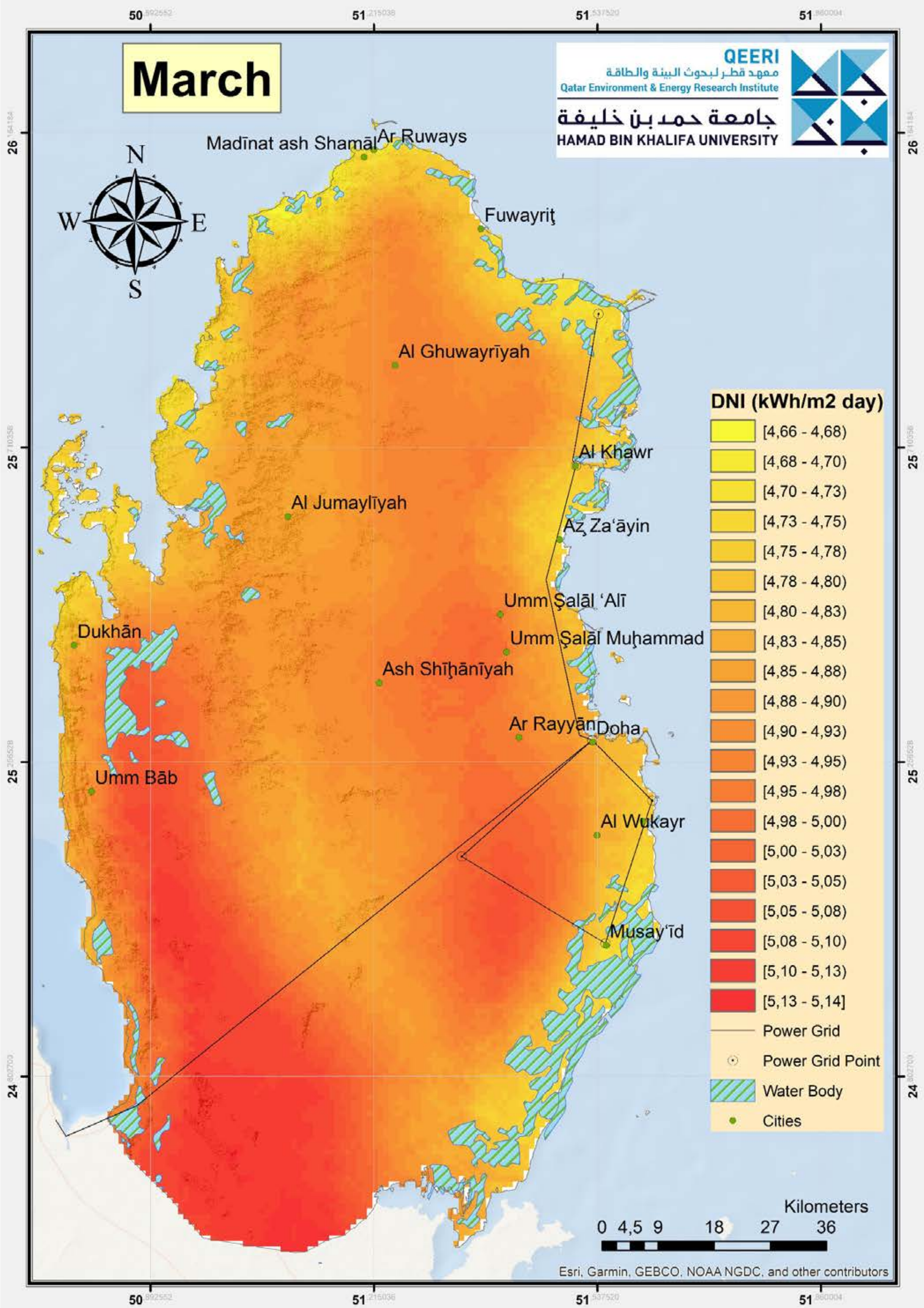
March
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Qatar Environment & Energy Research Institute
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Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[4,66 - 4,68)
[4,68 - 4,70)
[4,70 - 4,73)
[4,73 - 4,75)
[4,75 - 4,78)
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[4,83 - 4,85)
[4,85 - 4,88)
[4,88 - 4,90)
[4,90 - 4,93)
[4,93 - 4,95)
[4,95 - 4,98)
[4,98 - 5,00)
[5,00 - 5,03)
[5,03 - 5,05)
[5,05 - 5,08)
[5,08 - 5,10)
[5,10 - 5,13)
[5,13 - 5,14]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
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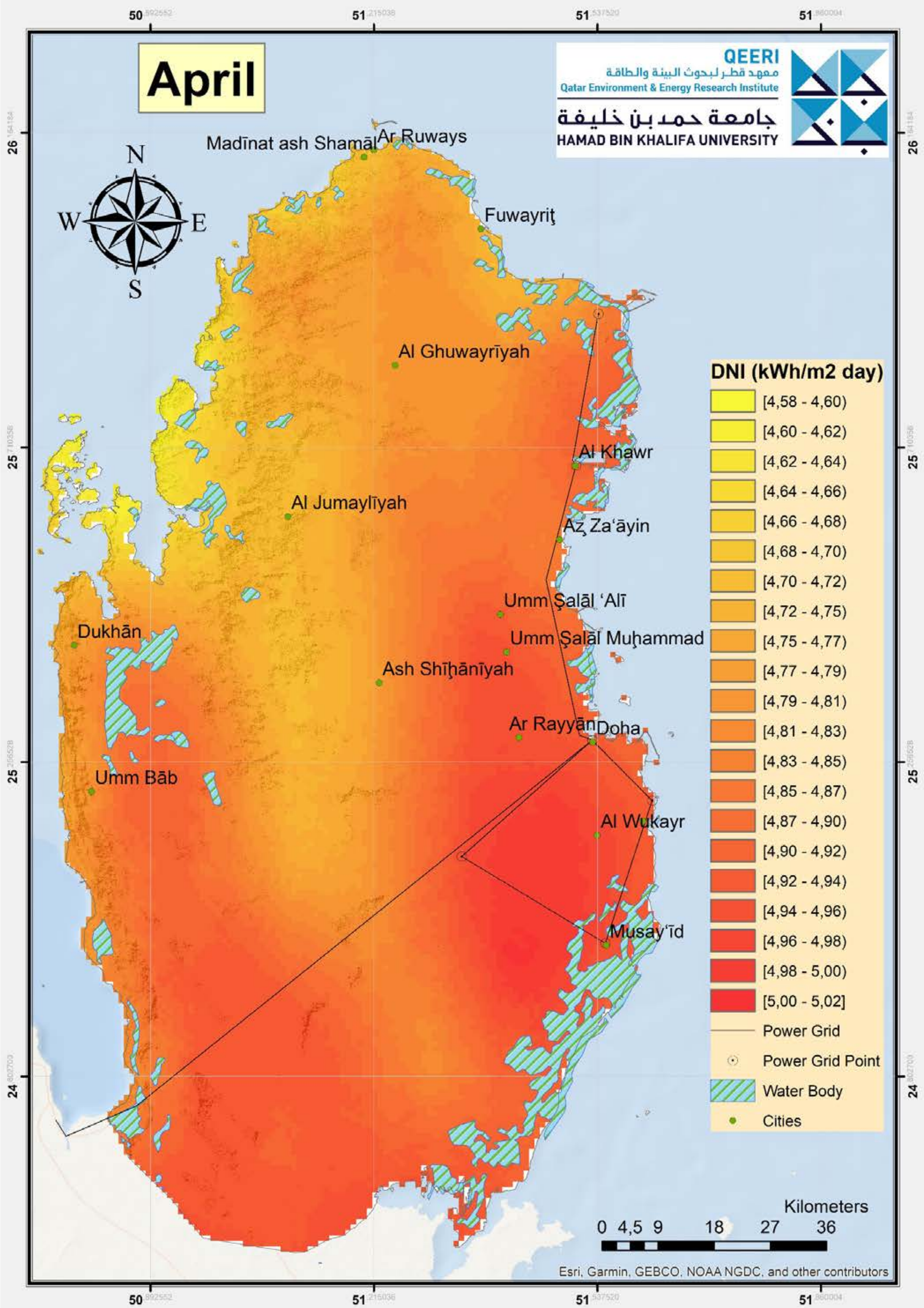
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


April
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Dukhān
Umm Şalāl Muḩammad
