Solar Regimes Report

Definition of solar regimes for Pakistan for site selection process and satellite data validation

Renewable Energy Mapping: Solar Pakistan, South Asia Region

WB Selection #11260861

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Contents

Overview **3**

The study-area and an overview of Pakistan's radiation budget **4**

Discrimination of solar regimes **6**

The Methodology 6

Solar regimes of GHI and DNI 7

GHI and DNI combined results – the solar regimes 8

Location, type and quantity of measurement stations **12**

ANNEX A – Detailed overview over solar regimes incl. PMD- and DISCO-sites **13**

Reference list **15**

Overview

The aim of this report is to determine a certain number of solar regimes for Pakistan, which will serve as foundation for the site selection process. This activity has to be conducted before the site selection meeting in Phase 1, so only a five year dataset (2001-2005) is available for the analysis. This still is a sufficient timespan to determine the solar regimes and this solution benefits to an earlier start of the important measurement campaign in Phase 2.

The study area features a high diversity of climate zones and very complex topography. Montane areas in the Himalayan Mountains in the north of the country, extensive plateaus and tablelands above 1500 m in the west, as well as coastal areas or large river basins makes scientific solar resource assessment a delicate business on the one hand, but also offers very strong potential for solar applications and a good opportunity to validate satellite models on the other hand.

Within some regions of the country, annual cloud coverage is highly variable. This depends on factors like the local climatology, season of year, mesoscale weather-patterns and local effects like topography or coastlines. Pakistan is mainly influenced by hot dessert or semiarid climate ("B") after the effective classification by Köppen-Geiger (Kottek et al, 2006). This is one indicator for a relatively extensive cloud-freeness in many regions within at least some seasons of the year. Only the northern areas of the country are influenced by (humid-) continental climate and shows very high annual variability of cloud cover.

The study-area and an overview of Pakistan's radiation budget

The analyzed area includes 1 180 380 cells/pixels, each of which represents one satellite count of irradiance within Pakistan (size of cells ~ 1 km x 1 km). As a foundation of this work, monthly sums and multi-year sums off irradiance have been processed for the years 2001 to 2005. The provinces of Balochistan, Sindh and the southern regions of Punjab receive the highest yearly sums of GHI (Global Horizontal Irradiance) and DNI (Direct Normal Irradiance) for the 5 year (see Figure 1 and Figure 2).

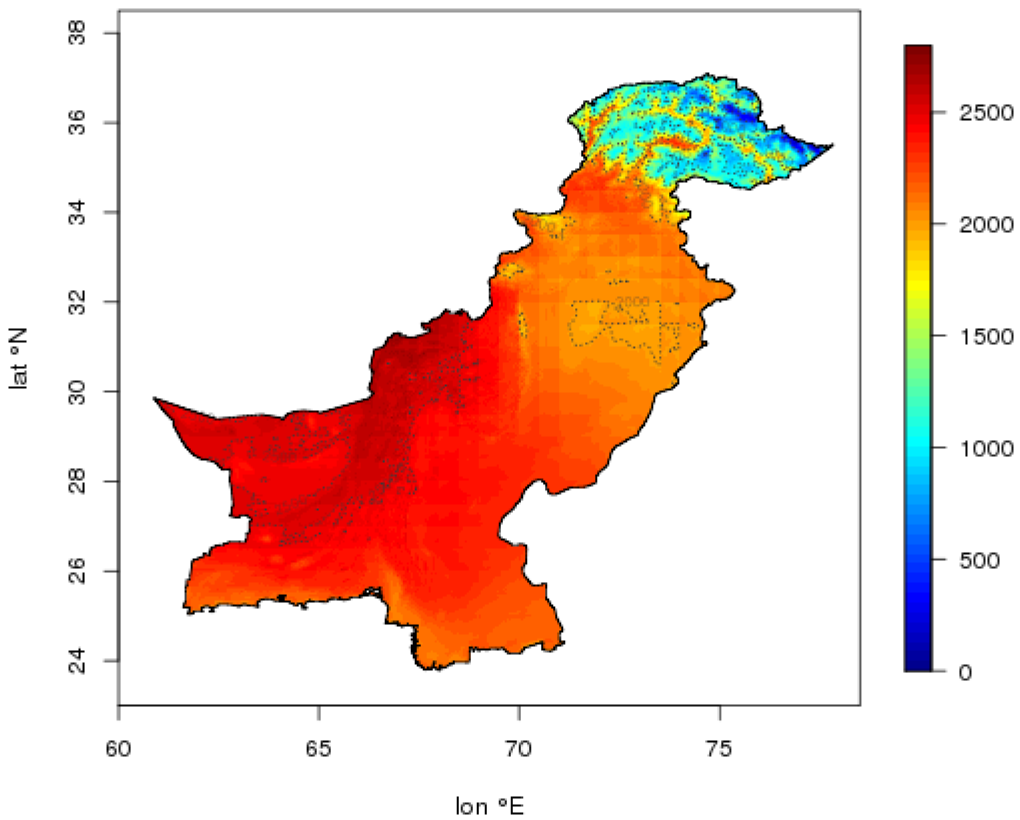


Figure 1: Annual average sum of DNI (2001-2005) in kWh/m² based on DLR satellite model.

