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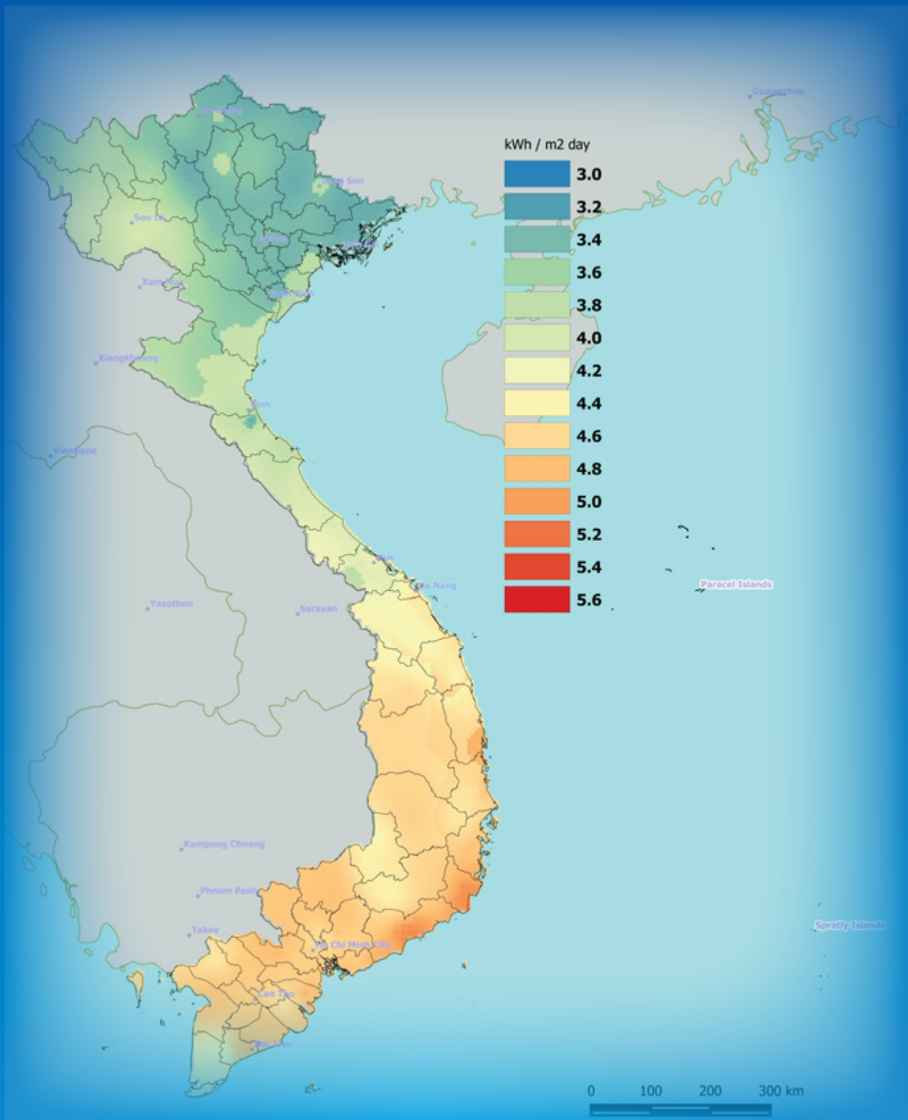

MAPS OF SOLAR RESOURCE AND POTENTIAL IN VIETNAM

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Summary

The deployment of solar energy projects in a country or in wide regions needs of prior precise information on the available solar resources. The solar resources information facilitates policies and decision-making processes of the different technologies to be used, as well as the investments; at the same time, the geographic analysis of solar resource assessment is frequently the first step in solar technology deployment in that particular region. Solar radiation incoming on the Earth's surface exhibits a large geographic variability due to its strong dependence on the atmospheric conditions and meteorology, and presents also highly variability in time. Therefore, the annual sum of incoming solar radiation can change significantly from year to year and from place to place in a country due to varying weather conditions.

For making decisions about energy policy, in addition to the solar radiation estimation, it will be necessary to analyze the potential use of the solar technologies in the country. The methodology and works for the potential assessments depend strongly on each specific technology. Thus, even for a specific technology, scenarios taking into account the type of applications, installations power, local incentives and/or its evolutions during the next years have to be considered. Renewable energy is often criticized for being too expensive although different studies around the world shows that certain unsubsidized renewable energy technologies are now cheaper than electricity from fossil fuels in certain countries. Even without considering the benefits associated with the expansion of energy from renewable sources; Solar energy provides with a wide variety of environmental and socioeconomic benefits, including diversification and security of energy supply, access to modern energy, enhanced regional and rural development opportunities, positive GDP impact and job creation. These benefits have already proven important in those countries with high renewable energy deployment levels, as is the case of Spain.

Under the framework of a project promoted by the Spanish Agency for International Development Cooperation (AECID) for strengthen the capacities of the Vietnamese government to take decisions concerning the solar energy sector, the General Directorate of Energy of Ministry of Industry and Trade of Vietnam (MoiT) and CIEMAT (representing a Spanish consortium formed by CIEMAT, CENER and IDAE) signed an agreement to address the Phase I of this project focused on mapping the solar resource and potential in Vietnam.

The Spanish consortium

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1. Introduction

Vietnam has one of South-East Asia's fastest-growing economies. Vietnam is relatively rich in diverse fossil energy resources, such as oil, gas and coal, as well as renewable energy such as hydro, biomass, solar and geothermal (Minh Do and Sharma, 2011). It has a large population living in rural areas, so that decentralized renewable energy technologies could play a role in the provision of electricity (Nguyen, 2007). In order to promote renewable energy, the government of Vietnam has approved the Master Plan for renewable Energy development for the period up to 2015, with vision towards 2025 (Khanh Toan et al., 2011). Among other actions the plan gives priority in the power development for rural and remote areas.

Vietnam is considered a nation with high solar potential, especially in the central and southern area of the country. Solar energy intensity on the average could reach 5 kWh / m^2. The intensity is lower in the North due to the annual winter-spring cloudy and drizzle sky. Vietnam has some experience in the development and deployment of solar energy systems. On the one hand, within the framework of R&D projects and academicism context some studies have been conducting, among others, by the Vietnamese Academy of Science and Technology, the Hanoi University of Science and Technology, and Ho Chi Minh City University, many of them are focused on photovoltaic-related issues. On the other side at industrial level, it is worth to mention the activities of companies, such as SELCO - Vietnam (http://www.selco-vietnam.com.vn) that has installed over 250 kWp and Solarlab (http://www.solarlab.hcmc.vn) that is another company with remarkable activity in PV. In addition, there has been also activity in the low temperature solar energy systems, isolated and rural electrification systems.

The Spanish Agency for International Development Cooperation (AECID) has promoted a project for strengthening the capacities of the Vietnamese government to take decisions concerning the solar energy sector. The Phase I of this project consist of mapping the solar resource and the solar potential for relevant solar technologies, and is being addressed by a Spanish consortium formed by CIEMAT (acting as leader), CENER and IDAE, who are collaborating with the General Directorate of Energy of

Ministry of Industry and Trade of Vietnam (MoiT).

The main objective of the phase I is to deliver an useful tool for impelling the deployment of solar energy systems for electricity generation along the country. The accomplishment of this aim includes the deliverance of maps of the solar radiation components associated to the PV and CSP technologies (i.e. global horizontal and direct normal irradiation maps), to estimate and mapping the solar potential of the main technologies and to analyse the spatial and temporal variability expected for solar radiation along the country.

Solar potential for selected technologies (CSP parabolic trough and grid connected PV flat plate) are computed from solar resource estimations to derived the denoted theoretical potential; in a second stage the methodologies for selecting the available zones for each technology are estimated using Geographic Information Systems (GIS) to map the technical solar potential according to each technology selected.

The socio-economic benefits associated to renewable energy are gaining prominence as a key driver for Renewable Energy Source (RES) deployment, including solar. The project presents a framework for analysing the potential and the ability to utilise Vietnam's solar resources. Vietnam solar and other renewable technologies potential is large and its deployment could only be possible by a concerted effort by policy makers to develop enabling frameworks to spur investment and facilitate market development through ambitious and effective policies. Assessing the multiple benefits of solar and the other RES will help the Vietnamese Government to measure the cost-effectiveness of their existing or future incentives and policies.

This report summarizes the works performed for developing solar resources and solar potential maps of Vietnam under the framework of the aforementioned project.

2. Climatic regions in Vietnam

Vietnam is located in South East Asia, extending between latitudes 9°N and 23°N. Eastern Vietnam has a long coastline on the Gulf Tongking and the South China Sea. The Vietnamese climate is dominated by the tropical monsoon, with high heat and humidity. From May until September, the Vietnamese climate is dominated by south to southeasterly winds. Between October and April, the north monsoon is dominant with northerly to northeasterly winds. There is a twice-yearly transition period of variable winds between each monsoon season.

Vietnam has a single rainy season between May and September (south monsoon). During the rest of the year, rains are infrequent and light. The annual rainfall is above 1000 mm in almost every country, and rises to between 2000 mm and 2500 mm on the hills, particularly in the region facing the sea.

The country is mountainous in the northwest and in the central highlands facing the South China Sea, rising to over 2450 m. In the north around Hanoi and in the south around Ho Chi Minh City, there are extensive low-lying regions in the Red River delta and the Mekong delta respectively.

According to the updated version of the Köppen-Geiger climatic classification (Peel et al., 2007) Vietnam has three climatic zones (*Fig. 1*): equatorial monsoon (Am), equatorial savannah with dry winter (Aw) and subtropical with dry winter (Cwa).

3. Sources of information

Three main sources of information have been used for generating the solar resource maps: ground measurements, satellite imagery and reanalysis of numerical weather prediction models (NWPM).

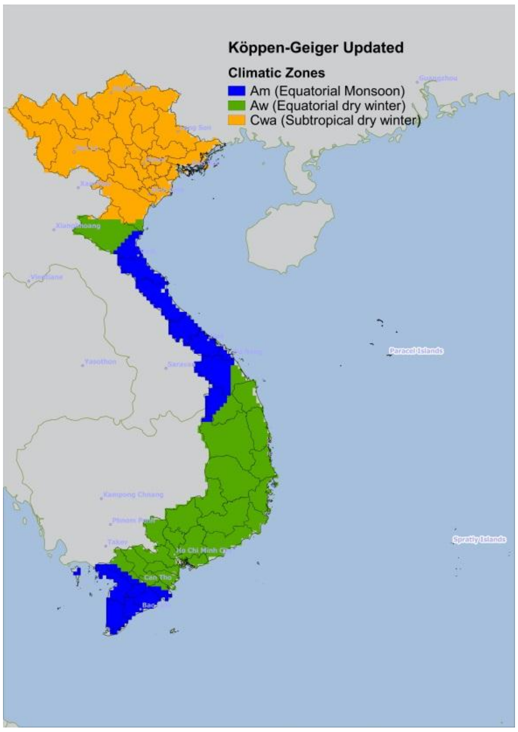

Fig. 1 Climatic zones in Vietnam according to Köppen-Geiger Climatic chart.

3.1 Ground measurements

Vietnam has a large and extensive database of sunshine duration measurements. Under the framework of this project the MoIT has supplied sunshine duration data collected and delivered by the Vietnamese National Hydro-Meteorological Service. The database comprises sunshine records for 30 years (1983-2012) from 171 stations distributed along the country.

Regarding solar radiation ground measurements, 14 automatic stations are measuring solar radiation components. MoIT has delivered hourly and daily data of solar global radiation on horizontal surface for 13 stations, belonging to the National Hydro-Meteorological Service of Vietnam. Most of them are operating from year 2012, Da Nang and Can Tho stations have some measurements from 2011, and Lang station has records from 2005 to 2011. However, in Thanh Boa station there were only available records in July 2012 and likewise in Da Lat station only January and February of 2012 contained measurements, so that 11 stations have been considered in the framework of this project. In the case of direct normal component of the solar radiation no measurements were available in the framework of the project.

Fig. 2 shows the distribution of both radiometric and sunshine duration ground stations.

3.2 Satellite imagery

Satellite imagery from visible channels of Meteosat IODC (Indian Ocean Data Coverage) and of MTSAT2 was compiled to this project. The former covered the period 2003-2012 and the MTSAT2 images were limited to 2008-2012. The MTSAT2 images were supplied by the MOiT from the National Hydro-Meteorological Service of Vietnam. The format was bitmap of 8 bits in radiometric resolution.

Fig. 3 shows one Meteosat IODC image illustrating the computational domain. The resolution of Meteosat images is around 5x5 km.

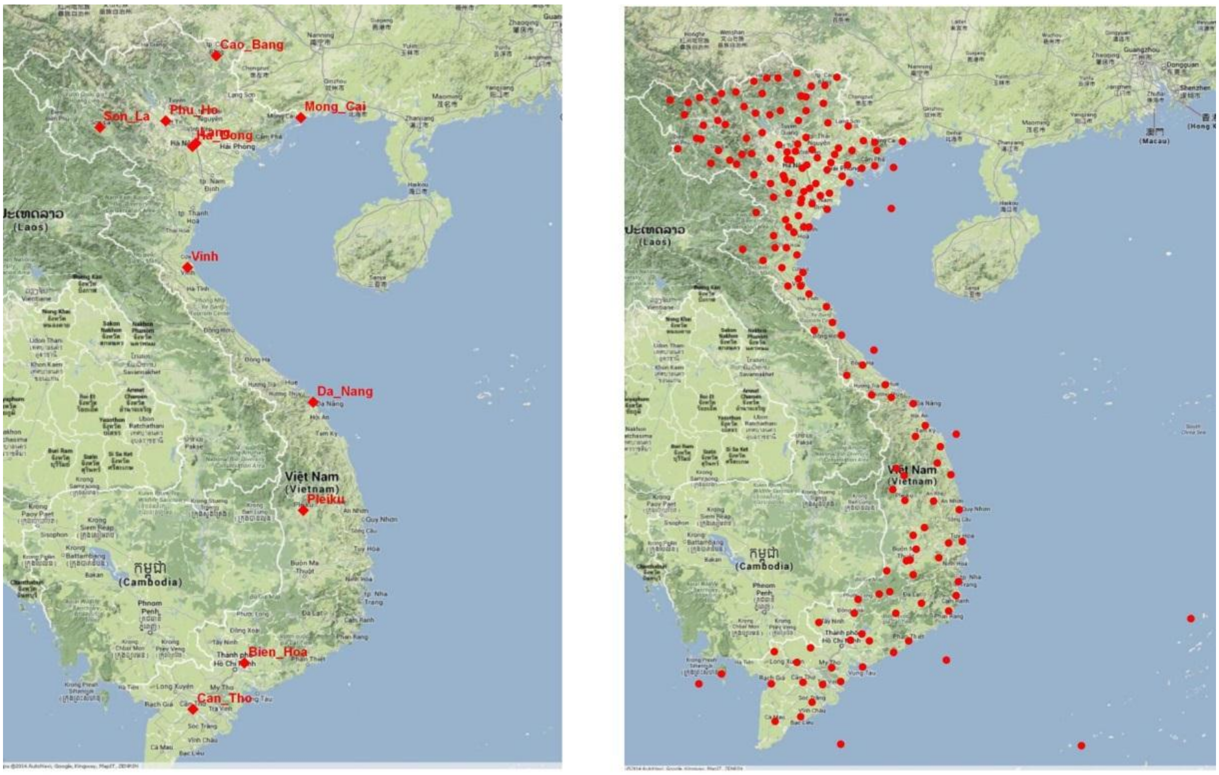

Fig. 2 Radiometric ground stations (on the left) and sunshine duration stations (on the right) in Vietnam.

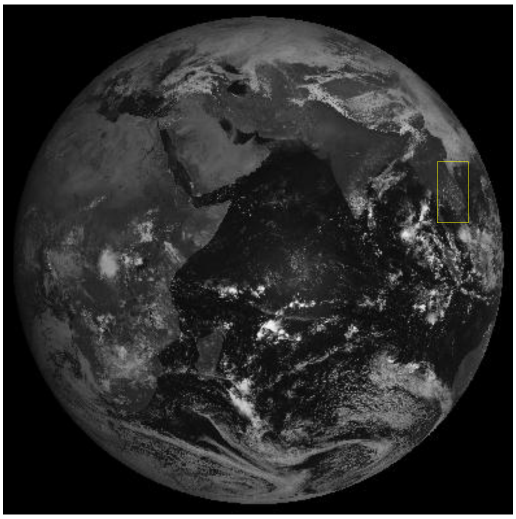

Fig. 3 Meteosat IODC full disk image (visible channel) showing the domain region for solar radiation estimations in Vietnam.

3.3 Information from numerical weather models

Solar global irradiation and additional meteorological variables have been computed with SKIRON model. SKIRON is a mesoscale numerical model based on the Eta prediction model, and uses input data from the Global Forecast System (GFS) (Kallos et al., 1997). SKIRON has been executed using GFS data as input providing hourly series with a spatial resolution of 5 x 5 km, which can be achieved both by the execution of the model at that resolution (Fernandez-Peruchena et al., 2011).

On the other hand, the knowledge of solar radiation components for clear sky conditions is frequently useful as estimating the upper bound of the solar resource expected for a specific site, and it also should contribute to explain part of the solar radiation variability expected. Clear sky models are basically parameterizations of the transmittance as a function of the sun position and of the composition of the atmosphere (i.e. aerosols, water vapor, ozone, etc.). It should be remarked that the most important atmospheric input data affecting to the transmittance are the aerosol optical depth (AOD) and the precipitable water content.

Daily values of aerosol optical depth (AOD) have been obtained for Vietnam region from MACC (Monitoring Atmospheric Composition and Climate) (http://www.gmes-atmosphere.eu/). MACC reanalysis data consist of gridded data with global coverage of atmospheric composition at recent years (daily values from 2003 to 2012) as well as forecasting with a spatial resolution of 1.125°x1.125° (Inness et al., 2012). Likewise, daily values of precipitable water were collected for the same period (2003-2012) from NCEP/NCAR reanalysis datasets (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) with a spatial resolution of 2.5°x2.5° (Kalnay et al., 1996).

4. Solar radiation components mapping

Solar radiation components, global horizontal irradiation (GHI) and direct normal irradiation (DNI), has been estimated from different sources of information and using different models as follows:

- Daily values of GHI and DNI for the period 2003-2012 were estimated from satellite imagery by a methodology based on the well-known Heliosat method (Dagestad and Olseth, 2007; Rigollier et al., 2004) that include many modifications from the original proposal regarding the cloud index, albedo computation, clear sky transmittance model, atmospheric input to boundary conditions and global to direct conversion methods (Polo J. et al., 2008; Polo et al., 2014; Polo et al., 2013; Zarzalejo et al., 2009; Zarzalejo et al., 2005).
- A model has been developed for estimating daily GHI values from sunshine duration and clear sky transmittance models output (Polo et al., 2015).
- Daily values of GHI were computed for the period 2003-2012 using SKIRON model.
- Daily GHI and DNI values under cloudless situations REST2 (Reference Evaluation of Solar Transmittance, 2-bands) model has been used (Gueymard, 2008). REST2 model has proven a very good performance and accuracy in different assessment studies (Gueymard, 2012; Gueymard, 2003a; Gueymard, 2003b; Reno et al., 2012). The input to REST2 model has been obtained from MACC and NCEP reanalysis.