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[4,58 - 4,60)
[4,60 - 4,62)
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[4,64 - 4,66)
[4,66 - 4,68)
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[4,81 - 4,83)
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[4,85 - 4,87)
[4,87 - 4,90)
[4,90 - 4,92)
[4,92 - 4,94)
[4,94 - 4,96)
[4,96 - 4,98)
[4,98 - 5,00)
[5,00 - 5,02]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
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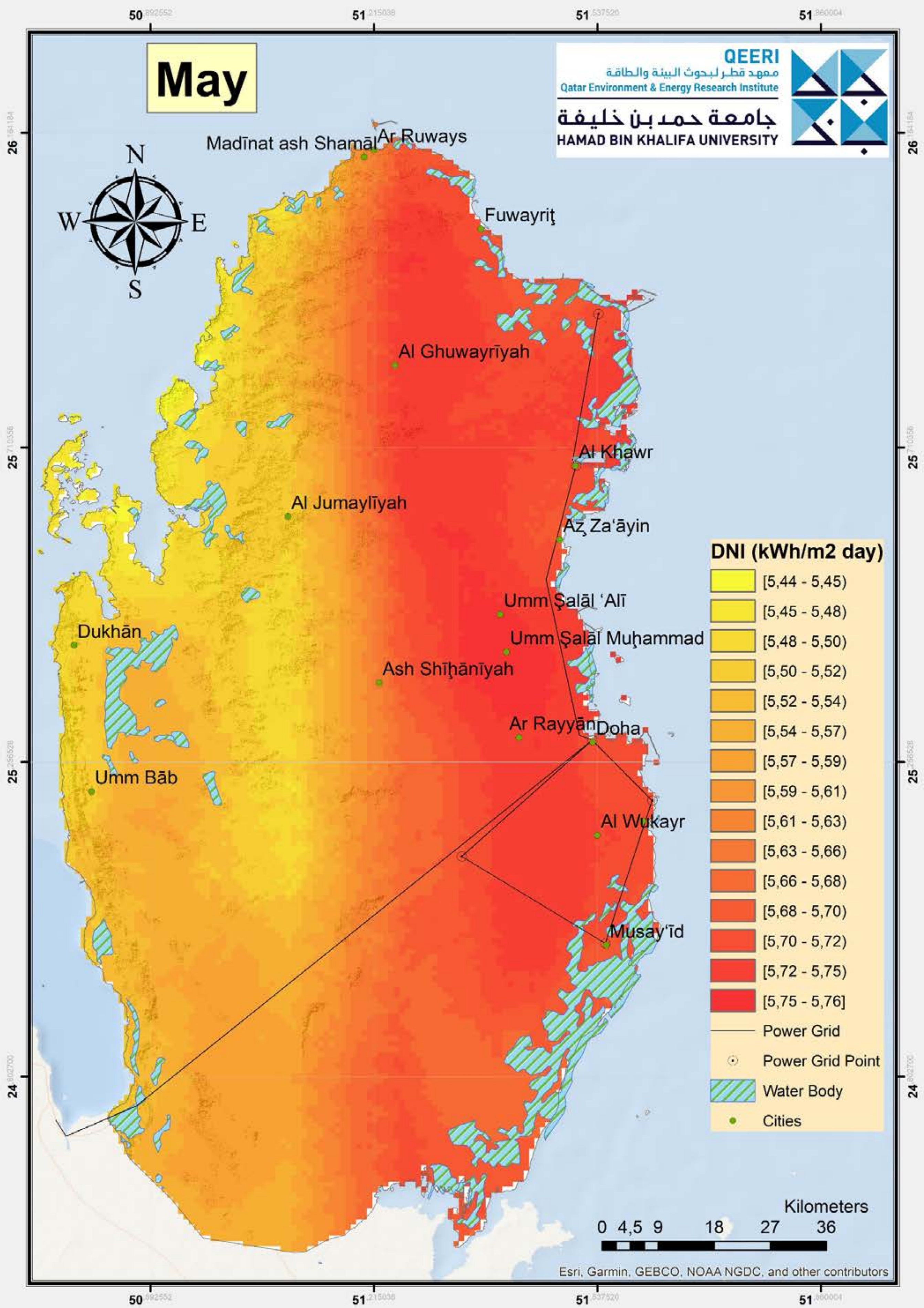
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


May
QEERI
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Umm Şalāl Muḩammad
Dukhān
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Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[5,44 - 5,45)
[5,45 - 5,48)