For DNI, particularly the Plateaus and Mountain regions of the Province Balochistan receive very high values of irradiance, exceeding yearly sums of 2500 kWh/m² in extensive areas. The estimated maximum value of 2746 KWh/m² for DNI is located in northern Balochistan. For GHI one can find a somewhat smoothed picture. Maximum values are still very high reaching more than 2200 kWh/m² in southwestern Pakistan. Both parameters show a S-N gradient with lowest values in the Provinces of Gilgit-Pakistan, Khyber Pakhtunkhwa and Azad Jammu, which can be referred to the topography and mountain climate (cloud cover).

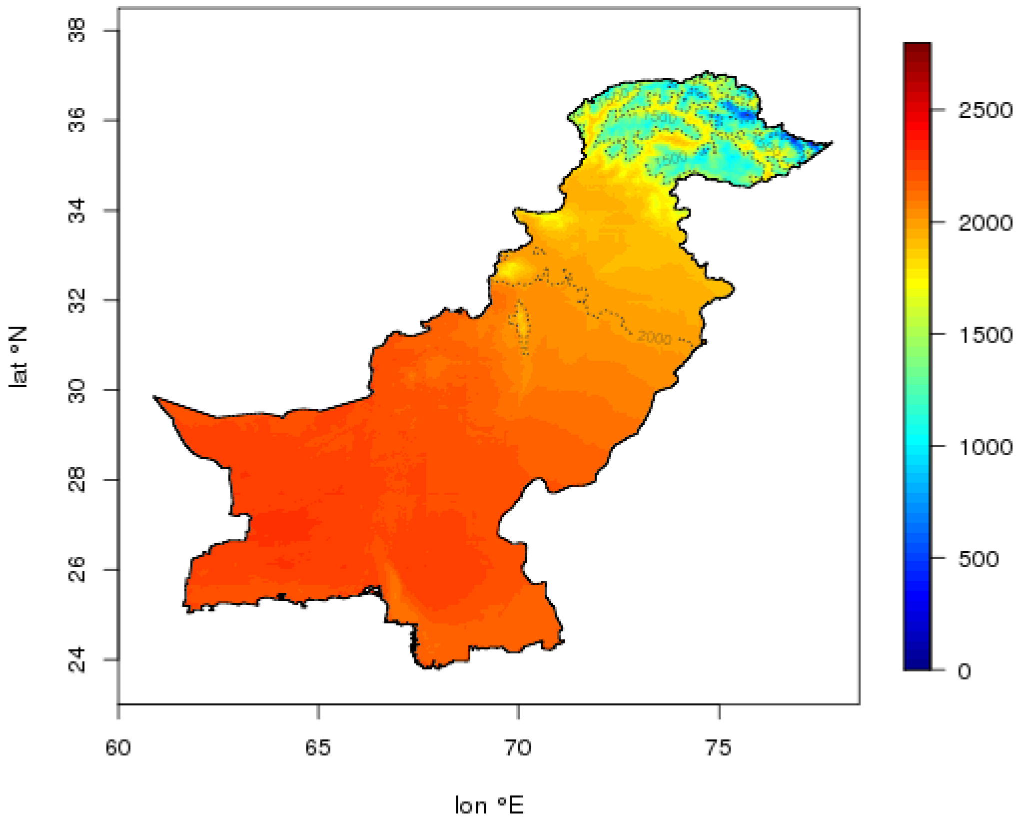


Figure 2: Annual average sum of GHI (2001-2005) in KWh/m² on DLR satellite model.

Nevertheless an overall mean value of 2041 KWh/m² for GHI indicates good potential for PV-applications. The same is the case for DNI, where an overall mean of 2159 KWh/m² highlights the widespread potential for CSP-plants.

Table 1 shows the percentage of land covered by different classes of irradiance sums, split into steps of 200 kWh.

KWH/m²	DNI	GHI
<1800	11,6%	13,4%
1800-2000	4,2%	15,5%
2000-2200	28,5%	32,3%
2200-2400	26,3%	38,7%
2400-2600	27,2%	x
>2600	2,2%	x

Table 1: Percentage of land covered by different irradiance classes.

The values within this table take into account the complete land area without regarding exclusion criteria. Nevertheless, it still gives a first glance on the distribution of different “irradiance classes” that can be found in the study region. In some regions within the DNI map of Figure 1, squared artefacts became visible (especially northern Punjab). These artefacts are a visible consequence of the aerosol dataset included to the irradiance processor, which has a spatial resolution of 0.5°x0.5°. To achieve most realistic and scientifically resilient results, no smoothing was applied to the map, as a bilinear interpolation of the MATCH raw data has already been performed in advance.

Discrimination of solar regimes

The most facile method to classify different solar regimes would be to create classes of multi-year sums for example in steps of 200 KWh as represented in Table 1. This approach is useful for some applications and gives a first glance of the annual irradiance conditions in specific regions. A more sophisticated approach is to detect intra-annual variations of irradiance combined with the multi-year-average irradiance sum of GHI and/or DNI. There are additional benefits of this kind of methodology. This approach shows not only the sheer availability of solar irradiance for a location, it additionally distinguishes the relation between variance and total availability. For validation purposes, it is important to analyze a variety of different climate-zones or solar regimes within a certain area. The variability of solar irradiance on the earth’s surface in the course of a year is an indirect indicator for many other climatological parameters like cloud-cover, temperature, wind-speed and –direction. These parameters show typical patterns that can be referred to classes of effective climate classifications and, thus, mirror the heterogeneity of a countries climate. It is suggested to position a certain amount of measurement equipment in each of those solar regimes to be able to adapt the satellite model in an effective and versatile way for the calculations needed to generate a validated solar atlas.