All these sources of information have been assessed with the available ground data from the 11 radiometric stations to investigate the degree of correlation of every dataset with the measurements. The main finding of this assessment was that correlation analysis using the canonical correlation analysis techniques has evidenced that satellite derived data and irradiation computed from sunshine duration are the datasets providing best results.

In addition a cluster analysis was performed based upon the sunshine duration measurement network using k-means algorithm (Polo et al., 2015).

According to this analysis three main zones of different behavior of solar radiation can be established in Vietnam (*Fig. 4*); the first region (green) covering basically the south of the country (and some part of the Northwest), the second region (blue) covers mainly the North Central Coast, and finally the third region (orange) is placed in the Red River Delta, Northeast and partially on the south central coast.

Fig. 4 Regionalization of Vietnam by cluster analysis from sunshine duration measurements.

It should be remarked the similarity between the regionalization resulting from the clustering and the Köppen-Geiger climatic zones of Vietnam (*Fig. 1*).

Therefore the daily GHI data has been computed by fitting a model based on a linear relationship between satellite derived data, H_{Sat}, and sunshine duration derived data, H_{Sun}. According to the regionalization evidenced by the cluster analysis (Polo et al., 2015), three different regions denoted as Orange (O), Blue (B) and Green (G) , in terms of solar radiation variability, have been established in Vietnam and thus a different expression has been fitted for each region,

$$\begin{cases} H_O = 0.2369\, H_{Sat} + 0.8342\, H_{Sun} - 0.5139 \\ H_B = 0.2471\, H_{Sat} + 0.7494\, H_{Sun} - 0.0761 \\ H_G = 0.0755\, H_{Sat} + 0.9376\, H_{Sun} - 0.2105 \end{cases}$$

Eq. (1)

Where H indicates daily GHI in kWh m^{-2} day^{-1}

The performance of this model in monthly means compared to measurements at 11 ground stations results in a mean bias error (MBE) of -0.05 kWh m^{-2} day^{-1} (which represents -1.2% in relative mean bias error) and a root mean square error (RMSE) of 0.32 kWh m^{-2} day^{-1} (8.3% in relative root mean square error).

In the case of DNI the estimations have been performed from the GHI satellite derived data by using DirInt model (Perez et al., 1992) for overcast conditions and REST2 model for cloudless days.

Therefore, daily values of GHI and DNI for the period 2003-2012 have been computed for Vietnam region at a spatial resolution of 0.05°x0.05°. Statistical procedures on that information have conducted to the final maps of annual average of daily GHI and DNI, and monthly average of daily GHI and DNI.

Fig. 5 and *Fig. 6* show the maps of annual average of daily GHI and DNI, respectively. The maps of monthly means of GHI and DNI are shown in Appendixes I and II, respectively.

The analysis of variability of solar radiation performed in Vietnam using statistical dispersion parameters and techniques based on the empirical orthogonal functions and principal component analysis (Monahan et al., 2009; Obled and Creutin, 1986) has evidenced the following findings:

- The variability of the global horizontal irradiation in Vietnam is represented in general terms by two main zones. The zone covered by Northeast, Red River Delta, North Central and South Central Coast is characterized by lower values of average daily irradiation with a decreasing trend with increasing the latitude. This region is also characterized by a higher dispersion of the daily irradiance, which is a region with higher variability of global horizontal irradiation. The second zone covers Central Highlands, Southeast and Mekong River Delta regions, which is characterized by higher values of daily irradiation with lower variability and solar irradiation is higher and more constant along the year.
- The variability of the direct normal irradiation in Vietnam is also represented generally by two main zones. The zone delimited by Northeast, Red River Delta, North Central and South Central Coast has a higher variability. The zone delimited by covers Central Highlands, Southeast and Mekong River Delta regions presents higher values of daily direct irradiation and lower variability along the year.

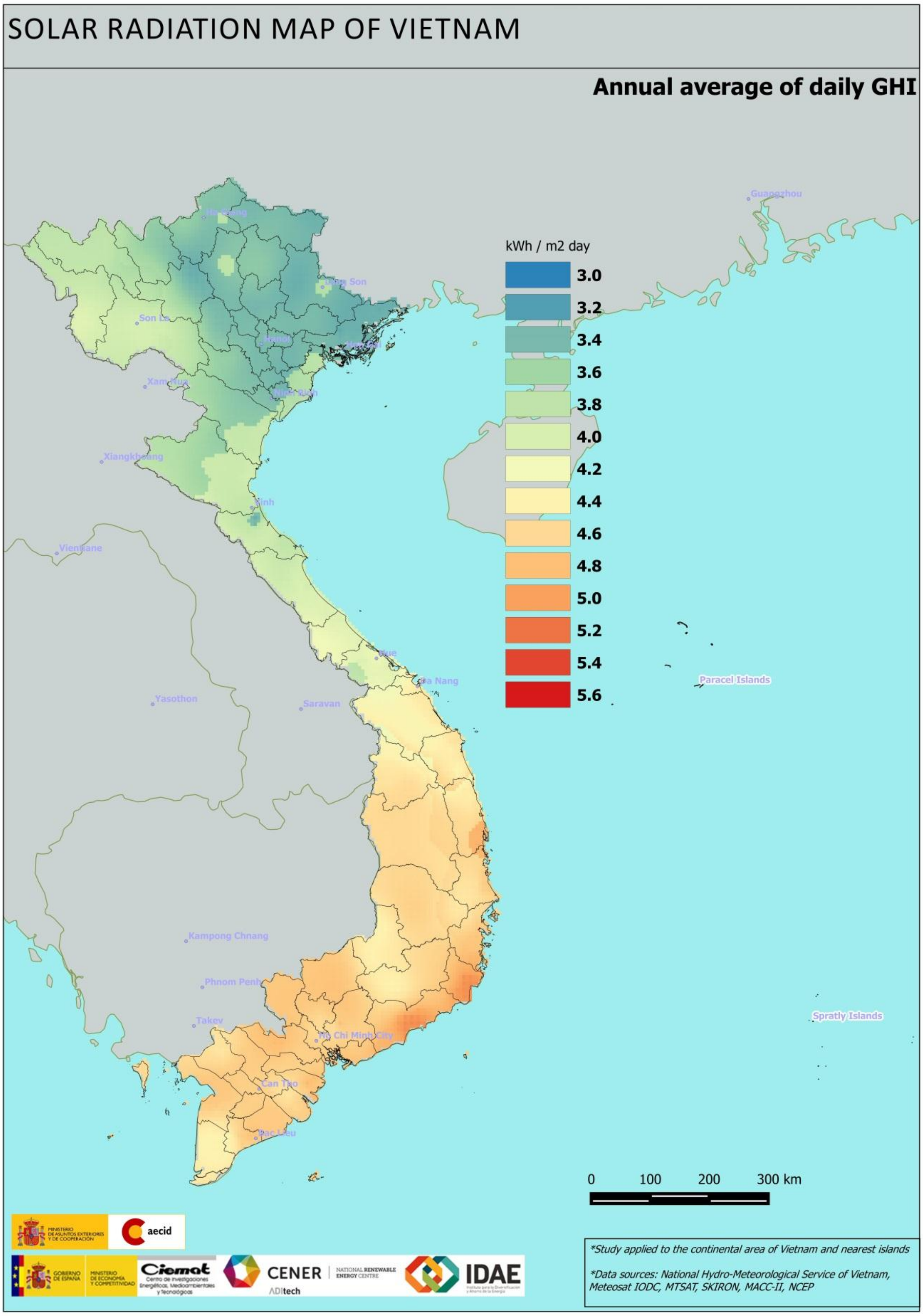

Fig. 5 Map of annual average of daily global horizontal irradiation (kWh m^{-2} day^{-1}) in Vietnam.

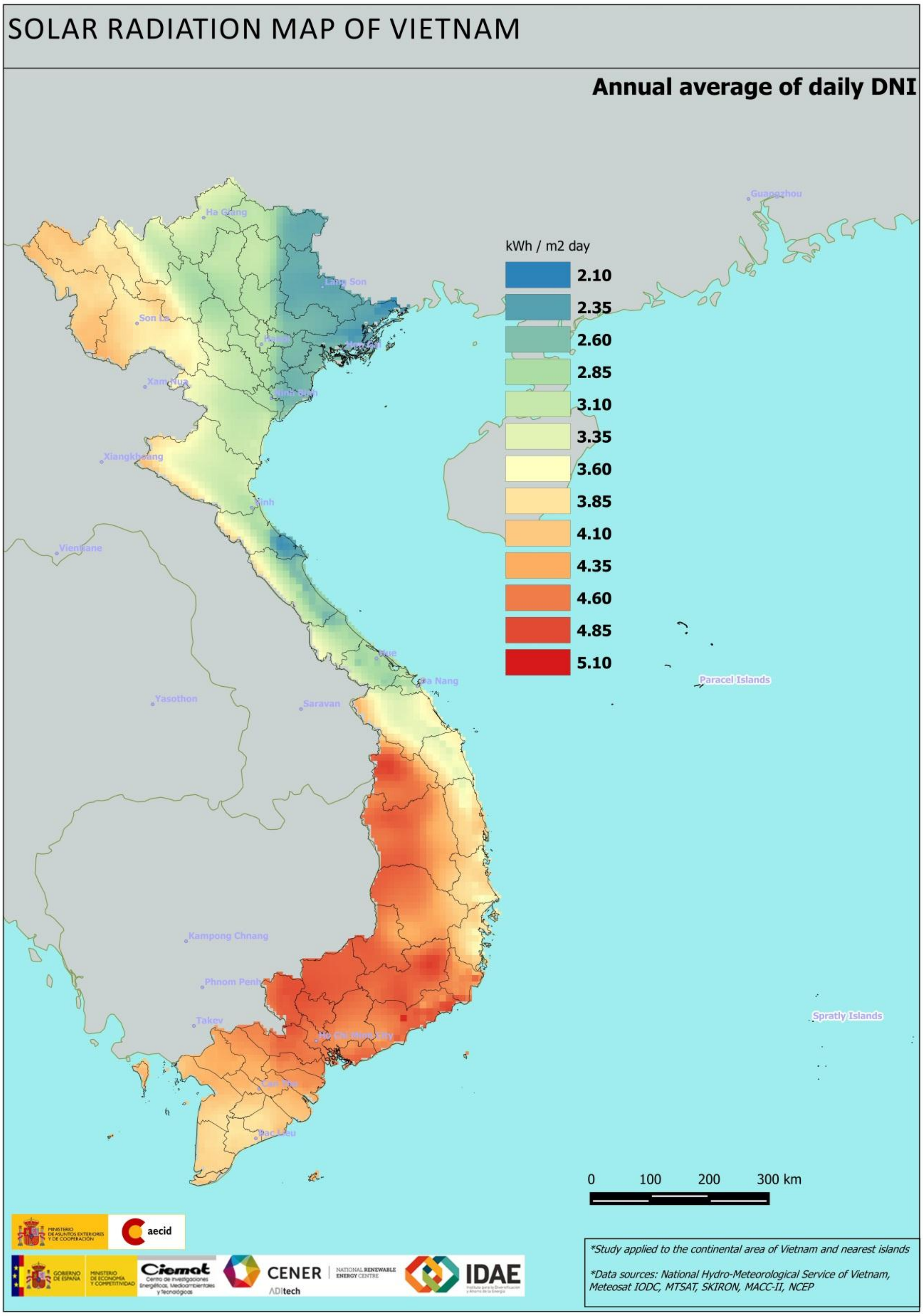

Fig. 6 Map of annual average of daily direct normal irradiation (kWh m^{-2} day^{-1}) in Vietnam.

5. Solar potential maps of Vietnam

The development of solar energy systems for electricity generation in a country depends strongly on several aspects such as energy policies, technology development, and of course local solar resource. Integration of most of the influencing aspects for determining the solar potential can be effectively performed with common Geographic Information Systems (GIS). Undoubtedly Geographical Information Systems (GIS) for energy planning are very valuable tools to visualize and analyze the energy resource potential, infrastructures, in a country, providing decision makers, project developers, investors and other stakeholders with tailored information and planning strategies. Therefore appropriate site selection for a solar power plant needs to take into account land, meteorology and infrastructure. In consequence, several methodologies have been proposed to determining solar potential in a region by incorporating local geographic information for identifying the suitable land areas for constructing a power plant according to a specific solar technology (Ayompe and Duffy, 2014; Boukelia and Mecibah, 2013; Domínguez and Amador, 2007; Freitas et al., 2015; Omitaomu et al., 2012; Purohit et al., 2013; Ramachandra and Shruthi, 2007; Sun et al., 2013).

5.1 Plant performance modelling

The determination of the solar potential for Vietnam has been done for two selected scenarios: CSP parabolic trough and grid-connected flat plate PV array. For each scenario a reference plant has been selected for modeling the power output according to the solar resource and to the latitude ranges.

5.1.1 Theoretical potential for CSP parabolic trough technology

The reference plant selected for CSP parabolic trough is a plant similar to ANDASOL plant placed in the south of Spain (Dinter and Gonzalez, 2014). The plant is a 50 MWe solar power plant with about 6 hours of thermal energy storage. Table 1 summarizes the main technical parameters of the power plant.

The CSP plant modeling has been done with software SimulCET (Garcia-Barberena et al., 2012), which simulates the whole energy conversion process that takes place in a parabolic trough plant using as input a year of hourly values of the main meteorological variables involved. In order to find an expression that relates the CSP power output with the annual DNI and latitude for the whole country, 58 cases have been identified according to the ranges of variation of both DNI and latitude. Latitude ranges from 8.5° to 23.5° N aproximately and intervals of 1.75° have been considered, DNI annual sums estimated for Vietnam vary from around 800 to 1900 kWh m^{-2} $year^{-1}$ and intervals of 100 kWh m^{-2} $year^{-1}$ have been used for selecting the modelling matrix of cases. For each of the 58 points a year of meteorological variables has been constructed as input to the modelling software. Solar radiation hourly values were obtained from satellite-derived data and the additional meteorological parameters were extrated from SKIRON Numerical Weather Prediction Model for the coincident period. As a result of the 58 simulations of annual power plant production in Vietnam a multivariate regression analysis has been done (determination coefficient R^2 of 0.93) to merge all the results in a simple expression of the annual power output,

$$P_{CSP} = 0.0451\, DNI - 0.3464\, Lat + 23.99$$
Eq. (2)

Where P_{CSP} denotes the annual energy output of the plant in GWh $year^{-1}$, *DNI* is the annual direct normal irradiation in kWh m^{-2} $year^{-1}$, and *Lat* is the latitude in decimal degrees.

Table 1 Technical data of the Parabolic Trough plant selected as reference for CSP systems.

Solar Field	
Collector Model	Eurotrough
Number of fields	4
Rows Separation	16.25 m
Collectors per Loop	4
Loop Orientation	North-South
Collector	
Collector Width (m)	5.75
Collector Length (m)	150
Absorber Inner Diameter (m)	0.066
Absorber Outer Diameter (m)	0.070
Effective Area Factor (%)	94.78
Mirror Reflectivity (%)	94.00
Tube Cover Transmissivity (%)	96.00
Tube Absorptivity (%)	95.00
Interception Factor (%)	97.00
Self-Shadowing Factor (%)	96.70
Soiling Factor (%)	94.00
Absorber Tube	Schott PTR70_2008*
Heat Transfer Fluid	Dowtherm A
Inlet Solar Field Temperature (ºC)	293
Outlet Solar Field Temperature (ºC)	393
Power Block	
Regenerative Ranking Cycle with Reheat. Wet cooling	
Nominal Power (MW)	50
Nominal Efficiency	0,3964 39, 64%
Oil Pump Efficiency	0,8
Storage	
Capacity (h)	6
Storage Fluid	Molten Salts
Hot Tank Temperature (ºC)	386
Cold Tank Temperature (ºC)	292

5.1.2 Theoretical potential for PV technology

In the case of grid-connected PV the reference plant selected is a flat plate PV array of about 1 MWe with the modules facing south and tilted an angle equal to latitude. Table 12 summarizes the main technical parameters of the power plant.

Following a similar methodology, PV performance simulations for the reference plant of a Flat Plate PV array have been done with System Advisor Model (SAM) (Freeman et al., 2013). SAM's photovoltaic performance model combines module and inverter sub-models to calculate a PV power system hourly AC output given a weather file and data describing the physical characteristics of the module, inverter and array. In order to study the effect of latitude in the PV generation a total of 15 points have been selected in the country and simulations of the selected plant at each point have been run. Multivariate regression analysis has evidenced a strong correlation of the PV plant generation and the annual GHI and latitude with a determination coefficient of R^2=0.99. Therefore, a linear relationship can be fitted to compute the annual photovoltaic power output, P_{PV} (expressed in MWh year^{-1}), from the annual sum of daily average, *GHI* (in kWh m^{-2} year^{-1}), and the latitude in decimal degrees (*Lat*).

$$P_{PV} = 0.542\,GHI - 8.8236\,Lat + 330.31$$

Eq. (3)

Table 2 Technical data of the Flat plate photovoltaic power plant selected as reference for PV systems.

PV array	
PV module	Atersa A-230 P
Number of modules	21 modules per string
Number of strings in parallel	192
Nominal power of module (W)	230
Nameplate capacity (kWdc)	930
Total surface of module array (m^2)	6566
Orientation	South
Tilt angle	Latitude
Inverter	
Model	AGILO 100.0-3 Outdoor
Nominal AC power of inverter (kW)	100
Number of inverters	9
Total power (kWac)	900

5.2 Theoretical and technical potential mapping

Equations (2) and (3) can be applied to the solar resource maps for determining the theoretical potential across the country for each technology or scenario selected in this work (CSP Parabolic Trough and Flat Plate PV plants). *Fig. 7* shows the theoretical potential along the country for each technology (CSP Parabolic Trough on the left and PV on the right). The theoretical potential takes into consideration only the solar resource availability; thus it assumes that every point of the solar resource map can be used for a solar plant deployment. However, since solar energy resource exploitation requires of large area for collection and conversion into energy, the specific characteristics of the land might result unfavorable for a solar power plant. Thus, for example appropriate site selection for a CSP project needs to take into account land, meteorology and infrastructure (Purohit et al., 2013). Therefore, technical restrictions might appear depending on the land characteristics that can be addressed by the generation of exclusion areas that should be applied to the theoretical potential to generate the denoted as technical potential. For PV the situation is similar but the restrictions to be applied might be slightly different. A detailed literature review has been done on the methodologies for studying the CSP potential using Geographic Information Systems (GIS) and restrictions with the land (Ayompe and Duffy, 2014; El Ouderni et al., 2013; Mahtta et al., 2014; Omitaomu et al., 2012; Purohit et al., 2013; Ramachandra and Shruthi, 2007). Likewise, a review of different methodologies and works for estimating the PV potential in large areas has also been done (Ayompe and Duffy, 2014; Freitas et al., 2015; Izquierdo et al., 2008; Sun et al., 2013; Suri et al., 2005; Suri et al., 2007; Tucho et al., 2014).

Basically, the assessment of land cover and use has consisted of removing water bodies and rivers. The land slope is also an essential factor, and for both scenarios land slope up to 3% has been considered suitable for plant deployment (Ziuku et al., 2014). Finally, an additional restriction of minimum value of annual DNI of 1500 kWh m^{-2} $year^{-1}$ has been imposed only to the CSP potential. Table 3 summarizes the exclusion criteria used for each solar technology considered.

