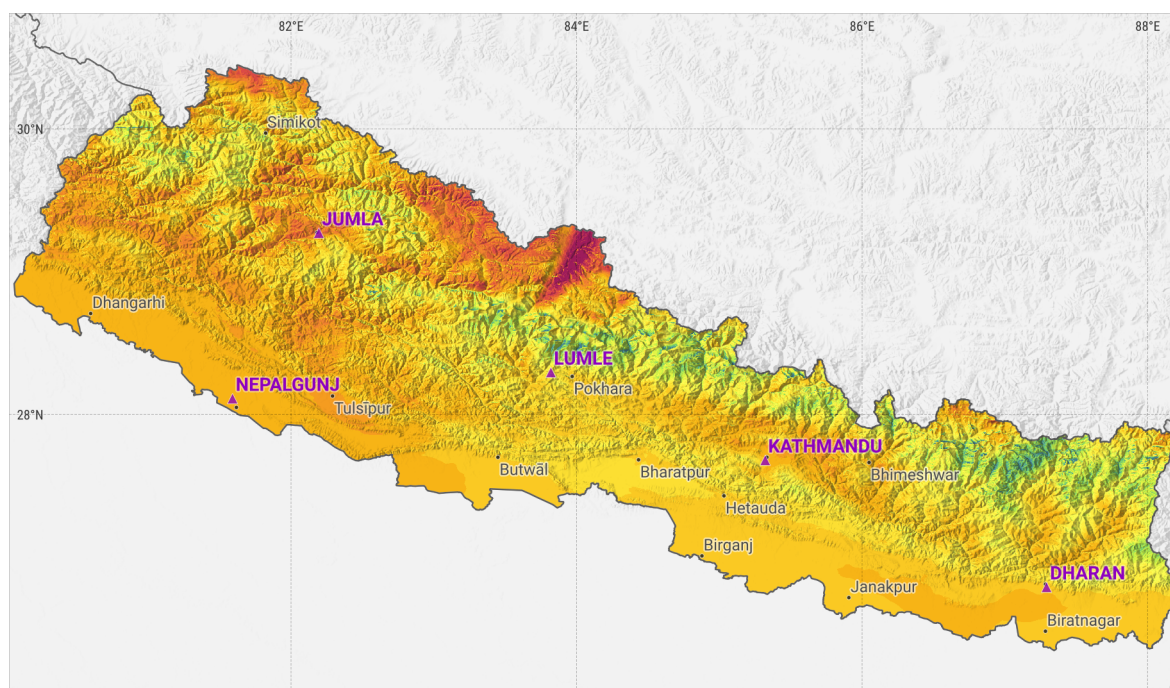


SOLAR RESOURCE MEASUREMENT CAMPAIGN - NEPAL

SOLAR ENERGY ATLAS OF NEPAL

April 2021



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The content of this document is the sole responsibility of the consultant authors. Any improved or validated solar resource data will be incorporated into the [Global Solar Atlas](#).

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Solar Energy Atlas of Nepal

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Acronyms

AC	Alternating current
AERONET	The AERONET (AErosol RObotic NETwork) is a ground-based remote sensing network dedicated to measuring atmospheric aerosol properties. It provides a long-term database of aerosol optical, microphysical and radiative parameters.
AOD	Aerosol Optical Depth at 670 nm. This is one of atmospheric parameters derived from MACC database and used in Solargis. It has a notable impact on the accuracy of solar calculations in arid zones.
CFSR	Climate Forecast System Reanalysis. The meteorological model operated by the US service NOAA.
CFSv2	The Climate Forecast System Version 2. CFSv2 meteorological models operated by the US service NOAA (Operational extension of Climate Forecast System Reanalysis, CFSR).
CPV	Concentrated Photovoltaic systems, which uses optics such as lenses or curved mirrors to concentrate a large amount of sunlight onto a small area of photovoltaic cells to generate electricity.
CSP	Concentrated solar power systems, which use mirrors or lenses to concentrate a large amount of sunlight onto a small area, where it is converted to heat for a heat engine connected to an electrical power generator.
DC	Direct current
DIF	Diffuse Horizontal Irradiation, if integrated solar energy is assumed. Diffuse Horizontal Irradiance, if solar power values are discussed.
DNI	Direct Normal Irradiation, if integrated solar energy is assumed. Direct Normal Irradiance, if solar power values are discussed.
ECMWF	European Centre for Medium-Range Weather Forecasts is independent intergovernmental organisation supported by 34 states, which provide operational medium- and extended-range forecasts and a computing facility for scientific research.
ERA5	Climate reanalysis dataset produced by European Centre for Medium Range Weather Forecasts (ECMWF), providing atmospheric, land-surface and sea-state parameters with estimates of uncertainty.
ESMAP	Energy Sector Management Assistance Program, a multi-donor trust fund administered by the World Bank
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites, an intergovernmental organisation for establishing, maintaining and exploiting European systems of operational meteorological satellites
GFS	Global Forecast System. The meteorological model operated by the US service NOAA.
GHI	Global Horizontal Irradiation, if integrated solar energy is assumed. Global Horizontal Irradiance, if solar power values are discussed.
GIS	Geographical Information System
GTI	Global Tilted (in-plane) Irradiation, if integrated solar energy is assumed. Global Tilted Irradiance, if solar power values are discussed.

KSI	Kolmogorov–Smirnov Index, a statistical index for comparing functions or samples
MACC	Monitoring Atmospheric Composition and Climate – meteorological model operated by the European service ECMWF (European Centre for Medium-Range Weather Forecasts)
Meteosat IODC (MFG and MSG)	Meteosat satellite operated by EUMETSAT organization, positioned over the Indian Ocean. MSG: Meteosat Second Generation; MFG: Meteosat First Generation
MERRA	Modern-Era Retrospective Analysis for Research and Applications, a NASA reanalysis for the satellite era using an Earth observing systems
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
NASA	National Aeronautics and Space Administration organization
NOAA NCEP	National Oceanic and Atmospheric Administration, National Centre for Environmental Prediction
NOAA ISD	NOAA Integrated Surface Database with meteorological data measured by ground-based measurement stations
NOCT	The Nominal Operating Cell Temperature, is defined as the temperature reached by open circuited cells in a module under the defined conditions: Irradiance on cell surface = 800 W/m ² , Air Temperature = 20°C, Wind Velocity = 1 m/s and mounted with open back side.
PV	Photovoltaic
PVOUT	Photovoltaic electricity output calculated from solar resource and air temperature time series.
RSR	Rotating Shadowband Radiometer
SOLIS	Solar Irradiance Scheme, Solar clear-sky model for converting meteorological satellite images into radiation data
SRTM	Shuttle Radar Topography Mission, a service collecting topographic data of Earth's land surfaces
STC	Standard Test Conditions, used for module performance rating to ensure the same measurement conditions: irradiance of 1,000 W/m ² , solar spectrum of AM 1.5 and module temperature at 25°C.
TEMP	Air Temperature at 2 metres
UV	Ultraviolet radiation

Glossary

AC power output of a PV power plant	Power output measured at the distribution grid at a connection point.
Aerosols	Small solid or liquid particles suspended in air, for example desert sand or soil particles, sea salts, burning biomass, pollen, industrial and traffic pollution.
All-sky irradiance	The amount of solar radiation reaching the Earth's surface is mainly determined by Earth-Sun geometry (the position of a point on the Earth's surface relative to the Sun which is determined by latitude, the time of year and the time of day) and the atmospheric conditions (the level of cloud cover and the optical transparency of atmosphere). All-sky irradiance is computed with all factors taken into account
Bias	Represents systematic deviation (over- or underestimation) and it is determined by systematic or seasonal issues in cloud identification algorithms, coarse resolution and regional imperfections of atmospheric data (aerosols, water vapour), terrain, sun position, satellite viewing angle, microclimate effects, high mountains, etc.
Clear-sky irradiance	The clear sky irradiance is calculated similarly to all-sky irradiance but without considering the impact of cloud cover.
Fixed-mounted modules	Photovoltaic modules assembled on fixed bearing structure in a defined tilt to the horizontal plane and oriented in fixed azimuth.
Frequency of data (30-minute, hourly, daily, monthly, yearly)	Period of aggregation of solar data that can be obtained from the Solargis database.
Installed DC capacity	Total sum of nominal power (label values) of all modules installed on photovoltaic power plant.
Long-term average	Average value of selected parameter (GHI, DNI, etc.) based on multiyear historical time series. Long-term averages provide a basic overview of solar resource availability and its seasonal variability.
P50 value	Best estimate or median value represents 50% probability of exceedance. For annual and monthly solar irradiation summaries it is close to average, since multiyear distribution of solar radiation resembles normal distribution.
P90 value	Conservative estimate, assuming 90% probability of exceedance (with a 90% probability the value should be exceeded). When assuming normal distribution, the P90 value is also a lower boundary of the 80% probability of occurrence. P90 value can be calculated by subtracting uncertainty from the P50 value. In this report we apply a simplified assumption of normal distribution of yearly values.
PV electricity production	AC power output of a PV power plant expressed as percentage part of installed DC capacity.
Root Mean Square Deviation (RMSD)	Represents spread of deviations given by random discrepancies between measured and modelled data and is calculated according to this formula:

$$RMSD = \sqrt{\frac{\sum_{k=1}^n (X_{measured}^k - X_{modeled}^k)^2}{n}}$$

On the modelling side, this could be low accuracy of cloud estimate (e.g. intermediate clouds), under/over estimation of atmospheric input data, terrain, microclimate and other effects, which are not captured by the model. Part of this

discrepancy is natural - a satellite monitors a large area (of approx. 3 x 4 km), while a sensor sees only a micro area of approx. 1 sq. centimetre. On the measurement side, the discrepancy may be determined by accuracy/quality and errors of the instrument, pollution of the detector, misalignment, data loggers, insufficient quality control, etc.

Solar irradiance	Solar power (instantaneous energy) falling on a unit area per unit time [W/m^2]. Solar resource or solar radiation is used when considering both irradiance and irradiation.
Solar irradiation	Amount of solar energy falling on a unit area over a stated time interval [Wh/m^2 or kWh/m^2].
Spatial grid resolution	In digital cartography the term applies to the minimum size of the grid cell or in other words, minimum size of the pixels in the digital map.

Executive summary

This report presents results of the solar resource assessment and photovoltaic potential mapping in Nepal. This project is a part of a broader technical assistance project covering biomass, solar and wind mapping funded by the Energy Sector Management Assistance Program (ESMAP) operated by the World Bank.

The information in this report is based mainly on the calculations by the Solargis model, validated and regionally adapted using ground measurements collected at five solar meteorological stations in Nepal, during the years 2018 to 2020. The ground-based solar resource measurements have been supplied by CSP Services, based in Germany and Spain and funded by the World Bank. The measurement campaign has been technically supported by companies PITCO Pakistan and PACE Nepal.

The report follows two objectives:

- To explain the methodologies and outcomes of the solar resource and photovoltaic power potential assessment, based on the combined use of solar and meteorological data from meteorological models and measurements. The report documents the solar energy potential in Nepal, including the uncertainty of the data as key inputs in the technical and financial evaluation of solar energy systems.
- To improve the awareness and knowledge of solar resource and photovoltaic potential by producing a comprehensive countrywide dataset and maps based on the accuracy-enhanced model. The report evaluates key solar climate features, and the geographic and time variability of solar power potential in the country.

The results of this report are also compared with the interim solar resource validation, in which the Solargis model has been validated by the ground measurements available in a wider region [41]. Compared to the exercise from year 2014, the solar resource uncertainty in this report is based on local data and thus it represents the regional model performance more accurately.

The validation of the model based on 24+ months measurements conducted at five solar meteorological stations in Nepal, made it possible to reduce the uncertainty of the original Solargis model. For yearly values of Direct Normal Irradiation (DNI), the uncertainty has been reduced from $\pm 12\%$ to $\pm 18\%$, for the original model, to the range of $\pm 9\%$ to $\pm 13\%$ for the regionally-adapted model. For yearly estimates of Global Horizontal Irradiation (GHI), the uncertainty reduction is seen from the original range of $\pm 6.0\%$ to $\pm 8.0\%$ to the range of $\pm 4.5\%$ to $\pm 6.5\%$ for the accuracy enhanced values (Note: in high mountains the uncertainty values are higher). The expected uncertainty in Nepal is split into low, medium and high uncertainty regions: Lower and medium uncertainty is seen in flat plains and monotonous hilly terrain, respectively. In complex terrain a higher model uncertainty is expected.

The key deliverable of this project is supplying country-wide data and maps, based on the extensive validation and regional adaptation of the solar model by high accuracy solar measurements acquired in Nepal. The data underlying this report are delivered in two formats:

- Raster GIS data for the whole territory of the Republic of Nepal, representing long-term monthly and yearly average values. This data layers are accompanied by geographical data layers in raster and vector data formats.
- High-resolution digital maps prepared for poster printing, as well as Google Earth maps.

The maps show that, throughout most of Nepal, yearly sum of global horizontal irradiation is in the range of 1900 to 2100 kWh/m². This translates to a specific yearly PV electricity output in the range of 1550 kWh/kWp to more than 1700 kWh/kWp. The seasonal variability is smaller, compared to other countries further away from the equator. This qualifies Nepal as a country with high potential for PV power generation.

The aggregated data for Nepal can be accessed online via an interactive map-based application, or as downloadable files and maps at <http://globalsolaratlas.info/>. The ground-measured data is accessible through <https://energydata.info/>.

1 Introduction

1.1 Solar resource data needs

Solar electricity offers a unique opportunity to achieve long-term sustainability goals, such as the development of a modern economy, healthy and educated society, clean environment, and improved geopolitical stability. Solar power plants exploit local solar resources; they do not require heavy support infrastructure, they are scalable, and improve electricity services. A key feature of solar electricity is that it is accessible at any location on Earth, thus providing development opportunities anywhere.

While solar resources are fuel to solar power plants, the local geographical and climate conditions determine the efficiency of their operation. Free fuel makes solar technology attractive; however, effective investment and technical decisions require **detailed, accurate and validated solar and meteorological data**. Accurate data are also needed for the cost-effective operation of solar power plant. High quality solar resource and meteorological data can be obtained by satellite-based meteorological models and by measuring instruments installed at meteorological stations.

High accuracy solar resource and meteorological data is needed for the development and operation of commercial solar power plants. Typically, detailed data describing the local climate is needed for a location of interest; however, high accuracy meteorological measurements for sites of interest are rarely available. Therefore, data from solar and meteorological **models** is used for evaluating the energy yield and performance assessment of the power plants. High accuracy equipment at **solar meteorological stations** is used to collect local data, which is then used for the regional and local adaptation of solar models making it possible to increase accuracy of solar resource and meteorological historical time series. At larger solar power plants, solar measurements are collected from the initial (prefeasibility) stage continuously over the entire project lifetime.

The combination of solar and meteorological data, from models and measurements, is used for the following tasks related to solar power generation:

1. Country-level evaluation and strategical assessment of solar energy potential
2. Prospecting and prefeasibility: selection of candidate sites for future power plants, and preliminary analysis
3. Project evaluation; solar and energy yield assessment, optimisation of a technical design and financing
4. Monitoring and performance assessment of solar power plants
5. Solar power forecasting and grid management.

This report addresses the first topic from the list above. It describes accuracy enhancement of geospatial solar resource data for Nepal and the region, based on the combined use of the solar model and measurements. The access to the outputs of this activity is provided via web-based Global Solar Atlas (<https://globalsolaratlas.info>).

1.2 Solar resource measurement and mapping in Nepal

Nepal has diverse potential for solar power generation. The Government of Nepal endorsed the “**Concept Paper on National Energy Crisis Prevention and Electricity Development Decade**” in 2016 to address the short-term energy crisis and to lay the basis for long-term sustainable development of the energy sector. The concept paper acknowledged that detailed study on the wind and solar resources has not been conducted.

As a response, the World Bank funded a study, interim solar resource evaluation, in which the Solargis model has been validated by the ground measurements available in a wider region [41]. Published in 2017, the study reviewed the existing publications and data sources and offered a **preliminary solar energy potential evaluation** based on

Solargis database. The study confirmed that the solar industry requires solar models that offer map-based and site-specific accurate data covering the entire country at a high level of a detail. Modern solar meteorological stations should be used for country-wide validation and accuracy enhancement solar models and to gain a better understanding of the local climate. The study also confirmed that for reducing the uncertainty of solar models in Nepal and the region, a comprehensive measurement campaign must be conducted. It also offered the geographical analysis for planning such a campaign.

In year 2018, the World Bank has commissioned **solar resource measurement campaign** in Nepal with funding from the Energy Sector Management Assistance Program (ESMAP). The solar resource measurement campaign has been implemented to collect high quality time-series data through ground-based measurements. The objective of the measurement campaign is to help producing a country-wide adapted and validated solar data model and maps for Nepal. This activity is still ongoing, and it is managed through Energy Sector Reform Program in Nepal.

Follow-up activity to the ground measurement campaign is covered by this project, commissioned by the World Bank in 2020. This activity focuses on **regional accuracy enhancement of satellite-based solar model**, based on new measurements, and on preparing geospatial data products and maps. The Solargis model is used, as it offers high-resolution global data to the solar industry with low uncertainty and proven reliability. The improved accuracy of solar and meteorological data contributes to cost effective development and operation of solar power plants in Nepal.

This report accompanies the delivery of Solargis geospatial data outputs based on the combination of the modelled and the measured data. All outputs are accessible as updates to the original deliverables accessible from **Global Solar Atlas** web site. The data is also integrated into online map-based photovoltaic energy calculator accessible at <https://globalsolaratlas.info>.

1.3 Objectives and structure of this study

This study reports the outcomes of the project *Solar Data and Map Validation and PV Potential Evaluation* under Energy Sector Reform Program in Nepal (P171183), funded by the World Bank. The validated and accurate data from the updated solar model help in cost effective development of solar renewable electricity generation in Nepal by:

- (i) Enhancing knowledge and awareness of solar resource potential
- (ii) Providing the sector and industry with the data and tools to better assess the location and commercial viability of potential solar projects
- (iii) Improving the utilization of solar resource data and mapping outputs.

The objective of this study is to describe the development of new, accurate and validated solar database for Nepal and neighbouring regions. The updated solar data will allow investment into solar energy projects with lower risk and will help to optimize site selection and project design for upcoming solar energy projects in the country and the region. This technical study helps in analysing the meteorological and geographical conditions and related solar energy potential of Nepal with lower uncertainty and higher confidence to solar and financial industry.

Following this introduction (**Chapter 1**), **Chapter 2** of this Solar Resource Atlas provides an outline of solar radiation basics and principles of photovoltaic power potential calculation. **Chapters 2.1 and 2.2** describe measuring and modelling approaches for developing reliable solar and meteorological data, including information about solar and meteorological data uncertainty. These chapters document the role of solar measurements in reducing the uncertainty of solar, meteorological and PV power potential data for the country. **Chapter 2.3** explain the relevance of solar resource and meteorological information for the energy evaluation of solar power technologies. An emphasis is given to photovoltaic (PV) technology, which has high potential for developing medium size and utility-scale projects close to load centres, as well as deployment of rooftop PV systems, off-grid, hybrid systems and mini-grids for community electrification.

Chapter 3 presents an analysis and evaluation of meteorological and solar resource data in Nepal. Five representative sites were selected for collection of ground measurements to show potential regional differences in

Nepal through tables and graphs. **Chapters 3.1 and 3.2** introduces ancillary geographical data that influence the performance of solar power plants. **Chapters 3.3 to 3.4** summarize geographical differences and seasonal variability of solar resources in Nepal, while **Chapter 3.5** presents the PV power generation potential of the country. The theoretical specific PV electricity output is calculated from the commonly used PV technology: a fixed system with crystalline-silicon (c-Si) PV modules, optimally tilted and oriented towards the Equator. **Chapter 3.6** summarizes the analytical information and presents conclusions.

Chapter 4 summarizes the technical features of the delivered data products. **Chapters 5 to 8** provide support information.

2 Methods and data

2.1 Solar resource data

2.1.1 Introduction

Solar resource (physical term solar radiation) is fuel to solar energy systems. The solar radiation available for solar energy systems at the ground level depends on processes in the atmosphere. This leads to a high spatial and temporal variability at the Earth's surface.

According to the generally adopted terminology, in solar radiation two terms are distinguished:

- **Solar irradiance** indicates power (instant energy) per second incident on a surface of 1 m² (unit: W/ m²).
- **Solar irradiation**, expressed in MJ/ m² or Wh/m²; it indicates the amount of incident solar energy per unit area during a lapse of time (hour, day, month, etc.).

Often, the term *irradiance* is used by the authors of numerous publications in both cases, which can sometimes cause confusion.

In **solar energy applications**, the following three solar resources are relevant:

- **Direct Normal Irradiation/Irradiance (DNI)**: it is the direct solar radiation from the solar disk and the region closest to the sun (circumsolar disk of 5° centred on the sun). DNI is the component that is important to concentrating solar collectors used in Concentrating Solar Power (CSP) and high-performance cells in Concentrating Photovoltaic (CPV) technologies.
- **Global Horizontal Irradiation/Irradiance (GHI)**: sum of direct and diffuse radiation received on a horizontal plane. GHI is a reference radiation for the comparison of climatic zones; it is also the essential parameter for calculation of radiation on a flat plate collector.
- **Global Tilted Irradiation/Irradiance (GTI)** or total radiation received on a surface with defined tilt and azimuth, fixed or sun-tracking. This is the sum of the scattered radiation, direct and reflected. A term Plane of Array (POA) irradiation//irradiance is also used. In the case of photovoltaic (PV) applications, GTI can occasionally be affected by shading from the surrounding terrain or objects, and GTI is then composed only from diffuse and reflected components. This typically occurs for sun at low angles over the horizon.

Solar radiation data can be acquired by two complementary approaches:

1. **Ground-mounted sensors** are good in providing high frequency and accurate data (for well-maintained, high accuracy measuring equipment) for a specific location.
2. **Satellite-based models** provide data with a lower frequency of measurement but cover a long history over larger areas. Satellite-models are not capable of producing instantaneous values at the same accuracy as ground sensors but provide robust and reliable aggregated values.

Chapter 2 summarizes approaches applied for measuring and computing solar resource parameters, for Nepal, and the main sources of uncertainty. It also discusses methods for combining data acquired by these two complementary approaches with the aim of maximizing strengths of both approaches.

2.1.2 ESMAP solar resource measurements in Nepal

Data from five measuring stations in Nepal was collected during a period of more than two years and then harmonized with the objective of acquiring reference solar radiation data for reducing the uncertainty of the solar radiation model. High quality data from these meteorological stations is available for this assessment (Tables 2.1 and 2.2, Figure 2.1, Map 2.1). Detailed information about the measurement sites is also available at the web sites <http://energydata.info/> and <http://globalsolaratlas.info/>.

More detailed information related to the outcomes of measurement campaign in Nepal can be found in the report “Regional adaptation of Solargis model based on solar measurement data in Nepal”, [12]. The report presents results of regional adaptation of the Solargis model based on all five solar meteorological sites, with estimate of relevant data uncertainties.