Moreover, project planners for PV and CSP sites my profit by the results of this method. It is not only the total sum of irradiance received by the plant which is important for energy production, it is also the homogeneity of irradiance over a time period that leads to a reliable energy supply of the population.

The Methodology

The analysis is based on a five-year dataset (2001-2005) for GHI and DNI in a 0.0083°x0.0083° resolution. For the evaluation monthly files are used. Therefore 60 files are available to process the monthly average sum as well as the monthly deviations. In a first step, single monthly sums are calculated, analyzed and stacked. To identify the variation of monthly means, the standard deviation is calculated for every cell within the dataset. The resulting values are an indicator for the quality of the location with respect to intra-annual variance. The **classes** (or **solar regimes**) are determined by thresholds that appear to be most suitable to create a high variety of solar regimes for validation purposes. As there are no known indicators for “solar climates” to validate satellite data, the idea of creating these thresholds is based on the area covered by the regimes. For both parameters (GHI and DNI) three solar regimes are defined. The thresholds are set in a way that every solar regime covers about one third of the country (see Table 2). The solar regimes of DNI and GHI are primarily identified separately from each other to get the clearest picture possible of the variance of irradiance conditions throughout Pakistan.

Solar regimes of GHI and DNI

For the sake of convenience, the different solar regimes are called classes within this chapter. Whilst in class 1 the monthly standard deviation of irradiance is smallest, the highest spread can be found in class 3 areas. As shown in Table 2, the thresholds for class 2 regions only cover a small range of values (5 kWh for GHI and 5,5 kWh for DNI), but this class also covers about 30% percent of Pakistan. The standard deviation ranges around 35-55 KWh for GHI and from 30-50 KWh for DNI for most cells.

Solar regime	Thresholds of monthly average Std. dev. (kWh)		Portion of total area (%)	
	GHI	*DNI*	GHI	DNI
Class 1	*<= 42,5*	*<= 31*	32,24	33,93
Class 2	*42,5-47,5*	*31-36,5*	31,83	32,48
Class 3	*>47,5*	*>36,5*	35,93	33,59

Table 2: Thresholds and portion of area covered by solar regime classes of GHI and DNI.

When these thresholds are transferred to a spatial projection, the 3 classes show specific patterns (Figure 3). While the boundaries of the GHI-classes seem to be effected mainly by latitude, DNI shows more complex patterns that reflect the influence of topography, the Indus river meadows as well as distance from the sea or cloud-cover.

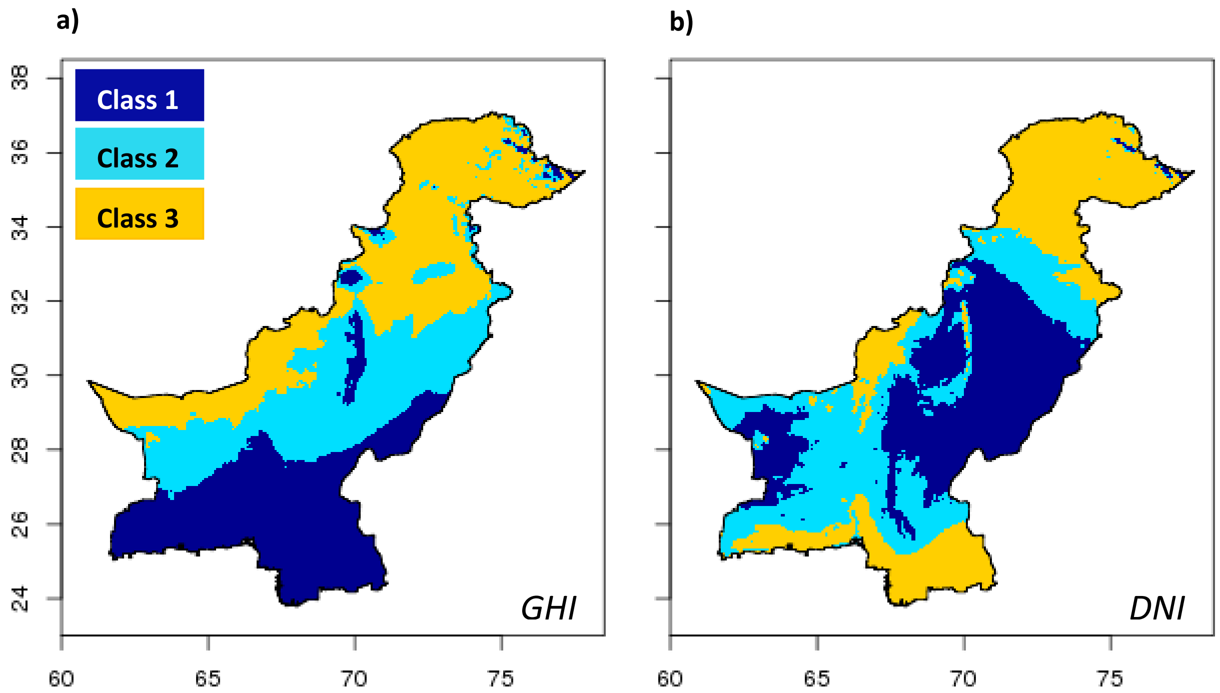


Figure 3: Preliminary classes of solar regimes, separated for GHI and DNI, based on the monthly standard deviation for the period 2001-2005.