Table 3 Exclusion criteria used in determining technical potential for CSP and PV systems.

Criterium	Exclusion CSP	Exclusion PV
Slope	>3%	>3%
Rivers and large water bodies	yes	yes
Roads	yes	yes
Railroads	yes	yes
Protected areas	N/A	N/A
Land uses	N/A	N/A
DNI level	< 1500 kWh m^{-2} day^{-1}	N/A
Minimum area	2 km^2	1 km^2

The different restrictions have been included in the software QGIS (Quantum Geographic Information System, http://www.qgis.org/) to generate the available areas for CSP parabolic Trough and for Flat Plate PV. Therefore, the combination of the theoretical potential derived from the application of expressions (2) and (3) to the solar resource, with the available land derived from the GIS analysis results in the technical potential for CSP Parabolic Trough and Plat Plate PV systems. *Fig. 8* and *Fig. 9* present the maps of the technical potential for each scenario, respectively. CSP potential is limited mainly to two regions in the south of Vietnam, the Central Highlands and the Southeast. PV potential is available in larger parts of the country including Southeast, Central Highlands, Mekong River Delta, all the coastal areas and Northeast regions of Vietnam.

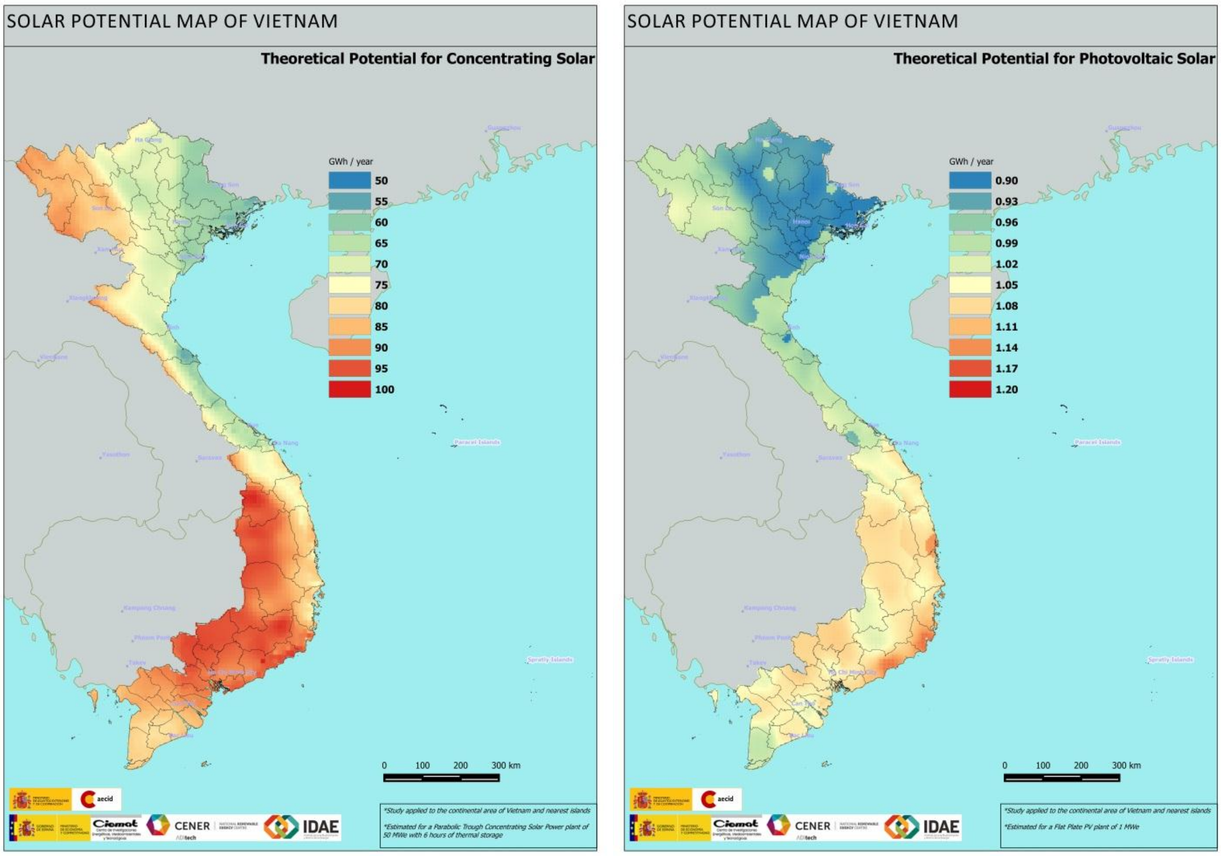

Fig. 7 Theoretical potential for CSP (left) and PV (right) in Vietnam

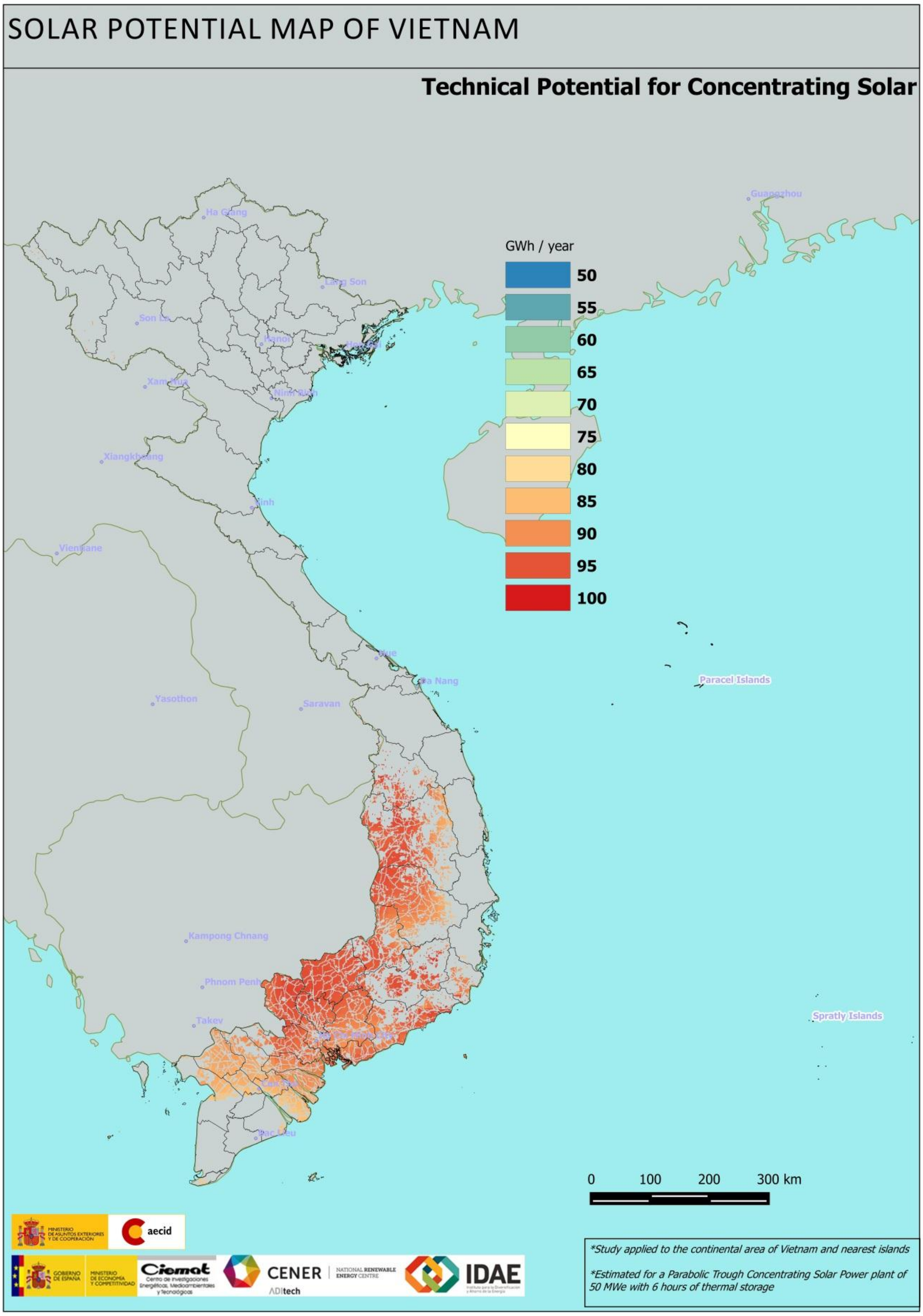

Fig. 8 Technical potential for CSP systems

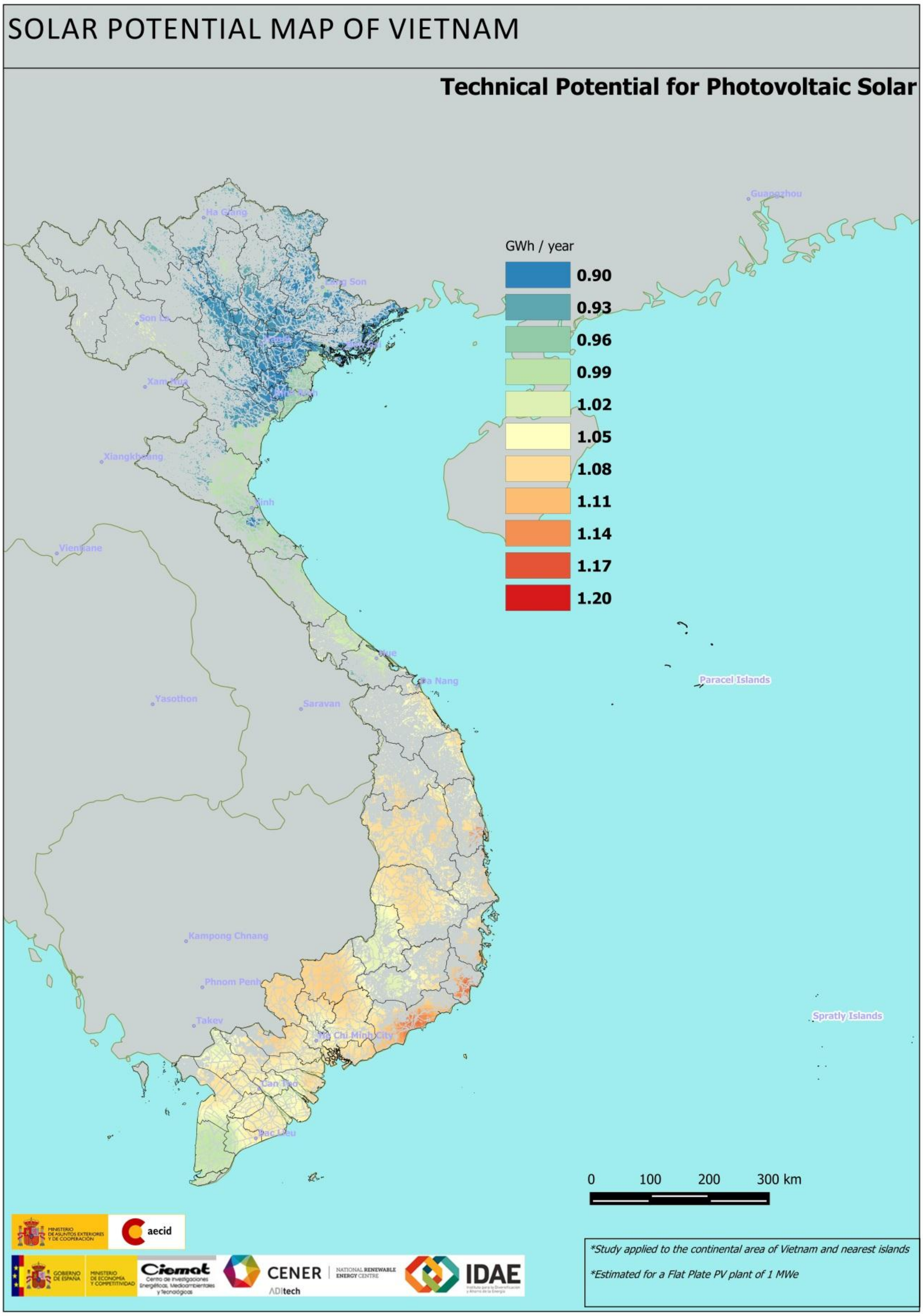

Fig. 9 Technical potential for PV systems

6. Final remarks

Mapping of solar resources is a useful tool for developers, manufactures, designers and decision-makers to promote the deployment of solar energy systems in a country. Based upon the Spanish experience in solar energy industry, the team formed by CIEMAT, CENER and IDAE has addressed the solar radiation and solar potential mapping of Vietnam for being delivered to the Vietnamese Ministry of Industry and Trade under the promotion of the Spanish Agency for International Cooperation and Development (AECID). Satellite derived data, data from reanalysis of numerical models, transmittance calculations and ground measurements have been effectively combined to produce the final maps of the most relevant components of solar radiation reaching the earth's surface for solar energy systems: the global horizontal and the direct normal irradiation.

Annual and monthly maps of solar global horizontal irradiation have been performed by a model mostly based on sunshine duration and satellite derived data with a good performance in terms of monthly means using 11 radiometric ground stations in Vietnam. The corresponding maps for direct normal irradiation were performed from only satellite-derived data since there were no experimental data available on this solar radiation component.

Solar resource maps show that global horizontal irradiation in annual daily average reaches around 3.4 kWh m^{-2} day^{-1} in the north of the country, about 3.8 kWh m^{-2} day^{-1} in the north central coast, and around 4.8 kWh m^{-2} day^{-1} in the south, central highlands and south central coast. In the case of direct normal irradiation the annual daily average is around 2.5 kWh m^{-2} day^{-1} in the north and central coast of the country and around 4.2 kWh m^{-2} day^{-1} in the south central coast and south; slightly higher values in the range of 4.7 kWh m^{-2} day^{-1} of direct normal irradiation are observed in the central highlands region. Therefore, a significant gradient is observed in solar radiation, particularly in the direct normal component, between the north and the south of the country.

Due to the limited ground information available complete assessment of the solar radiation estimation was not conducted. The estimations of global radiation showed a good performance; no bias and root mean square errors below 10% for monthly means of global irradiation on horizontal surface. In the case of direct normal irradiation no assessment was performed due to unavailability of ground data, however the root mean squared error is expected to be below 20% in the basis of other studies of the methodology applied to different sites.

The solar potential for Vietnam has been estimated and mapped from several hypothesis and scenarios concerning the solar resource availability and the solar technology systems to be taken into account. Solar resource availability has been obtained from the solar resource mapping for Vietnam estimated from satellite imagery, ground measurements and reanalysis of several atmospheric and meteorological variables. The scenarios considered for determining the solar potential has included two main technologies: a Parabolic Trough of 50 MWe with 6 hours of thermal storage as CSP reference plant, and a Flat Plate grid-connected PV plant of around 1 MWe.

Simulations of the net energy produced for each reference plants have been performed in order to cover the wide range of variability of both solar resources (GHI and DNI) and latitude. The results of such simulations have allowed the development of simple expressions for estimating the energy produced by the plant as a function of the annual solar irradiance (GHI for PV and DNI for CSP) and of the latitude of the site. These simple expressions have been used to estimate the theoretical solar potential according to each solar technology considered. The theoretical potential according to the technology selected and the solar resource estimated across the country is placed in the range of 60-100 GWh $year^{-1}$ for CSP systems, and 0.8-1.2 GWh $year^{-1}$ in the case of PV systems.

The technical potential for each technology has been estimated from the theoretical potential by incorporating restrictions to the land availability according to the methodologies reported in the literature. The main restrictions are focused on the slope of the land, since slopes greater than 3% makes economically unfeasible the deployment of a solar power plant and on water bodies and roads mainly. An additional restriction of DNI greater to 1500 kWh m^{-2} $year^{-1}$ has been also imposed to CSP. The result of all the land restrictions in a geographic information system has determined the available areas for solar power plants deployment according to each technology. The areas available for CSP systems are limited to Central Highlands and Southeast regions of Vietnam. In the case of PV, the available areas are limited to Southeast, Central Highlands, Mekong River Delta, all the coastal areas and Northeast regions of Vietnam.

7. Acknowledgments

This work has been performed under the framework of the Project "Impulse to the development of the renewable energy in Vietnam based on the Spanish experience" being led by the General Directorate of Energy of Ministry of Industry and Trade of Vietnam (GDoE – MoIT) with the collaboration as initiator of the Spanish Agency for International Development Cooperation (AECID). The authors wish to acknowledge the National Hydro-meteorological Service of Vietnam for delivering ground data and MTSAT2 imagery. The authors wish also to thank so much the support and collaboration of Mónica Corrales, Maite Martín-Crespo and Mar Rodriguez from AECID.