Table 2.1: Location of solar meteorological stations in Nepal

No.	Site name	Province	Latitude [°]	Longitude [°]	Altitude [m a.s.l.]	Measurement station host
1	Dharan	Province No. 1	26.79291°	87.29263°	315	Institute of Engineering, Purwanchal Campus
2	Jumla	Karnali	29.27237°	82.19351°	2363	Hotel Kanjirowa
3	Kathmandu	Bagmati	27.68157°	85.31868°	1315	Institute of Engineering, Pulchowk Campus
4	Lumle	Gandaki	28.29666°	83.81800°	1742	DHM Agro-Meteorological Station
5	Nepalgunj	Lumbini	28.11302°	81.58899°	150	Agricultural Research Council, Regional Agricultural Research Station

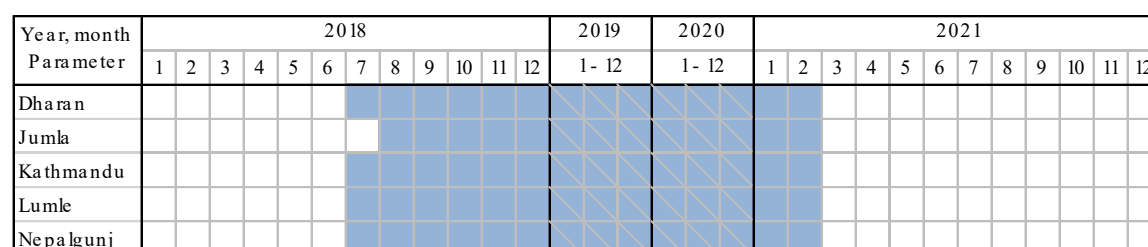
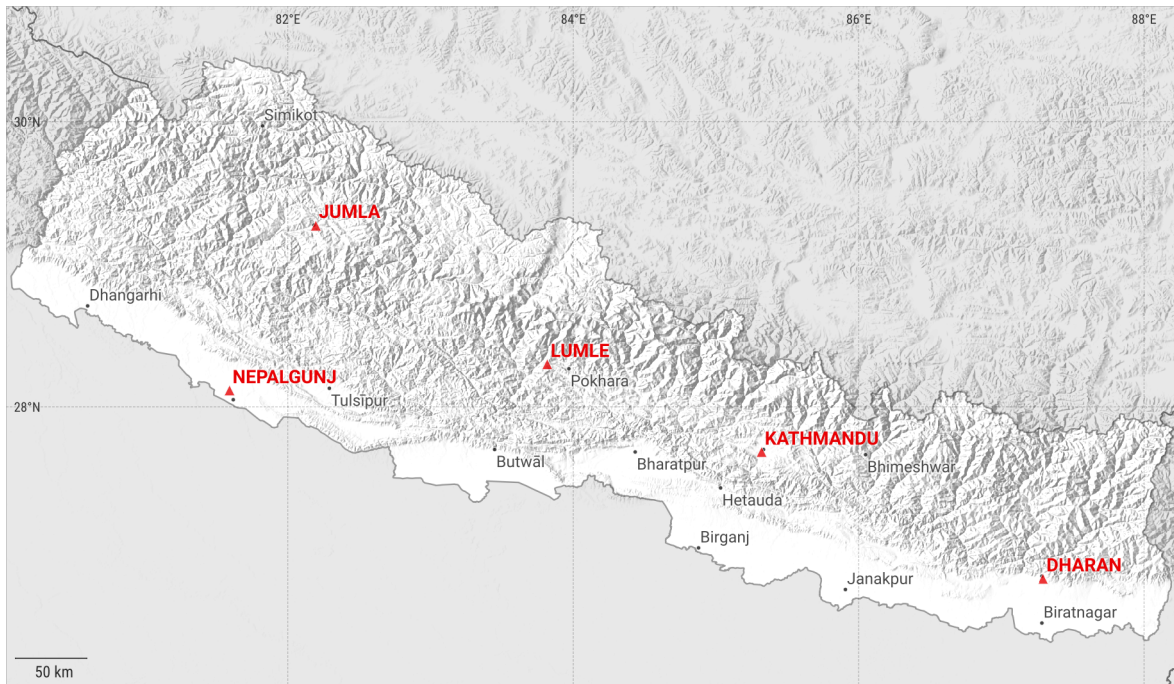


Figure 2.1: Solar resource data availability.

Table 2.2: Overview information on solar meteorological stations in Nepal

No.	Site name	Type	Solar parameters	Time step	Period of data used in study
1	Dharan	TIER1	GHI, DNI, DIF	1 min	1 July 2018 – 28 February 2021
2	Jumla	TIER1	GHI, DNI, DIF	1 min	1 August 2018 – 28 February 2021
3	Kathmandu	TIER1	GHI, DNI, DIF	1 min	1 July 2018 – 28 February 2021
4	Lumle	TIER1	GHI, DNI, DIF	1 min	1 July 2018 – 28 February 2021
5	Nepalgunj	TIER1	GHI, DNI, DIF	1 min	1 July 2018 – 28 February 2021



Map 2.1: Position of the solar meteorological stations used for the model validation

2.1.3 Solargis satellite-based model

Models using satellite and atmospheric data have become a standard for calculating solar resource time series and maps. The same models are also used for real-time data delivery for system monitoring and solar resource forecasting. Data from reliable operational solar models are routinely used by the solar industry.

In this study, we applied a model developed and operated by the company Solargis. This model operationally calculates high-resolution solar resource data and other meteorological parameters. Its geographical extent covers most of the land surface between 60° North and 55° South latitudes. A comprehensive overview of the Solargis model was made available in several publications [9, 10, 11]. The related uncertainty and requirements for bankability are discussed in [12, 13, 14].

In the Solargis approach, solar irradiance is calculated in 5 steps:

1. Calculation of clear-sky irradiance, assuming all atmospheric effects except clouds,
2. Calculation of cloud properties from satellite data,
3. Integration of clear-sky irradiance and cloud effects and calculation of global horizontal irradiance (GHI),
4. Calculation of direct normal irradiance (DNI) from GHI and clear-sky irradiance,
5. Calculation of global tilted irradiance (GTI) from GHI and DNI.

Models used in individual calculation steps are parameterized by a set of inputs characterizing the cloud properties, state of the atmosphere and terrain conditions.

The **clear-sky irradiance** is calculated by the simplified SOLIS model [15]. This model allows the fast calculation of clear-sky irradiance from the set of input parameters. Sun position is a deterministic parameter, and it is described by the algorithms with satisfactory accuracy. Stochastic variability of clear-sky atmospheric conditions is determined by changing concentrations of atmospheric constituents, namely aerosols, water vapour and ozone. Global atmospheric data, representing these constituents, are routinely calculated by world atmospheric data centres:

- In Solargis, the new generation **aerosol data set** representing Atmospheric Optical Depth (AOD) is used. The core data set, representing a period from 2003 to the present, is from the MACC-II/CAMS project (ECMWF) [16, 17]. An important feature of this data set is that it captures daily variability of aerosols and allows simulating more precisely the events with extreme atmospheric load of aerosol particles. Thus, it reduces uncertainty of instantaneous estimates of GHI and especially DNI, and it allows for improved statistical distribution of irradiance values [18, 19]. For years 1999 to 2002, data from the MERRA-2 model (NASA) [20] is used and it is homogenized with MACC-II/CAMS model are used. The Solargis calculation accuracy of the clear-sky irradiance is especially sensitive to information on aerosols.
- **Water vapour** is also highly variable in space and time, but it has lower impact on the values of solar radiation, compared to aerosols. The daily GFS and CFSR values (NOAA NCEP) are used in Solargis, thus representing the daily variability from 1999 to the present [21, 22, 23].
- **Ozone** absorbs solar radiation at wavelengths shorter than 0.3 μm , thus having negligible influence on the broadband solar radiation.

The **clouds** are the most influencing factor modulating clear-sky irradiance. The effect of clouds is calculated from satellite data in the form of the cloud index (cloud transmittance). The cloud index is derived by relating irradiance recorded by the satellite in several spectral channels and surface albedo to the cloud optical properties. In this study, a data from the Meteosat MFG and MSG satellites is used. Data is available for a period from 1999 to the present (24-hour delay) in a time step of 30 and 15 minutes. In Solargis, the modified calculation scheme by Cano has been adopted to retrieve cloud optical properties from the satellite data [25]. Several improvements have been introduced to better cope with specific situations such as snow, ice, or high albedo areas (arid zones and deserts), and complex terrain.

To calculate **Global Horizontal Irradiance (GHI)** for all atmospheric and cloud conditions, the clear-sky global horizontal irradiance is coupled with the cloud index. From GHI, other solar irradiance components (direct, diffuse and reflected) are calculated. **Direct Normal Irradiance (DNI)** is calculated by the modified Dirindex model [26]. Diffuse horizontal irradiance is derived from GHI and DNI.

Calculation of **Global Tilted Irradiance (GTI)** from GHI deals with direct and diffuse components separately. While calculation of the direct component is straightforward, estimation of diffuse irradiance for a tilted surface is more complex, and it is affected by limited information regarding shading effects and albedo of nearby objects. For converting diffuse horizontal irradiance for a tilted surface, the Perez diffuse transposition model is used [27]. The reflected component is also approximated considering that knowledge of local conditions is limited.

A model for the simulation of **terrain** effects (elevation and shading) based on high-resolution elevation and horizon data is used in the standard Solargis methodology [28]. The model by Ruiz Arias is used to achieve enhanced spatial representation – from the resolution of satellite (several km) to the resolution of the digital terrain model.

Solargis model version 2.2 has been used for computing the data. **Table 2.3** summarize technical parameters of the model inputs and of the primary outputs.

Table 2.3: Input data for Solargis solar radiation model and related GHI and DNI outputs for Nepal

Inputs into the Solargis model	Source of input data	Time representation	Original time step	Approx. grid resolution
Cloud index	Meteosat MFG IODC Meteosat MSG IODC satellites (EUMETSAT)	1999 to 2017/11 2017/02 to date	30 minutes 15 minutes	2.8 x 3.3 km 3.3 x 4.0 km
Atmospheric optical depth (aerosols)*	MACC/CAMS* (ECMWF) MERRA-2 (NASA)	2003 to date 1999 to 2002	3 hours 1 hour	75 km and 125 km 50 km
Water vapour	CFSR/GFS (NOAA)	1999 to date	1 hour	35 and 55 km
Elevation and horizon	SRTM-3 (SRTM)	-	-	250 m
Solargis primary data outputs (GHI and DNI)	-	1999 to date	15 minutes	250 m

2.1.4 Measured vs. satellite data – adaptation of solar model

For a qualified solar resource assessment, it is important to understand the characteristics of ground measurements and satellite-modelled data (Table 2.4). The ground measurements and satellite data complement each other, and it is beneficial to correlate them and adapt the satellite model for the specific site or region.

Within this project, regional model adaptation has been performed using the data from five measuring stations (Table 2.1, Map 2.1). The model adapted for regional conditions provides long history solar resource time series as well as recent data with lower uncertainty.

The model adaptation procedure has two steps:

1. Identification of systematic differences between hourly satellite data and local measurements for the period when both data sets overlap;
2. Development of a correction method that is applied for the whole period represented by the satellite time series over the whole region.

In the case of regional adaptation, the method aims to identify and reduce regional systematic deviations of a model compared to the measured data, typically driven by the insufficient characterization of aerosols or specific cloud patterns. The result of regional adaptation is an improved solar resource database in the regional of Nepal, with overall reduction of systematic errors.

The solar measurements and regional adaptation extends the knowledge of uncertainty of the solar radiation models in conditions of Nepal, and a wider region, which are characterised by higher concentration of aerosols and high mountains. The new knowledge developed from the analysis of ground measurements creates an important base for further model developments and improvements.

Table 2.4: Comparing solar data from solar measuring stations and from satellite models

	Data from solar measuring stations	Data from satellite-based models (Solargis)
Availability/ accessibility	Available only for limited number of sites. Mostly, data covers only recent years.	Data are available for any location within latitudes 60° N and 55° S. Data covers long period, in Nepal, historical data for more than 22 years.
Original spatial resolution	Data represent the microclimate of a site.	Satellite models represent area with complex spatial resolution: clouds are mapped at approx. 3 km grid cell, aerosols at 50-125 km and water vapour at 34 km. Terrain can be modelled at spatial resolution of up to 250 m. Methods for enhancement of spatial resolution are used.
Original time resolution	Seconds to minutes.	15 and 30 minutes in South Asia.
Quality	Data need to go through rigorous quality control, gap filling and cross-comparison.	Quality control of the input data is necessary. Outputs are regularly validated. Under normal operation, the data have only minimum occurrence of gaps, which are filled by intelligent algorithms.
Stability	Instruments need regular cleaning and control. Instruments, measuring practices, maintenance and calibration may change over time. Thus, regular calibration is needed. Long-term stability is typically a challenge.	If data are geometrically and radiometrically pre-processed, a complete history of data can be calculated with one single set of algorithms. Data computed by an operational satellite model may change slightly over time, as the model and its input data evolve. Thus, regular reanalysis and temporal harmonization of inputs is used in state-of-the-art models.
Uncertainty	Uncertainty is related to the accuracy of the instruments, maintenance and operation of the equipment, measurement practices, and quality control.	Uncertainty is given by the characteristics of the model, resolution and accuracy of the input data. Uncertainty of models is higher than high quality local measurements. The data may not exactly represent the local microclimate, but are usually stable and may show systematic deviation, which can be reduced by good quality local measurements (regional adaptation or site adaptation of the model).

2.1.5 Validation and regional adaptation of Solargis model

Regional model adaptation has been performed to reduce overall model uncertainty in the region. [Tables 2.5 and 2.6](#) show the Solargis model quality indicators for solar primary parameters, DNI and GHI, after the regional model adaptation. The uncertainty is evaluated for the model version that has been regionally adapted.

All information shown in this report is derived from the regionally adapted Solargis model.

Comparison of the validation statistics, computed for the solar meteorological sites in Nepal, shows overall stability of the Solargis model and of the underlying input data. Locally, an increased bias exceeding expectations was identified (Dharan station), which reflects the limited accuracy of the model and its input data, as well as the range of representation of ground measurements. The statistics show that the model uncertainty has been reduced after the regional adaptation. The Solargis model validation statistics for Nepal are comparable to those achieved in other regions [\[30, 31\]](#).

Table 2.5: Direct Normal Irradiance: bias before and after regional model adaptation

Meteo station	Original DNI data		DNI after regional adaptation	
	Bias [kWh/m ²]	Bias [%]	Bias [kWh/m ²]	Bias [%]
Dharan	-37	-12.3	-3	-1.1
Jumla	-45	-8.3	8	1.5
Kathmandu	-15	-4.5	-2	-0.7
Lumle	9	2.7	-8	-2.6
Nepalgunj	-13	-4.3	-5	-1.5
Mean	-20	-5.3	-2.0	-0.9
Standard deviation	21.4	5.6	6.0	1.5

Table 2.6: Global Horizontal Irradiance: bias before and after regional model adaptation

Meteo station	Original GHI data		GHI after regional adaptation	
	Bias [kWh/m ²]	Bias [%]	Bias [kWh/m ²]	Bias [%]
Dharan	-6	-1.4	1	0.2
Jumla	-28	-5.7	-21	-4.1
Kathmandu	5	1.1	7	1.6
Lumle	28	7.4	19	5.1
Nepalgunj	9	2.2	9	2.2
Mean	1.6	0.7	3.0	1.0
Standard deviation	20.6	4.8	14.9	3.4

Table 2.7 Direct Normal Irradiance: RMSD and KSI before and after regional model adaptation

Meteo station	Original DNI data				DNI after regional adaptation			
	RMSD Hourly [%]	RMDS Daily [%]	RMSD Monthly [%]	KSI [-]	RMSD Hourly [%]	RMDS Daily [%]	RMSD Monthly [%]	KSI [-]
Dharan	42.1	28.4	18.1	188	43.2	29.4	6.0	97
Jumla	35.3	21.8	11.3	225	36.0	19.8	4.2	73
Kathmandu	46.4	29.0	11.0	106	49.1	31.8	5.0	99
Lumle	52.4	30.9	15.0	170	48.8	27.9	6.7	128
Nepalgunj	34.1	23.6	9.5	96	33.3	22.8	4.4	47
Mean	42.1	26.7	13.0	157	42.1	26.3	5.3	89

Table 2.8 Global Horizontal Irradiance: RMSD and KSI before and after regional model adaptation

Meteo station	Original GHI data				GHI after regional adaptation			
	RMSD Hourly [%]	RMDS Daily [%]	RMSD Monthly [%]	KSI [-]	RMSD Hourly [%]	RMDS Daily [%]	RMSD Monthly [%]	KSI [-]
Dharan	20.7	11.0	3.4	32	21.0	11.4	2.7	23
Jumla	23.0	13.9	8.4	139	22.9	13.3	7.0	102
Kathmandu	24.8	12.1	3.5	28	25.2	12.7	3.1	34
Lumle	31.1	16.3	10.5	149	29.9	14.5	7.1	109
Nepalgunj	16.3	9.2	3.1	48	16.9	10.2	3.8	52
Mean	23.2	12.5	5.8	79	23.2	12.4	4.7	64

2.1.6 Uncertainty of solar resource estimates

The **uncertainty of regionally adapted satellite-based DNI and GHI** is determined by uncertainty of the model, ground measurements, and the model adaptation method. More specifically it depends on [15]:

1. Parameterization and adaptation of **numerical models integrated in Solargis** for the given data inputs and their ability to generate accurate results for various geographical and time-variable conditions:
 - Data inputs into Solargis model: accuracy of Meteosat satellite data, MACC-II/CAMS and MERRA-2 aerosols and CFSR/GFS water vapour
 - Solis clear-sky model and its capability to properly characterize various states of the atmosphere
 - Simulation accuracy of the Solargis cloud transmittance algorithms, being able to properly distinguish different states of various surface types, albedo, clouds and fog
 - Diffuse and direct decomposition by Perez model
 - Transposition from global horizontal to in-plane irradiance (for GTI) by Perez model
 - Terrain shading and disaggregation by Ruiz-Arias model.
2. Uncertainty of the **ground-measurements**, which is determined by:
 - Accuracy of the instruments
 - Maintenance practices, including sensor cleaning, service and calibration
 - Data post-processing and quality control procedures.
3. Uncertainty of the **model adaptation** at regional scale and residual uncertainty after adaptation

The uncertainty from the interannual variability of solar resource is not considered in this study.

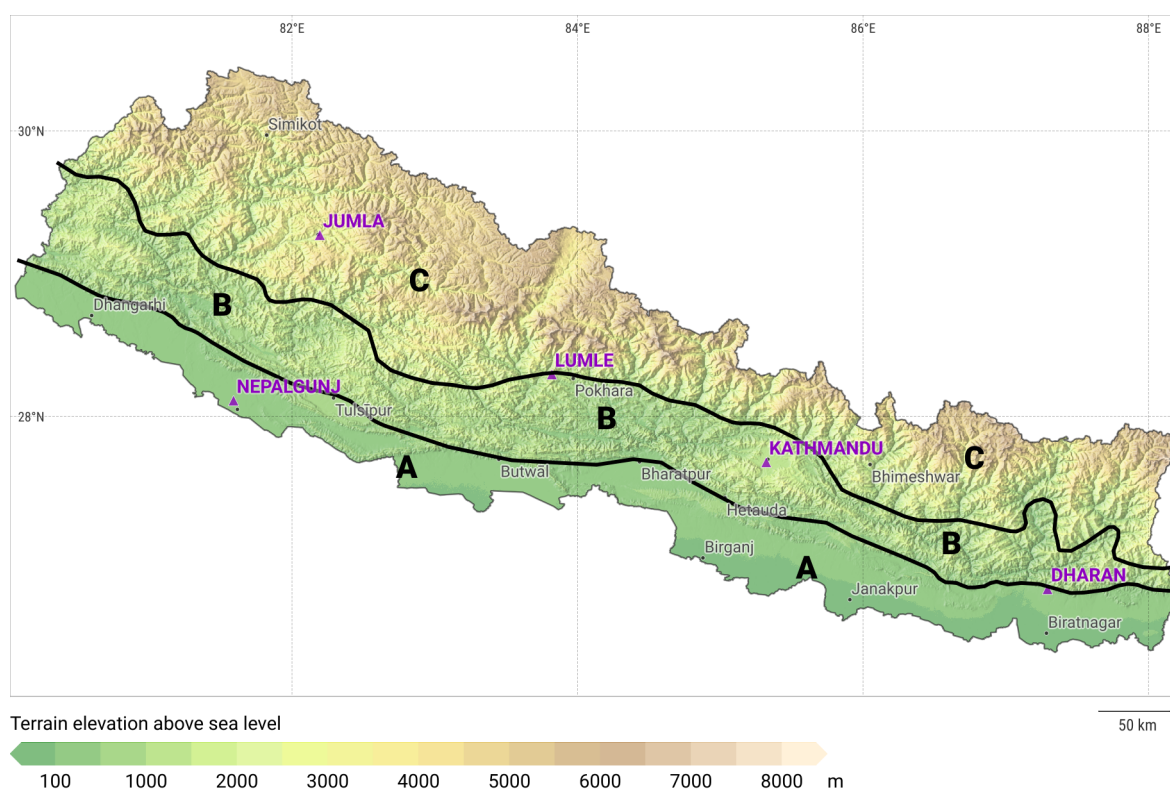
Accuracy statistics, such as bias (Chapter 2.1.5) characterize the accuracy of the Solargis model in the given validation points, relative to the ground measurements. The validation statistics are affected by local geography and by the quality and reliability of ground-measured data. Therefore, the validation statistics only indicate performance of the model in this region.

The majority of Nepal territory has uncertainty of the regionally-adapted model yearly values in the range of $\pm 4.5\%$ to $\pm 6.5\%$ for GHI, and $\pm 9\%$ to $\pm 13\%$ for DNI, respectively. We expect higher uncertainty in high mountains (Table 2.9, Map 2.2).

Table 2.9: Uncertainty of the model estimate for original and regionally-adapted annual GHI, DNI and GTI and how does it compare to the best-achievable uncertainty case.

	Direct Normal Irradiation		Global Horizontal Irradiation		Global Tilted Irradiation	
	Low	Medium	Low	Medium	Low	Medium
Original data	< ±12.0%	< ±18%	< ±6.0%	< ±8.0%	< ±7.0%	< ±9.0%
After adaptation	±9.0%	< ±13%	±4.5%	< ±6.5%	±5.0% to ±6.0%	< ±8.0%
Best achievable	±3.5%	-	±2.5%	-	±3.0%	

The lowest (best achievable) uncertainty in [Table 2.9](#) can only be achieved by the model site-adaptation so that it would represent only the very local microclimate of the site recorded in the ground measurements. In the case of the regional adaptation, used in this study, the uncertainty is usually higher. Moreover, a residual discrepancy between ground measurements, and the model data can be found after regional adaptation ([Tables 2.7 and 2.8](#)). This model adaptation approach is designed to correct only regional discrepancy patterns, not to resolve site-specific issues.