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[5,50 - 5,52)
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[5,72 - 5,75)
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0 4,5 9 18 27 36
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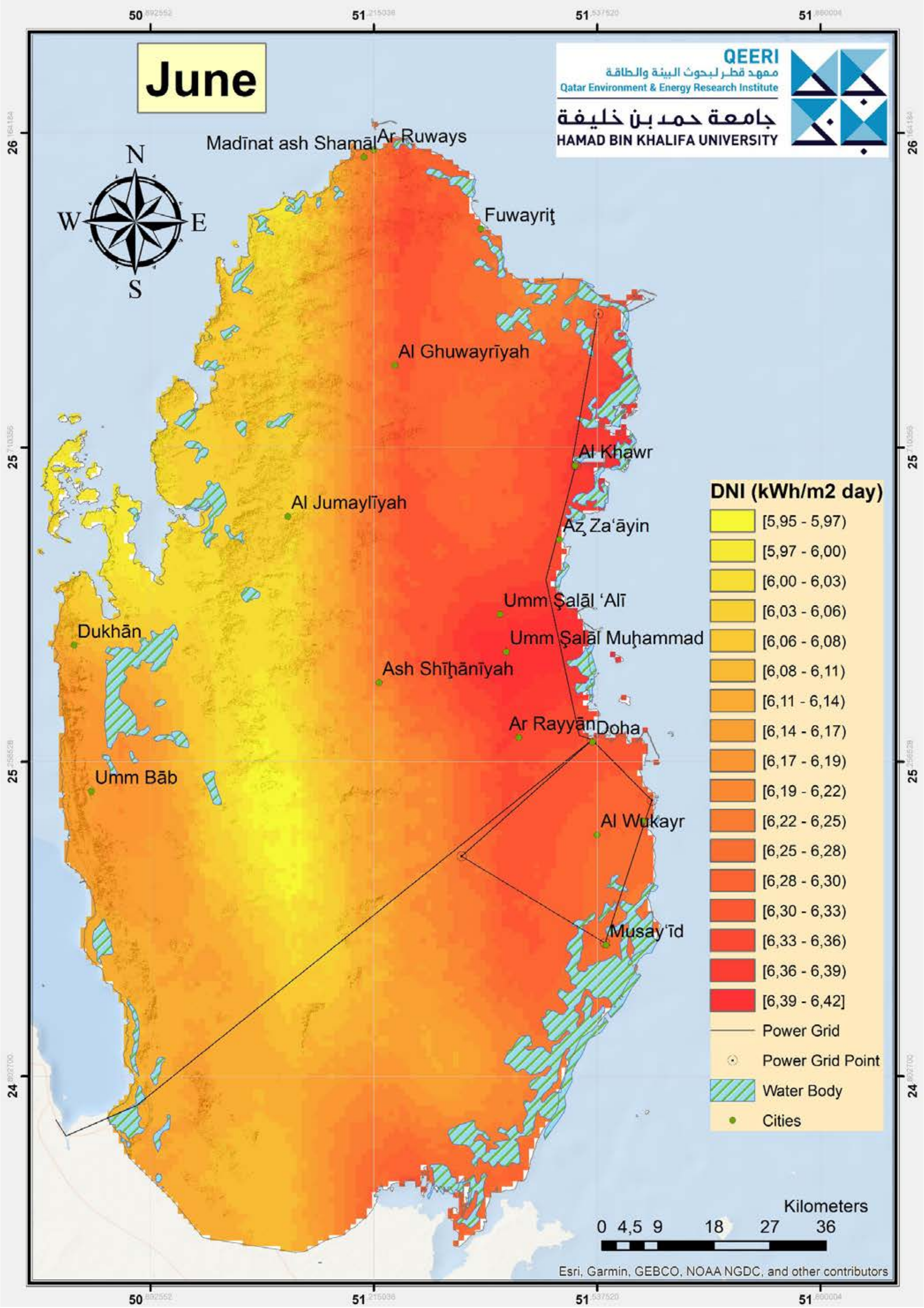
June
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Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
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[6,22 - 6,25)
[6,25 - 6,28)
[6,28 - 6,30)
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[6,33 - 6,36)
[6,36 - 6,39)
[6,39 - 6,42]
Power Grid
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Kilometers
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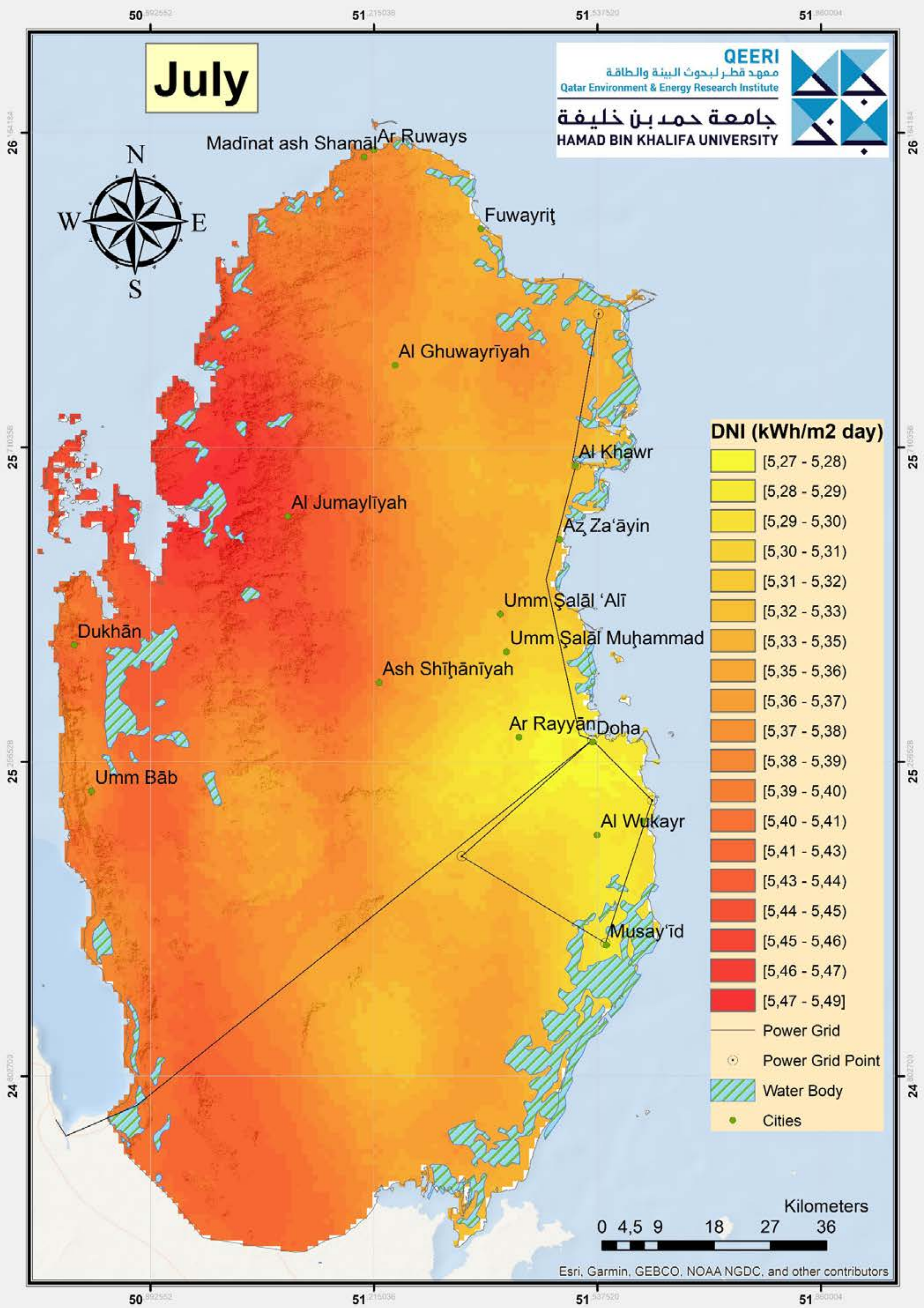
July
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Al Khawr
Al Jumaylīyah
Az̧ Za‘āyin