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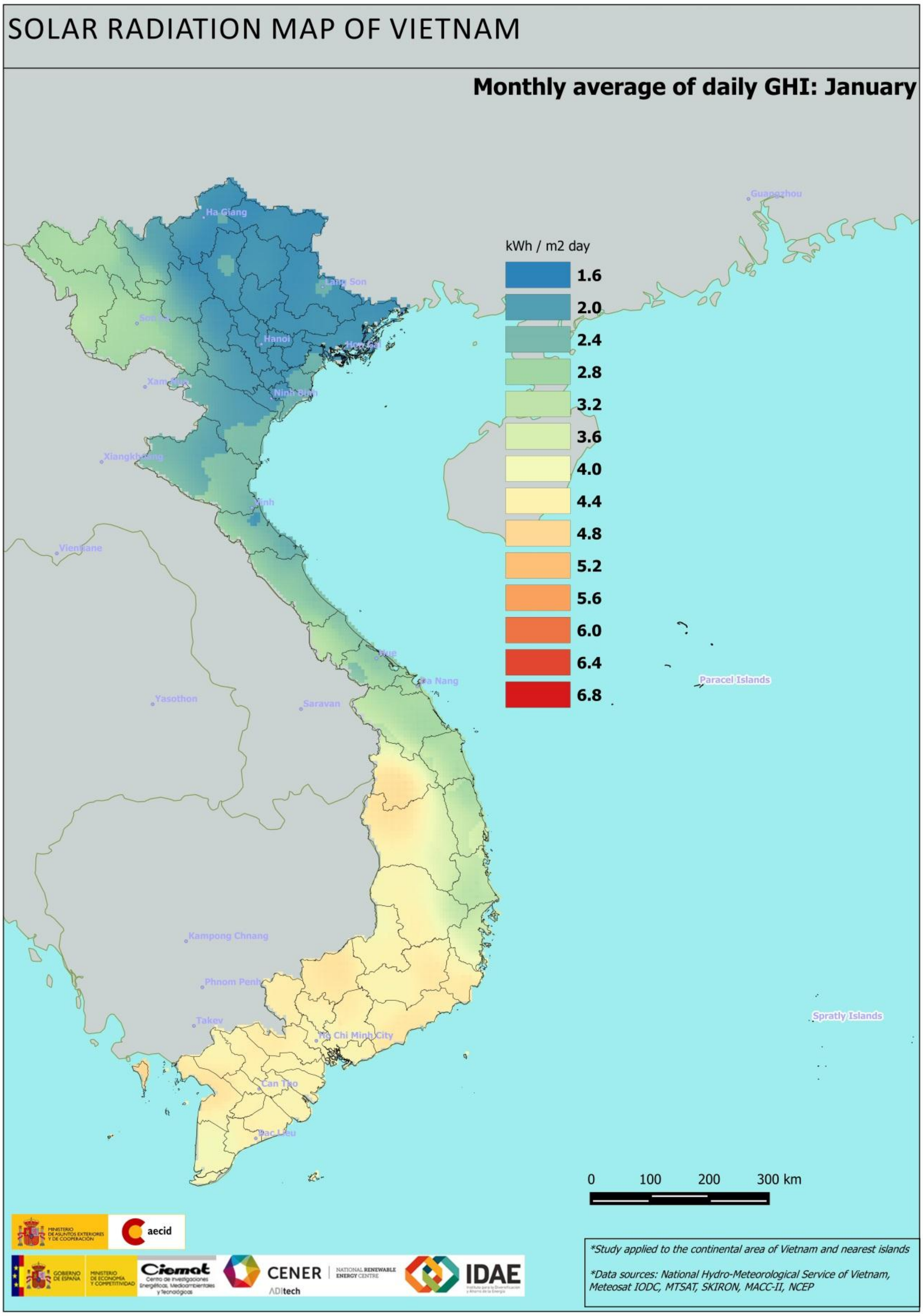
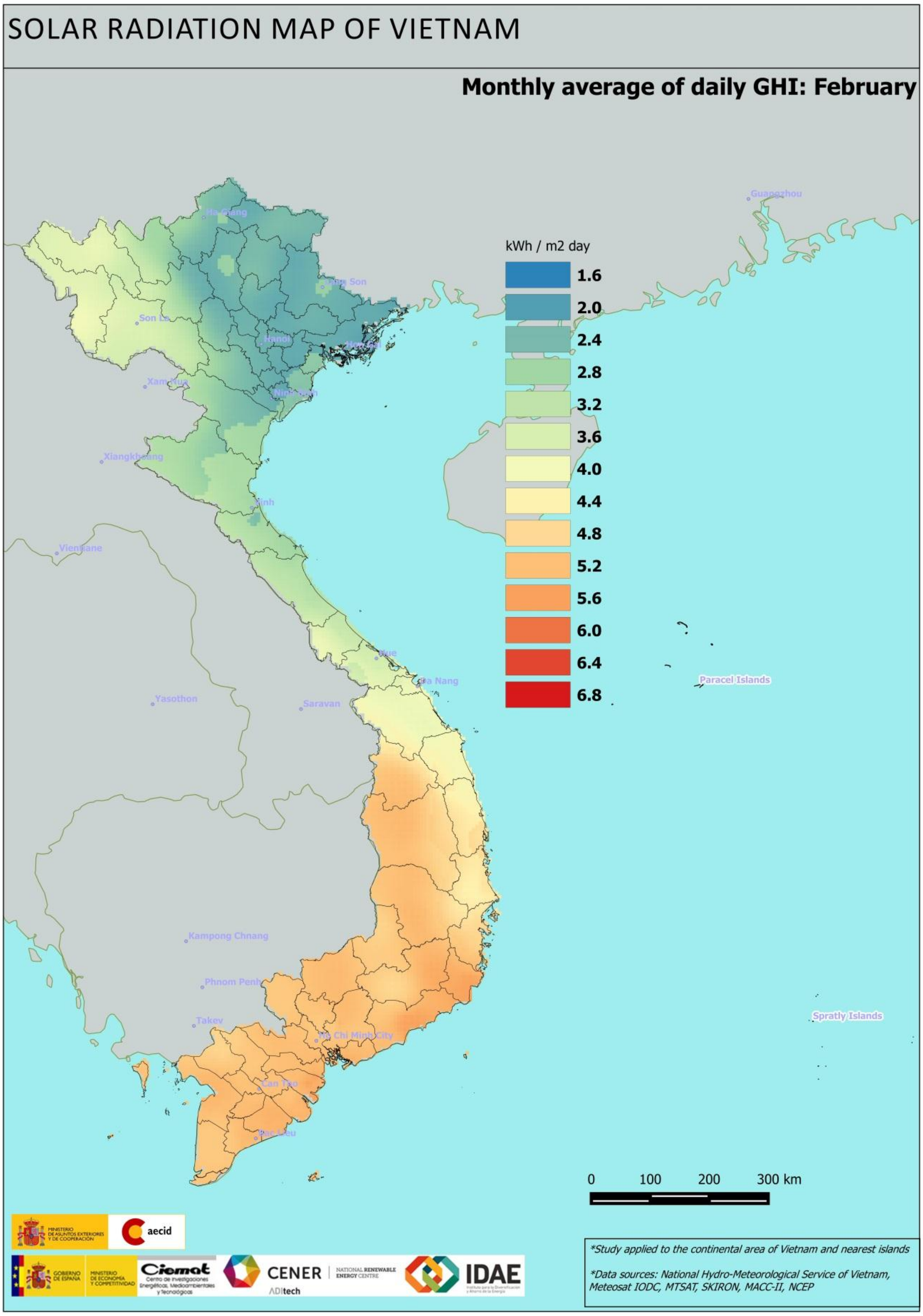
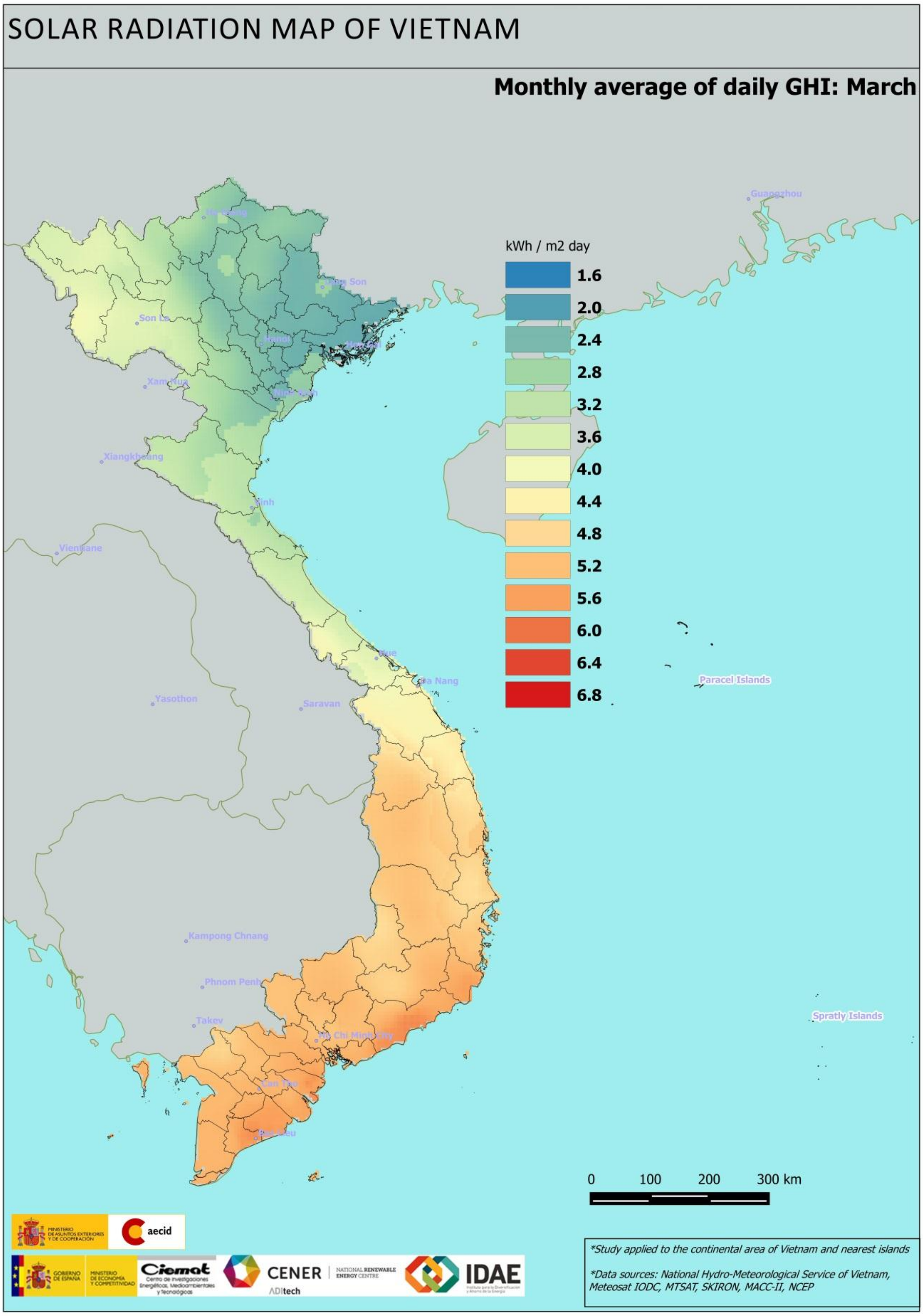
Appendix I

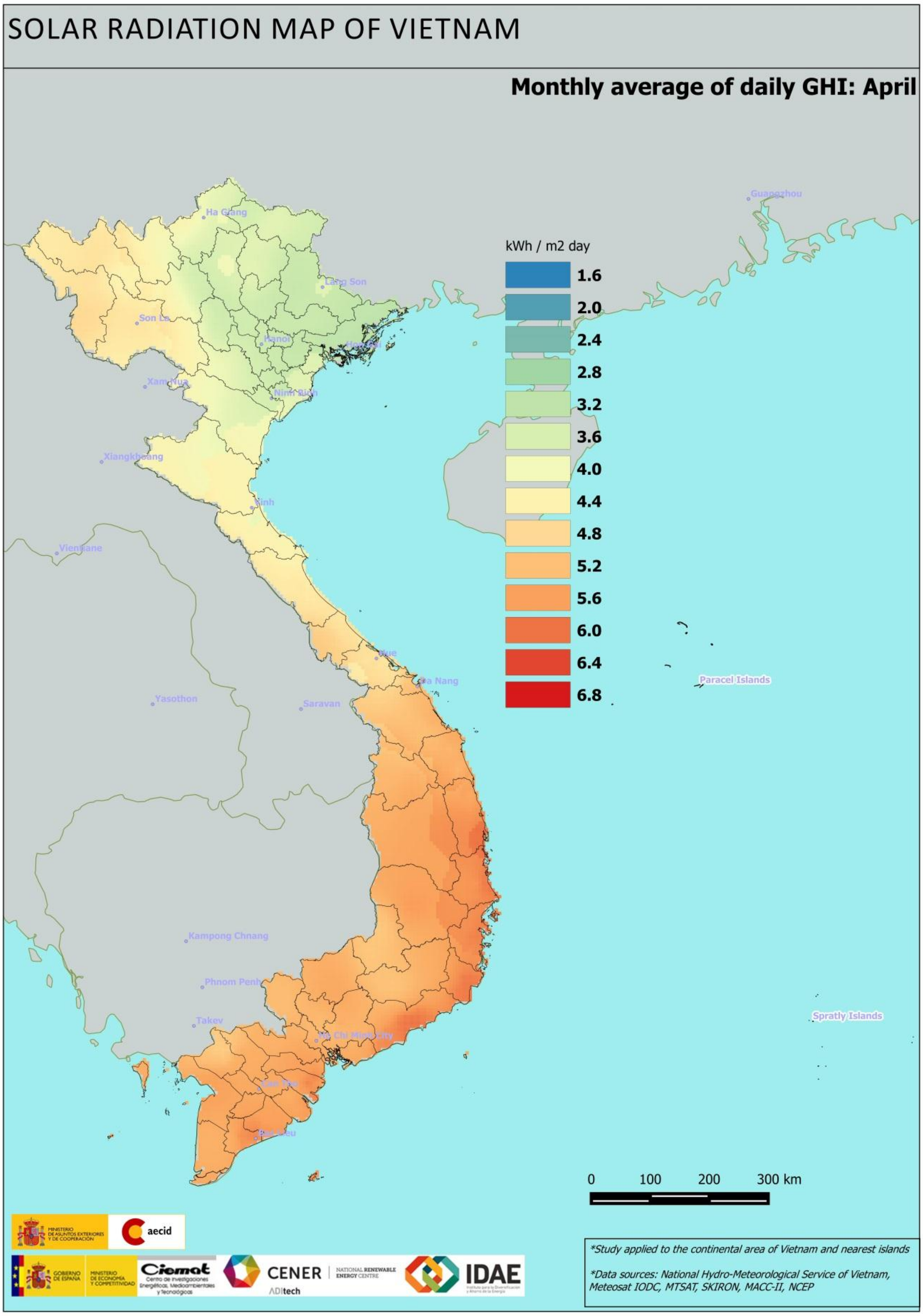
Maps of monthly means of daily solar irradiation

Global Horizontal Irradiation


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: January
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Ha Giang
Lang Son
Hanoi
Ninh Binh
Vinh
Hue
Da Nang
Guangzhou
Vientiane
Yasothon
Saravan
Paracel Islands
Kampong Chhnang
Phnom Penh
Takeo
Ho Chi Minh City
Can Tho
Bac Lieu
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: February
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Son La
Yasothon
Saravan
Paracel Islands
Kampong Chnang
Takev
Spratly Islands
0
100
200
300 km
aecid
CENER
IDAE
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: March
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Son La
Xam Nua
Xiangkhoang
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chnang
Phnom Penh
Takev
Spratly Islands
0 100 200 300 km
aecid
CENER
IDAE
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: April
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Ha Giang
Lang Son
Son La
Hanoi
Xam Nua
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takev
Guangzhou
Paracel Islands
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
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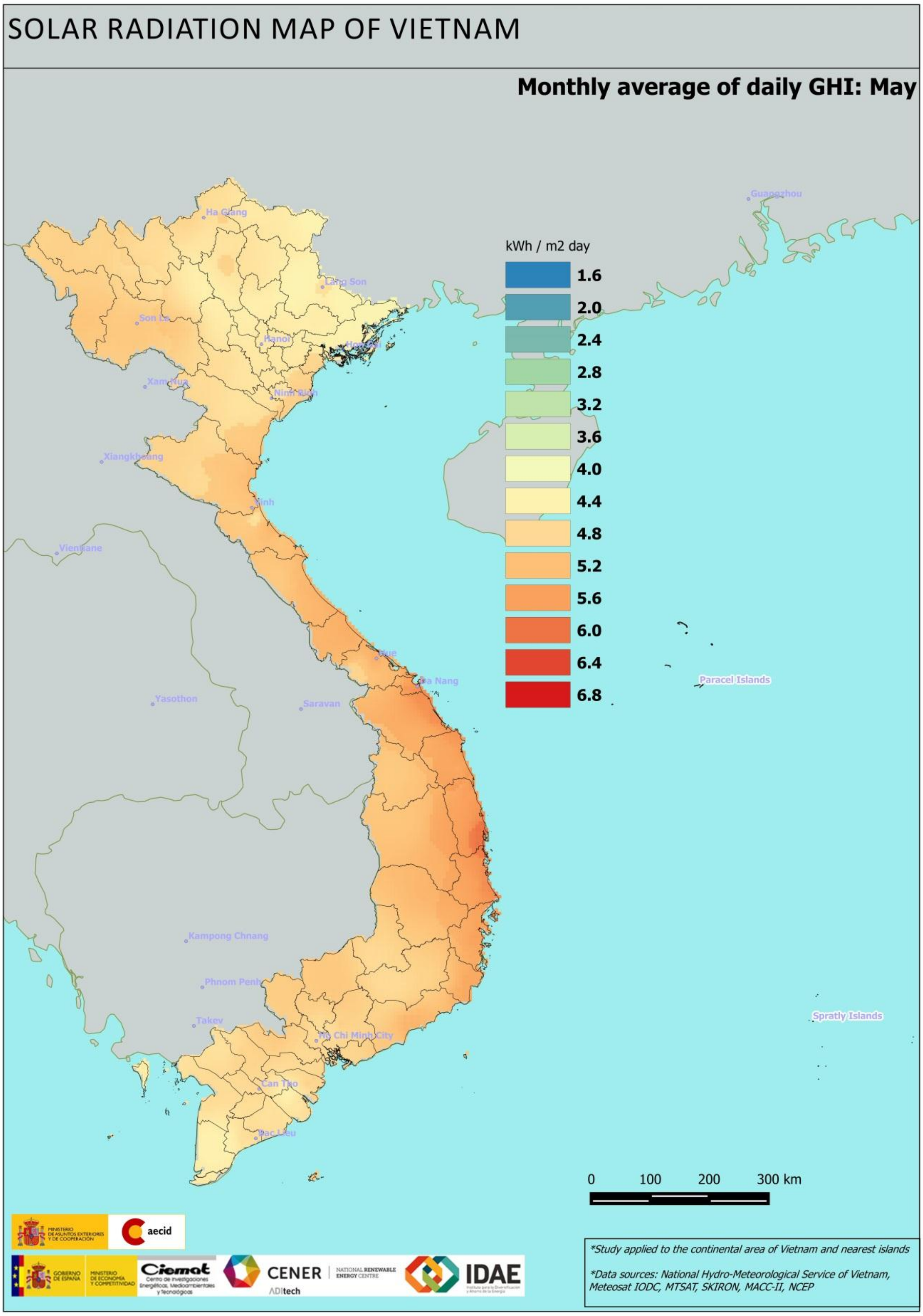
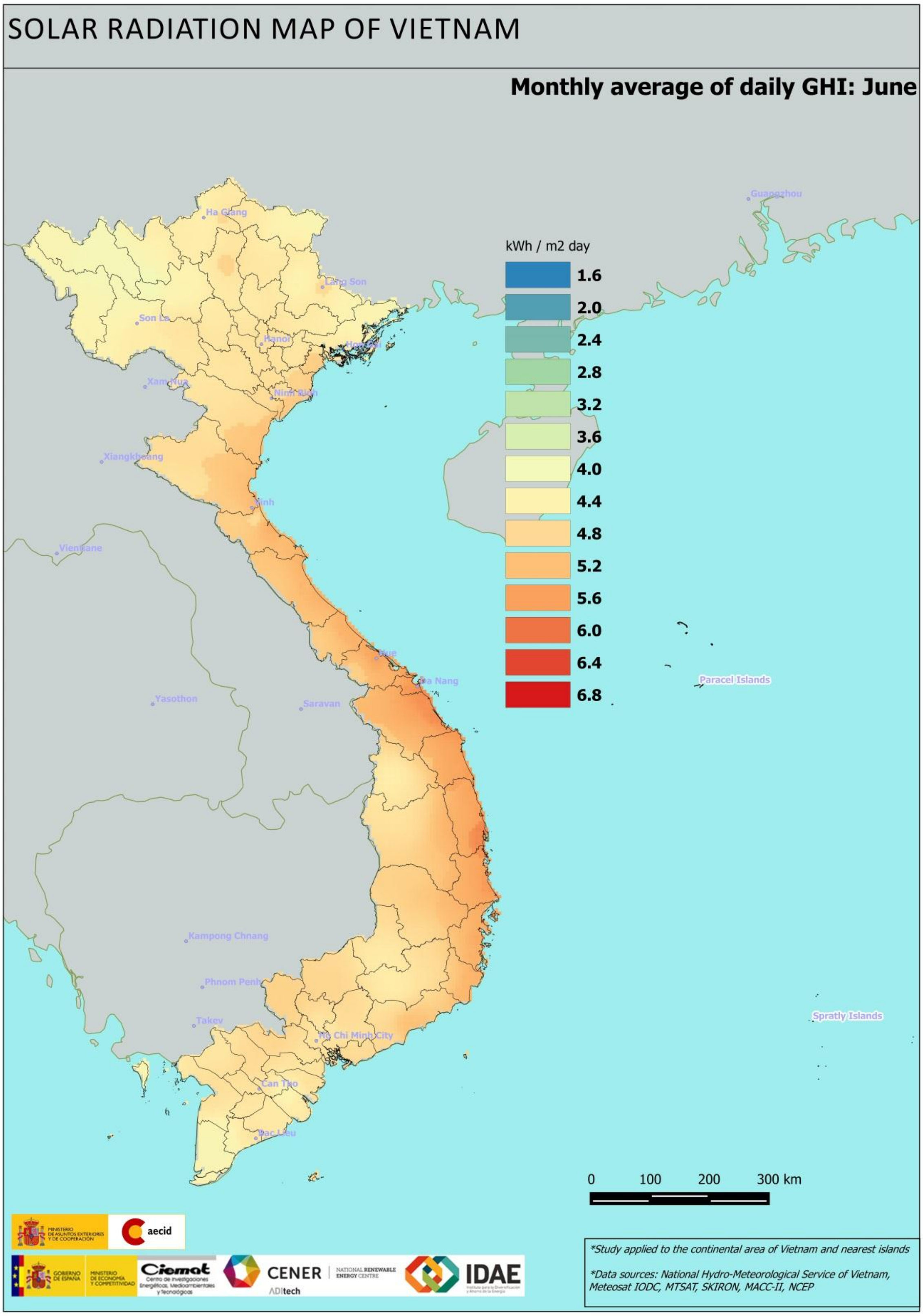

SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: May
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Ha Giang
Lang Son
Son La
Hanoi
Xam Nua
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chnang
Phnom Penh
Takev
Ho Chi Minh City
Can Tho
Bac Lieu
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: June
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Ha Giang
Lang Son
Son La
Hanoi
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takev
Ho Chi Minh City
Can Tho
Bac Lieu
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP
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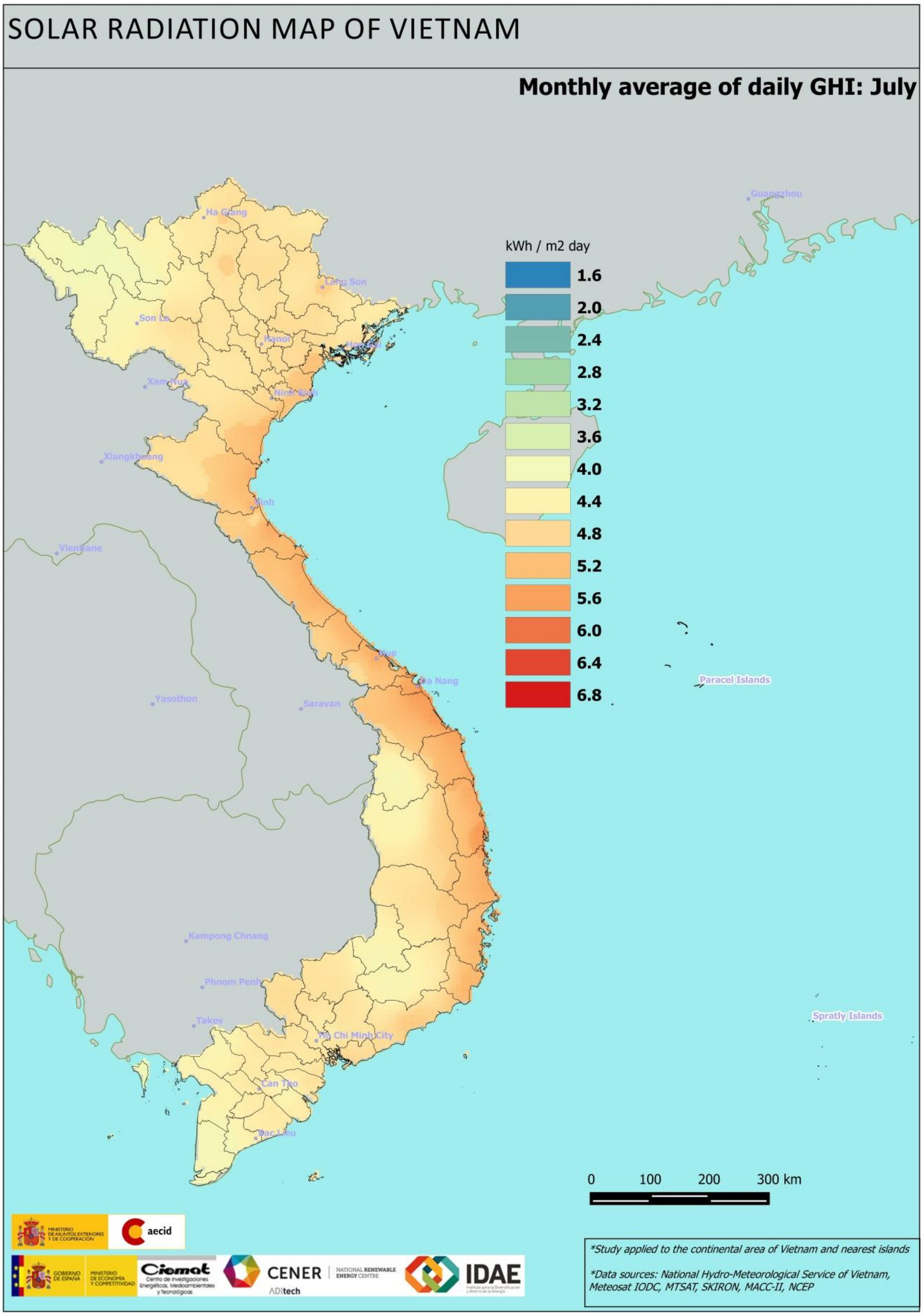
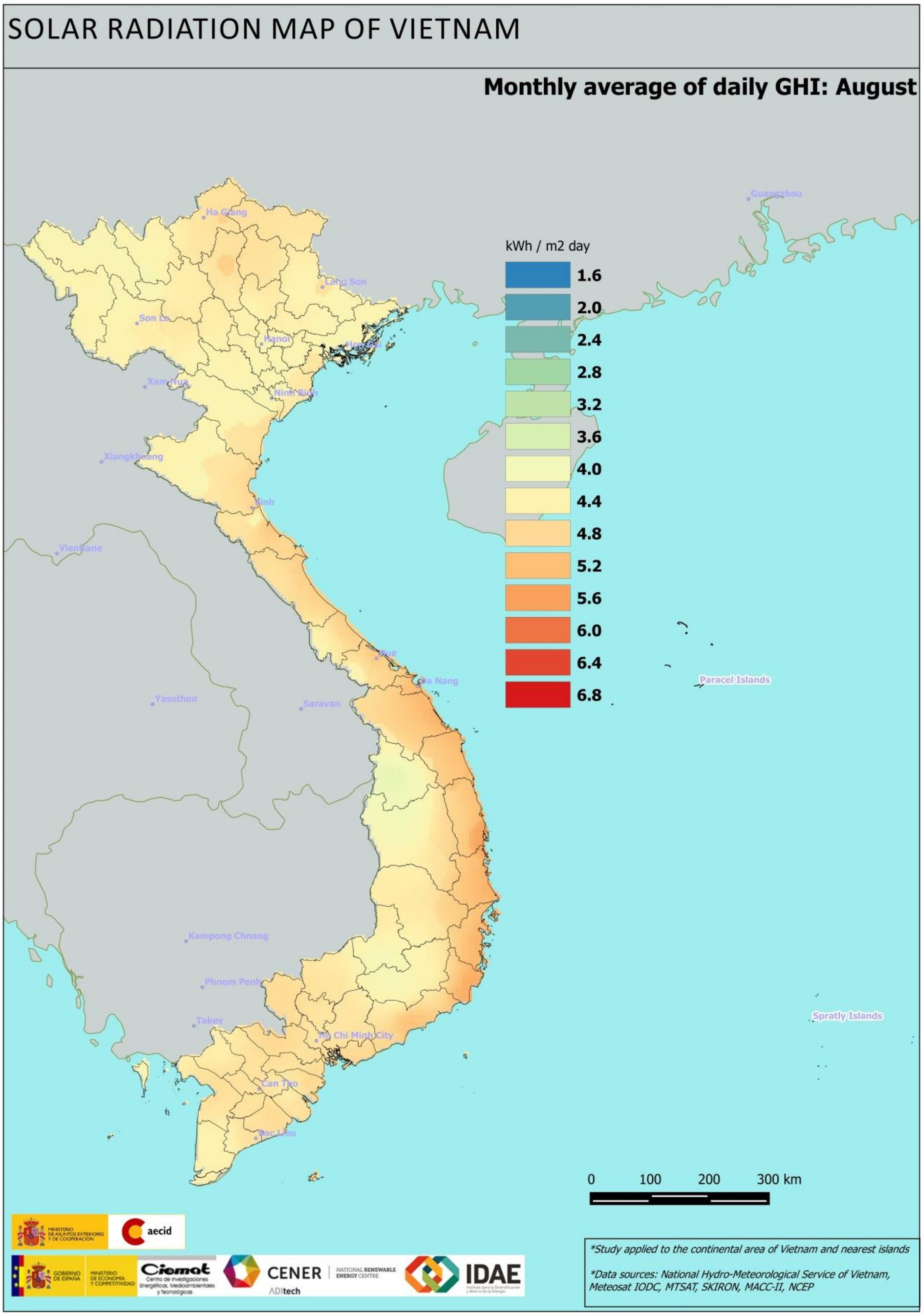

SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: July
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Ha Giang
Son La
Hanoi
Xam Nua
Xiangkhoang
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takev
Ho Chi Minh City
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP



SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: August
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Paracel Islands
Spratly Islands
Kampong Chnang
Phnom Penh
Yasothon
Saravan
Vientiane
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP
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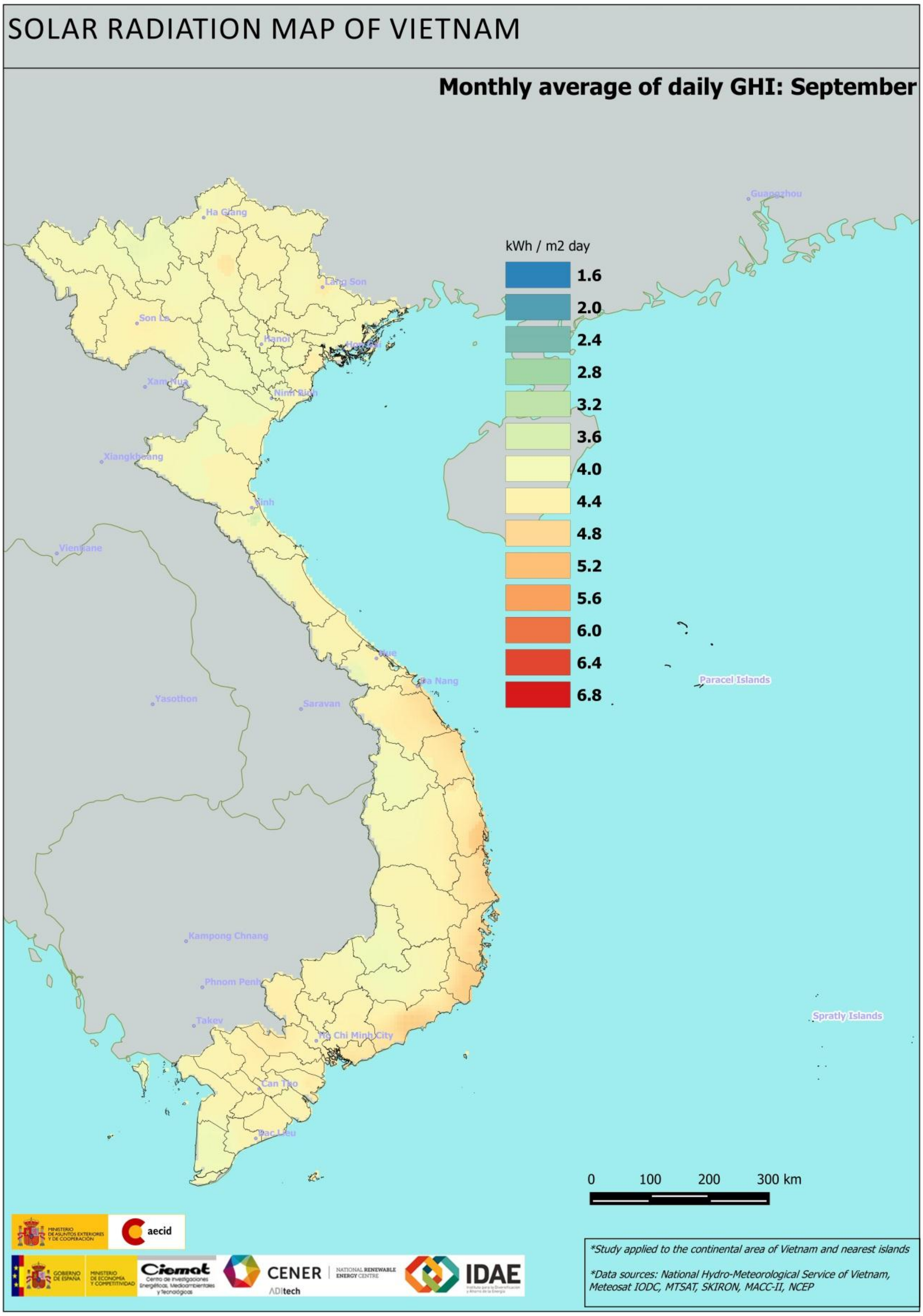
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: September
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Ha Giang
Lang Son
Son La
Hanoi
Ninh Binh
Xam Nua
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Saravan
Yasothon
Kampong Chnang
Phnom Penh
Takev
Ho Chi Minh City
Can Tho
Bac Lieu
Guangzhou
Paracel Islands
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP
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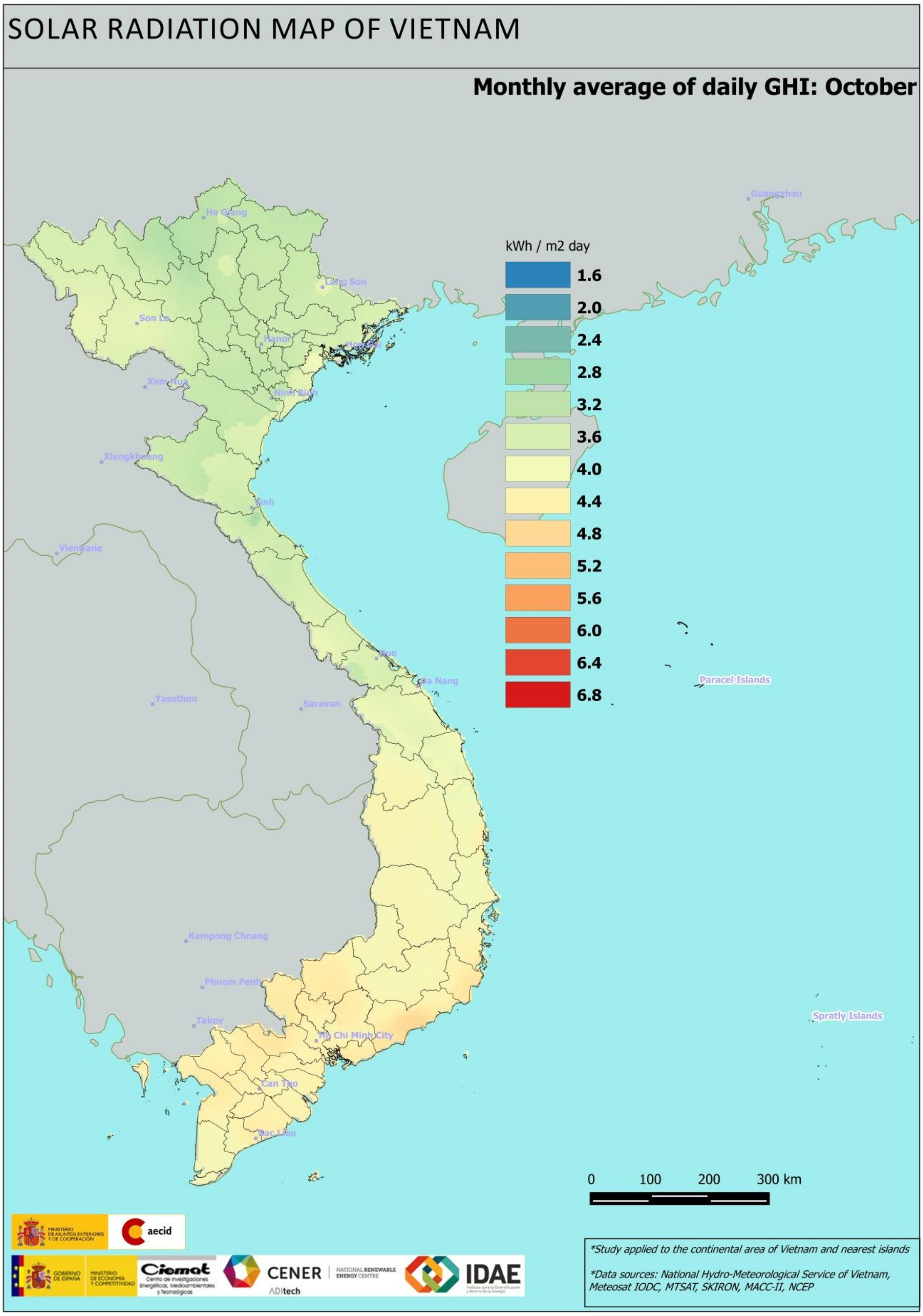
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: October
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Ha Giang
Lang Son
Son La
Hanoi
Xam Nua
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chnang
Phnom Penh
Takeo
Ho Chi Minh City
Can Tho
Bac Lieu
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP
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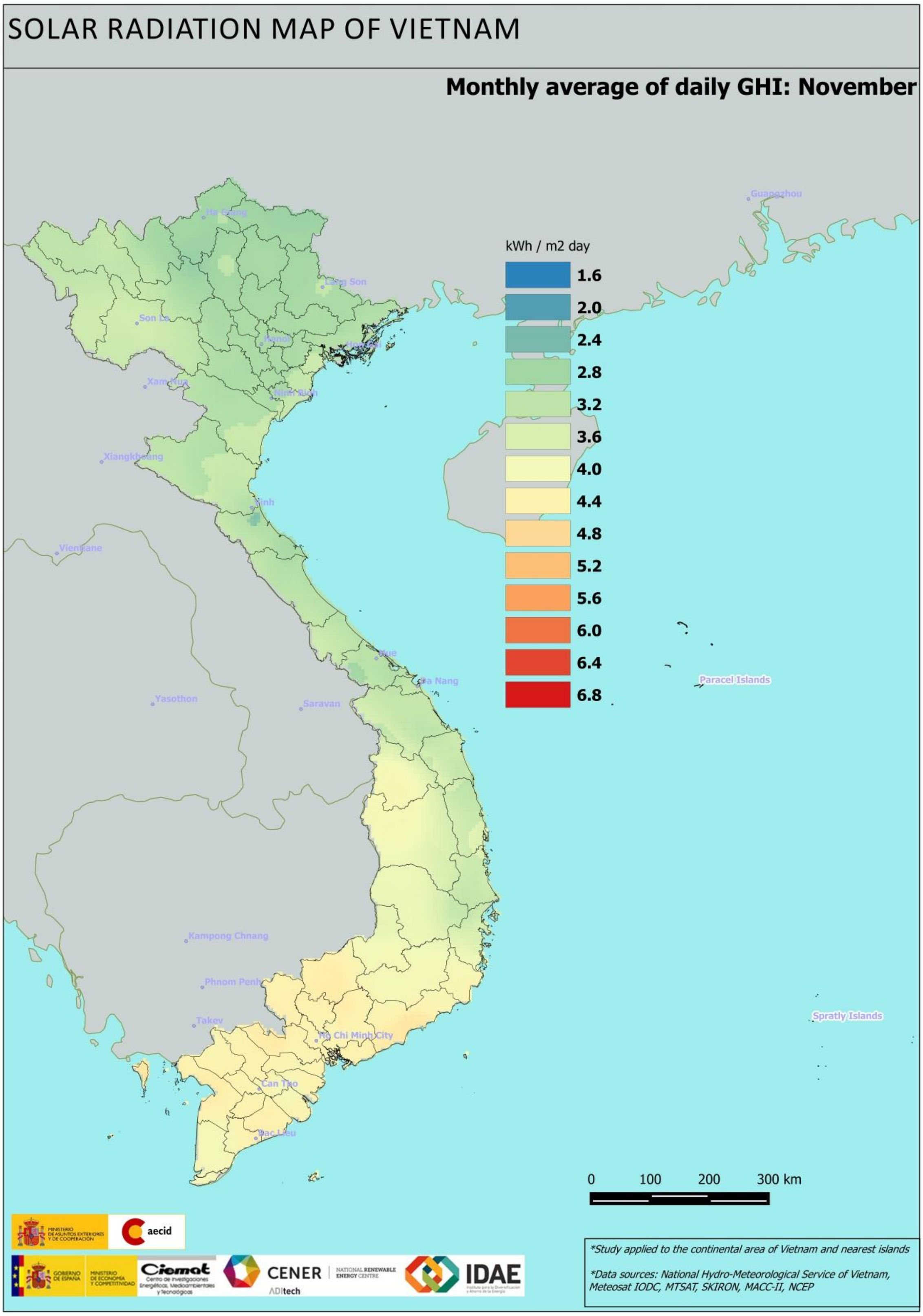
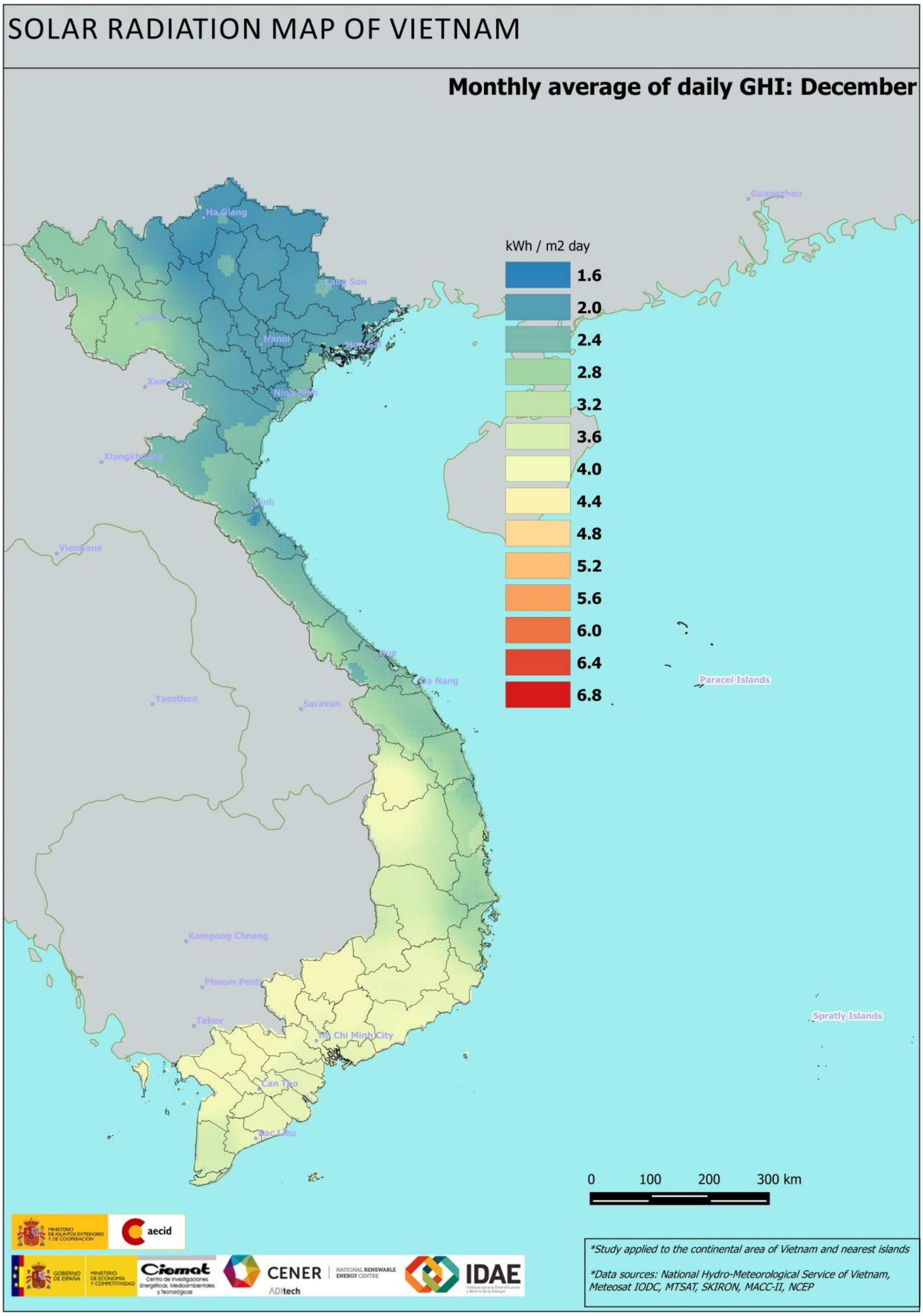
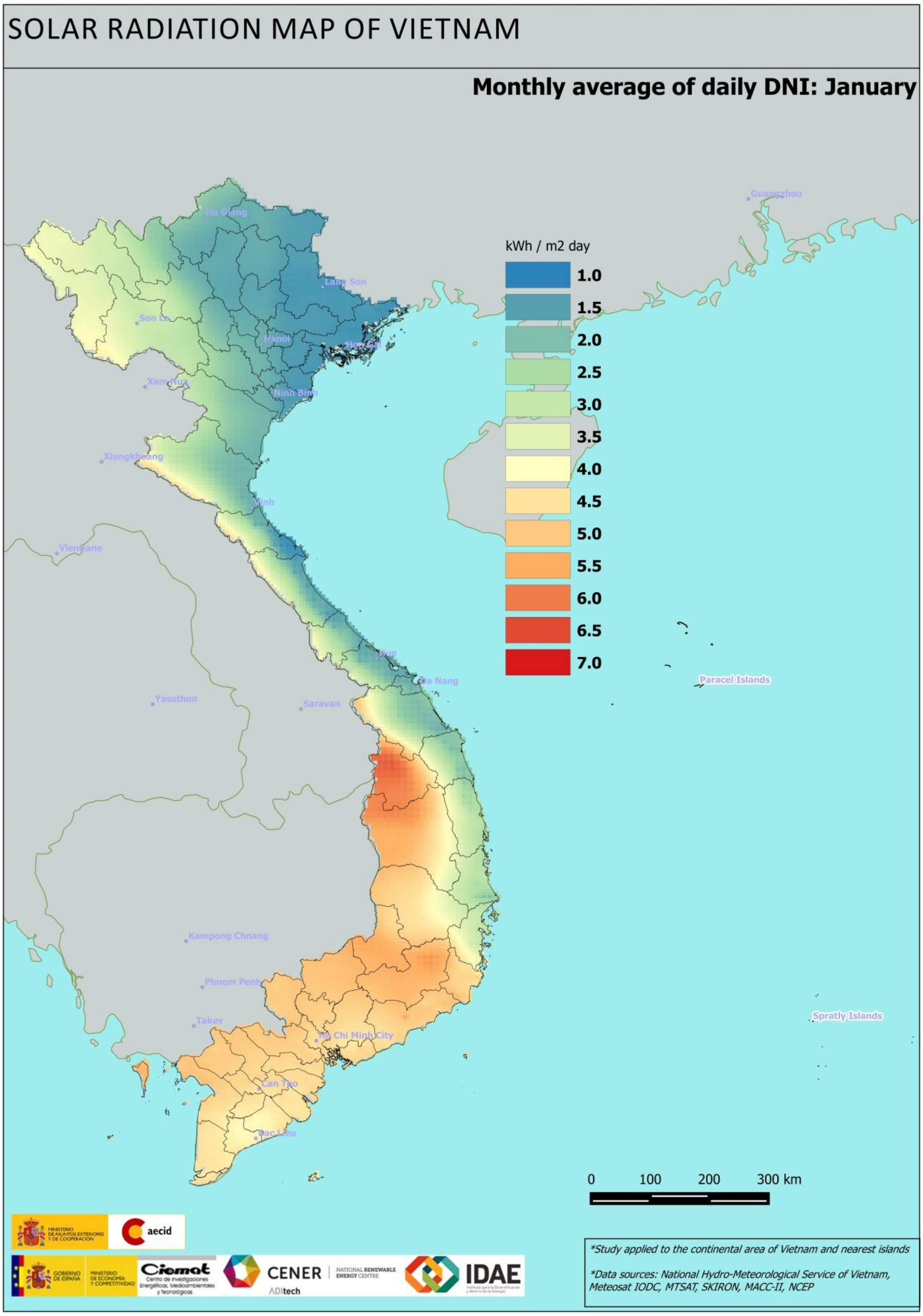

SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: November
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Guangzhou
Son La
Xam Nua
Xiangkhoang
Vientiane
Yasothon
Saravan
Paracel Islands
Kampong Chnang
Phnom Penh
Takev
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily GHI: December
kWh / m2 day
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
Ha Giang
Hanoi
Vientiane
Hue
Yasothon
Saravan
Kampong Chhnang
Ho Chi Minh City
Guangzhou
Paracel Islands
Spratly Islands
0 100 200 300 km
aecid
Ciemat
CENER
NATIONAL RENEWABLE ENERGY CENTRE
IDAE
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP

Appendix II

Maps of monthly means of daily solar irradiation

Direct Normal Irradiation


SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: January
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Lang Son
Son La
Hanoi
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takev
Ho Chi Minh City
Can Tho
Bac Lieu
Spratly Islands
0 100 200 300 km
*Study applied to the continental area of Vietnam and nearest islands
*Data sources: National Hydro-Meteorological Service of Vietnam, Meteosat IODC, MTSAT, SKIRON, MACC-II, NCEP
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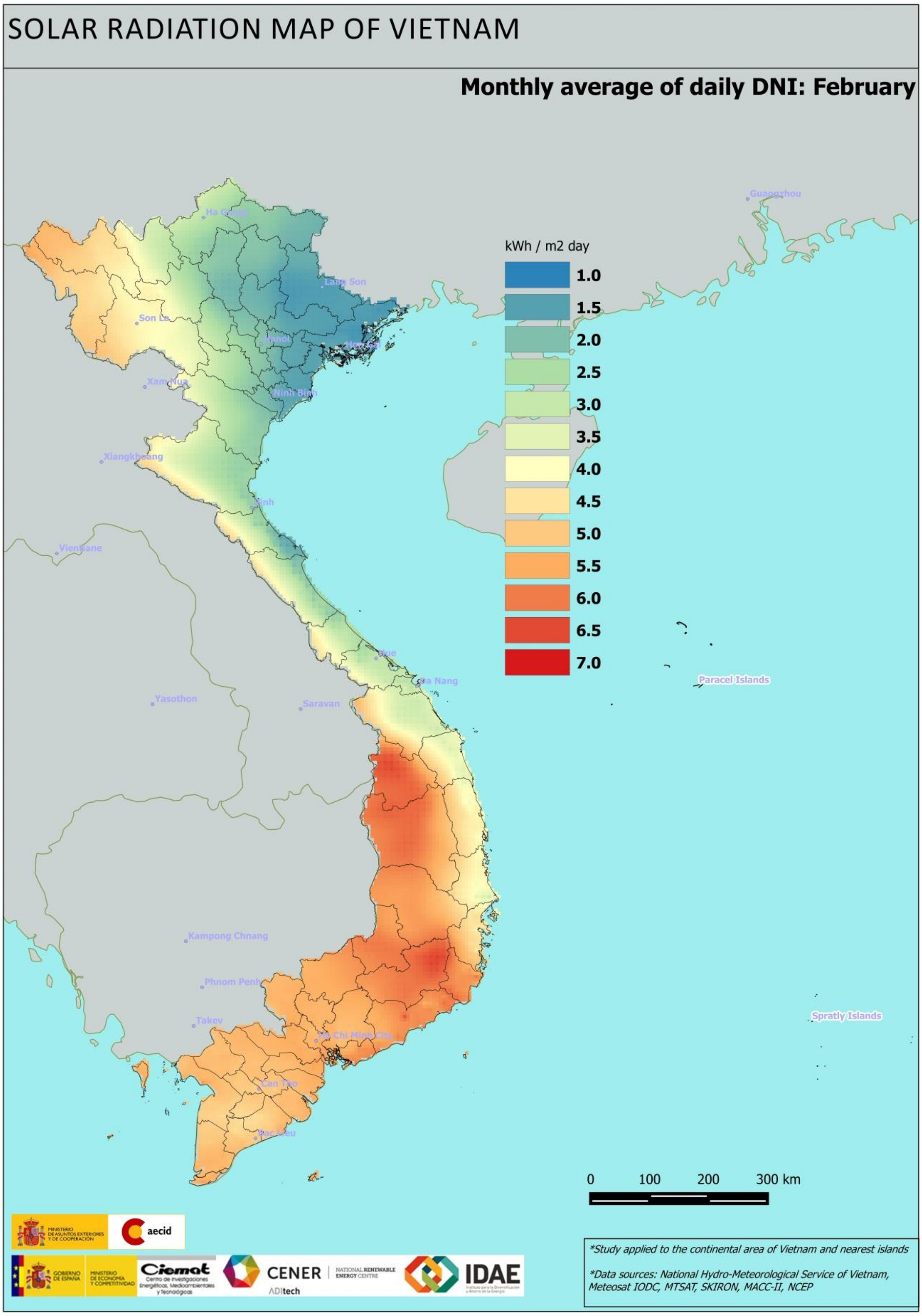
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: February
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Lang Son
Son La
Ninh Binh
Xiangkhoang
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takev
Spratly Islands
0
100
200
300 km
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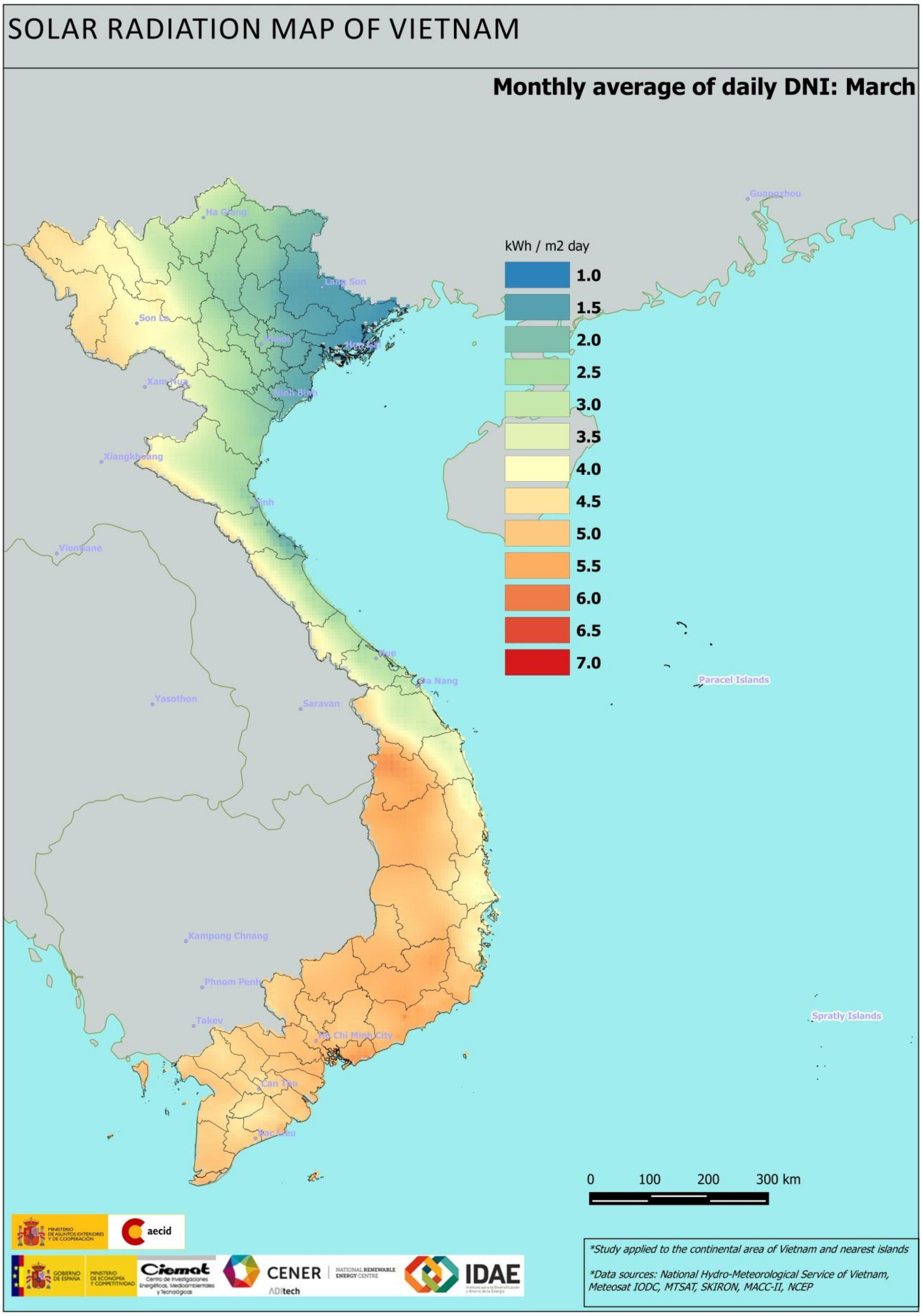
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: March
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Ha Giang
Lang Son
Son La
Xiangkhoang
Vientiane
Hue
Da Nang
Yasothon
Saravan
Paracel Islands
Kampong Chhnang
Takev
Spratly Islands
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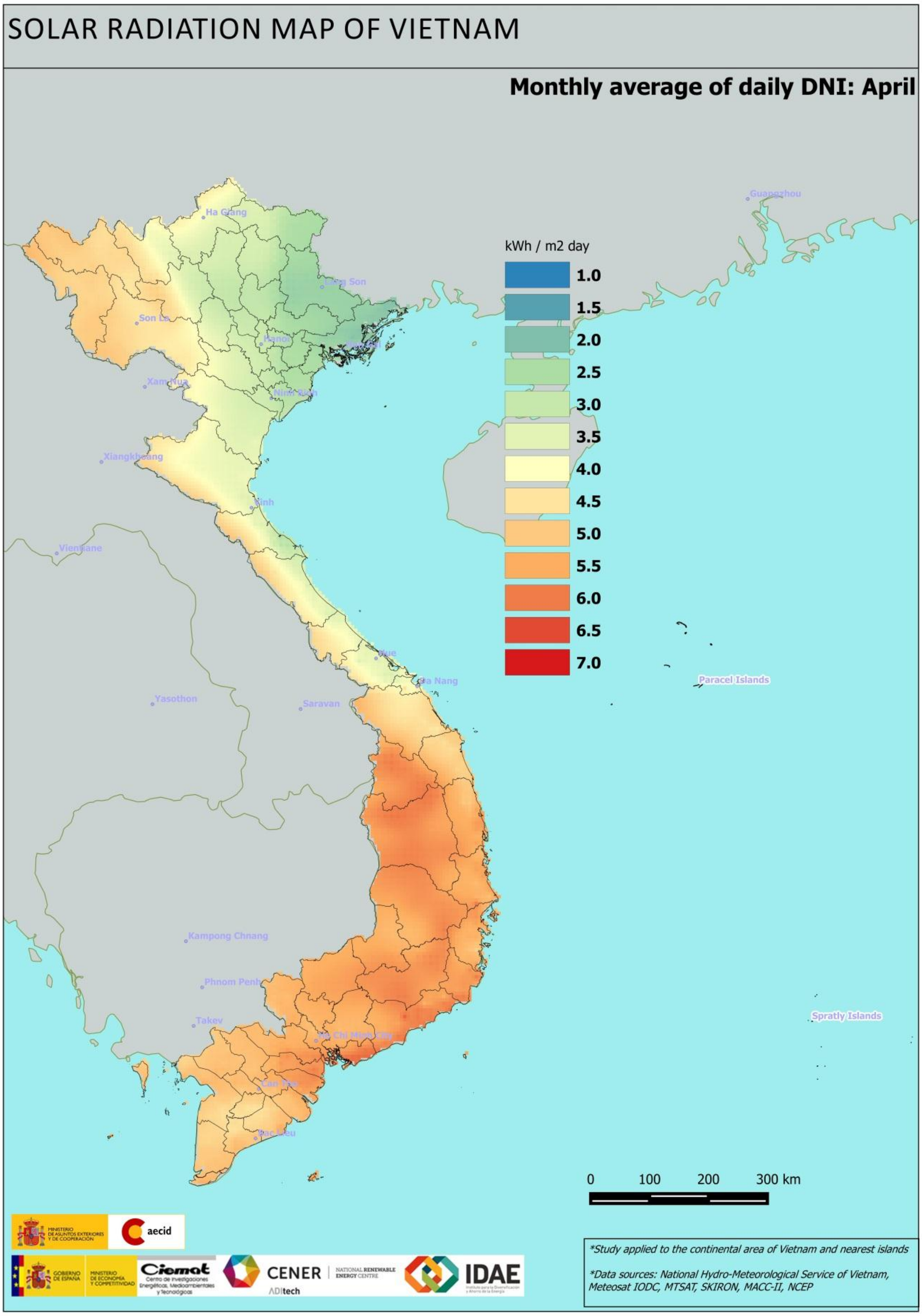
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: April
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Ha Giang
Son La
Guangzhou
Vientiane
Yasothon
Saravan
Da Nang
Paracel Islands
Kampong Chnang
Spratly Islands
0 100 200 300 km
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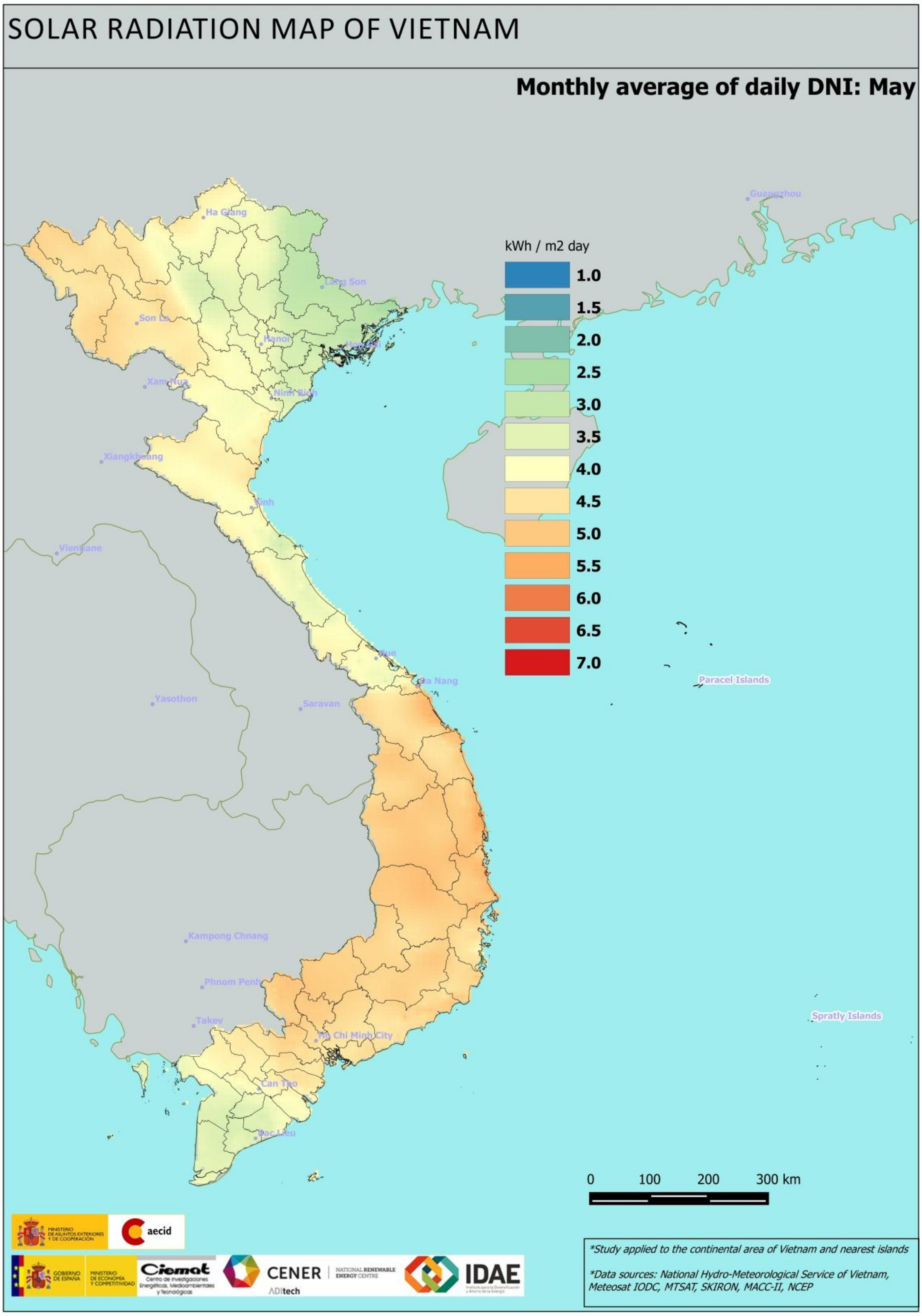
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: May
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Ha Giang
Lang Son
Son La
Hanoi
Xam Nua
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Yasothon
Saravan
Kampong Chnang
Phnom Penh
Takev
Ho Chi Minh City
Can Tho
Bac Lieu
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Paracel Islands
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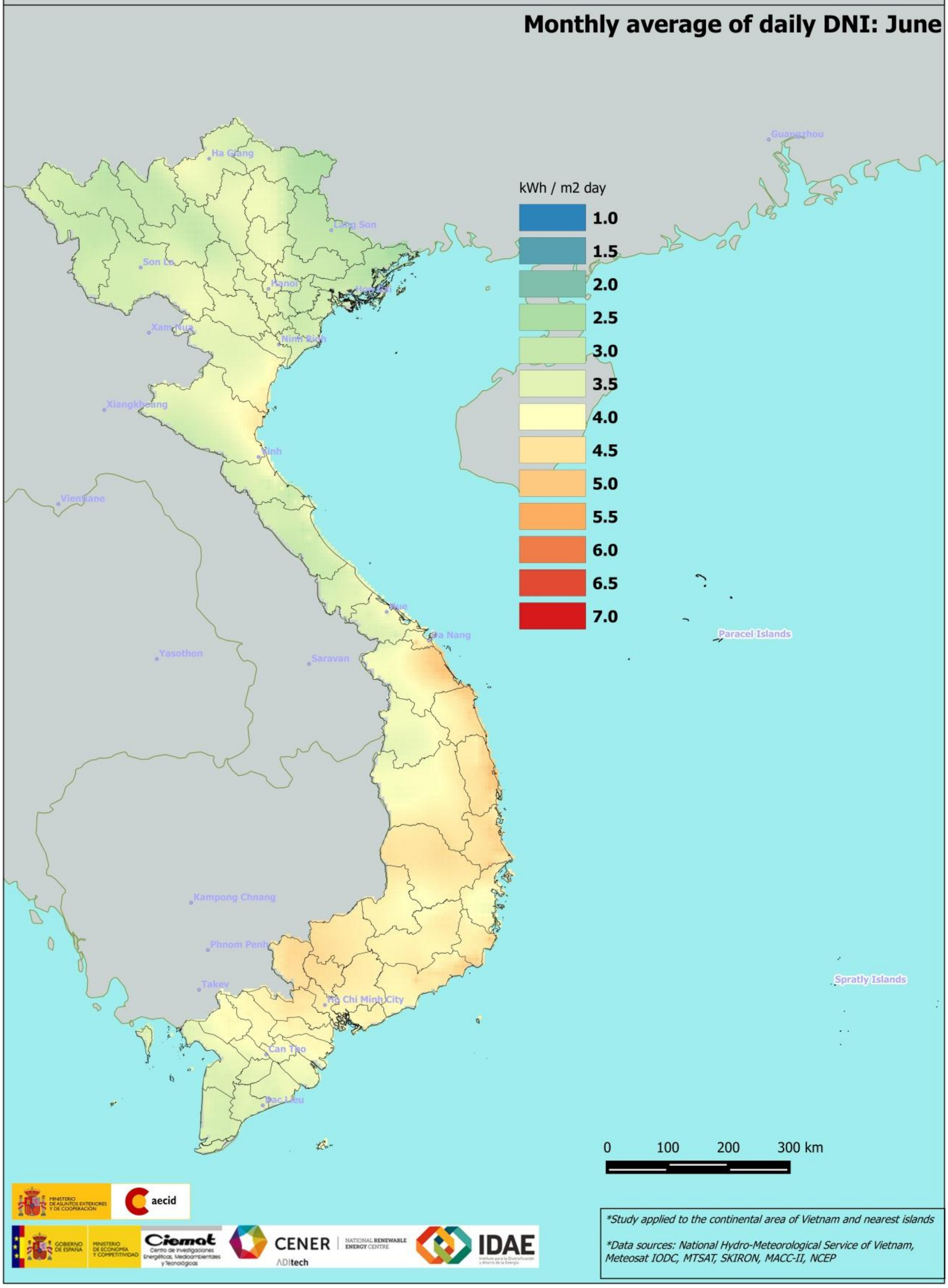
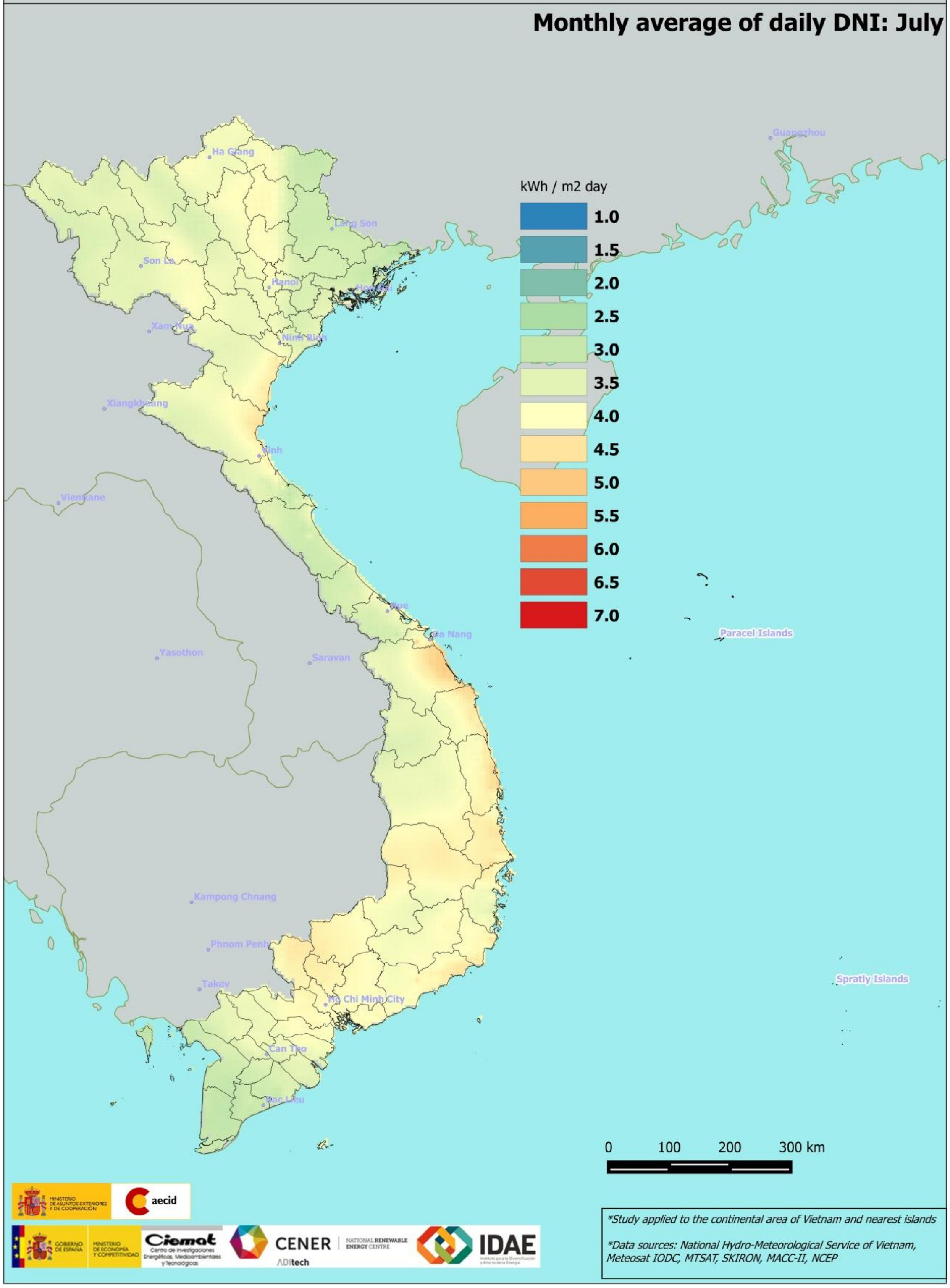
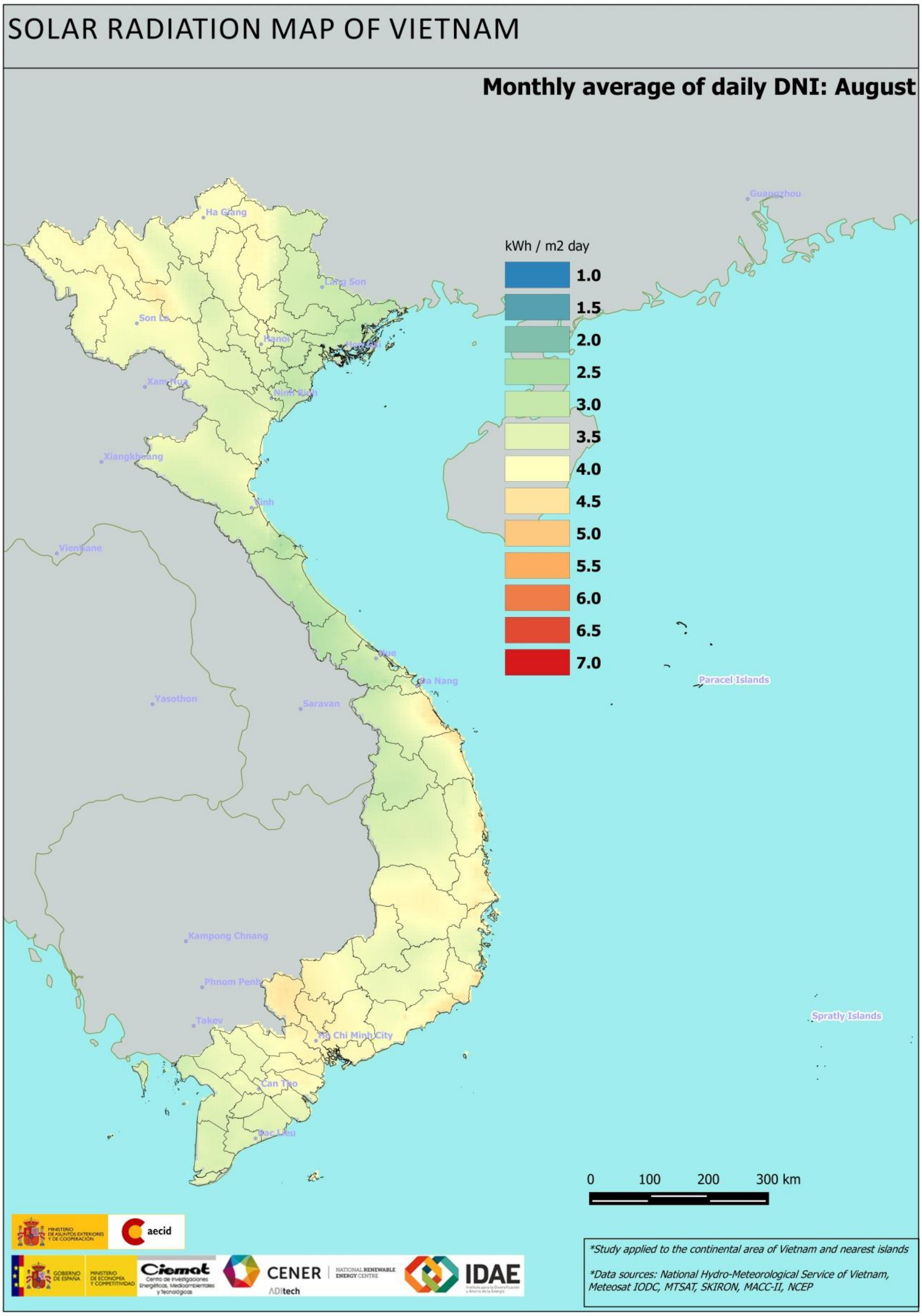
SOLAR RADIATION MAP OF VIETNAM