GHI and DNI combined results – the solar regimes

To display a combination of the results from Figure 3 in a single plot, a color-code based on the matrix of Table 3 has been developed. It illustrates how a combination of the three by three classes of GHI and DNI leads to nine preliminary classes, displaying the monthly variation of irradiance for both parameters. The code "LL" stands for "low" deviation in both, GHI and DNI, while "MH" may stand for "medium" deviation for GHI, and "high" deviation for DNI, for instance. Once these classes are projected onto a map, the result is a very patchy and confusing picture, displaying a high number of small-scale solar regimes. To avoid this, some combinations have been consolidated and a more manageable number of six solar regimes is the result. This was achieved as follows: In cases where two classes differ from each other between the parameters (combinations LM, MH, LH), they are merged to one class, no matter which of parameter shows the higher/lower deviation. The benefit of this aggregation is much higher than the cost of losing some classes and the results are definitely more transparent in the end. Furthermore, there will be a limited number of measurement stations available for the project and for some classes it will make sense to put up more than only a sole station for the final evaluation.

		DNI		
		Class 1	**Class 2**	**Class 3**
GHI	**Class 1**	LL	LM	LH
	Class 2	LM	MM	MH
	Class 3	LH	MH	HH

Table 3: Matrix showing the combination of GHI and DNI classes.

Once these six resulting solar regimes are displayed on a map, a complex, but still a straightforward classification is the result. As mentioned above, not only the monthly deviation should be included into the site selection process, but also the sums of irradiance. One of the most common values used in solar resource assessment is the average multi-year sum of GHI and DNI in kWh/m², so these are indicated by contour-lines on top of the solar regimes (see Figure 4 and Figure 5).

Below some representative examples will be described for the figures below. The solar regime "LL" (lowest deviations for both parameters) only cover 7,1 % of the area (see Table 4) and it can be found mainly along the border to India and along the Indus river valley. Even though this regime is coded in green color and its "low-low" denotation, it is not an indicator for the general quality of the area in terms of solar irradiance. It solely is an indicator for the monthly constancy of solar irradiance and as a result of that, one can expect a relatively small variance of DNI and GHI, whilst the overall irradiance sum for both of these parameters may still be small. An optimal approach for site selection would be to put up two or more measurement sites within one solar regime. One station then may be set up in the area of a solar regime where the sum of GHI/DNI is low, another station may be located where the sum of GHI/DNI is highest within the same regime. This may be subject to further discussion before the long-list is created.