Umm Şalāl ‘Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay‘īd
DNI (kWh/m2 day)
[5,27 - 5,28)
[5,28 - 5,29)
[5,29 - 5,30)
[5,30 - 5,31)
[5,31 - 5,32)
[5,32 - 5,33)
[5,33 - 5,35)
[5,35 - 5,36)
[5,36 - 5,37)
[5,37 - 5,38)
[5,38 - 5,39)
[5,39 - 5,40)
[5,40 - 5,41)
[5,41 - 5,43)
[5,43 - 5,44)
[5,44 - 5,45)
[5,45 - 5,46)
[5,46 - 5,47)
[5,47 - 5,49]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
50.892552
51.215038
51.537520
51.860004
26
25
25
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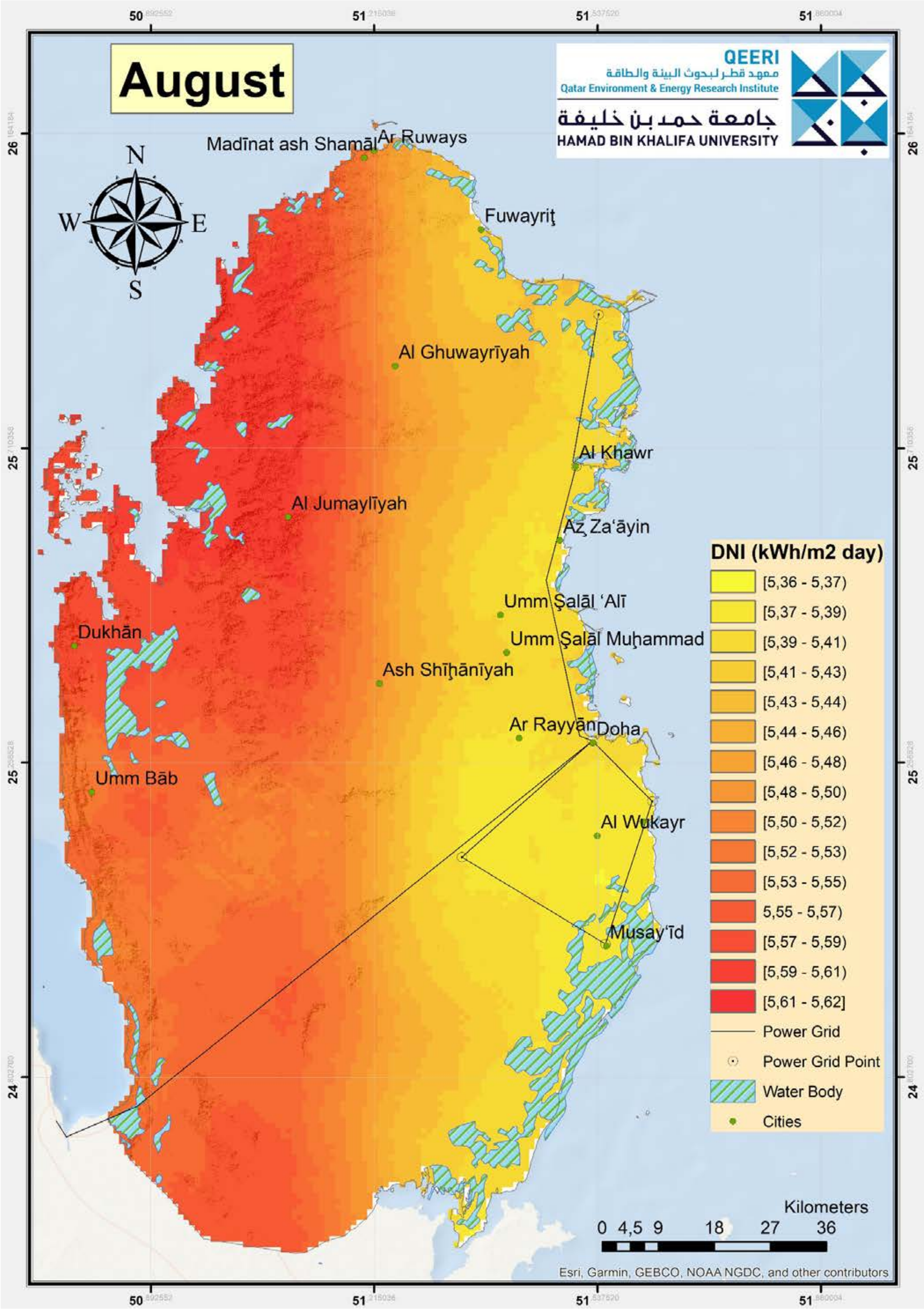
August
QEERI
معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
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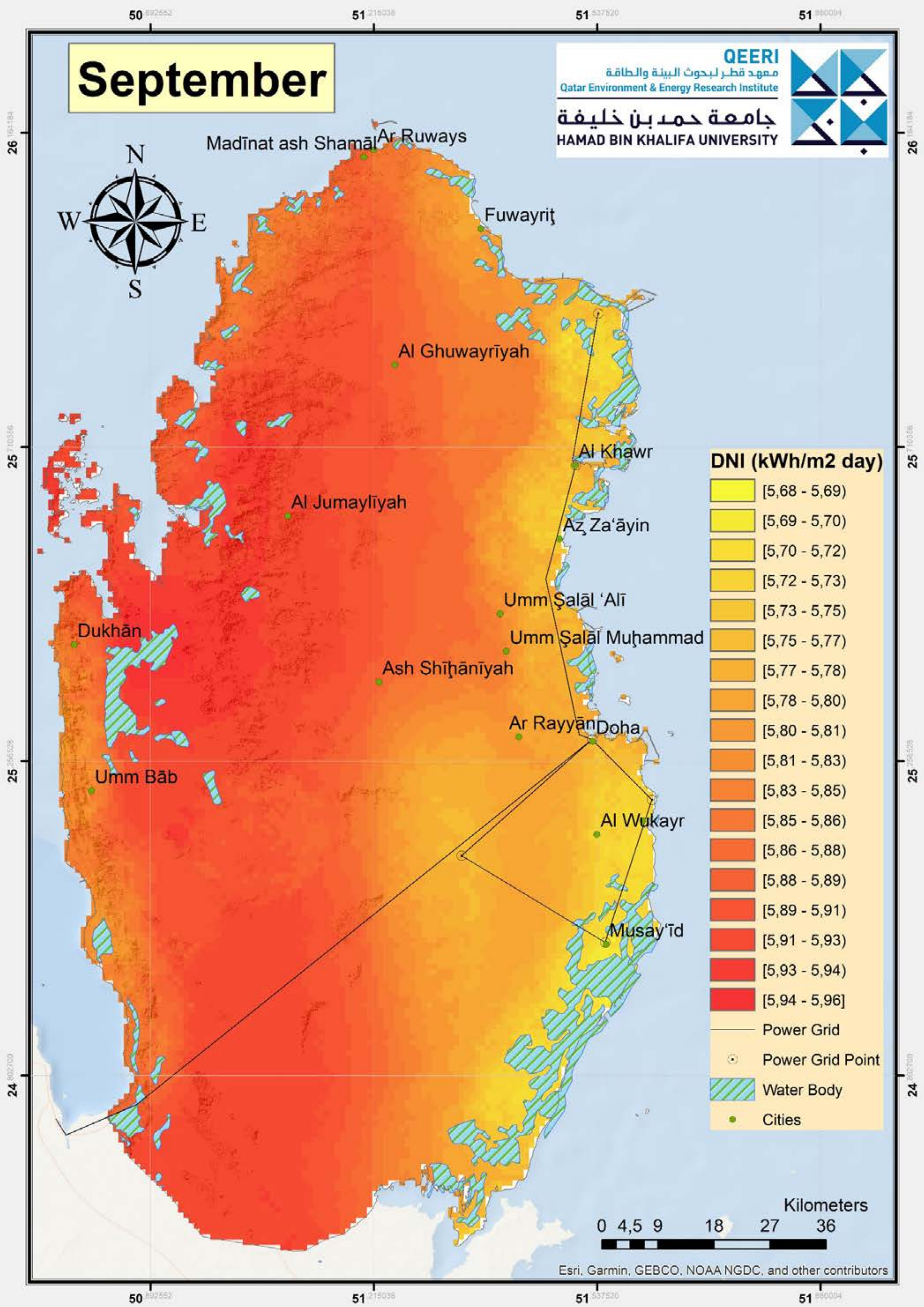
Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az̧ Za‘āyin
Umm Şalāl ‘Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay‘īd
DNI (kWh/m2 day)