SOLAR RADIATION MAP OF VIETNAM




SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: August
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Ha Giang
Lang Son
Son La
Hanoi
Xam Nua
Ninh Binh
Xiangkhoang
Vinh
Vientiane
Hue
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chnang
Phnom Penh
Takev
Ho Chi Minh City
Spratly Islands
Can Tho
Bac Lieu
0 100 200 300 km
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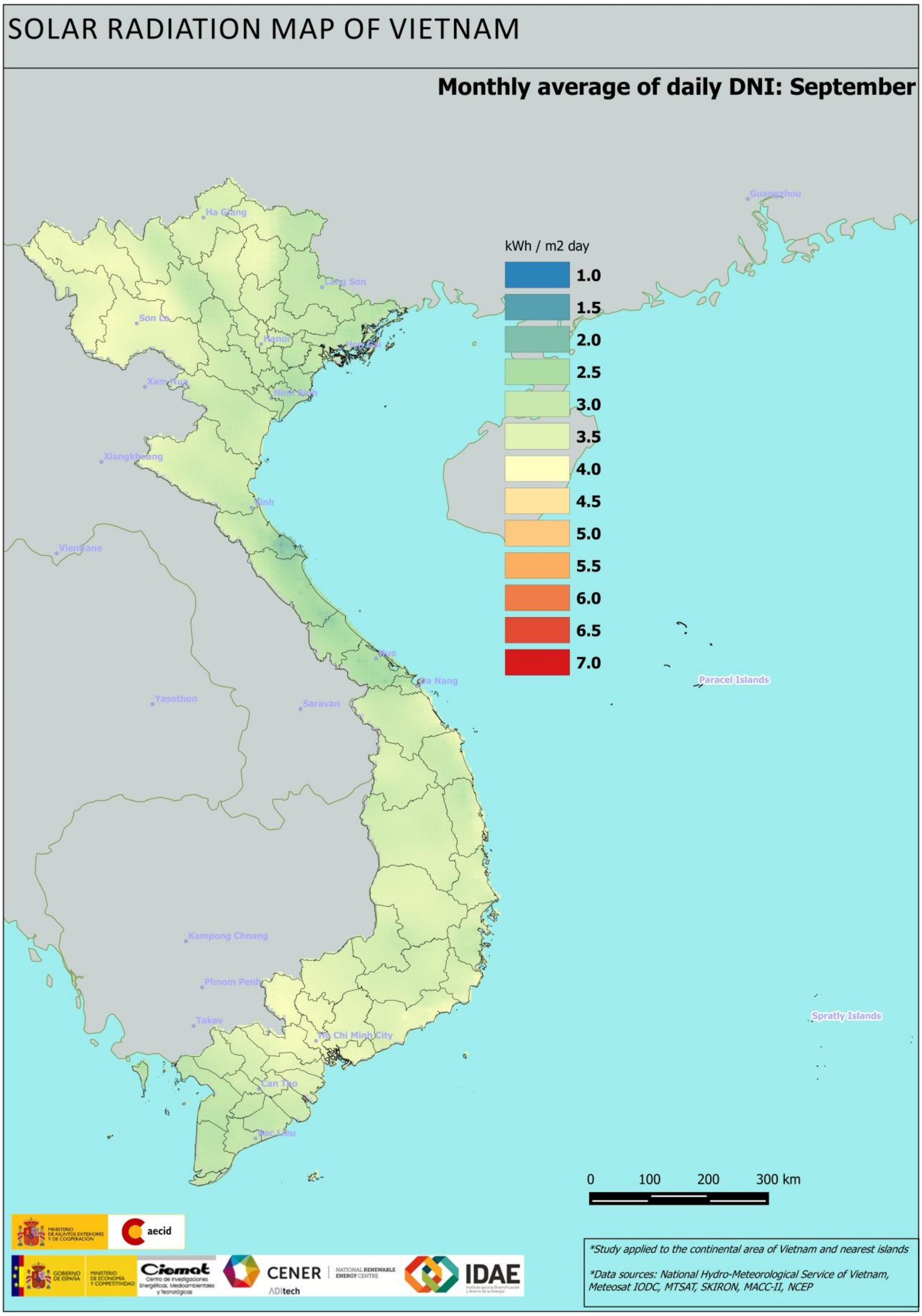
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: September
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Ha Giang
Son La
Xiangkhoang
Vientiane
Hue
Yasothon
Saravan
Paracel Islands
Kampong Chhnang
Ho Chi Minh City
Spratly Islands
0
100
200
300 km
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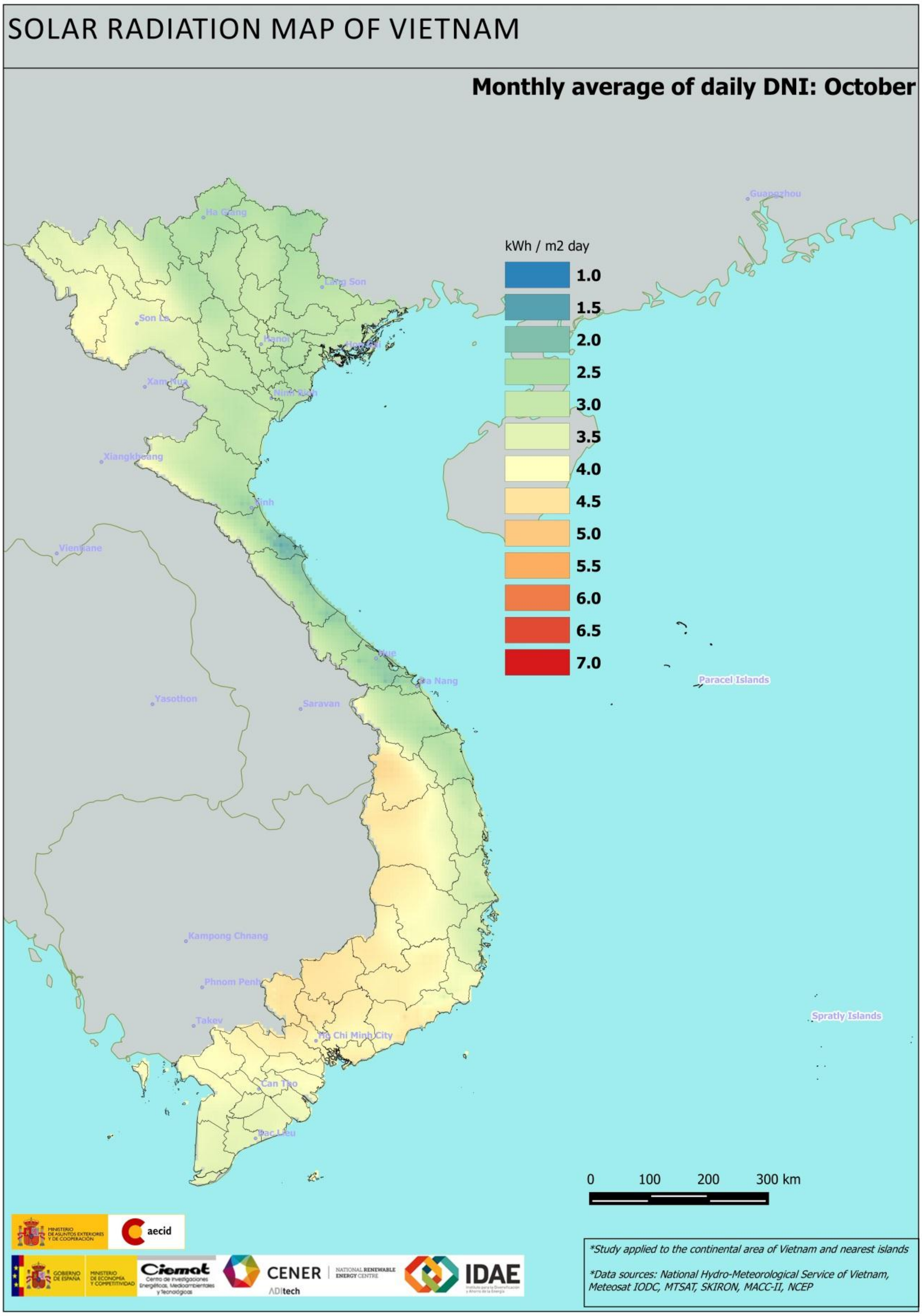
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: October
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Son La
Xiangkhoang
Da Nang
Paracel Islands
Yasothon
Saravan
Kampong Chnang
Spratly Islands
0 100 200 300 km
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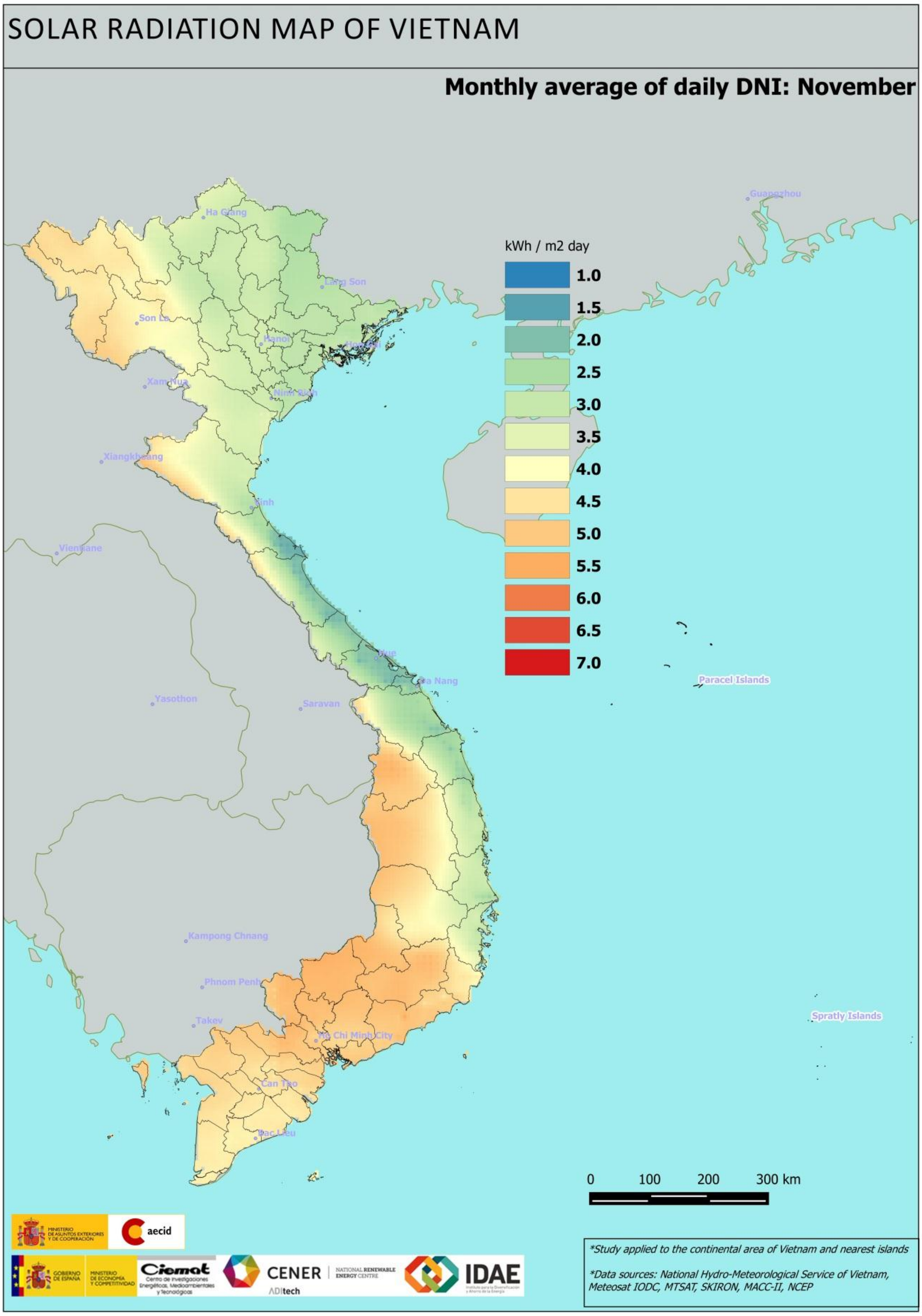
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: November
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Ha Giang
Son La
Yasothon
Saravan
Da Nang
Paracel Islands
Kampong Chhnang
Takev
Spratly Islands
0
100
200
300 km
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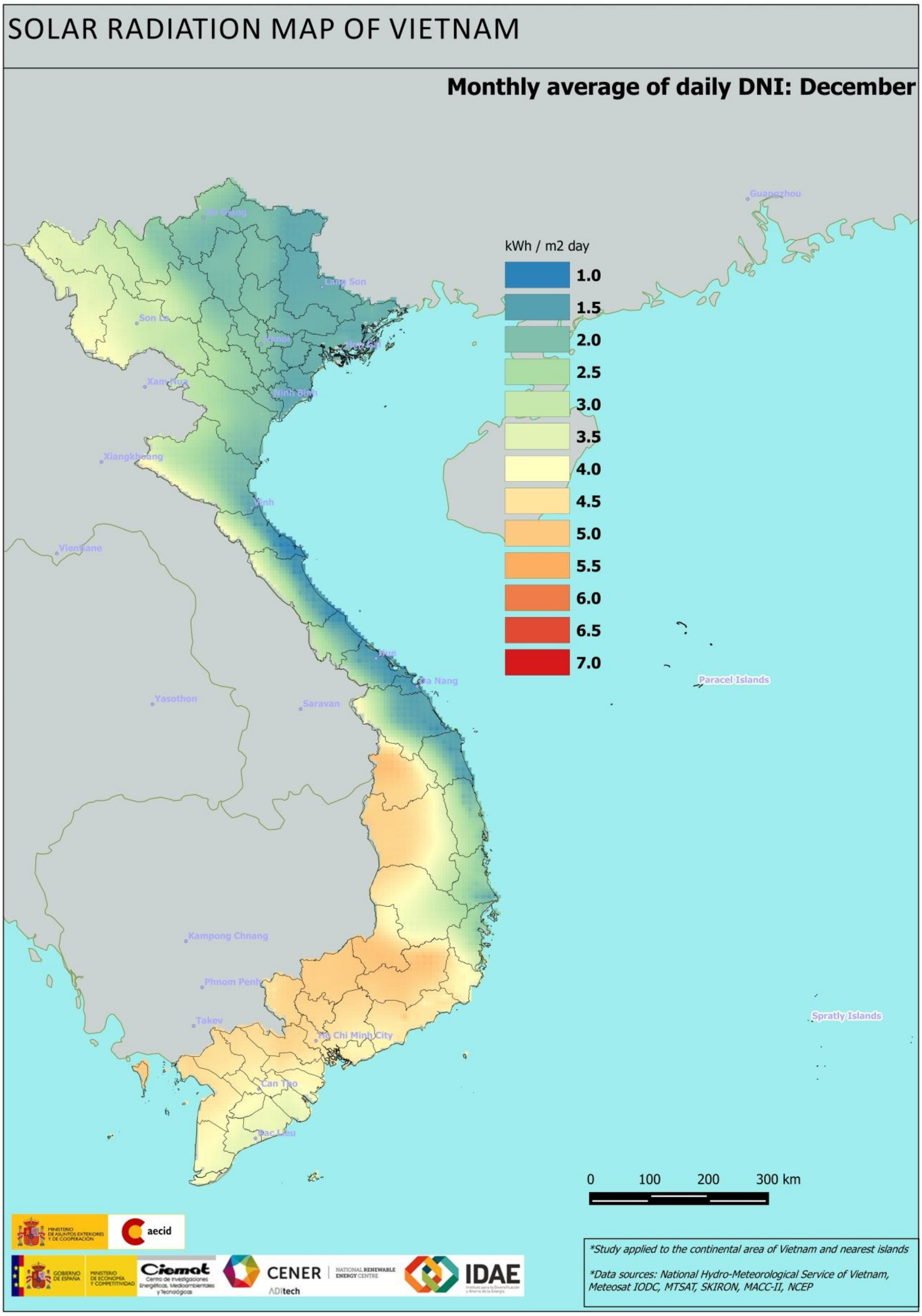
SOLAR RADIATION MAP OF VIETNAM
Monthly average of daily DNI: December
kWh / m2 day
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Guangzhou
Son La
Xiangkhoang
Vientiane
Da Nang
Paracel Islands
Yasothon
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Kampong Chnang
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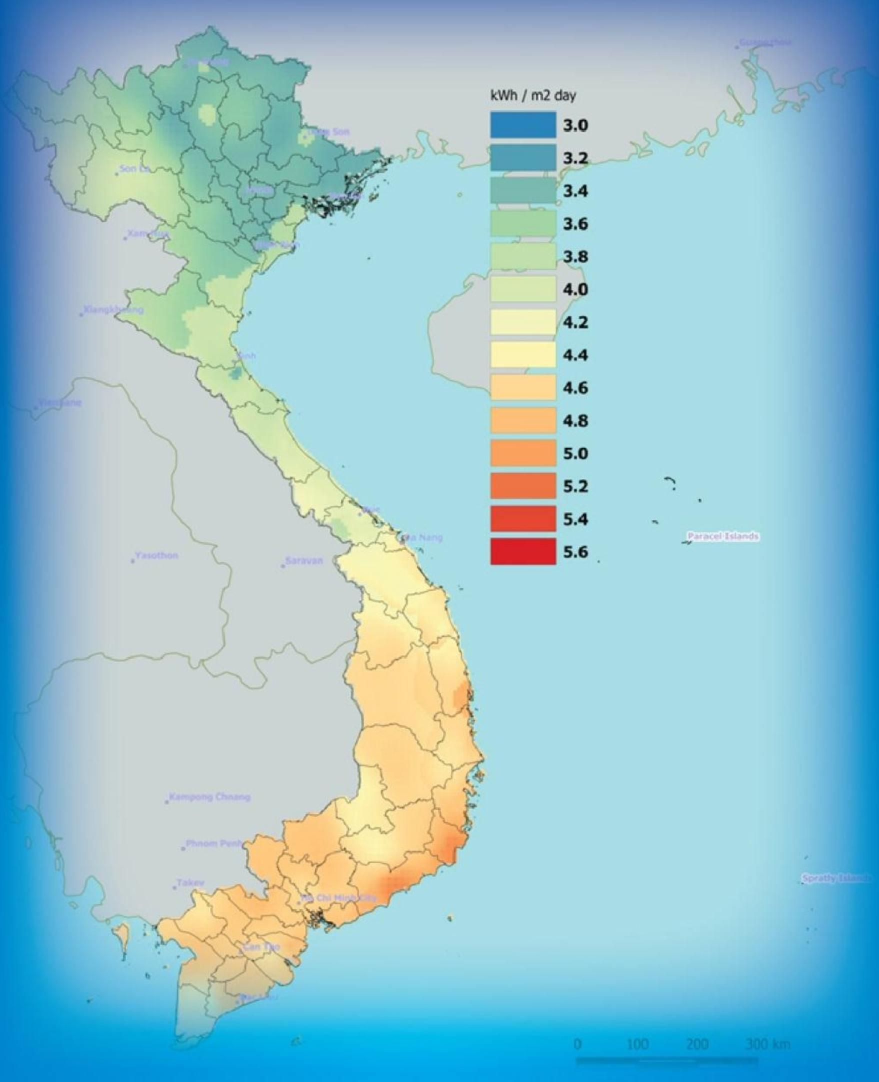
kWh / m2 day
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
Paracel Islands
Yasothon
Saravan
Kampong Chhnang
Phnom Penh
Takeo
Spratly Islands
0
100
200
300 km