Map 2.2: Geographic distribution of the regionally adapted model uncertainty in Nepal
A: Terai - Lowlands; B: Siwalik - Middle mountains, C: Himalaya – High mountains

2.2 Air temperature data

2.2.1 Measured vs. modelled data

Meteorological parameters are an important part of a solar energy project assessment as they determine the operating conditions and the effectiveness of solar power plant operations. The most important meteorological parameter for the operation of photovoltaic power plants is air temperature, which directly impacts power production (energy yield is decreasing when temperature is increasing). Meteorological data can be collected by two approaches: (1) by measuring at meteorological sites and (2) computing by meteorological models.

The requirements for the meteorological data for solar energy projects are:

- Long and continuous record of data, preferably covering the same time period as satellite-based solar resource data,
- Data should reliably represent the local climate,
- Data should be accurate, quality-controlled and without gaps.

Table 2.10: Comparing air temperature data from meteorological stations and weather models

	Meteorological station data	Data from meteorological models
Availability/ accessibility	Available only for selected sites. Data may cover different periods of time	Data are available for any location. Data cover long continuous and equal period of time (decades)
Original spatial resolution	Local measurement representing microclimate with all local weather occurrences	Regional simulation, representing regional weather patterns with relatively coarse grid resolution. Therefore, local values can be smoothed, especially extreme values.
Original time resolution	From 1 minute to 1 hour	1 hour
Quality	Data has to go through rigorous quality control, gap filling and cross-comparison.	No need of special quality control. No gaps, relatively stable outputs if data processing systematically controlled.
Stability	Sensors, measuring practices, maintenance and calibration may change over time. Thus, achieving long-term stability needs systematic attention.	In case of reanalysis, long history of data is calculated with one single stable model. Data for operational models may slightly change over time, as model development evolves
Uncertainty	Uncertainty is related to the quality and maintenance of sensors and measurement practices, usually sufficient for solar energy applications.	Uncertainty is given by the resolution and accuracy of the model. Uncertainty of meteorological models is higher than uncertainty of high-quality measurements. The model data may not exactly represent the local microclimate; accuracy can be enhanced by correlating them with the ground measurements.

Several models are available: a good option is to use ERA5 European Atmospheric Reanalysis (source ECMWF) and [22]. The outputs of this model are implemented in Solargis.

The role of meteorological ground measurements in solar energy development is twofold:

- Measurements are used for the validation and accuracy enhancement of historical data derived from the solar and meteorological models
- High frequency measurements (typically one-minute data) are used for improved understanding of the microclimate of the site, especially for capturing the extremes.

Data from the two sources described above have their advantages and disadvantages (Table 2.10). Air temperature derived from the meteorological models has lower spatial and temporal resolution compared to ground

measurements, and lower accuracy. Thus, the modelled parameters characterize regional climate patterns rather than the local microclimate. Extreme values, in particular, may not be well represented.

2.2.2 Air temperature: method and validation

In this project, the air temperature data is delivered. It is derived from the meteorological model ERA5 (Table 2.9). As explained in Chapter 2.2.1, the numerical weather models have lower spatial and temporal resolution compared to the solar resource data. The original spatial resolution of the models is enhanced to 1 km for air temperature by spatial disaggregation and the use of the Digital Elevation Model SRTM-3.

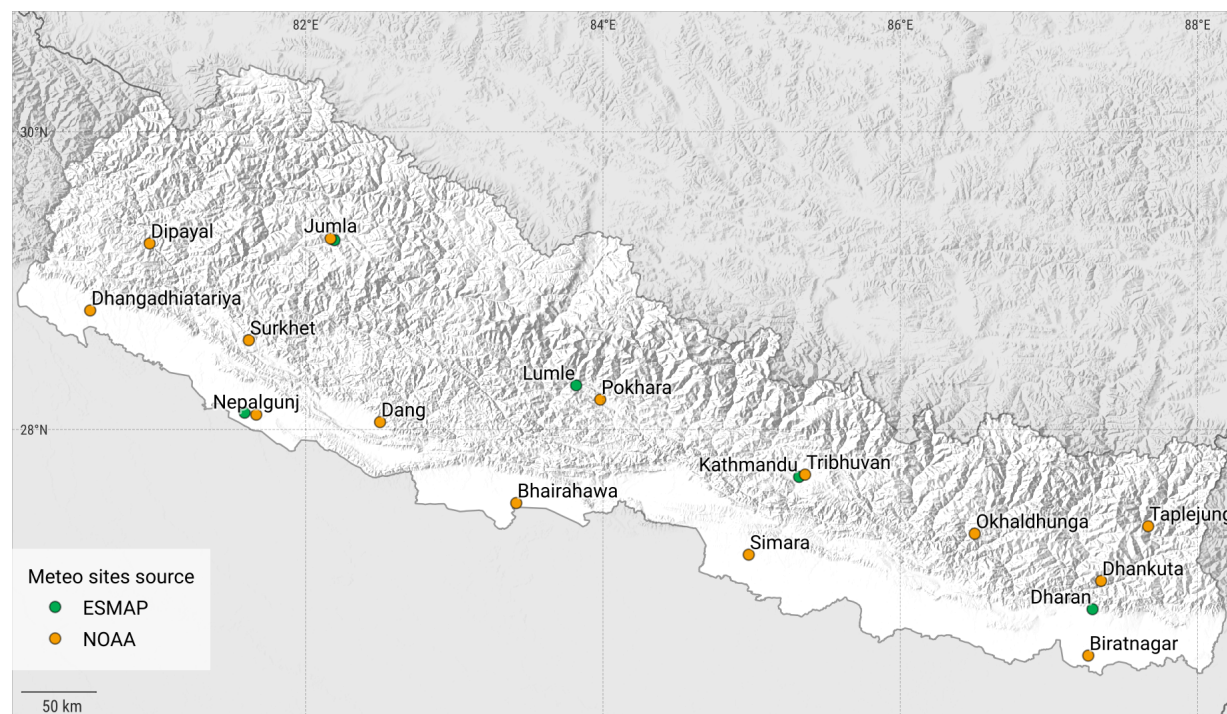
Table 2.11: Original source of Solargis air temperature at 2 m for Nepal: ERA5.

ERA5 Reanalysis model	
Time period	1999 to recent time
Original spatial resolution	25 x 25 km
Original time resolution	1 hour

Table 2.12: Air temperature at 2 m: accuracy indicators of the model outputs [°C].

Meteorological station	Source	Latitude	Longitude	Elevation	Validation period	Bias mean	RMSD hourly	RMSD daily	RMSD month
Dharan	ESMAP	26.7929	87.2926	315	07/2018 - 02/2021	-0.5	2.2	1.4	1.0
Jumla	ESMAP	29.2724	82.1935	2363	08/2018 - 02/2021	-0.2	3.3	2.0	0.8
Kathmandu	ESMAP	27.6816	85.3187	1315	07/2018 - 02/2021	-0.5	1.8	0.9	0.6
Lumle	ESMAP	28.2967	83.8189	1742	07/2018 - 02/2021	-0.4	2.4	1.4	1.0
Nepalguni	ESMAP	28.1130	81.5889	150	07/2018 - 02/2021	0.1	1.7	0.7	0.3
Dipayal	NOAA	29.250	80.950	617	01/2010 - 12/2020	0.7	3.9	2.5	1.7
Dhangadhiatariy	NOAA	28.800	80.550	187	01/2010 - 12/2020	0.7	2.3	1.4	0.8
Surkhet	NOAA	28.600	81.617	720	01/2010 - 12/2020	-0.3	2.5	1.7	0.4
Nepalguni	NOAA	28.100	81.667	165	01/2010 - 12/2020	0.4	2.2	1.3	0.5
Jumla	NOAA	29.283	82.167	2300	01/2010 - 12/2020	-1.3	4.2	2.9	1.6
Danq	NOAA	28.050	82.500	634	01/2010 - 12/2020	0.0	2.3	1.1	0.2
Pokhara	NOAA	28.201	83.981	827	01/2010 - 12/2020	-0.8	2.6	1.5	0.8
Bhairahawa	NOAA	27.506	83.416	109	01/2010 - 12/2020	0.6	2.3	1.8	0.9
Simara	NOAA	27.159	84.980	137	01/2010 - 12/2020	0.8	2.6	1.8	1.1
Tribhuvan	NOAA	27.697	85.359	1338	01/2010 - 12/2020	-0.3	1.7	1.0	0.4
Okhaldhunga	NOAA	27.300	86.500	1720	01/2010 - 12/2020	-0.7	2.4	1.8	1.1
Taplejung	NOAA	27.350	87.667	1732	01/2010 - 12/2020	-0.7	2.3	1.5	0.9
Dhankuta	NOAA	26.983	87.350	1210	01/2010 - 12/2020	-1.4	2.5	2.0	1.5
Biratnagar	NOAA	26.481	87.264	72	01/2010 - 12/2020	0.8	2.4	1.7	1.0

For validation of the meteorological model in Nepal, we have used the data collected at five meteorological stations (Table 2.12, Map. 2.3) from ESMAP project and meteorological stations from NOAA ISD Network. The summary of basic statistical parameters is presented in Table 2.12.



Map 2.3: Position of the solar meteorological stations used for air temperature model validation

2.2.3 Uncertainty of air temperature

In general, the data from the meteorological models represent larger area, and it is not capable of representing accurately the microclimate of a particular site. The modelled air temperature in Nepal fits quite well the measured data, representing both seasonal and daily patterns. The main issue identified is the underestimation of night-time temperature (meteorological stations Dharan, Jumla, Lumle), and underestimation of day time temperature (station Jumla) by the model.

Nepal is diverse in terms of geographical layout and the quality of air temperature model data may vary depending on the specific location and the uncertainty is higher in a complex terrain. Based on the validation analysis, the typical uncertainty of the model estimate for air temperature is summarised in Table 2.13.

Table 2.13: Expected typical uncertainty of air temperature in Nepal

	Unit	Annual	Monthly	Hourly
Air temperature at 2 m	°C	±1.5	±2.0	±3.5

2.3 Simulation of solar photovoltaic potential

Solar radiation is the most important parameter for PV power simulation, as it is fuel for solar power plants. The intensity of global irradiance received by the tilted surface of PV modules (GTI) is calculated from two primary parameters stored in the Solargis database and delivered in this project:

- Global Horizontal Irradiance (GHI)
- Direct Normal Irradiance (DNI)

There are two main types of solar energy technologies: photovoltaic (PV) and concentrating solar power (CSP). Photovoltaics have high potential in Nepal, and this technology is discussed in [this Chapter](#). CSP technology is not expected to be implemented in Nepal.

Photovoltaic technology exploits global horizontal or tilted irradiation, which is the sum of direct and diffuse components. To simulate power production from a PV system, global irradiance received by a flat surface of PV modules must be calculated. Due to clouds, PV power generation reacts to changes in solar radiation in a matter of seconds or minutes (depending on the size of a module field), thus intermittency (short-term variability) of the PV power production is to be considered. Similarly, the effect of seasonal variability is to be considered as well.

For possible PV installations, several technical options are available. They are briefly described below.

Two types of mounting of PV modules can be considered:

- PV modules mounted on the ground in a fixed position or on sun-trackers
- PV modules mounted on rooftops or façades of buildings

Three types of PV systems can be considered for Nepal:

- Grid-connected PV power plants
- Mini-grid PV systems
- Off-grid PV systems

The majority of larger PV power plants are built in an **open space** and often these have **PV modules mounted at a fixed position**. Fixed mounting structures offer a simple and efficient choice for implementing PV power plants. A well-designed structure is robust and ensures long-life performance, even during harsh weather conditions, at low maintenance costs. **Sun-tracking systems** are another alternative for the design of a PV module field. Solar trackers adjust the orientation of the PV modules during the day towards the sun, so the PV modules collect more solar radiation.

Roof or façade mounted PV systems are typically small to medium size, i.e. ranging from hundreds of watts to hundreds of kilowatts. Modules can be mounted on rooftops, façades or can be directly integrated as part of a building structure. PV modules in this type of system are often installed in a suboptimal position (deviating from the optimum angle), and this results in a lower performance efficiency. Some reduction of PV power output can be expected due to nearby shading structures. Trees, masts, neighbouring buildings, roof structures or self-shading of PV modules determine the reduced PV system performance.

Mini-grid PV systems include power generation facility and distribution grids connecting the local consumers. The typical size of installed PV systems is in the range of 10s to 100s of kWp. Mini-grids may be adapted to meet the requirements of local needs, they can be combined with diesel generators and battery storage. This option appears to be most economic for supply of electricity for small rural communities.

Off-grid PV systems are systems that are not connected into a distribution grid. They are usually equipped with energy storage (classic lead acid or modern-type batteries, such as Li-on) and/or connected to diesel generators. Batteries are maintained through charge controllers for protection against overcharging or deep discharge. Depending on size and functionality of the off-grid PV system, it can work with AC (together with inverter) or DC voltage source.

In this study, the PV power potential is studied for a system with fixed-mounted monofacial PV modules, still one of the most popular technologies. Installed capacity of a PV power plant is usually determined by the available space and options to maintain the stability of the local grid.

2.3.1 Principles of PV electricity simulation

Results of PV electricity simulation, presented in Chapter 3.5, are based on software developed by Solargis. This Chapter summarizes key elements of the simulation chain.

Table 2.14: Specification of Solargis database used in the PV calculation in this study

Data inputs for PV simulation	Global tilted irradiation (GTI) derived from GHI and DNI Air temperature at 2 m (TEMP)
Spatial grid resolution (approximate) of data inputs	GHI, DNI, GTI: 250 m (9 arc-sec) TEMP: 1 km (2 arc-min)
Time resolution	15-minute
Geographical extent (this study)	Federal Democratic Republic of Nepal
Period covered by data (this study)	01/1999 to 12/2020

The PV software implemented by Solargis has scientifically proven methods [33 to 38] and uses full historical time series of solar radiation and air temperature data on the input (Table 2.14). Data and model quality are checked using field tests and ground measurements.

In PV energy simulation procedure, there are several energy losses that occur in the individual steps of energy conversion (Figure 2.2):

1. **Losses due to terrain shading** caused by far horizon. On the other hand, shading of local features such as nearby building, structures or vegetation is not considered in the calculation,
2. Energy conversion in PV modules is reduced by **losses due to angular reflectivity**, which depends on the relative position of the sun and plane of the module and **temperature losses**, caused by the performance of PV modules working outside of STC conditions defined in datasheets,
3. DC output of PV array is further reduced by **losses due to dirt or soiling** depending mainly on the environmental factors and module cleaning, **losses by inter-row shading** caused by preceding rows of modules, **mismatch** and **DC cabling losses**, which are caused by slight differences between the nominal power of each module and small losses on cable connections,
4. DC to AC energy conversion is performed by an inverter. The efficiency of this conversion step is reduced by **inverter losses**, given by the inverter efficiency function. Further factors reducing AC energy output are **losses in AC cabling** and **transformer losses** (applies only to large-scale open space systems),
5. **Availability**. This empirical parameter quantifies electricity losses incurred by the shutdown of a PV power plant due to maintenance or failures, including issues in the power grid. Availability of well operated PV systems is approximately 99%.

According to experience in many countries, the crystalline silicon PV modules show a relatively low performance reduction over time. The rate of the performance degradation is higher at the beginning of exposure, and then stabilizes at a lower level. Initial degradation may be close to the value of 0.8% for the first year and 0.5% or less for subsequent years [37]. The performance ageing of PV modules is not considered in this study. The calculation results of PV power potential for Nepal are shown in Chapter 3.6.

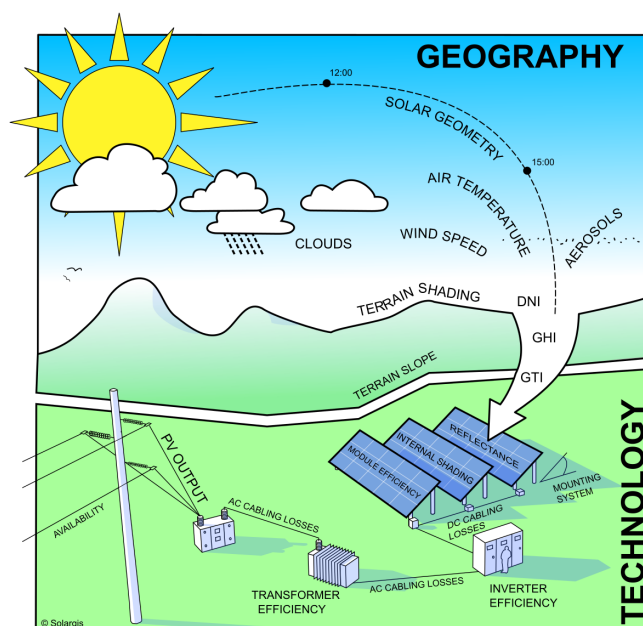


Figure 2.2: Simplified Solargis PV simulation chain

2.3.2 Technical configuration of reference PV system

Theoretical photovoltaic power production in Nepal has been calculated using numerical models developed and implemented in-house by Solargis. As introduced in [Chapters 2.1 and 2.2](#), 15-minute **time series of solar radiation and air temperature**, representing last 22 years, are used as an input to the simulation. The models are developed based on the advanced algorithms, expert knowledge and recommendations given in [\[39\]](#) and tested using monitoring results from existing PV power plants. [Table 2.16](#) summarizes losses and related uncertainty throughout the PV computing chain.

PV electricity potential is calculated based on a set of assumptions shown in [Tables 2.15 and 2.16](#). These assumptions are approximate values, and they will differ in the site-specific projects. As can be seen, the uncertainty of the solar resource is the key element of energy simulation.

Table 2.15: Reference configuration - photovoltaic power plant with fixed-mounted PV modules

Feature	Description
Nominal capacity	Configuration represents a typical PV power plant of 1 MWp or higher. All calculations are scaled to 1 kWp, so that they can be easily multiplied for any installed capacity.
Modules	Crystalline silicon modules with positive power tolerance. Nominal Operating Cell Temperature (NOCT) 46°C and temperature coefficient of the Pmax -0.438 %/K
Inverters	Central inverter with declared datasheet efficiency (Euro efficiency) 98.0%
Mounting of PV modules	Fixed mounting structures facing South with optimum tilt (the range from 22° to 38°). Relative row spacing 2.5 (ratio of absolute spacing and table width)
Transformer	Medium voltage power transformer

Table 2.16: Yearly energy losses and related uncertainty in PV power simulation: Fixed mounting

Simulation step		Losses	Uncertainty	Notes
		[%]	[± %]	
1	Global Tilted Irradiation (model estimate with terrain shading)	N/A	6.0	Annual Global Irradiation falling on the surface of PV modules
2	Module surface angular reflectivity (numerical model)	-2.1 to -2.6	1.0	Slightly polluted surface is assumed in the calculation of the module surface reflectivity
	Conversion in modules relative to STC (numerical model)	-2.2 to -9.6	3.5	Depends on the temperature and irradiance. NOCT of 46°C is considered
3	Polluted surface of modules (empirical estimate)	-4.0 to -8.0	1.5	Losses due to snow, dirt, dust, soiling, and bird droppings
	Power tolerance (value from the data sheet)	0.0	0.0	Value given in the module technical data sheet (modules with positive power tolerance)
	Module inter-row shading (model estimate)	-0.1 to -0.5	0.5	Partial shading of strings by modules from adjacent rows
	Mismatch between modules (empirical estimate)	-0.5	0.5	Well-sorted modules and lower mismatch are considered.
	DC cable losses (empirical estimate)	-2.0	1.5	This value can be calculated from the electrical design
4	Conversion in the inverter (value from the technical data sheet)	-2.0	0.5	Given by the Euro efficiency of the inverter, which is considered at 97.5%
	AC cable losses (empirical estimate)	-0.5	0.5	Standard AC connection is assumed
	Transformer losses (empirical estimate)	-1.0	0.5	Standard transformer is assumed
5	Availability	0.0	2.5	100% technical availability is considered; the uncertainty considered here assumes a well-integrated system; the real value strongly depends on the efficiency of PV integration into the existing grid.
Range of cumulative losses and indicative uncertainty		-13.6 to -24.1	7.8	These values are indicative and do not consider the project specific features and performance degradation of a PV system over its lifetime

Map 3.17 shows theoretical potential power production of a PV system installed with a typical technology configuration for open space PV power plants. The technical parameters are described in **Table 2.15**.

In this study, the reference configuration for the PV potential calculation is a PV system with crystalline-silicon (c-Si) modules mounted in a fixed position on a table facing South and inclined at an angle close to optimum, i.e. at the angle at which the yearly sum of global tilted irradiation received by PV modules is maximized (a range between 23° and 38°). The fixed-mounting of PV modules is very common and provides a robust solution with minimal maintenance effort. Geographic differences in potential PV production are shown for five selected sites, collocated with ESMAP solar meteorological stations (**Chapter 3.6**).

The results presented in **Chapter 3.6** do not consider the performance degradation of PV modules due to aging; they also lack the required level of detail. Thus, these results cannot be used for financial assumptions of any specific project. Detailed assessment of energy yield for a specific power plant is within the scope of a site-specific bankable expert study.

3 Solar resource and PV potential of Nepal

3.1 Geography

This report analyses solar and meteorological data for Nepal, which determine solar power production and influence its performance efficiency. We also analyse other geographical factors that influence the development and operation of solar power plants.

Nepal is located in South Asia, approximately between latitudes 30° and 26° North and longitudes 80° and 88° East. We demonstrate the variability of the solar resource and photovoltaic power potential in two forms:

- At the **country level** in the form of maps
- Graphs and tables for **five selected sites** that, to a large extent, represent the variability of the climate and solar power potential (the sites are collocated with the ESMAP solar meteorological stations).

The position of these sites is summarised in [Table 2.1](#) and [Map 2.1](#). The data in the tables and graphs shown in [Chapter 3](#) relate to these five sites.