[5,36 - 5,37)
[5,37 - 5,39)
[5,39 - 5,41)
[5,41 - 5,43)
[5,43 - 5,44)
[5,44 - 5,46)
[5,46 - 5,48)
[5,48 - 5,50)
[5,50 - 5,52)
[5,52 - 5,53)
[5,53 - 5,55)
5,55 - 5,57)
[5,57 - 5,59)
[5,59 - 5,61)
[5,61 - 5,62]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


September
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جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
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Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az̧ Za'āyin
Umm Şalāl 'Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[5,68 - 5,69)
[5,69 - 5,70)
[5,70 - 5,72)
[5,72 - 5,73)
[5,73 - 5,75)
[5,75 - 5,77)
[5,77 - 5,78)
[5,78 - 5,80)
[5,80 - 5,81)
[5,81 - 5,83)
[5,83 - 5,85)
[5,85 - 5,86)
[5,86 - 5,88)
[5,88 - 5,89)
[5,89 - 5,91)
[5,91 - 5,93)
[5,93 - 5,94)
[5,94 - 5,96]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
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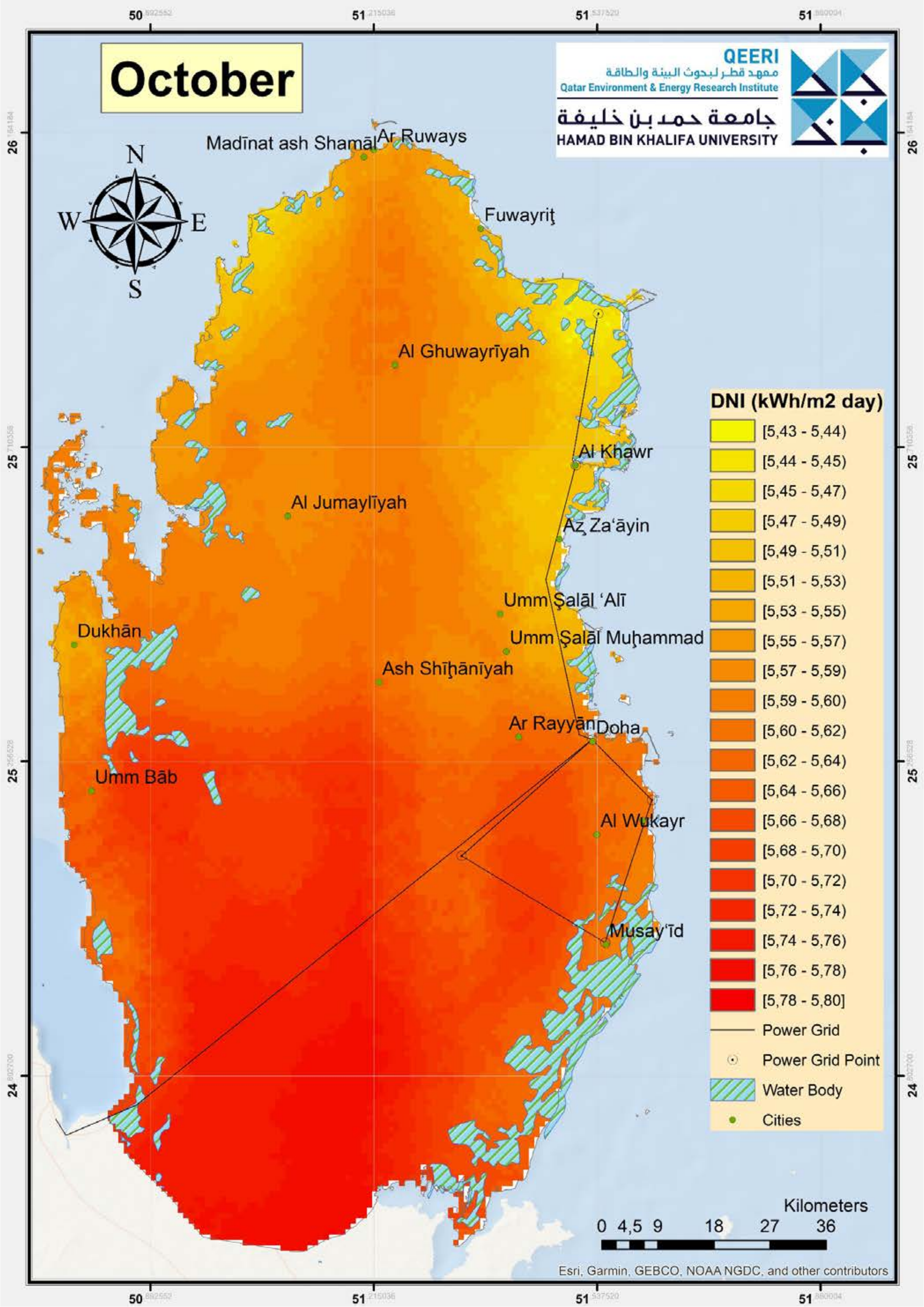
October
QEERI
معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
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Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az Za'āyin
Umm Şalāl 'Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[5,43 - 5,44)
[5,44 - 5,45)
[5,45 - 5,47)
[5,47 - 5,49)
[5,49 - 5,51)
[5,51 - 5,53)
[5,53 - 5,55)
[5,55 - 5,57)
[5,57 - 5,59)
[5,59 - 5,60)
[5,60 - 5,62)
[5,62 - 5,64)
[5,64 - 5,66)
[5,66 - 5,68)
[5,68 - 5,70)
[5,70 - 5,72)
[5,72 - 5,74)
[5,74 - 5,76)
[5,76 - 5,78)
[5,78 - 5,80]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
50 892552
51 215036
51 537520
51 860004
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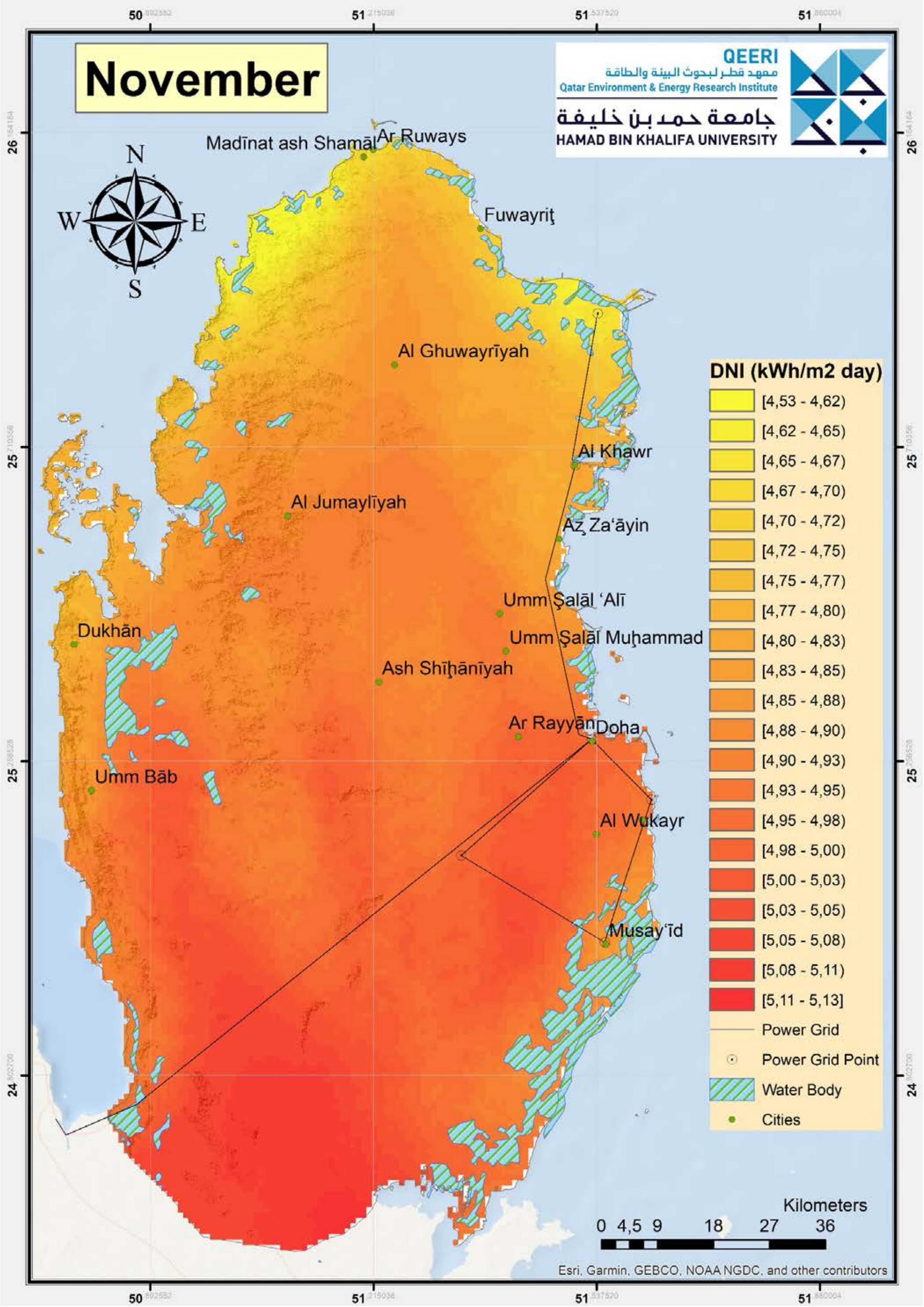
November
QEERI