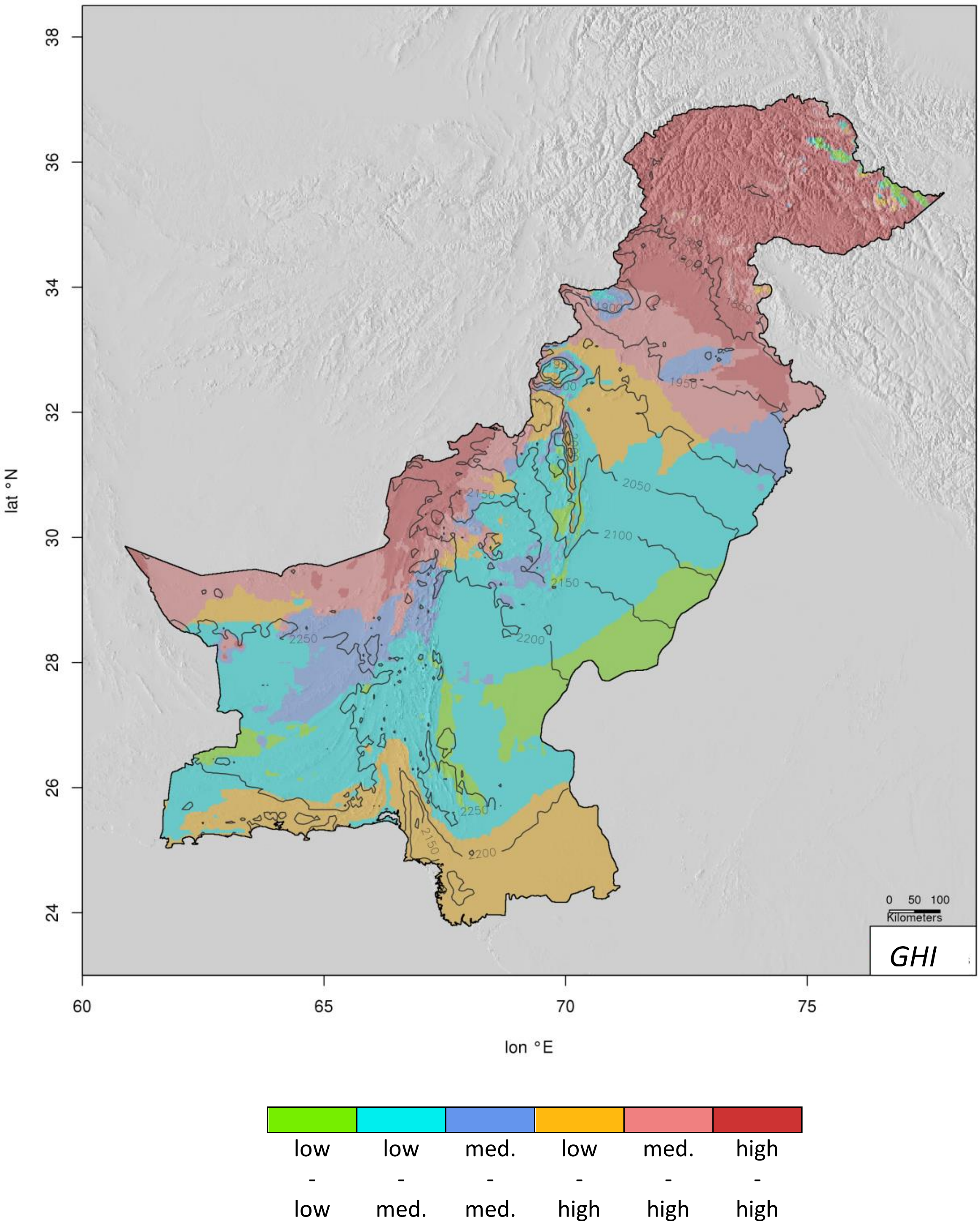


Figure 4: Color-coded solar regimes and GHI sums in (KWh/m²) indicated by contour lines. Contours only showing values exceeding 1800 kWh.

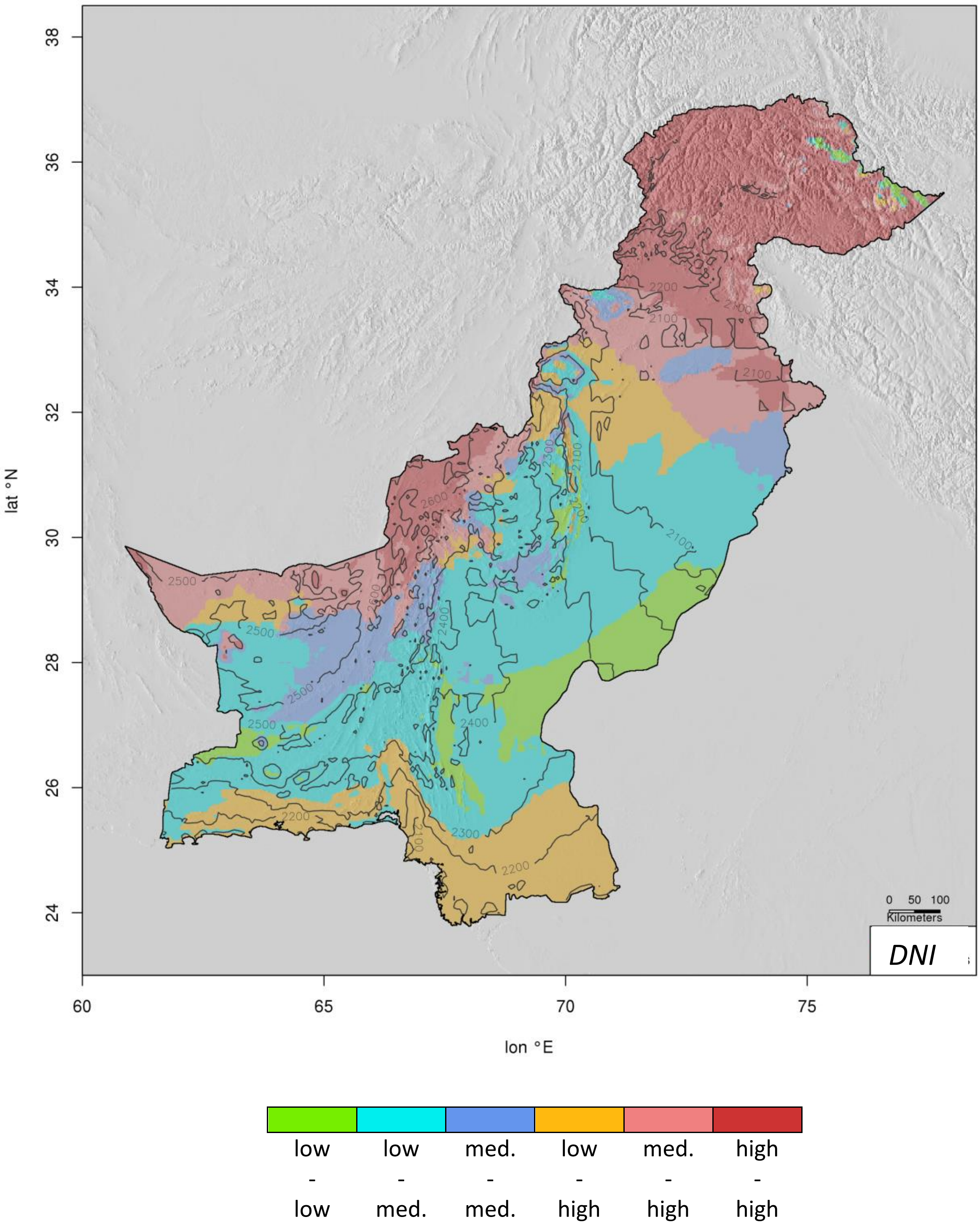


Figure 5: Color-coded solar regimes and DNI sums in (KWh/m²) indicated by contour lines. Contours only show values exceeding 2000 kWh.

If the solar regime covers big areas or is dispersed over the country in small patterns, an even higher number of stations could be helpful for validating this regime. This ensures the highest possible variety of "solar climates" measured by stations and allows DLR to see the strengths and weaknesses of the satellite model throughout the whole bandwidth of solar regimes available in Pakistan.

With more than 35% of coverage, the LM-regime covers the greatest part of the study area of the six solar regimes. It would make most sense to set up at least two, better three stations within this region as it covers a big area and a vast range of irradiance sums in an area between Islamabad, Hyderabad and Gwadar.