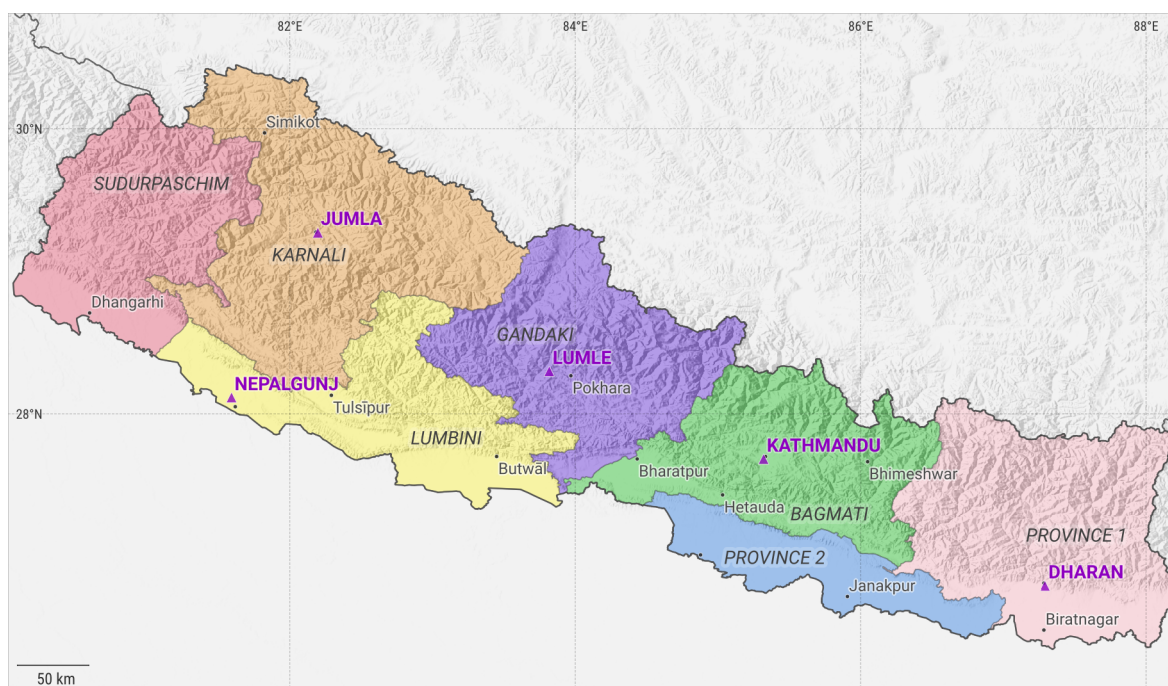
Geographic information and maps bring additional value to the solar data. Geographical characteristics of the country from a regional to local scale may represent technical and environmental prerequisites, as well as constraints, for solar energy development.

In this report, we collected the following data that has some relevance to solar energy:

- Map of the administrative division and important cities/towns informs about the country spatial organization and population distribution ([Map 3.1](#))
- Terrain, where elevation and slope inclination may pose physical limitations for solar development ([Maps 3.2](#) and [3.3](#))
- Rainfall (precipitation) has impact on efficiency and operation (modules cleaning effect) of the PV installations ([Map 3.4](#))
- Snow cover has impact on efficiency and operation of the PV installations ([Map 3.5](#))
- Land cover defines primary areas used for human economic activities and settlements and possible land availability for solar PV installations ([Map 3.6](#))
- Road network, defining accessibility of sites for location of PV power plants ([Map 3.7](#))
- Population density is a good indicator of electricity consumption ([Map 3.8](#)).
- Protected areas limit size of the power station and intensity of land use for the related infrastructure ([Map 3.9](#))

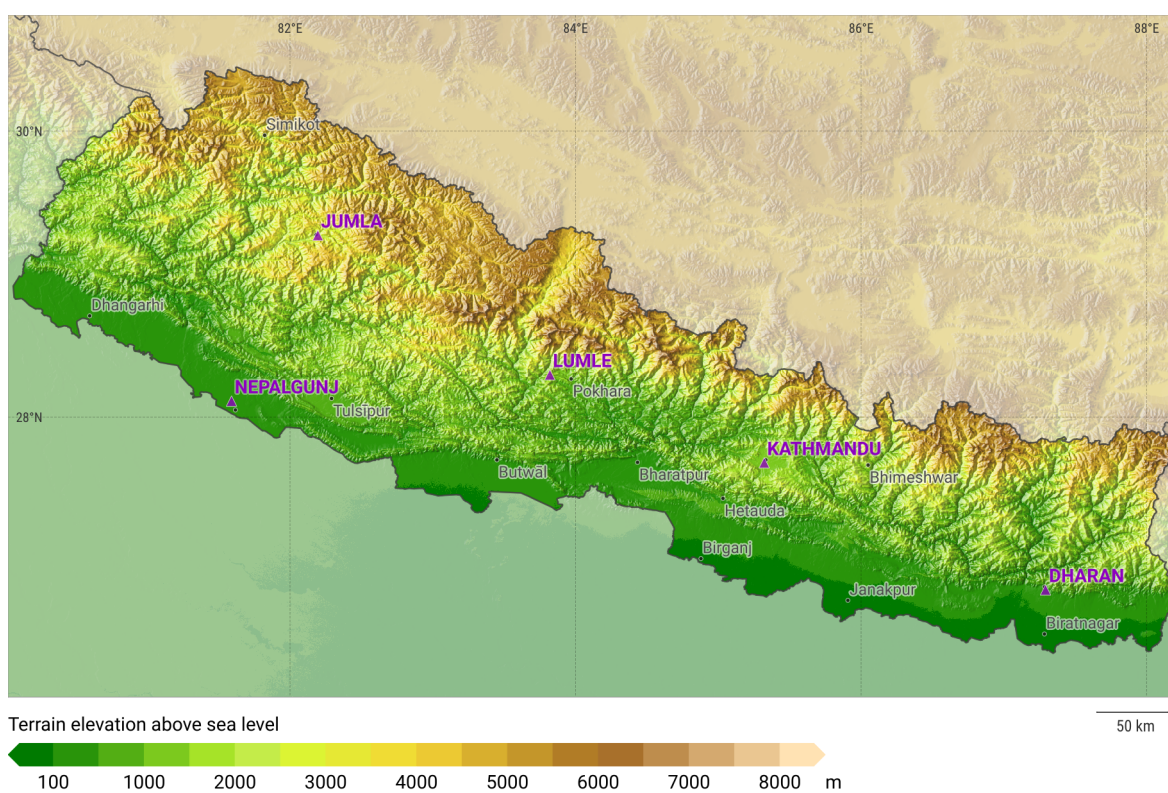
Most of the above-mentioned maps can be consulted also online, see:

- <https://globalsolaratlas.info/>
- <https://apps.solargis.com/prospect/>



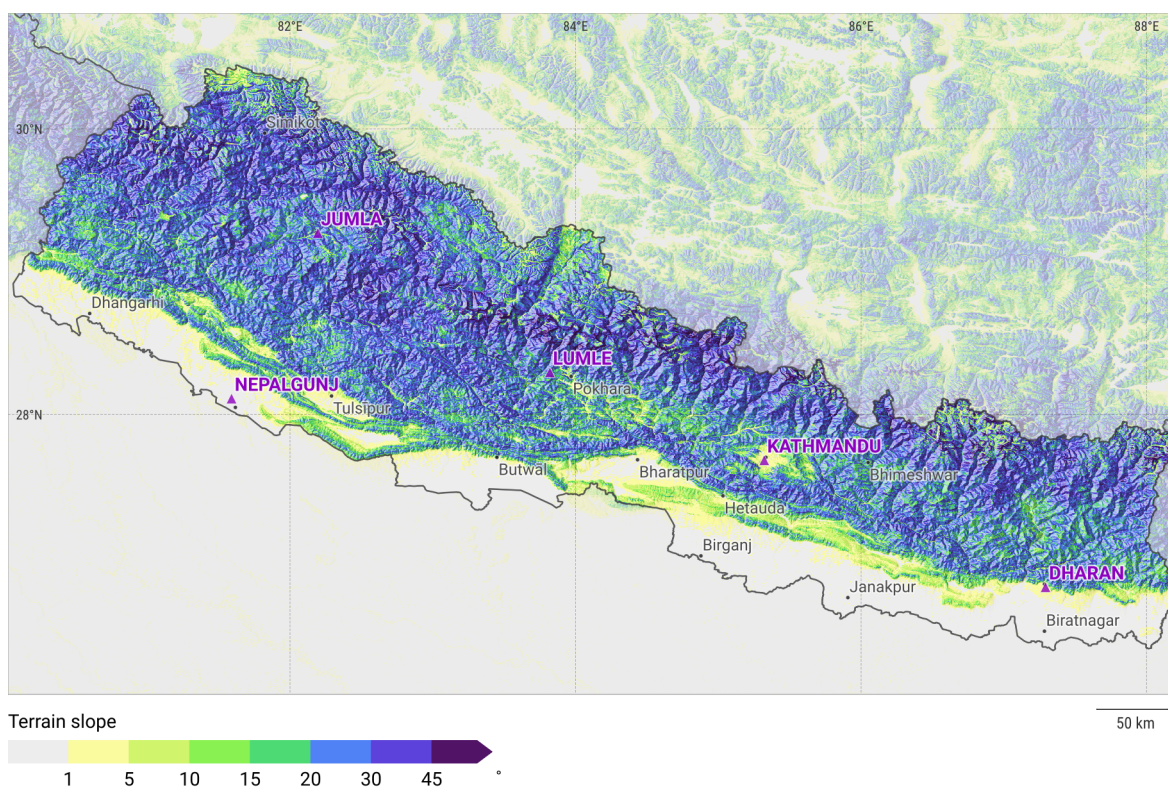
Map 3.1: Administrative division, towns and cities in Nepal.

Source: Administrative boundaries by Cartography Unit GSDPM (World Bank Group), GeoNames, adapted by Solargis.
For reference, position of five solar meteo sites is shown.



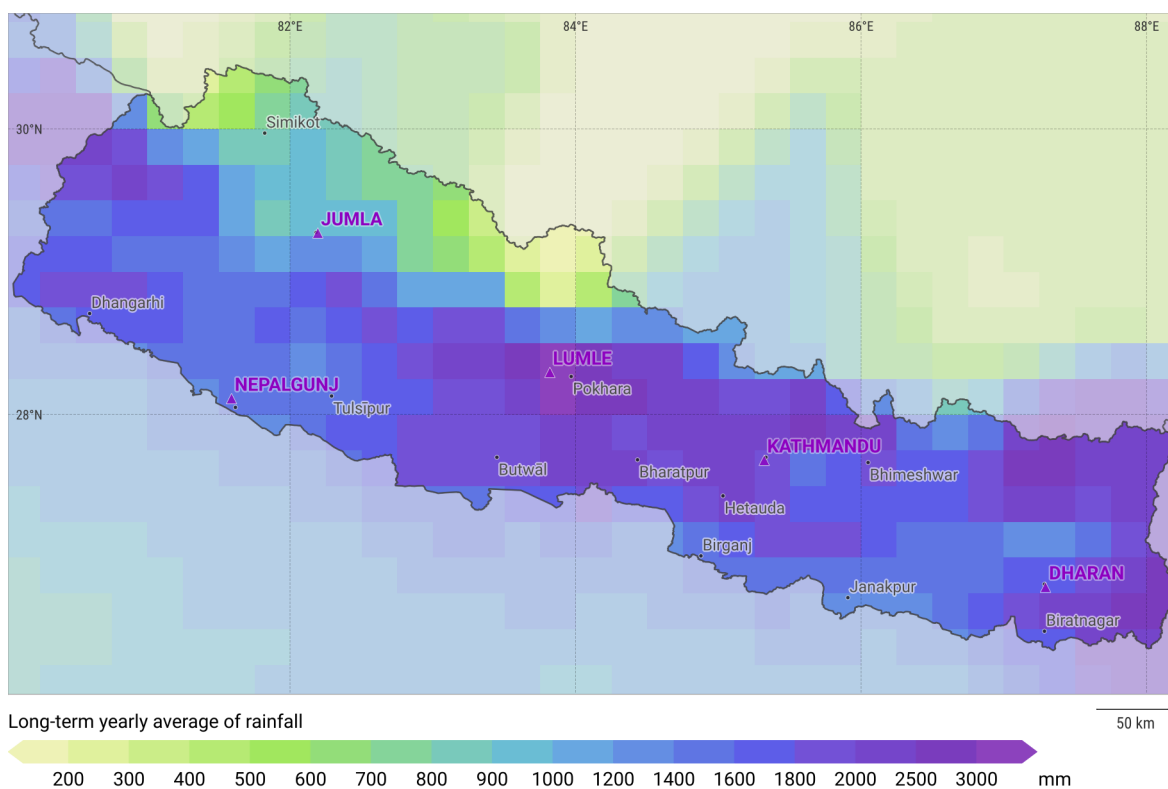
Map 3.2: Terrain elevation above sea level.

Source: SRTM v4.1. For reference, position of five solar meteo sites is shown.



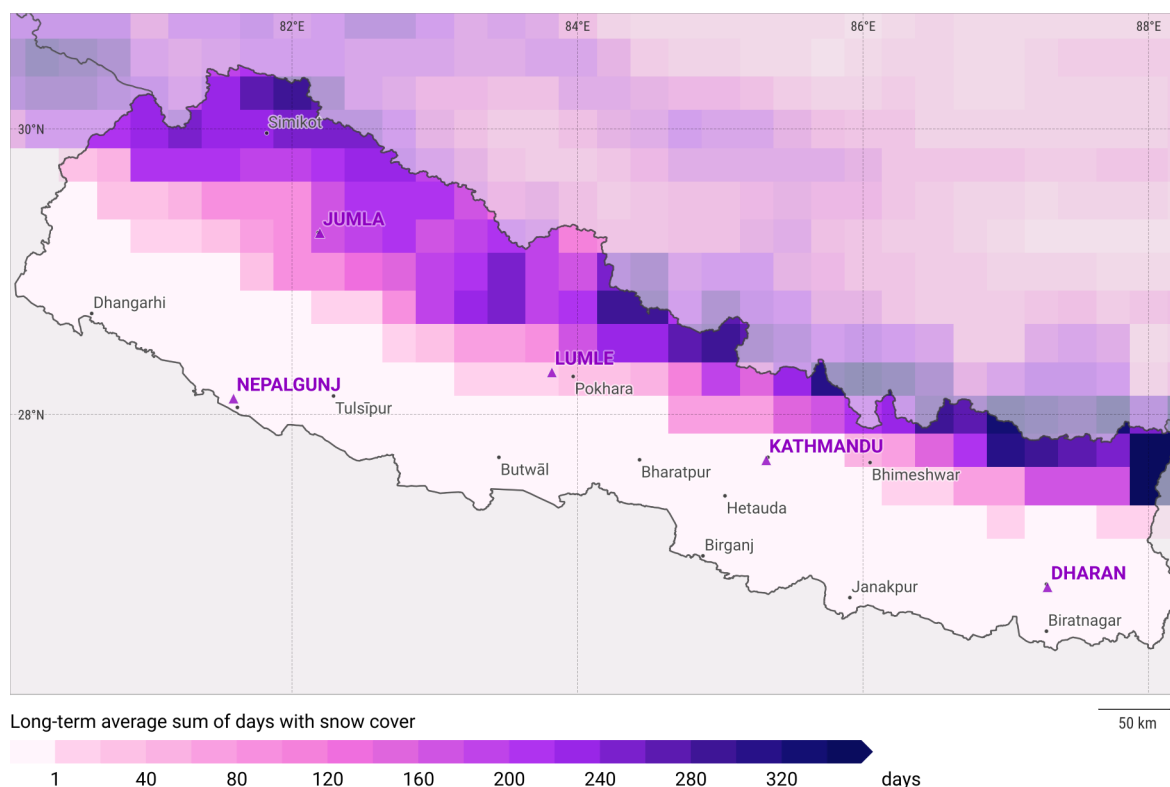
Map 3.3: Terrain slope.

Based on: SRTM v4.1 data, calculated by Solargis. For reference, position of five solar meteo sites is shown.



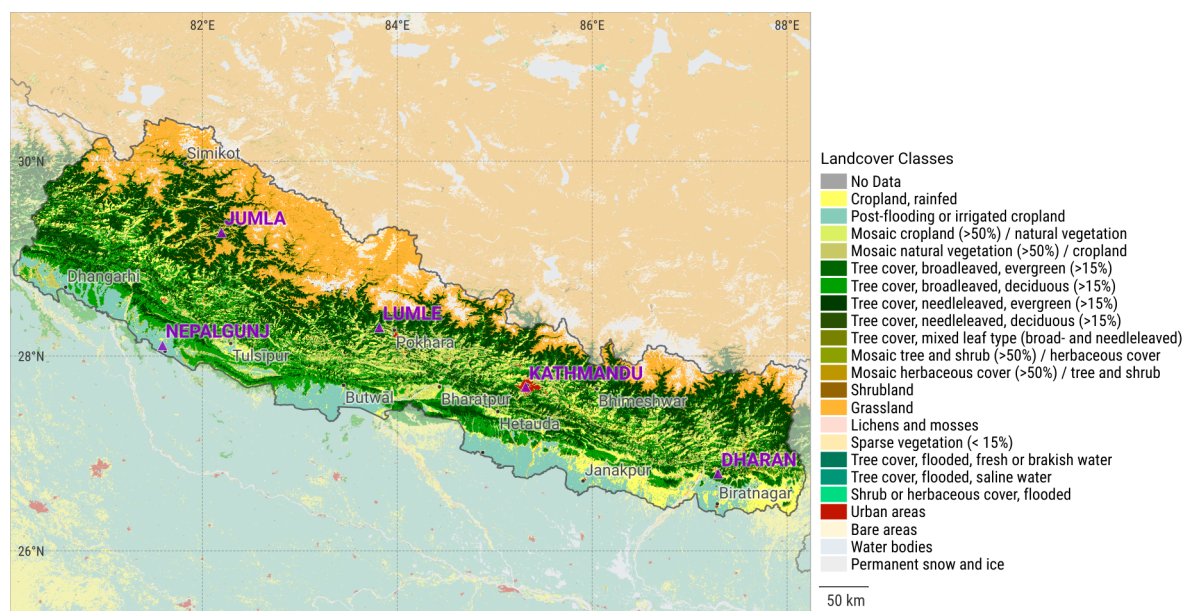
Map 3.4: Long-term yearly average of rainfall (sum of precipitation).

Source: Global Precipitation Climatology Centre (DWD). For reference, position of five solar meteo sites is shown.



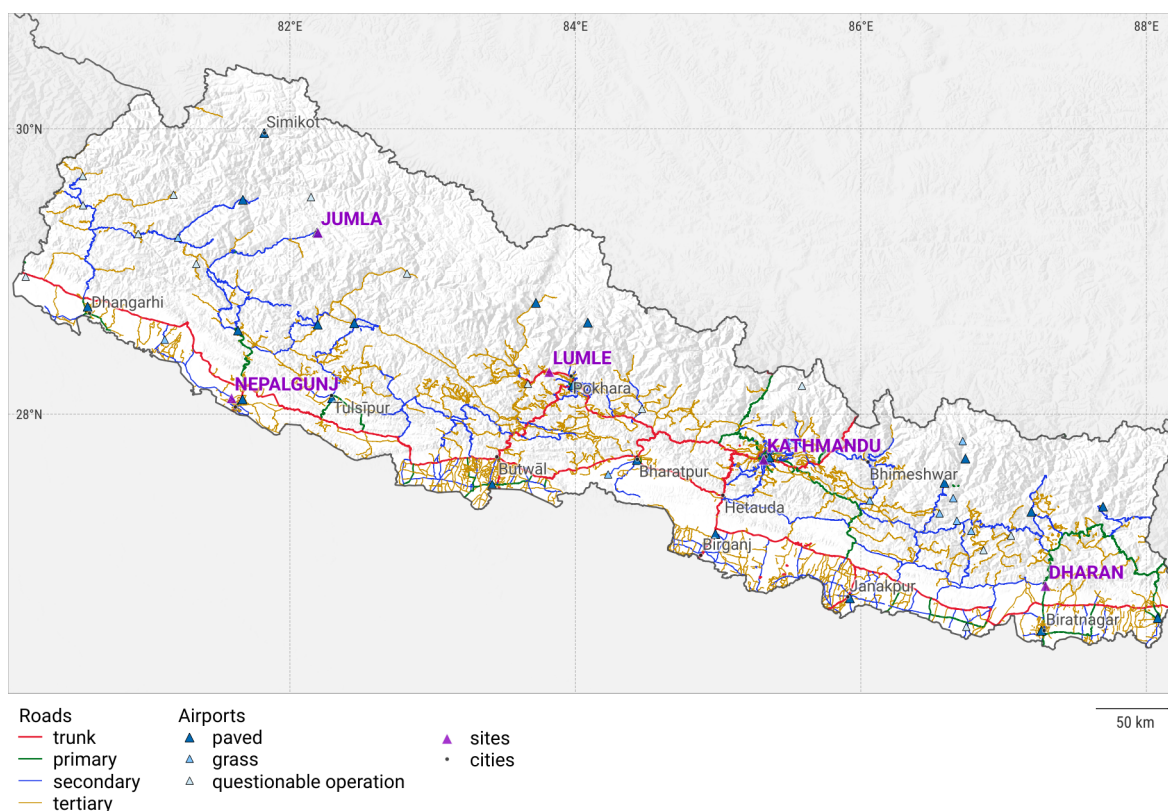
Map 3.5: Long-term yearly average sum of snow cover.

Source: Global Precipitation Climatology Centre (DWD). For reference, position of five solar meteo sites is shown.



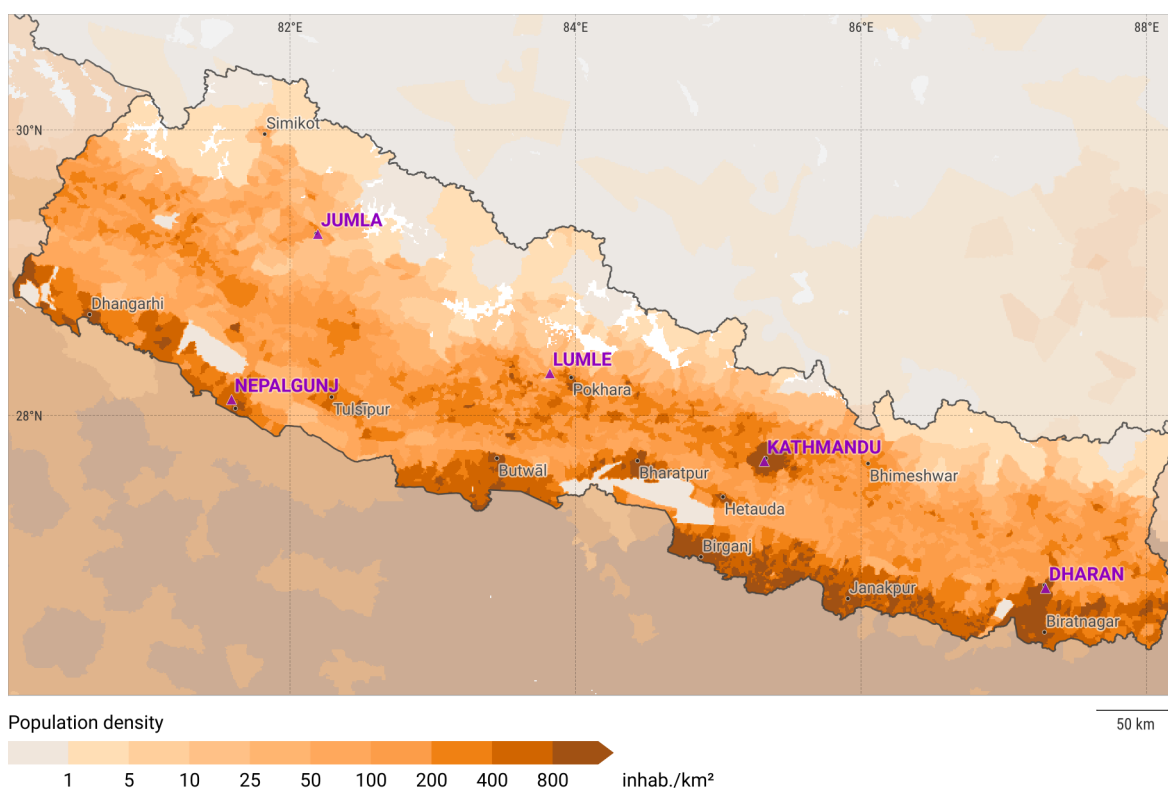
Map 3.6: Land cover.