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Qatar Environment & Energy Research Institute
جامعة حمد بن خليفة
HAMAD BIN KHALIFA UNIVERSITY
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Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az̧ Za'āyin
Umm Şalāl 'Alī
Dukhān
Umm Şalāl Muḩammad
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay'īd
DNI (kWh/m2 day)
[4,53 - 4,62)
[4,62 - 4,65)
[4,65 - 4,67)
[4,67 - 4,70)
[4,70 - 4,72)
[4,72 - 4,75)
[4,75 - 4,77)
[4,77 - 4,80)
[4,80 - 4,83)
[4,83 - 4,85)
[4,85 - 4,88)
[4,88 - 4,90)
[4,90 - 4,93)
[4,93 - 4,95)
[4,95 - 4,98)
[4,98 - 5,00)
[5,00 - 5,03)
[5,03 - 5,05)
[5,05 - 5,08)
[5,08 - 5,11)
[5,11 - 5,13]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
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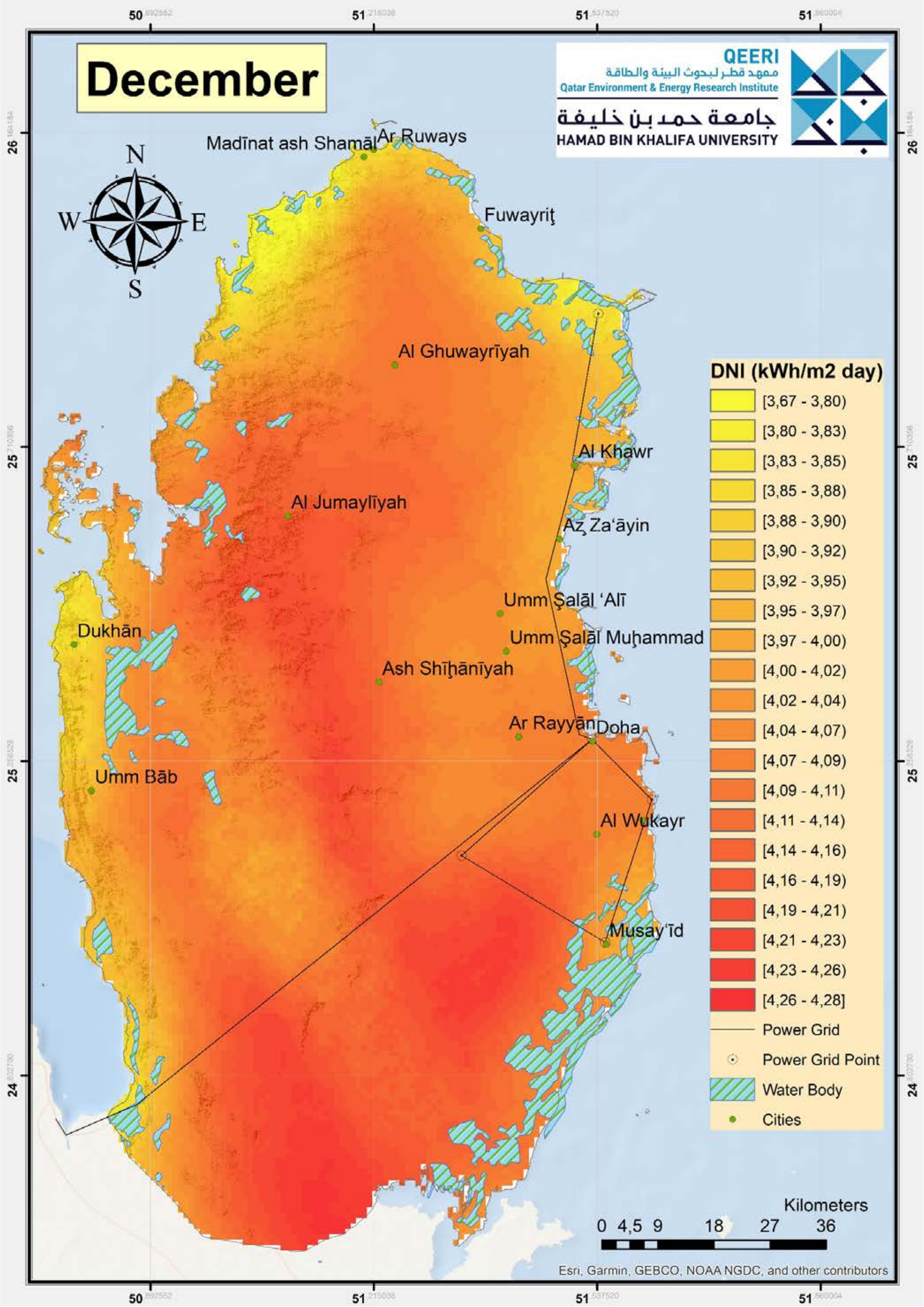
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


December
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HAMAD BIN KHALIFA UNIVERSITY
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Madīnat ash Shamāl
Ar Ruways
Fuwayriţ
Al Ghuwayrīyah
Al Khawr
Al Jumaylīyah
Az̧ Za‘āyin
Umm Şalāl ‘Alī
Umm Şalāl Muḩammad
Dukhān
Ash Shīḩānīyah
Ar Rayyān
Doha
Umm Bāb
Al Wukayr
Musay‘īd
DNI (kWh/m2 day)
[3,67 - 3,80)
[3,80 - 3,83)
[3,83 - 3,85)
[3,85 - 3,88)
[3,88 - 3,90)
[3,90 - 3,92)
[3,92 - 3,95)
[3,95 - 3,97)
[3,97 - 4,00)
[4,00 - 4,02)
[4,02 - 4,04)
[4,04 - 4,07)
[4,07 - 4,09)
[4,09 - 4,11)
[4,11 - 4,14)
[4,14 - 4,16)
[4,16 - 4,19)
[4,19 - 4,21)
[4,21 - 4,23)
[4,23 - 4,26)
[4,26 - 4,28]
Power Grid
Power Grid Point
Water Body
Cities
Kilometers
0 4,5 9 18 27 36
Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
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