Solar regime	Portion of total area (%)
LL	7,1
LM	35,3
MM	8,2
LH	16,7
MH	12,6
HH	20,1

Table 4: Portions of area covered by solar regimes

To emphasize the fact that the 6 solar regimes do not give an indication of the quality of a certain site for a solar plant, the irradiance conditions estimated for the Quetta area may be examined as a regional example. Quetta is situated within the LL-regime and therefore shows high monthly variations of DNI and of GHI. The yearly sums, in turn, are amongst the highest for the whole country. A time series (2001-2005) for a location close to the University of Balochistan revealed yearly sums of over 2200 kWh/m² for GHI and more than 2550 kWh/m² for DNI. A measurement site in the Quetta region would deliver valuable data to validate the satellite model's performance in complex terrain/plateaus. The boxplot (Figure 6) shows how evenly distributed the values are distributed within the solar regimes (with exception of the HH-regime coded in red). Particularly GHI sums mainly range from about 1900 kWh to 2200 kWh, with only a slightly higher range for DNI within the upper and the lower quartile. Outliers are not shown in this plot.

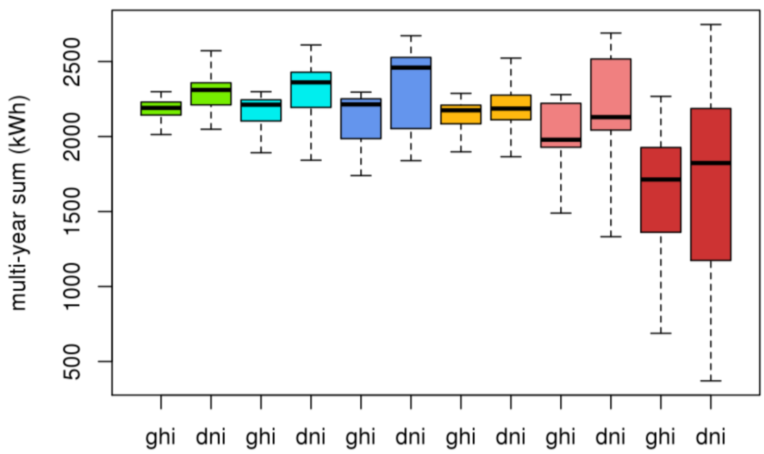


Figure 6: Distribution of multi-year-mean sums of GHI/DNI within the solar regimes (no outliers are drawn)

Location, type and quantity of measurement stations

As defined by the TORs, 6 measurement sites (one TIER 1 and five TIER 2) are the minimum requirement for satellite data validation within the project. This would result in setting up one station per solar regime. A higher number of stations by solar regime would lead to more valuable results overall. Currently, there already some potential sites available to set up solar measurement equipment. PMD and Distribution Company (DISCO) location are possible locations for measurement sites, as a certain degree of infrastructure is given here. These site's locations are projected onto the four maps of Annex A. The locations of these sites have been provided by local partners and the exact coordinates have to be confirmed. The plots show dotted contour lines of GHI and give a more detailed overview of different parts of Pakistan than Figure 4 does. Generally, for most solar regimes, two measurement sites seem to be a sufficient amount. Nevertheless, a detailed look on regional conditions needs to be done before adding a site to the site long-list, which is required for the site selection meeting. Below some recommendations for measurement sites are given for each solar regime:

HH-Regime: As shown in Table 4, this class covers the 2nd biggest area of the solar regimes. It also covers a very high range of sums (DNI and GHI) and, thus, offers a high variety of possible locations for measurement sites. *Recommendation:* Two sites - one site in Islamabad area and one site in Quetta. Islamabad and surroundings should offer a lot of potential sites to set up a station. Quetta, however, receives much more irradiance throughout the year, and delivers valuable data through its location on a high plateau.

MH-Regime: Only covers about 13% of the land area in the western and northern parts of Pakistan. This class is situated mainly in the direct adjacency to the HH-Regime, but generally shows higher values of DNI/GHI than HH-Regime. Recommendation: One site in the in the northwest (Parachinar).