Source: ESA Climate Change Initiative - Land Cover led by UCLouvain (2017)
For reference, position of five solar meteo sites is shown.



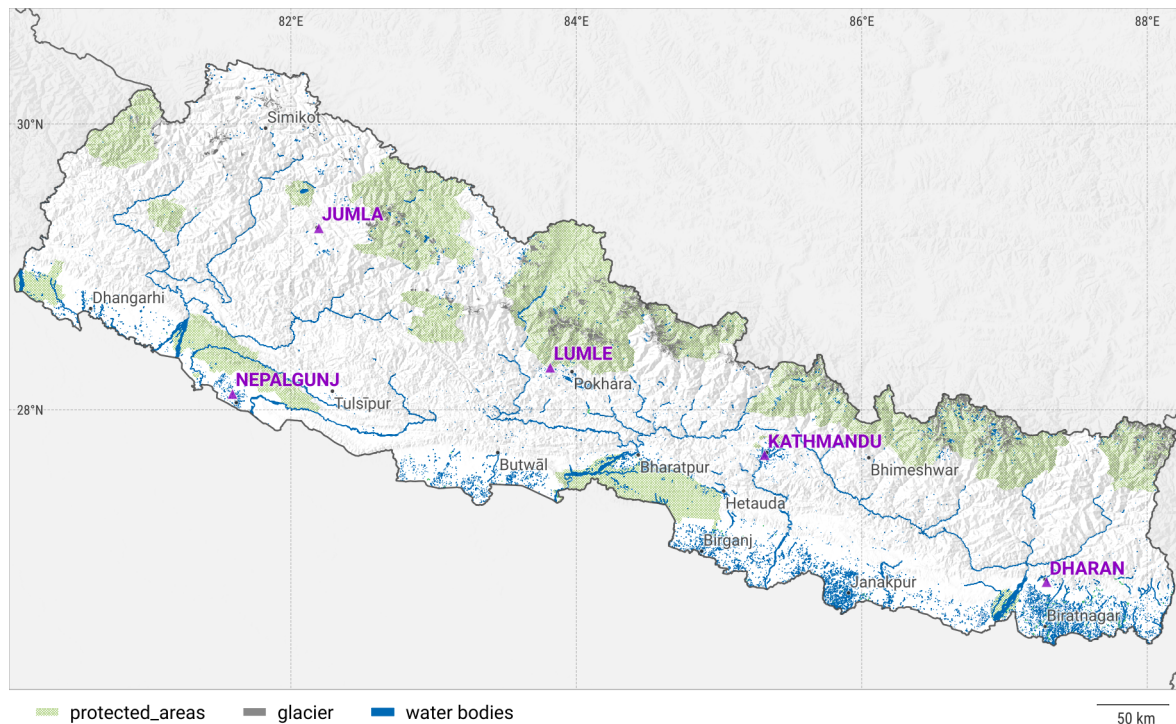
Map 3.7: Transport corridors.

Source: OpenStreetMap.org contributors. For reference, position of five solar meteo sites is shown.



Map 3.8: Population density.

Source: Gridded Population of the World (GPW v4). For reference, position of five solar meteo sites is shown.



Map 3.9: Position of protected areas, glaciers and water bodies.

Source: IUCN. For reference, position of five solar meteo sites is shown.

From the geographical viewpoint, Nepal is very diverse country, spreading from subtropical monsoon lowlands at 100 m elevation above sea level through highlands of the central zone ranging from 700 to 3000 m up to more than 8000 m high mountains covered by perpetual snow and ice.

The map of the land cover shows the human settlements and areas of economic activities (industry, agriculture) that require electrical power. These regions are mainly in the lowlands and major valleys. Smaller settlements are dispersed throughout mountains with deep river valleys, which are remote in some cases. The more complex orographic conditions (terrain) are generally less populated and are typically unsuitable for large-scale solar energy development; however, they are suitable for smaller, off-grid or hybrid PV installations.

In the most recent statistics by the World Bank (Data Indicators, 2019), the overall access to Electricity in Nepal stands at 89.9%, with the rural share at 88.8% and Urban at 94.2% [40].

3.2 Air temperature

Air temperature determines the operating environment and performance efficiency of the solar power systems. Air temperature is one of the inputs in the energy simulation models. [Map 3.10](#) and [Map 3.11](#) show the yearly and monthly long-term averages. The long-term averages of air temperature are derived from the ERA5 model (see [Chapter 2.2](#)) by Solargis post-processing.

In the case of PV power plants, higher air temperature reduces the power conversion efficiency of the PV modules, as well as on other components (inverters, transformers, etc.).

Monthly averages of daily values show the seasonal variation of air temperature at five sites in Nepal ([Figure 3.1](#)). See [Chapter 2.2](#) discussing the uncertainty of the air temperature model estimates.

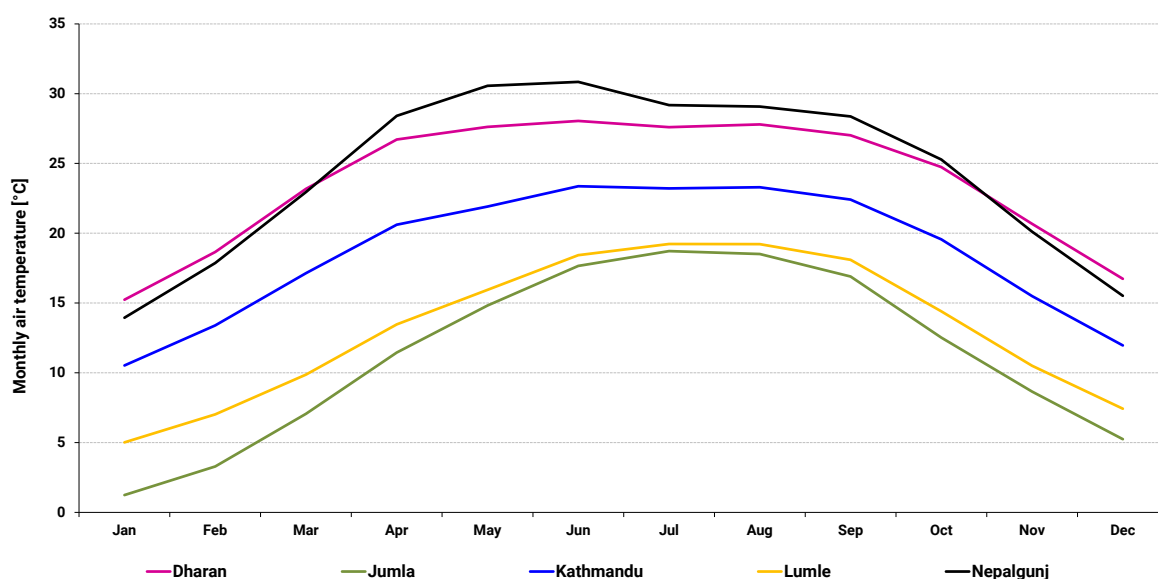
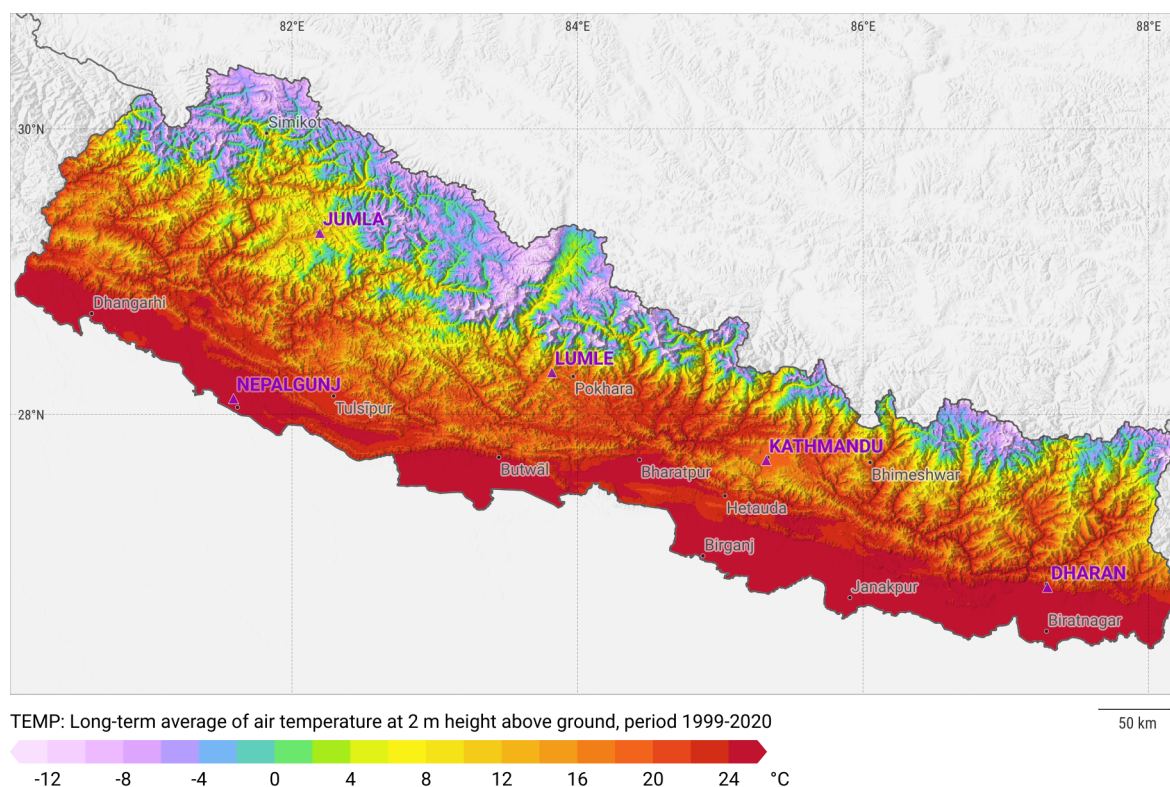


Figure 3.1: Monthly averages of air-temperature at 2 m for selected sites.

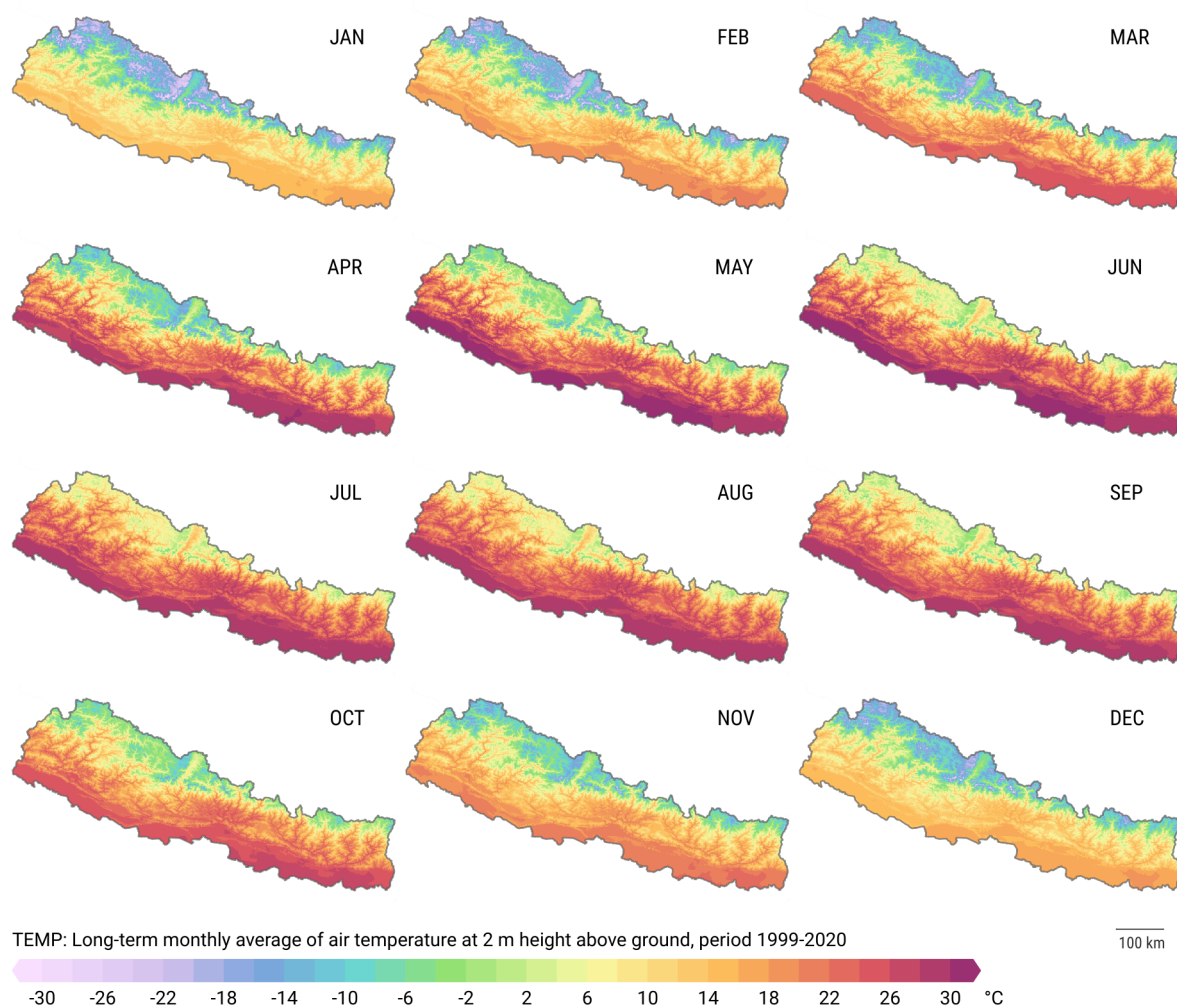
[Table 3.1](#) shows monthly averages of air temperature at five selected sites; the statistics is calculated over a 24-hour diurnal cycle.

Table 3.1: Monthly averages of air-temperature at 2 m at 5 sites

Month	Temperature [°C]				
	Dharan	Jumla	Kathmandu	Lumle	Nepalgunj
January	15.2	1.2	10.5	5.0	13.9
February	18.7	3.3	13.4	7.0	17.9
March	23.2	7.1	17.1	9.9	23.0
April	26.7	11.5	20.6	13.5	28.4
May	27.6	14.8	21.9	15.9	30.6
June	28.0	17.7	23.4	18.4	30.8
July	27.6	18.7	23.2	19.2	29.2
August	27.8	18.5	23.3	19.2	29.1
September	27.0	16.9	22.4	18.1	28.4
October	24.7	12.5	19.6	14.4	25.3
November	20.7	8.7	15.5	10.5	20.1
December	16.7	5.2	12.0	7.4	15.5
YEAR	23.7	11.3	18.6	13.2	24.3



Map 3.10: Long-term yearly average of air temperature at 2 metres, period 1999-2020.
Source: Model ERA5, post-processed by Solargis



Map 3.11: Long-term monthly average of air temperature at 2 metres, period 1999-2020.
Source: Model ERA5, post-processed by Solargis

3.3 Global Horizontal Irradiation

Global Horizontal Irradiation (GHI) is a primary fuel for solar energy systems. It is used as a reference value for comparing geographical conditions related to PV electricity systems, as it eliminates possible variations influenced by the choice of components and the PV system design.

Table 3.2 shows long-term average of daily totals of Global Horizontal Irradiation (GHI) for a period 1999 to 2020 for five selected sites.

Figure 3.2 compares daily values of GHI at selected sites. When comparing GHI for these sites, they demonstrate a very similar pattern. The highest GHI values are observed in April and May.

The highest variability of GHI between sites is observed in January. Generally, yearly variability between the selected sites is moderate: for five sites, standard deviation of yearly GHI values is 5.9%.

Table 3.2: Daily averages of Global Horizontal Irradiation at 5 sites

Month	Global Horizontal Irradiation [kWh/m ²]					Variability between sites [%]
	Dharan	Jumla	Kathmandu	Lumle	Nepalgunj	
January	3.52	3.99	3.73	3.82	2.99	10.6
February	4.34	4.85	4.45	4.36	4.44	4.6
March	5.64	6.20	5.58	5.46	6.00	5.4
April	6.16	6.68	6.05	5.97	6.76	5.8
May	5.85	6.91	5.80	5.74	6.77	9.2
June	5.13	6.05	5.29	5.07	5.77	7.9
July	4.62	4.69	4.54	4.01	4.87	7.1
August	4.73	4.74	4.62	4.07	4.80	6.5
September	4.39	5.24	4.51	4.18	4.80	8.9
October	4.68	5.70	4.95	4.62	4.92	8.7
November	4.21	4.77	4.19	3.94	4.08	7.5
December	3.64	4.10	3.65	3.58	3.21	8.8
YEAR	4.74	5.33	4.78	4.57	4.95	5.9

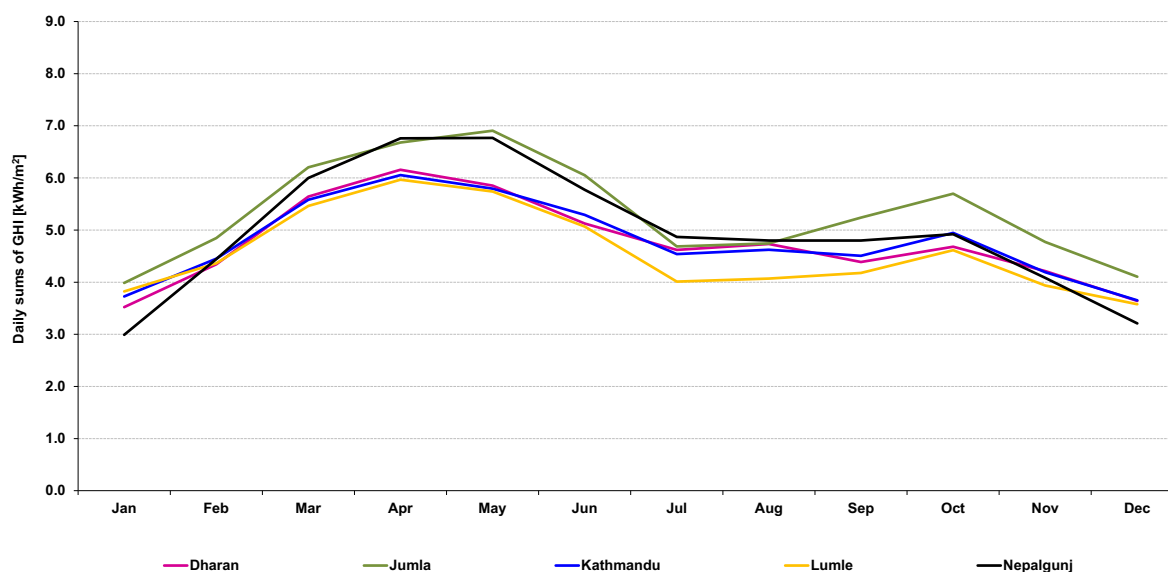


Figure 3.2: Long-term monthly averages of Global Horizontal Irradiation.

Weather changes in cycles and has also stochastic nature. Therefore, annual solar radiation in each year can deviate from the long-term average in the range of few percent. The estimation of the interannual variability shows the magnitude of this change (Figure 3.3).

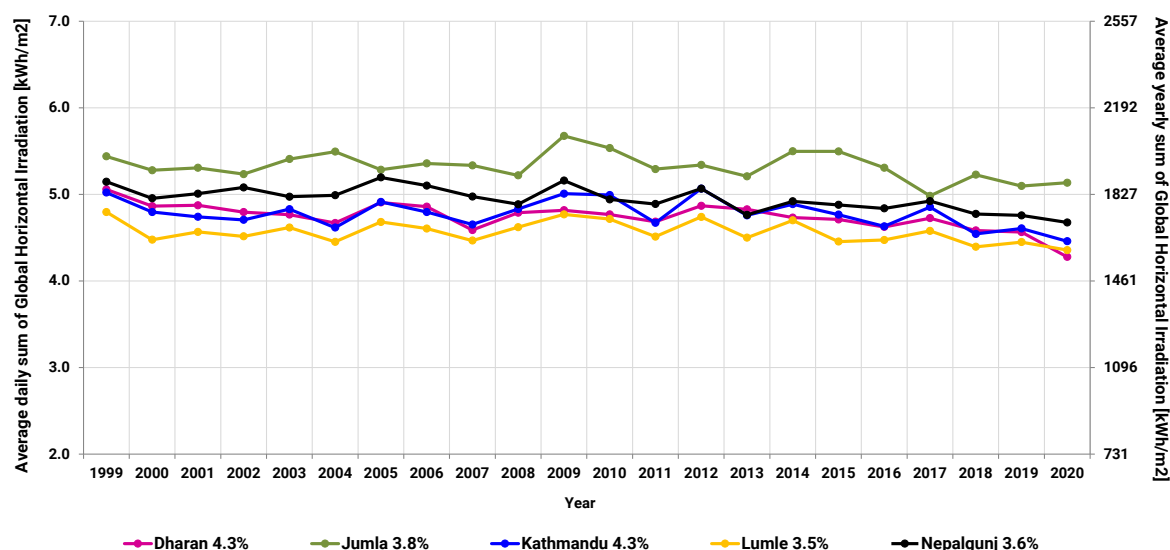
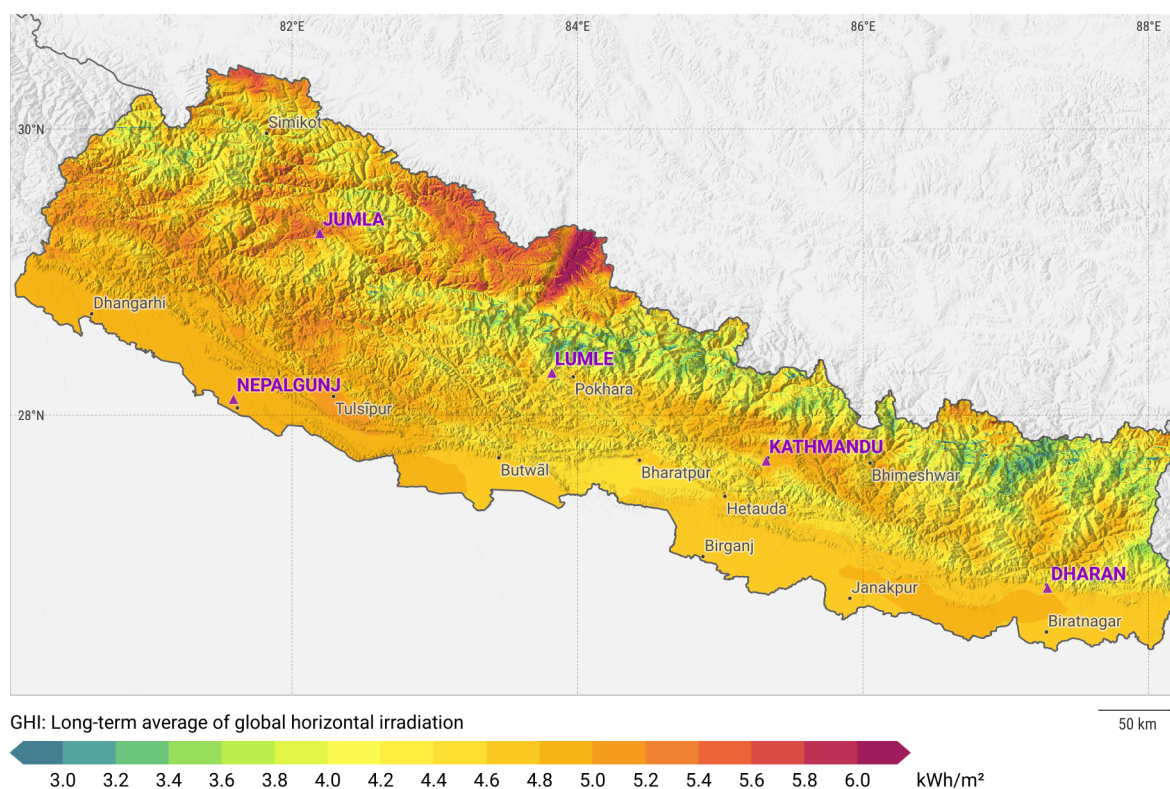
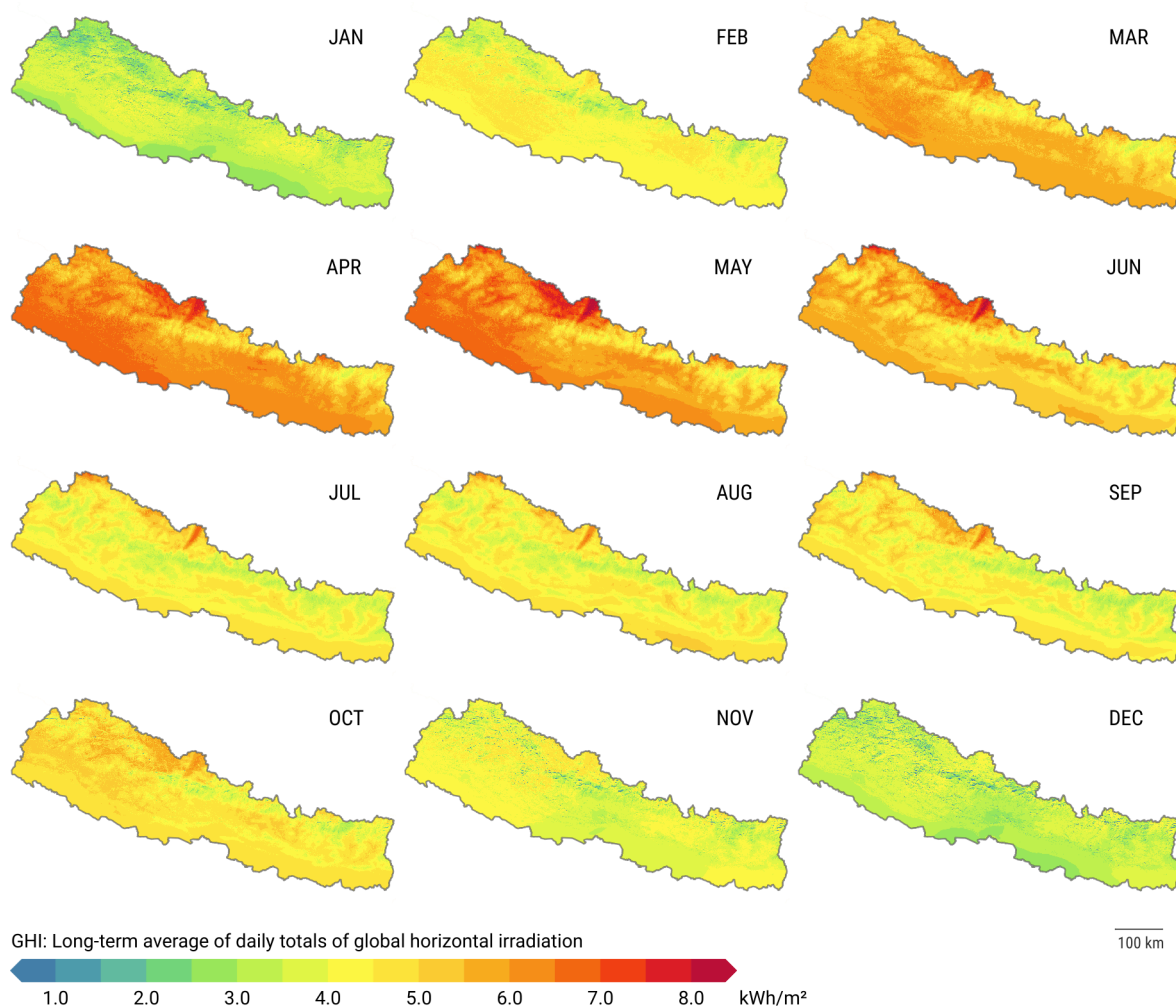


Figure 3.3: Interannual variability of Global Horizontal Irradiation for selected sites.

The interannual variability of GHI for the representative sites is calculated from the unbiased standard deviation of GHI over 22 years taking into consideration the long-term, normal distribution of the annual sums. All sites show similar patterns of GHI changes over the recorded period (Figure 3.3). More stable GHI (the lowest interannual variability) is observed at Lumle site. Highest variability of all sites is observed at Kathmandu and Dharan sites (standard deviation of 4.3%).



Map 3.12: Global Horizontal Irradiation – long-term average of daily and yearly totals.
Source: Solargis



Map 3.13: Global Horizontal Irradiation – long-term monthly average of daily totals.
Source: Solargis

The highest GHI is identified in the North and North-western parts of Nepal, where average daily totals reach 5.6 kWh/m^2 (yearly sum about 2045 kWh/m^2) or more (Map 3.12). The season of highest global horizontal irradiation with daily totals up to 7.0 kWh/km^2 lasts three months (from March to May, Map 3.13). The lowest documented GHI values are in December and January for all selected sites.

Map 3.14 shows the ratio of diffuse to global horizontal irradiation. This ratio is important for the performance of PV systems and may have impact during the optimisation process of PV technology. A higher ratio of diffuse to global horizontal irradiation (DIF/GHI) indicates less stable weather, higher occurrence of clouds, higher atmospheric pollution, or water vapour. In general, higher values occur in the central and South-eastern part country (above 55%). In the North and North-west of the country, the values fall below 30%.

Lower DIF/GHI values are identified generally from October to March, and highest being in period June to September. This indicates that the potential for concentrated solar technologies (CSP, CPV) in Nepal is low due to high DIF/GHI ratio and seasonality of solar radiation.

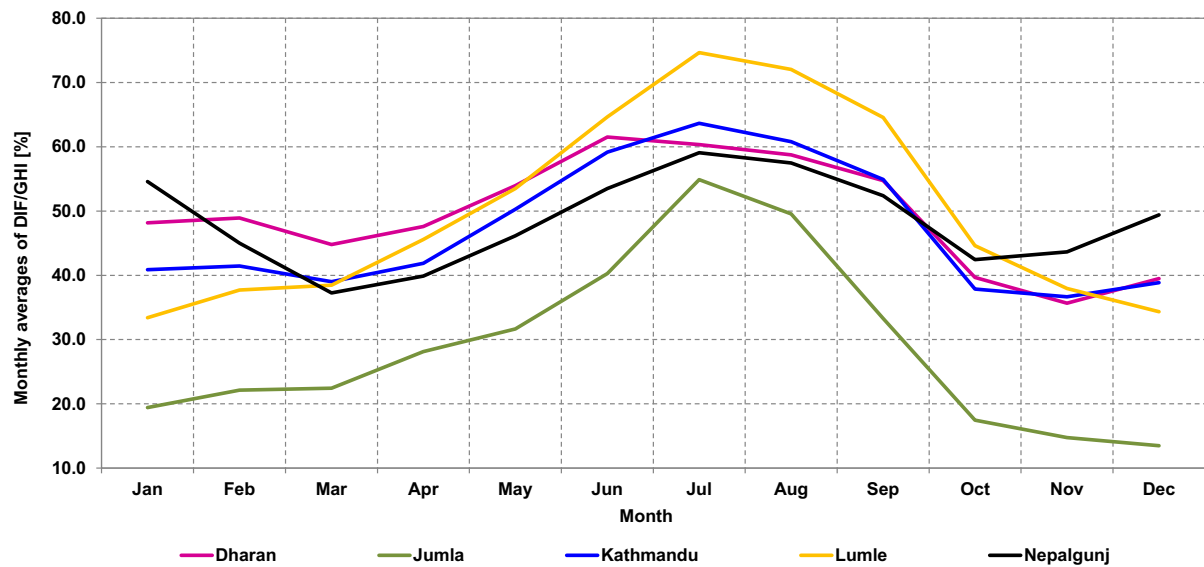
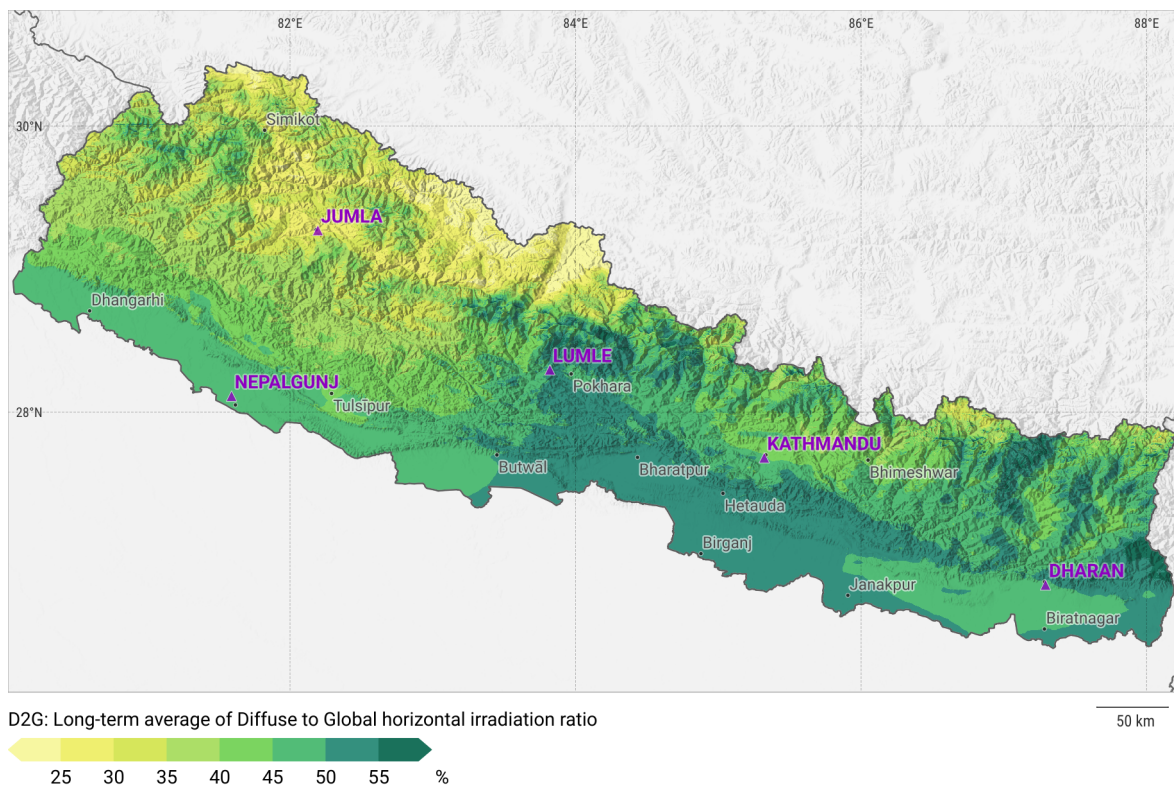


Figure 3.4: Monthly averages of DIF/GHI.



Map 3.14: Long-term average for ratio of diffuse and global irradiation (DIF/GHI).

Source: Solargis

3.4 Direct Normal Irradiation

Direct Normal Irradiation (DNI) is important solar resource parameter needed for the computation of Global Tilted Irradiation (GTI), which is an input parameter for evaluation of PV power potential (Chapter 3.5).

Table 3.3 and Figure 3.5 show long-term average daily totals of DNI for the five selected sites, during the period from 1999 to 2020. The highest DNI is reached in Jumla.

Table 3.3: Daily averages of Direct Normal Irradiation at five sites

Month	Direct Normal Irradiation [kWh/m ²]					Variability between sites [%]
	Dharan	Jumla	Kathmandu	Lumle	Nepalgunj	
January	3.49	6.64	4.29	5.19	2.66	34.6
February	3.68	6.94	4.48	4.79	4.16	26.2
March	4.55	7.67	5.21	5.08	5.68	21.4
April	4.27	6.82	4.96	4.35	5.56	20.2
May	3.43	6.33	3.94	3.42	4.73	27.9
June	2.50	4.80	2.86	2.27	3.44	31.9
July	2.41	2.73	2.17	1.27	2.54	25.6
August	2.59	3.20	2.39	1.46	2.65	25.7
September	2.84	5.23	2.90	2.08	3.26	36.2
October	4.64	8.17	5.05	4.21	4.65	30.1
November	5.09	8.11	4.99	4.71	4.34	27.8
December	4.47	7.61	4.56	4.97	3.34	31.8
YEAR	3.66	6.18	3.98	3.65	3.91	25.1

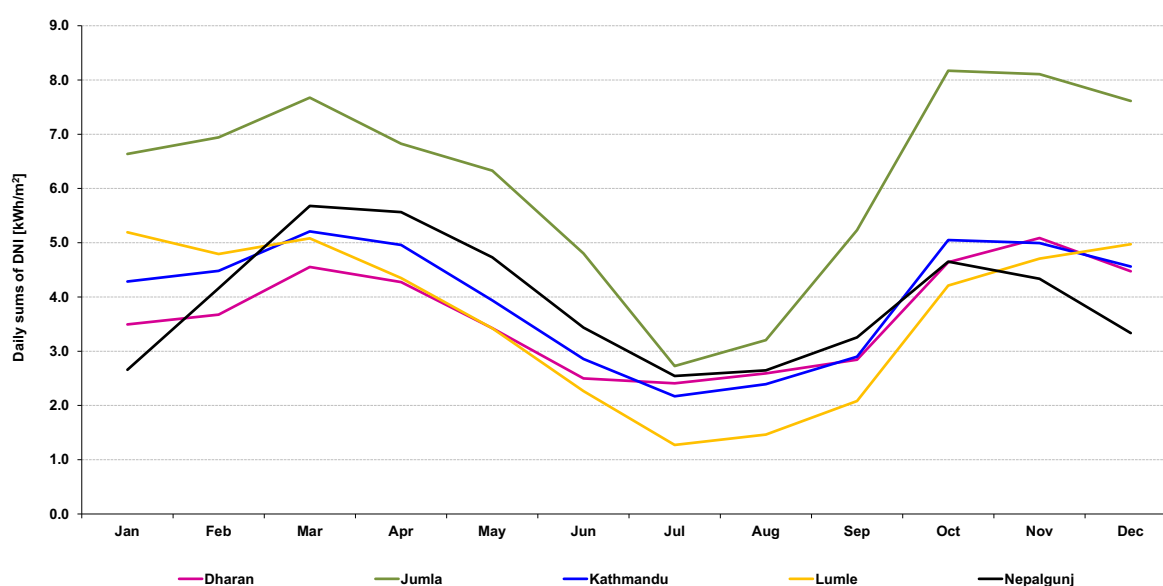


Figure 3.5: Daily averages of Direct Normal Irradiation at selected sites.

Interannual variability of DNI for selected sites (Figure 3.6) is calculated from the unbiased standard deviation of yearly DNI over 22 years and it is based on a simplified assumption of normal distribution of the yearly sums. Five sites show similar patterns of DNI variability over recorded period of time. The most stable DNI (the lowest interannual variability) is observed in Jumla.

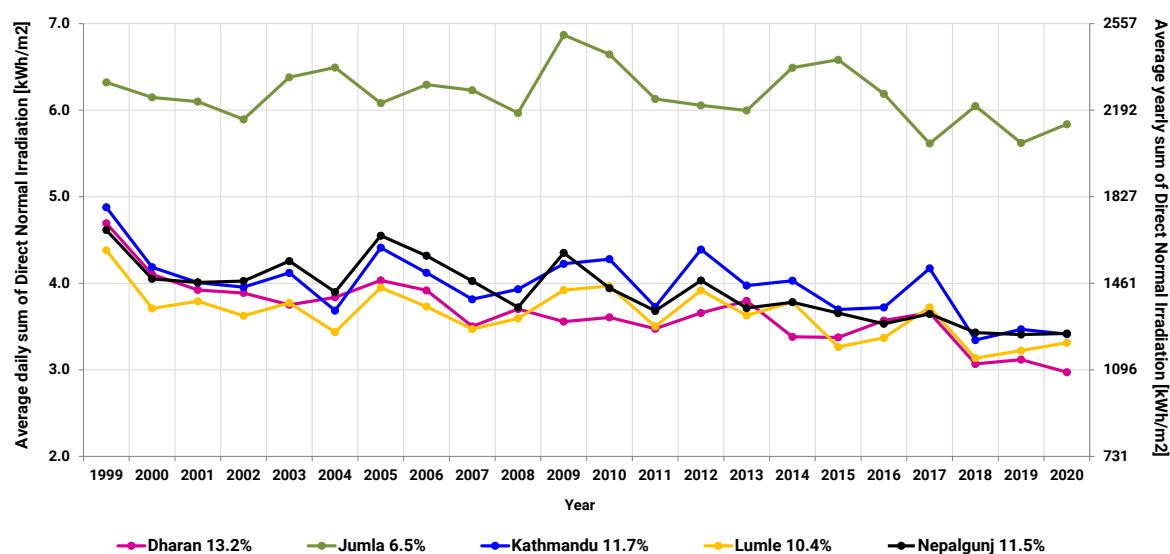
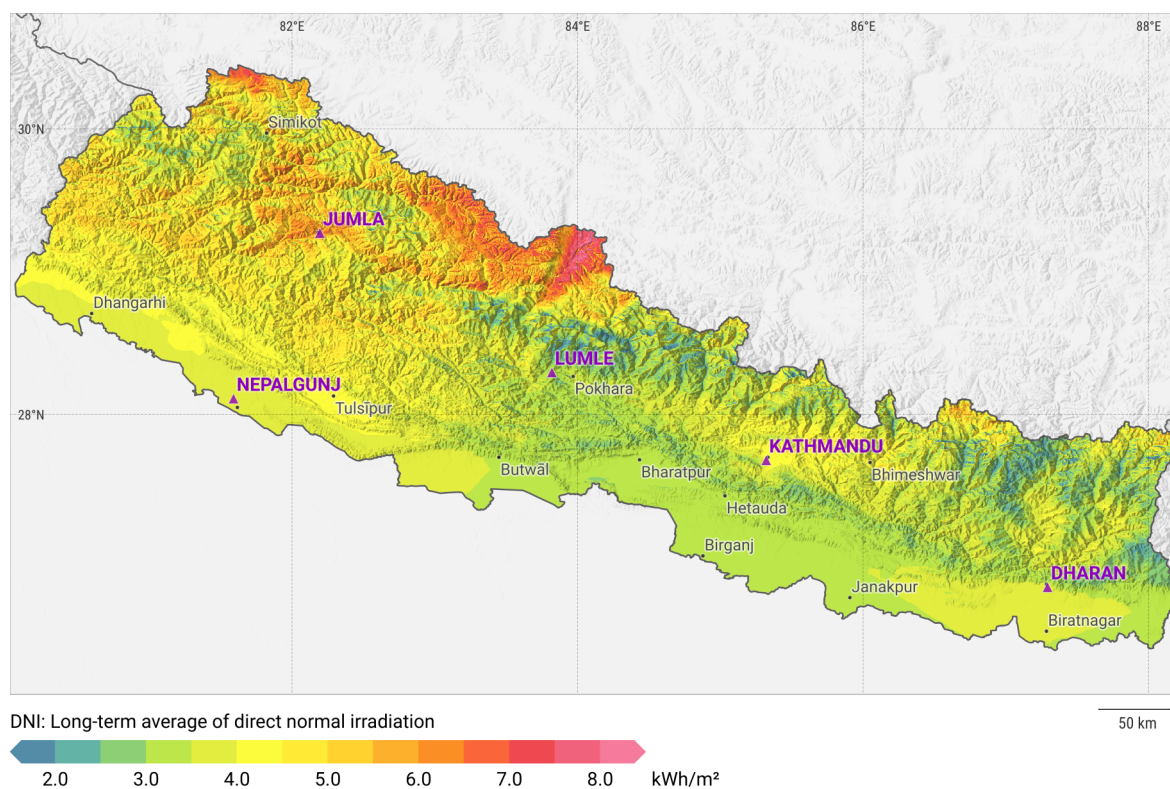
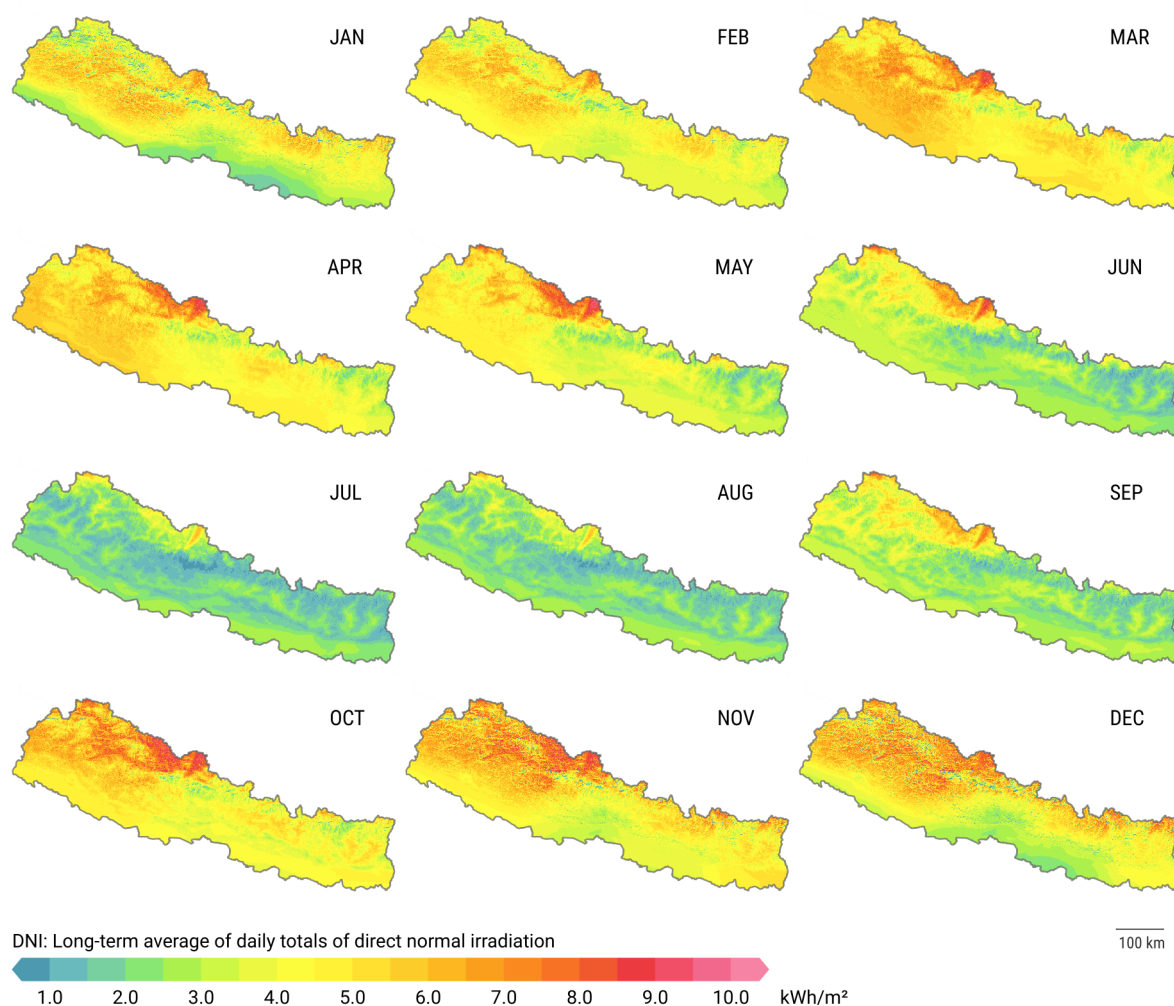


Figure 3.6: Interannual variability of Direct Normal Irradiation at selected sites



Map 3.15: Direct Normal Irradiation – long-term average of daily and yearly totals.
Source: Solargis

The highest DNI is observed the Northern Nepal, representing average daily totals over 7.0 kWh/m^2 (equal to yearly sum of about 2557 kWh/m^2 , [Map 3.15](#)). High DNI occurs in two seasons: between February and April and October to November, often exceeding the daily totals of 6.0 kWh/m^2 ([Map 3.16](#)). However, in July and August DNI daily totals drop significantly.