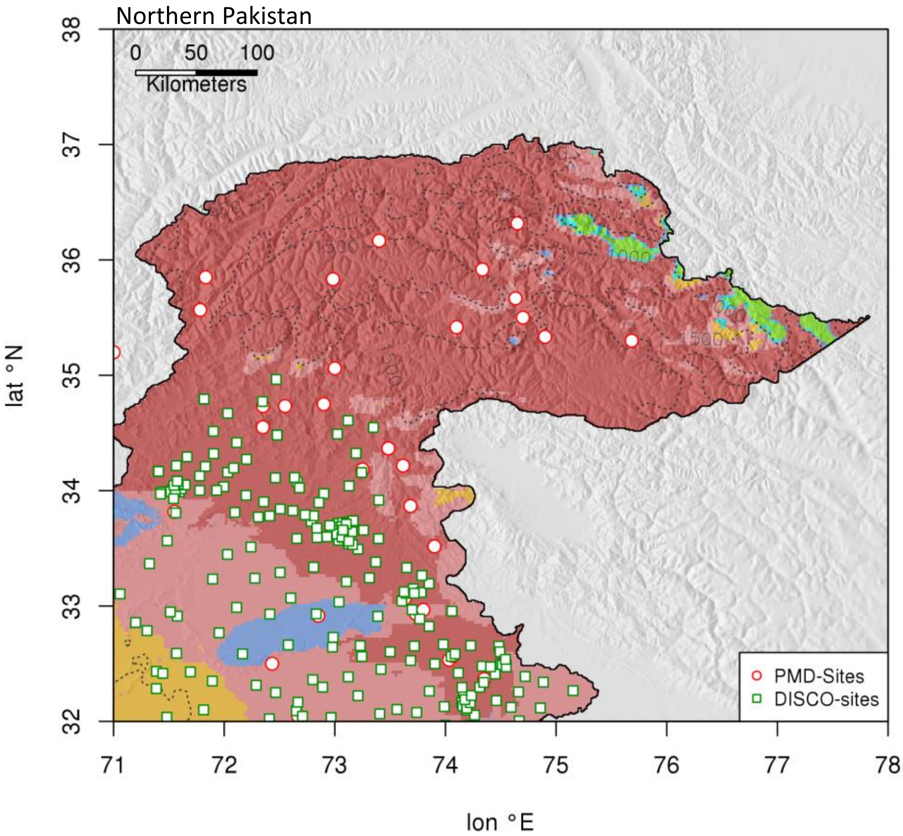
LH-Regime: This class mainly is representative for the coastal areas and shows a high contrast between direct normal irradiance and global horizontal irradiance. *Recommendation:* Three sites overall - one site in Karachi (TIER 1?) because of its reachability and its oceanic influence. The second site may be located the Dera Ismail Khan area and the third site in Nokkundi which is valuable to validate the impact of dust load of the atmosphere originating in the Sistan basin/Hamoon area (UNEP, 2006).

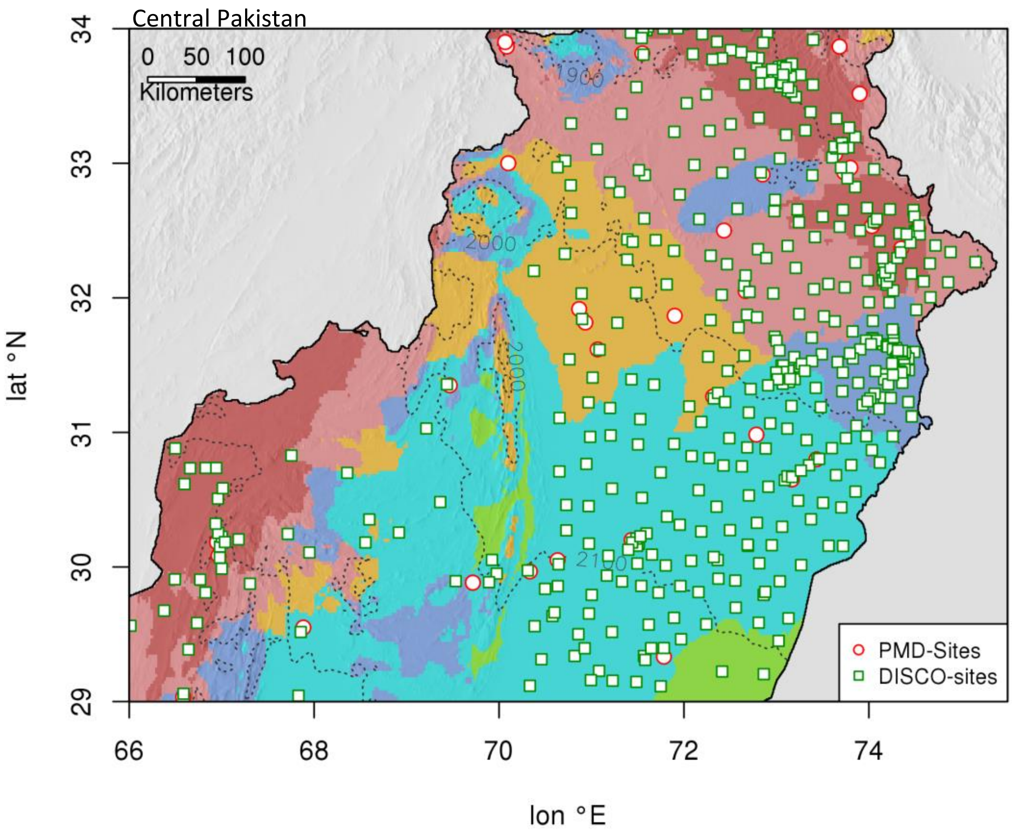
MM-Regime: One of the classes that covers the smallest area. Within this regime DNI as well as GHI show a medium month-to-month variance of irradiance. This class is scattered all over the country in small patches and is difficult to allocate to a specific topographic pattern. *Recommendation:* One site in Lahore region to receive data from within the "winter-fog"region (Hameed et al., 2000)

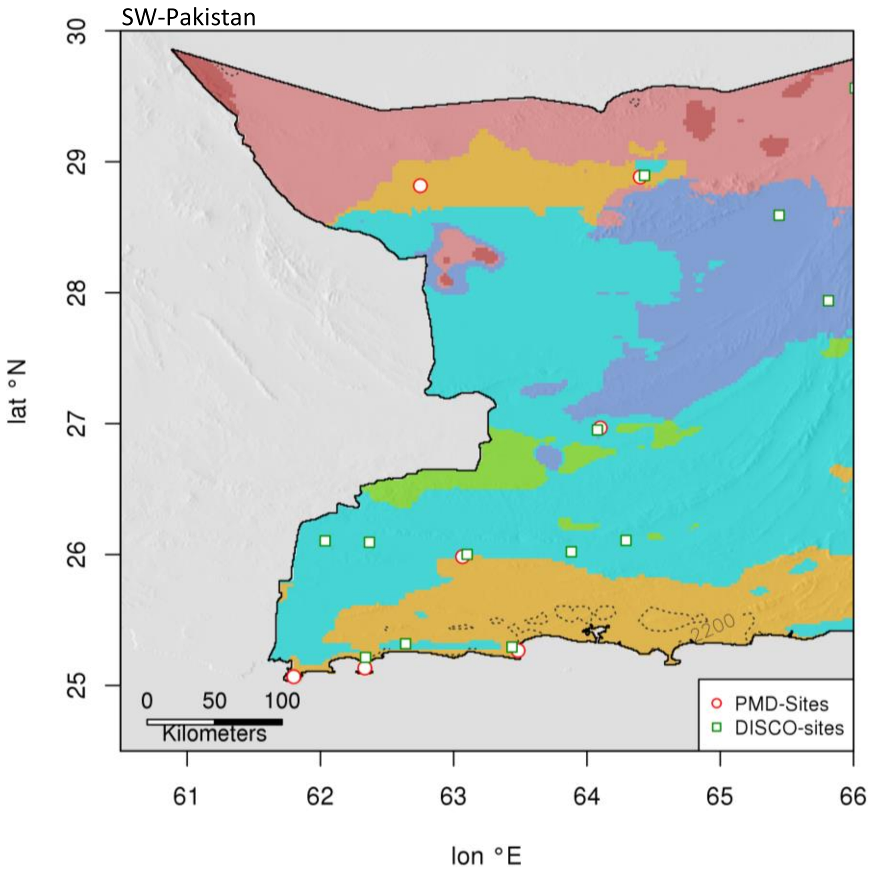
LM-Regime: Covers the biggest area of all solar regimes and therefore is representative for Pakistan's solar climate. *Recommendation: Two or three sites – one in the center (Multan area), the second site close to Khuzdar and/or the third site in the Tandojam-Hyderabad area.*

LL-Regime: The smallest class in the analysis, which mainly is located in the east of the country with lowest variance of monthly sums for GHI and DNI. *Recommendation: One site east of Bahalwal Pur.*

ANNEX A – Detailed overview over solar regimes incl. PMD- and DISCO-sites



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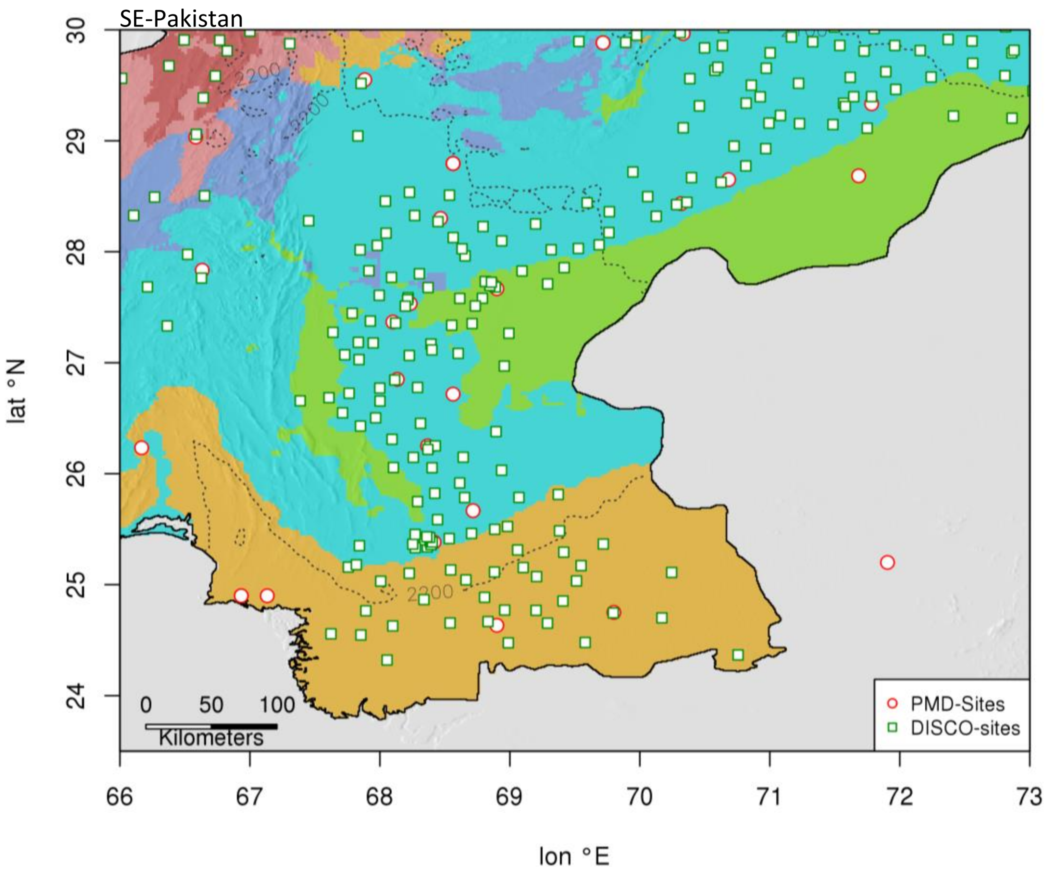
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DISCO-sites

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