Map 3.16: Direct Normal Irradiation – long-term monthly average of daily totals.
Source: Solargis

3.5 Photovoltaic power potential: Fixed modules at optimum angle

The PV potential from a reference system for five representative sites is shown in Table 3.4. Despite the geographic distribution of selected sites, electricity production from a PV power system is similar for all sites and follows a combined pattern of global solar irradiation and air temperature. Considering five selected sites, the difference between PV production from the “best” site (Jumla, 4.88 kWh/kWp) and “the least productive” site (Dharan, 3.92 kWh/kWp), is 20%. Also, monthly power production profiles are very similar for all sites. The highest production occurs in March and April (Table 3.5 and Figure 3.7).

Table 3.4: Annual performance parameters of a PV system with modules fixed at the optimum angle

	Dharan	Jumla	Kathmandu	Lumle	Nepalgunj
PVOUT Average daily total [kWh/kWp]	3.92	4.88	4.08	4.06	4.04
PVOUT Average yearly total [kWh/kWp]	1433	1781	1492	1484	1474
Annual ratio of DIF/GHI	49.8%	29.2%	47.3%	50.2%	47.8%
System PR	75.5%	79.3%	77.4%	79.5%	74.7%

PVOUT - PV electricity yield for fixed-mounted modules at optimum angle; DIF/GHI – Ratio of Diffuse/Global horizontal irradiation;
PR - Performance ratio for fixed-mounted PV modules

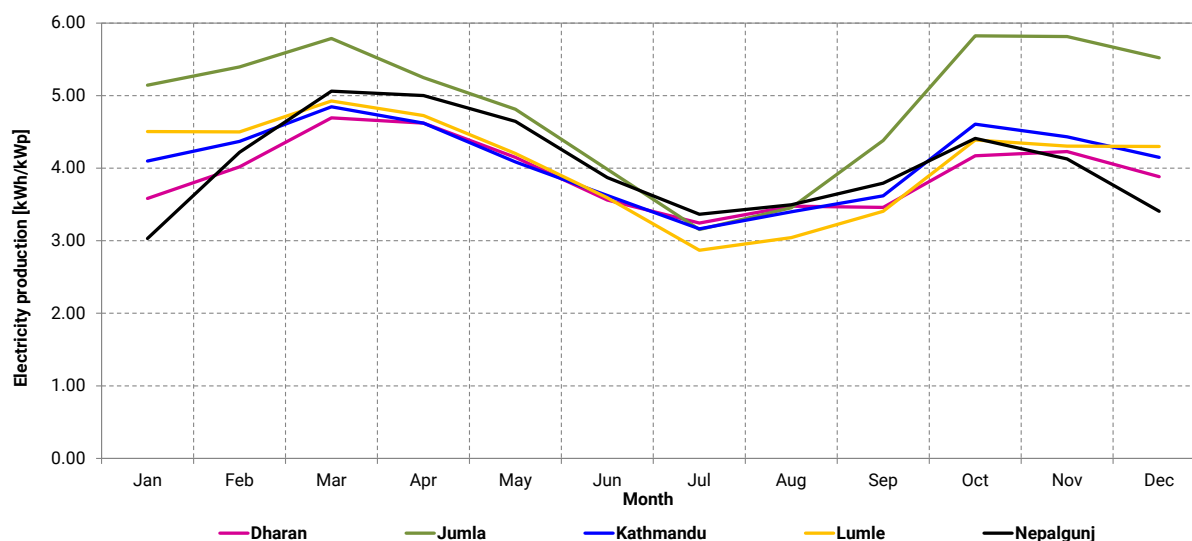


Figure 3.7: Monthly averages of daily totals of power production from the fixed tilted PV systems with a nominal peak power of 1 kW at five sites [kWh/kWp]

Table 3.5: Average daily sums of PV electricity output from an ground mounted fixed PV system with a nominal peak power of 1 kW [kWh/kWp]

Site	Average daily sum of electricity production [kWh/kWp]												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Dharan	3.58	4.02	4.69	4.62	4.15	3.56	3.24	3.48	3.46	4.17	4.23	3.88	3.92
Jumla	5.14	5.40	5.79	5.25	4.81	3.99	3.15	3.45	4.38	5.82	5.81	5.52	4.88
Kathmandu	4.10	4.37	4.85	4.62	4.09	3.62	3.16	3.40	3.62	4.61	4.43	4.15	4.08
Lumle	4.50	4.50	4.93	4.73	4.20	3.59	2.87	3.04	3.41	4.39	4.30	4.30	4.06
Nepalgunj	3.03	4.22	5.06	5.00	4.65	3.87	3.37	3.49	3.79	4.41	4.13	3.41	4.04

Maps 3.17 and 3.18 show yearly and monthly production from a PV power system, and Figure 3.7 breaks down the values for the five sites. The season of relatively high PV yield is long enough for the effective operation of a PV system. As shown in Chapter 3.5, in case of fixed mounted systems it is recommended to install modules inclined, with angle close to the optimum tilt towards equator rather than on a horizontal surface. Besides higher yield, a benefit of tilted modules is improved self-cleaning of the surface pollution by rain.

The monthly and yearly performance ratios (PR) of a reference installation for the selected sites are shown in Table 3.6 and Figure 3.8. The range of yearly PR for the selected sites is between 74.7% and 79.5%, with Lumle being the site with the highest PR (Chapter 2.3).

Table 3.6: Monthly and annual Performance Ratio of a free-standing PV system with fixed modules

Site	Monthly Performance Ratio [%]												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Dharan	78.9	77.2	74.8	73.6	73.9	74.3	74.5	74.5	74.5	75.1	76.8	78.5	75.5
Jumla	83.3	81.9	80.0	78.3	77.6	77.1	77.1	77.2	77.2	78.3	80.0	81.6	79.3
Kathmandu	80.7	79.0	77.1	75.6	75.8	75.8	76.0	75.9	76.1	76.9	78.8	80.5	77.4
Lumle	82.7	81.2	79.5	78.1	78.1	77.8	77.4	77.5	77.9	78.9	80.7	82.2	79.5
Nepalgunj	79.0	77.2	74.4	72.2	72.1	72.5	73.7	73.7	73.9	74.7	77.0	78.8	74.7

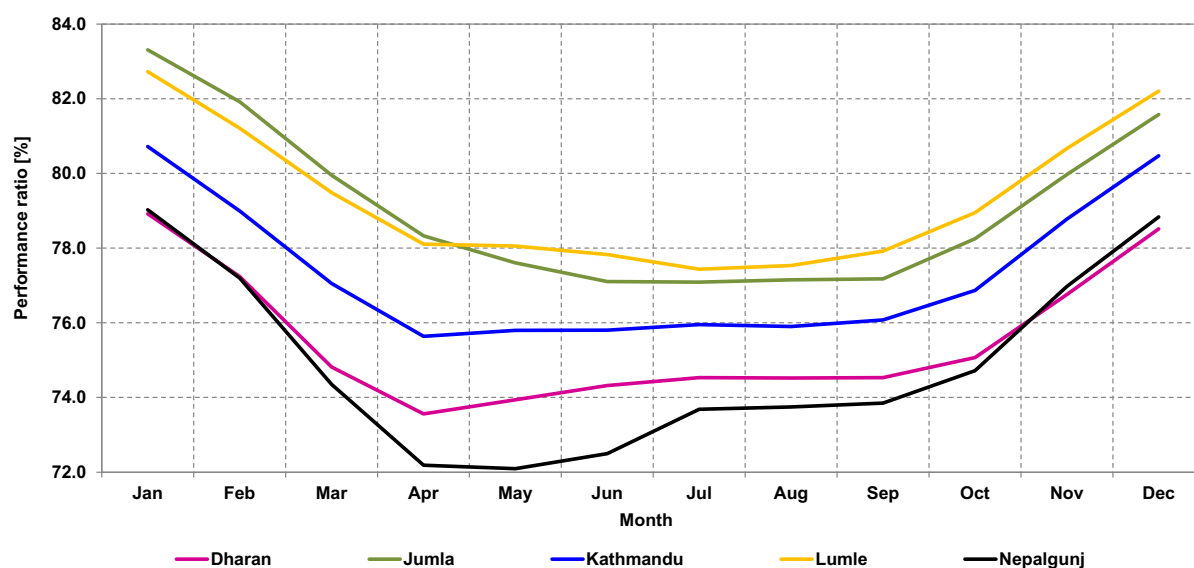
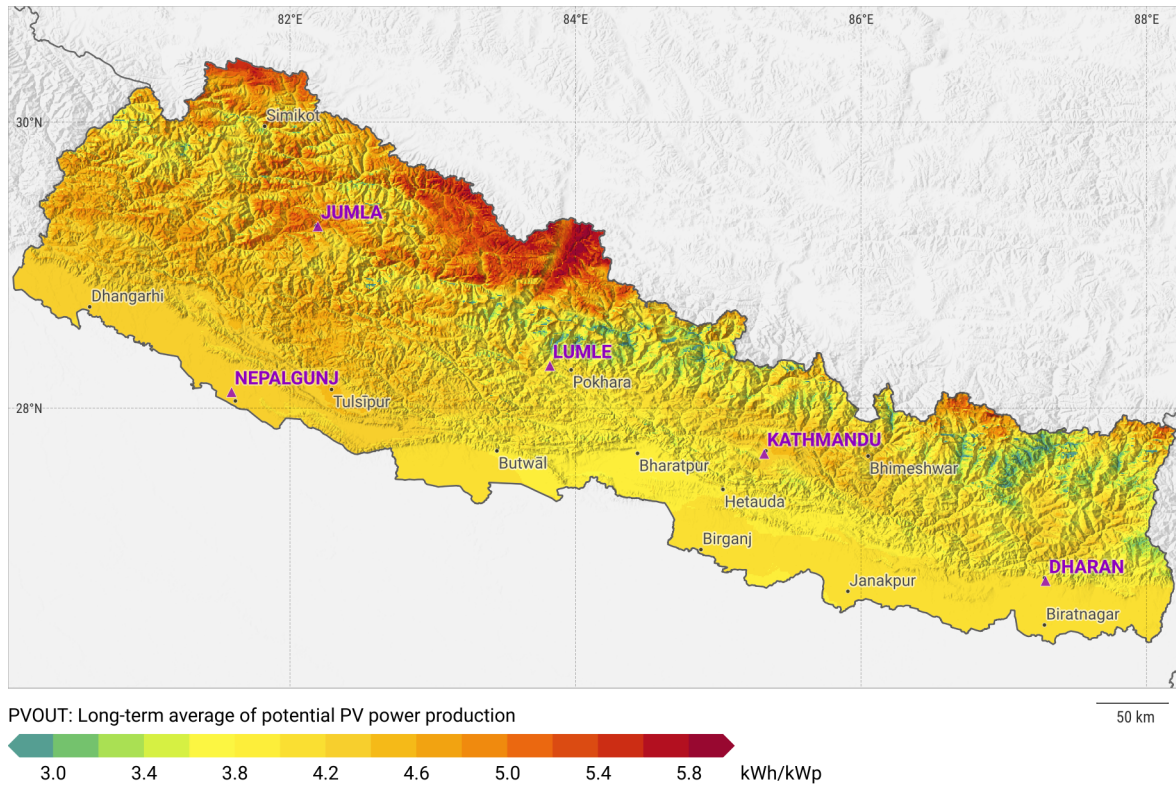


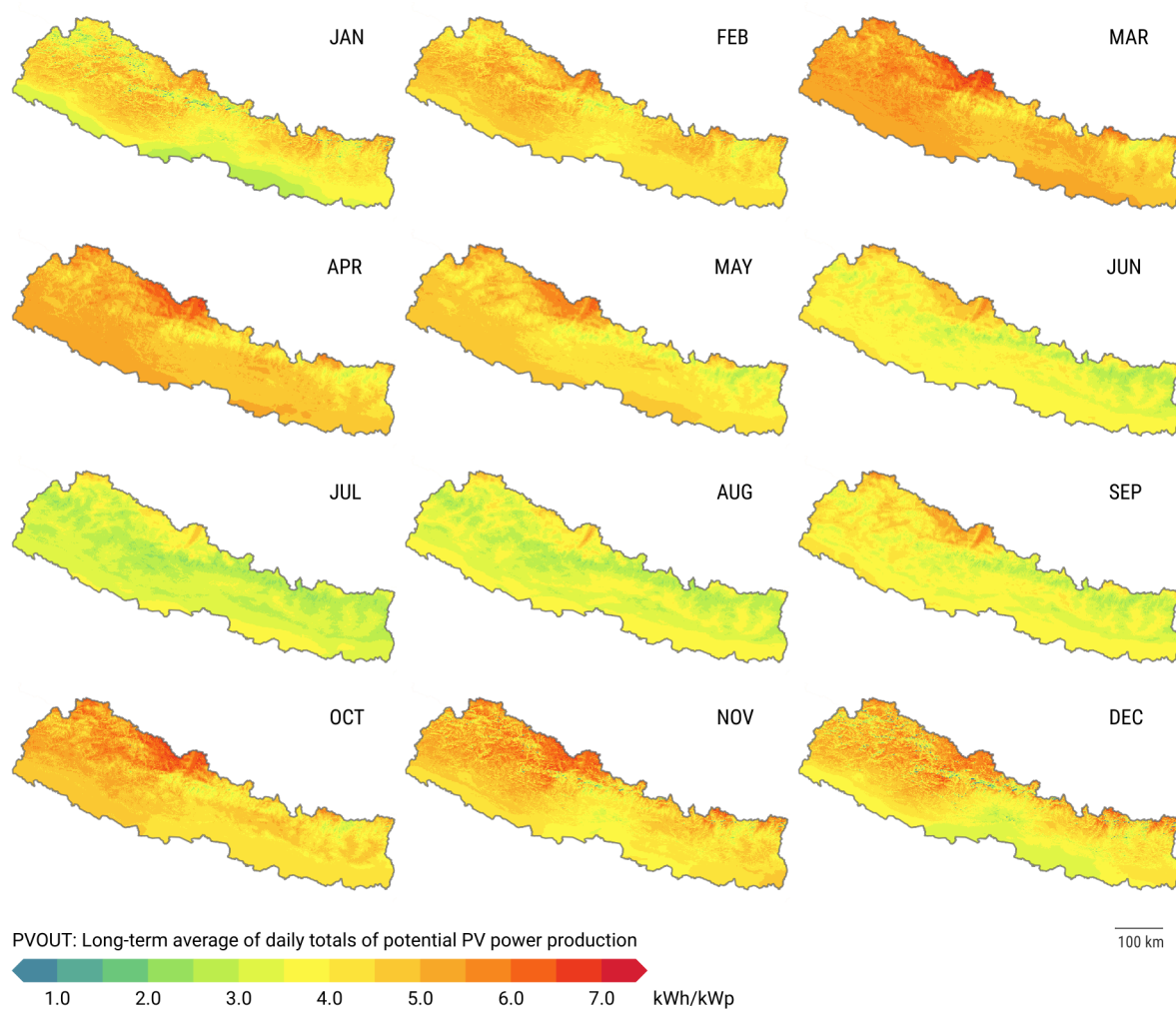
Figure 3.8: Monthly performance ratio of a PV system at selected sites. Fixed mounted modules at optimum tilt towards equator are considered

Map 3.17 shows the average daily total of specific PV electricity output from a typical open-space PV system with optimally tilted c-Si modules and a nominal peak power of 1 kW (thus the values are in kWh/kWp). Calculating PV output for 1 kWp of installed power makes it simple to scale the PV power production relative to the size of a power plant. Besides the technology choice, the electricity production depends on the geographical position of the power plant.



Map 3.17: PV electricity output from an open space fixed-mounted PV system with PV modules mounted at optimum tilt towards equator and a nominal peak power of 1 kWp. Long-term averages of daily and yearly totals.

In most regions of Nepal, the average daily sums of the specific PV power production from a reference system vary between 3.8 kWh/kWp (equals to yearly sum of about 1390 kWh/kWp) and 4.8 kWh/kWp (about 1750 kWh/kWp per year). The best months for PV power production are March, April and October, with highest values exceeding locally 5.8 kWh/kWp.



Map 3.18: PV power generation potential for an open-space fixed-mounted PV system.
Long-term monthly averages of daily totals.
Source: Solargis

3.6 Evaluation

The chapters above describe various aspects of PV power generation potential in Nepal, and its relevance for the development and operation of photovoltaic systems. In most regions, the average daily sums of the specific PV power production from a reference system vary between 3.8 kWh/kWp (this equals to yearly sum of about 1390 kWh/kWp) and 4.8 kWh/kWp (about 1750 kWh/kWp per year).

While the above-described PV power potential values position Nepal among the countries with average solar potential, very interesting feature is low seasonal variability: the ratio between months with maximum and minimum GHI is about 1.66 in Kathmandu, which is better than the ratio for e.g. Uppington in South Africa (2.29) or Sevilla in Spain (3.54) ([Figure 3.9](#)).

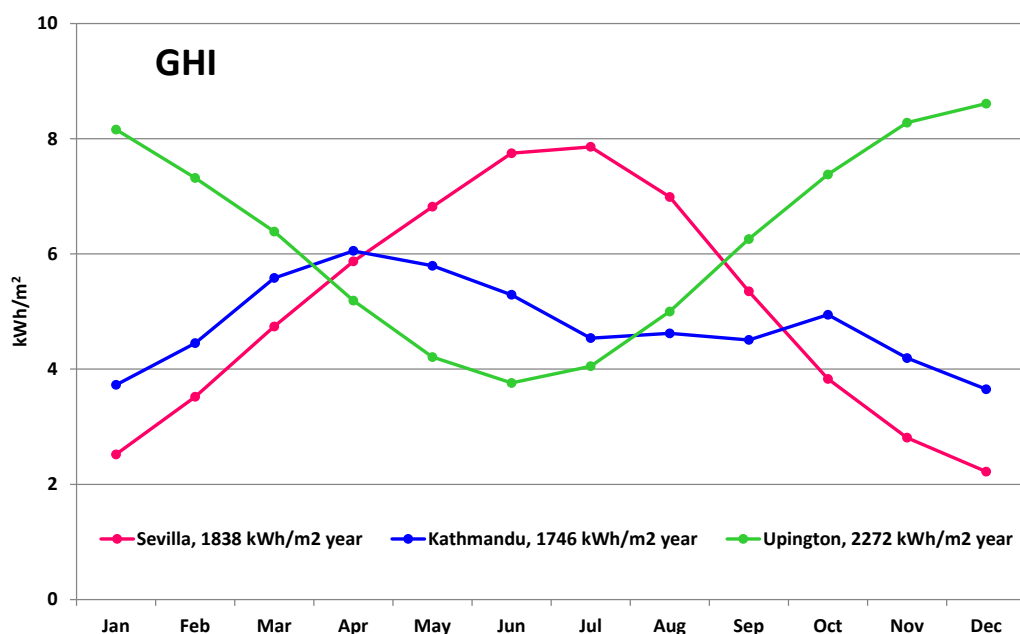


Figure 3.9: Comparing seasonal variability in three locations for GHI

4 Data delivered for Nepal

This Chapter describes technical features of data and maps /delivered for Nepal:

1. Site-specific time series and TMY data

The data for five sites, corresponding to the locations of solar meteorological stations, can be accessed through the web site <https://energydata.info/>:

- High accuracy **1-minute measurements** (time series) acquired over a period of 24 months (2018-2020)
- High accuracy model-adapted **15-minute historical time series and hourly Typical Meteorological Year (TMY)** data generated by the Solargis model. The data represent history of years 1999 to 2020

2. Country-wide spatial data (GIS files) and maps

These outputs can be accessed as downloadable GIS files and maps through the map-based web application <https://globalsolaratlas.info/>:

- Harmonized solar and meteorological **GIS-based data**. Regionally adapted solar resource, photovoltaic power potential and air temperature raster data layers for Nepal represent the long-term yearly and monthly averages, calculated for a period from 1999 to 2020.
- **Maps** – ready-to-print image files in poster-size format and medium-size format

More information about site specific data products is available in [29]. The information about spatial data products is available in chapters below.

The delivered data and maps offer a good basis for knowledge-based decision making and country-wide strategic planning. More detailed solar resource data, real-time data for solar monitoring, performance assessment and forecasting can be further provided by Solargis database.

4.1 Spatial data products

High-resolution Solargis data have been delivered in the format suitable for a GIS software. The *Primary data* represent solar resource, air temperature and PV power potential. The *Supporting data* include various vector data, such as administrative borders, cities, position of solar meteorological stations, etc. [Tables 4.1](#) and [4.2](#) show information about the data layers. Technical specification is summarized in [Tables 4.3](#) and [4.4](#). File name convention, used for the individual data sets, is described in [Table 4.5](#).

Metadata is delivered with the data files in two formats, according to ISO 19115:2003/19139 standards:

- PDF - human readable
- XML - for machine-to-machine communication

The snapshots of most of the data can be viewed on the maps in [Chapter 3](#).

Table 4.1: General information about GIS data layers

Geographical extent	Republic of Nepal, including approx. 10 km buffer zone along the country border between 26°N and 31°N, 79°E and 89°E
Map projection	Geographic (Latitude/Longitude), datum WGS84 (also known as GCS_WGS84; EPSG: 4326)
Data formats	ESRI ASCII raster data format (asc) GeoTIFF raster data format (tif)

Notes:

- Data layers of both formats (asc and tif) contain the same information; the operator is free to choose the preferential data format. Data layers can be also converted to other standard GIS raster formats.
- More information about ESRI ASCII grid format can be found at http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/ESRI_ASCII_raster_format/009t0000000z000000/
- More information about GeoTIFF format can be found at <https://trac.osgeo.org/geotiff/>

Table 4.2: Description of primary GIS data layers

Acronym	Full name	Unit	Type of use	Type of data layers
GHI	Global Horizontal Irradiation	kWh/m ²	Reference information for the assessment of flat-plate PV (photovoltaic) and solar heating technologies (e.g. hot water)	Long-term yearly and monthly average of daily totals
DNI	Direct Normal Irradiation	kWh/m ²	Assessment of Concentrated PV (CPV) and Concentrated Solar Power (CSP) technologies, but also calculation of GTI for fixed mounting and sun-tracking flat plate PV	Long-term yearly and monthly average of daily totals
DIF	Diffuse Horizontal Irradiation	kWh/m ²	Complementary parameter to GHI and DNI	Long-term yearly and monthly average of daily totals
GTI	Global Irradiation at optimum tilt towards equator	kWh/m ²	Assessment of solar resource for PV technologies	Long-term yearly and monthly average of daily totals
OPTA	Optimum tilt	°	Optimum tilt of PV modules to maximise the yearly yield	Long-term average
PVOUT	Photovoltaic power potential	kWh/kWp	Assessment of power production potential for a PV power plant with free-standing fixed-mounted c-Si modules, optimally tilted towards equator to maximize yearly PV production	Long-term yearly and monthly average of daily totals
TEMP	Air Temperature at 2 m above ground level	°C	Defines operating environment of solar power plants	Long-term (diurnal) annual and monthly averages

Table 4.3: Characteristics of the raster output data files

Characteristics	Range of values
West – East	79:00:00E – 89:00:00E
North – South	26:00:00N – 31:00:00N
Resolution GHI, DNI, GTI, DIF, PVOUT	00:00:09 (4000 columns x 2000 rows)
Resolution TEMP	00:00:30 (1200 columns x 600 rows)
Resolution OPTA	00:02:00 (300 columns x 150 rows)
Data type	Float
No data value	-9999, NaN

Table 4.4: Technical specification of primary GIS data layers

Acronym	Full name	Data format	Spatial resolution (pixel size)	Time representation	No. of data layers
GHI	Global Horizontal Irradiation	Raster	9 arc-sec. (approx. 245 x 275 m)	1999 – 2020	12+1
DNI	Direct Normal Irradiation	Raster	9 arc-sec. (approx. 245 x 275 m)	1999 – 2020	12+1
DIF	Diffuse Horizontal Irradiation	Raster	9 arc-sec. (approx. 245 x 275 m)	1999 – 2020	12+1
GTI	Global Irradiation at optimum tilt towards equator	Raster	9 arc-sec. (approx. 245 x 275 m)	1999 – 2020	12+1
OPTA	Optimum tilt	Raster	2 arcmin (approx. 3300 x 3700 m)	-	1
PVOUT	Photovoltaic power potential	Raster	30 arc-sec. (approx. 825 x 925 m)	1999 – 2020	12+1
TEMP	Air Temperature at 2 m above ground level	Raster	30 arc-sec. (approx 825 x 925 m)	1999 – 2020	12+1

Data layers are provided as separate files in a tree structure, organized according to

- File format (ASCII or GEOTIF)
- Time summarization (*yearly* and *monthly*)
- Complementary files: Project files (*.prj) and ESRI ASCII grid files (*.asc)

Total size of unpacked data layers is 3.0 GB, packed (with ZIP compression) 0.7 GB respectively.

The support GIS data are provided in a vector format (ESRI shapefile, [Table 4.6](#)).

Table 4.5: File name convention for GIS data

Acronym	Full name	Filename pattern	Number of files
GHI	Global Horizontal Irradiation, long-term yearly average of daily totals	GHI.ext	1+1
GHI	Global Horizontal Irradiation, long-term monthly averages of daily totals	GHI_MM.ext	12+12
DNI	Direct Normal Irradiation, long-term yearly average of daily totals	DNI.ext	1+1
DNI	Direct Normal Irradiation, long-term monthly averages of daily totals	DNI_MM.ext	12+12
DIF	Diffuse Horizontal Irradiation, long-term yearly average of daily totals	DIF.ext	1+1
DIF	Diffuse Horizontal Irradiation, long-term monthly averages of daily totals	DIF_MM.ext	12+12
GTI	Global Irradiation at optimum tilt towards equator, long-term yearly average of daily totals	GTI.ext	1+1
GTI	Global Irradiation at optimum tilt towards equator, long-term monthly averages of daily totals	GTI_MM.ext	12+12
PVOUT	Photovoltaic power potential, long-term yearly average of daily totals	PVOUT.ext	1+1
PVOUT	Photovoltaic power potential, long-term monthly averages of daily totals	PVOUT_MM.ext	12+12
TEMP	Air Temperature at 2 m above ground, long-term yearly average	TEMP.ext	1+1
TEMP	Air Temperature at 2 m above ground, long-term monthly averages	TEMP_MM.ext	12+12

Explanation:

- MM: month of data – from 01 to 12
- ext: file extension (*asc* or *tif*)

Table 4.6: Support GIS data

Data type	Source	Data format
City location	OpenStreetMap.org contributors, GeoNames.org, adapted by Solargis	Point shapefile
Administrative borders	GADM v3.6	Polyline shapefile
Road network	OpenStreetMap.org contributors, adapted by Solargis	Polyline shapefile
Solar meteorological stations	ESMAP	Point shapefile

4.2 Project in QGIS format

For easy manipulation with GIS data files, selected vector and raster data files are integrated into ready-to-open QGIS project file with colour styles and annotations (see Figure 4.1). QGIS is state-of-art open-source GIS software allowing visualization, query and analysis on the provided data. QGIS includes a rich toolbox to manipulate data. More information about the software and download packages can be found at <http://qgis.org>.

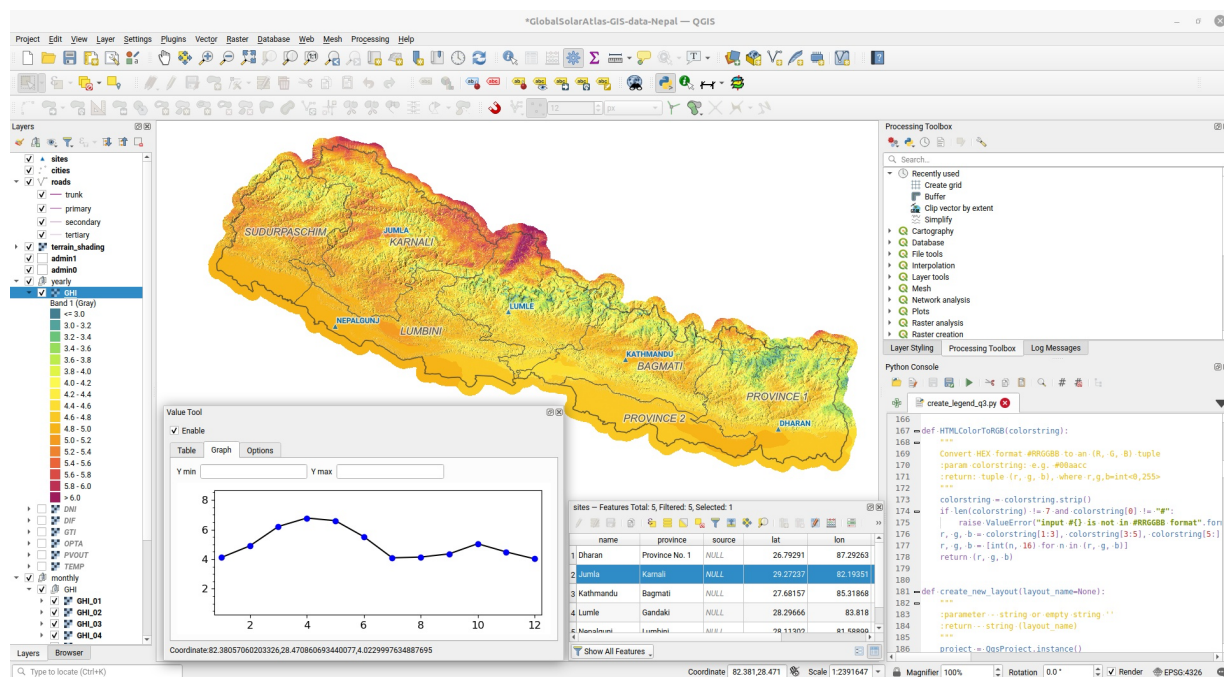


Figure 4.1: Screenshot of the map and data in the QGIS v3.16 environment

4.3 Map images

Besides GIS data layers, digital maps are also delivered for selected data layers for presentation purposes. Digital images (maps) are prepared in two types; each suitable for different purpose:

- High-resolution **poster maps**, printing size 120 x 80 cm, prepared as the colour-coded maps in a TIFF format at 300 dpi density and lossless compression
- **Mid-size maps** suitable for A4 printing or on-screen presentation, prepared in PNG format at 300 dpi density and lossless compression

The following three parameters are processed in the form of maps:

- Global Horizontal Irradiation – Yearly average of the daily totals
- Direct Normal Irradiation – Yearly average of the daily totals
- Photovoltaic electricity production from a free-standing power plant with optimally tilted c-Si modules – Yearly average of the daily totals

The maps will be released to be downloadable from the Download section of Global Solar Atlas (see Figure 4.2): <http://globalsolaratlas.info/downloads/nepal>

GLOBAL SOLAR ATLAS
Home About Us Downloads Map PV study Download About v Contact

Map and data downloads

Download maps for your country or region

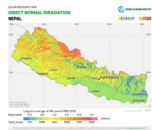
Solar resource and PV power potential maps and GIS data can be downloaded from this section. Maps and data are available for 147 countries (eligible for the support from Development Assistance Committee acting under OECD) and selected regions. Please use the table below to select a region or a country. The maps and data have been prepared by Solargis for The World Bank. They are provided under CC BY 4.0 license with the following mandatory and binding addition (see [Terms of use](#) for more information).

Region or Nepal

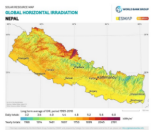
Nepal

MID-SIZE MAPS

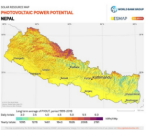
This set of maps is optimized for on-screen presentations (e.g. PowerPoint, Web, etc.) and for letter page printing (A4 format or similar). The maps are provided in the loss-less PNG format, with the approximate size 1 to 4 MPN.



Direct normal irradiation
Optimal print size: 106 x 134 mm
Format: PNG, 1.62 MB
[Download](#)



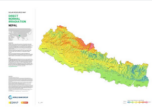
Global horizontal irradiation
Optimal print size: 106 x 134 mm
Format: PNG, 1.62 MB
[Download](#)



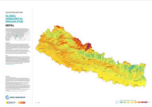
Photovoltaic power potential
Optimal print size: 106 x 134 mm
Format: PNG, 1.62 MB
[Download](#)

POSTER MAPS

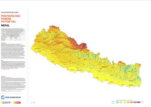
Ready-to-print image files for poster-size formats (plotter, wall-printing, foam boards, solid boards, large stickers, etc.). The files are provided in the loss-less TIF format with the approximate size of 100 MPN.



Direct normal irradiation
Optimal print size: 1200 x 800 mm
Format: TIF, 39.01 MB
[Download](#)



Global horizontal irradiation
Optimal print size: 1200 x 800 mm
Format: TIF, 31.8 MB
[Download](#)



Photovoltaic power potential
Optimal print size: 1200 x 800 mm
Format: TIF, 25.01 MB
[Download](#)

GIS DATA

Data can be used for visualization, further processing, and geo-analysis in all [mainstream GIS software](#) with raster data processing capabilities (such as open source [QGIS](#), commercial [ESRI ArcGIS](#) products and others).

LTaym_AngDailyTotals	GIS data - LTaym_AngDailyTotals (AAGIS) Data format: AAGIS File size: 14.23 MB
	GIS data - LTaym_AngDailyTotals (GeoTIFF) Data format: GeoTIFF File size: 21.04 MB
LTaym_YearlyMonthlyTotals	GIS data - LTaym_YearlyMonthlyTotals (AAGIS) Data format: AAGIS File size: 13.41 MB
	GIS data - LTaym_YearlyMonthlyTotals (GeoTIFF) Data format: GeoTIFF File size: 23.03 MB

Figure 4.2: Screenshot of the Download section at Global Solar Atlas (May 2021)
(<https://globalsolaratlas.info/downloads/nepal>)

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8 References

- [1] Paul W. Stackhouse, Jr., Zhang T., Westberg D., Barnett A.J., Bristow T., Macpherson B., Hoell J. M., 2018. POWER Release 8 (with GIS Applications) Methodology (Data Parameters, Sources, & Validation), Data Version 8.0.1. https://power.larc.nasa.gov/documents/POWER_Data_v8_methodology.pdf. Web visited on 3 Oct 2018
- [2] Šúri M., Wald L., Huld T., Dunlop E., Albuissou M., 2005. Integration of HelioClim-1 database into PVGIS to estimate solar electricity potential in Africa. In: Palz W., Ossenbrink H., Helm P., (eds.) 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 6-10 June 2005, Barcelona, pp. 2989-2992" <https://www.researchgate.net/publication/43406677>
- [3] Huld T., Müller R.W., Gambardella A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy* 86 (6), 1803–1815. DOI: 10.1016/j.solener.2012.03.006
- [4] Lefèvre M., Wald L., Diabaté L., 2007. "Using reduced data sets ISCCP-B2 from the Meteosat satellites to assess surface solar irradiance". *Solar Energy*, 81, 240-253. doi:10.1016/j.solener.2006.03.008
- [5] ARMINES/MINES ParisTech/TRANSVALOR/ ECMWF – COPERNICUS Atmosphere Monitoring Service. Monthly and yearly average Global Horizontal Irradiation maps from CAMS Radiation Service over Africa. "JADE" volume, April 2018
- [6] Meteoronorm handbook, Version 7.3, Part II: Theory. Meteotest, 2018
- [7] Global Solar Atlas, 2016. The World Bank Group. <https://globalsolaratlas.info>.
- [8] Marcel Suri, Tomas Cebecauer, Branislav Schnierer, Artur Skoczek, Daniel Chrkavy, Nada Suriova, Juraj Betak, 2018. Annual Solar Resource Report for solar meteorological stations after completion of 24 months of measurements. Republic of Nepal, Ref. Nr. 128-07/2018, <https://www.esmap.org/node/55906>.
- [9] Perez R., Cebecauer T., Suri M., 2014. Semi-Empirical Satellite Models. In Kleissl J. (ed.) *Solar Energy Forecasting and Resource Assessment*. Academic press.
- [10] Cebecauer T., Šúri M., Perez R., High performance MSG satellite model for operational solar energy applications. ASSES National Solar Conference, Phoenix, USA, 2010.
- [11] Šúri M., Cebecauer T., Perez P., Quality procedures of SolarGIS for provision site-specific solar resource information. Conference SolarPACES 2010, September 2010, Perpignan, France.
- [12] Šúri M., Cebecauer T., 2014. Satellite-based solar resource data: Model validation statistics versus user's uncertainty. ASSES SOLAR 2014 Conference, San Francisco, 7-9 July 2014.
- [13] Cebecauer T., Suri M., Gueymard C., Uncertainty sources in satellite-derived Direct Normal Irradiance: How can prediction accuracy be improved globally? Proceedings of the SolarPACES Conference, Granada, Spain, 20-23 Sept 2011.
- [14] Šúri M., Cebecauer T., Requirements and standards for bankable DNI data products in CSP projects, Proceedings of the SolarPACES 2011 Conference, September 2011, Granada, Spain.
- [15] Ineichen P., A broadband simplified version of the Solis clear sky model, 2008. *Solar Energy*, 82, 8, 758-762.
- [16] Morcrette J., Boucher O., Jones L., Salmond D., Bechtold P., Beljaars A., Benedetti A., Bonet A., Kaiser J.W., Razinger M., Schulz M., Serrar S., Simmons A.J., Sofiev M., Suttie M., Tompkins A., Uncht A., GEMS-AER team, 2009. Aerosol analysis and forecast in the ECMWF Integrated Forecast System. Part I: Forward modelling. *Journal of Geophysical Research*, 114.
- [17] Benedictow A. et al. 2012. Validation report of the MACC reanalysis of global atmospheric composition: Period 2003-2010, MACC-II Deliverable D_83.1.
- [18] Cebecauer T., Perez R., Suri M., Comparing performance of SolarGIS and SUNY satellite models using monthly and daily aerosol data. Proceedings of the ISES Solar World Congress 2011, 28 August – 2 September 2011, Kassel, Germany.
- [19] Cebecauer T., Šúri M., Accuracy improvements of satellite-derived solar resource based on GEMS re-analysis aerosols. Conference SolarPACES 2010, September 2010, Perpignan, France.
- [20] Molod, A., Takacs, L., Suarez, M., and Bacmeister, J., 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015
- [21] GFS model. <http://www.nco.ncep.noaa.gov/pmb/products/gfs/>
- [22] European Centre for Medium-Range Weather Forecasts. 2017, updated monthly. ERA5 Reanalysis. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. <https://doi.org/10.5065/D6X34W69>. Accessed 30-04-2019.

- [23] MERRA-2 Overview: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Ronald Gelaro, et al., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1
- [24] CFSR model. <https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr/>
- [25] CFSv2 model <http://www.cpc.ncep.noaa.gov/products/CFSv2/CFSv2seasonal.shtml>
- [26] Cano D., Monget J.M., Albuissou M., Guillard H., Regas N., Wald L., 1986. A method for the determination of the global solar radiation from meteorological satellite data. *Solar Energy*, 37, 1, 31–39.
- [27] Perez R., Ineichen P., Maxwell E., Seals R. and Zelenka A., 1992. Dynamic global-to-direct irradiance conversion models. *ASHRAE Transactions-Research Series*, pp. 354-369.
- [28] Perez, R., Seals R., Ineichen P., Stewart R., Menicucci D., 1987. A new simplified version of the Perez diffuse irradiance model for tilted surfaces. *Solar Energy*, 39, 221-232.
- [29] Ruiz-Arias J. A., Cebecauer T., Tovar-Pescador J., Šúri M., Spatial disaggregation of satellite-derived irradiance using a high-resolution digital elevation model. *Solar Energy*, 84, 1644-1657, 2010.
- [30] Marcel Suri, Tomas Cebecauer, Marcel Suri, Branislav Schnierer, Nada Suriova, Juraj Betak, Daniel Chrkavy, Artur Skoczek, 2019. Solar Model Validation Report; Regional adaptation of Solargis model based on data acquired in 24-months solar measurement campaign; Republic of Nepal, Ref. Nr. 128-08/2019. <https://www.esmap.org/node/55906>.
- [31] Ineichen P. Long term satellite hourly, daily and monthly global, beam and diffuse irradiance validation. Interannual variability analysis. University of Geneva/IEA SHC Task 46, 2013. <http://www.unige.ch/energie/forel/energie/equipe/ineichen/annexes-iae.html>
- [32] Cebecauer T., Suri M., 2015. Site-adaptation of satellite-based DNI and GHI time series: overview and Solargis approach. SolarPACES conference, September 2015, Cape Town, North Africa.
- [33] King D.L., Boyson W.E. and Kratochvil J.A., Photovoltaic array performance model, SAND2004-3535, Sandia National Laboratories, 2004.
- [34] Huld T., Šúri M., Dunlop E.D., Geographical variation of the conversion efficiency of crystalline silicon photovoltaic modules in Europe. *Progress in Photovoltaics: Research and Applications*, 16, 595-607, 2008.
- [35] Huld T., Gottschalg R., Beyer H. G., Topic M., Mapping the performance of PV modules, effects of module type and data averaging, *Solar Energy*, 84, 2, 324-338, 2010.
- [36] Huld T., Friesen G., Skoczek A., Kenny R.P., Sample T., Field M., Dunlop E.D., 2011. A power-rating model for crystalline silicon PV modules. *Solar Energy Materials and Solar Cells*, 95, 12, 3359-3369.
- [37] Skoczek A., Sample T., Dunlop E. D., The results of performance measurements of field-aged crystalline silicon photovoltaic modules, *Progress in Photovoltaics: Research and Applications*, 17, 227-240, 2009.
- [38] Martin N., Ruiz J.M. Calculation of the PV modules angular losses under field conditions by means of an analytical model. *Solar Energy Material and Solar Cells*, 70, 25–38, 2001.
- [39] The German Energy Society, 2008: Planning and Installing Photovoltaic Systems. A guide for installers, architects and engineers. Second edition. Earthscan, London, Sterling VA.
- [40] Access to electricity, Nepal. (n.d.). The World Bank, Indicators. <https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2019&locations=NP&start=1996&view=chart>
- [41] Solar resource and photovoltaic potential of Nepal (English). Energy Sector Management Assistance Program Washington, D.C., World Bank Group, 2017. <http://documents.worldbank.org/curated/en/585921519658176633/Solar-resource-and-photovoltaic-potential-of-Nepal>

Support information

Background on Solargis

Solargis is a technology company offering energy-related meteorological data, software, and consultancy services to solar energy. We support industry in the site qualification, planning, financing, and operation of solar energy systems for 20+ years. We develop and operate the high-resolution global database and applications integrated within Solargis® information system. Accurate, standardised, and validated data help to reduce the weather-related risks and costs in system planning, performance assessment, forecasting and management of distributed solar power.



ISO 9001
LL-C (Certification)

Solargis is ISO 9001:2015 certified company for quality management.

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All maps in this report are prepared by Solargis

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<https://solargis.com>

