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ESMAP
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SOLAR RESOURCE AND PV POTENTIAL OF THE MALDIVES

SOLAR RESOURCE ATLAS

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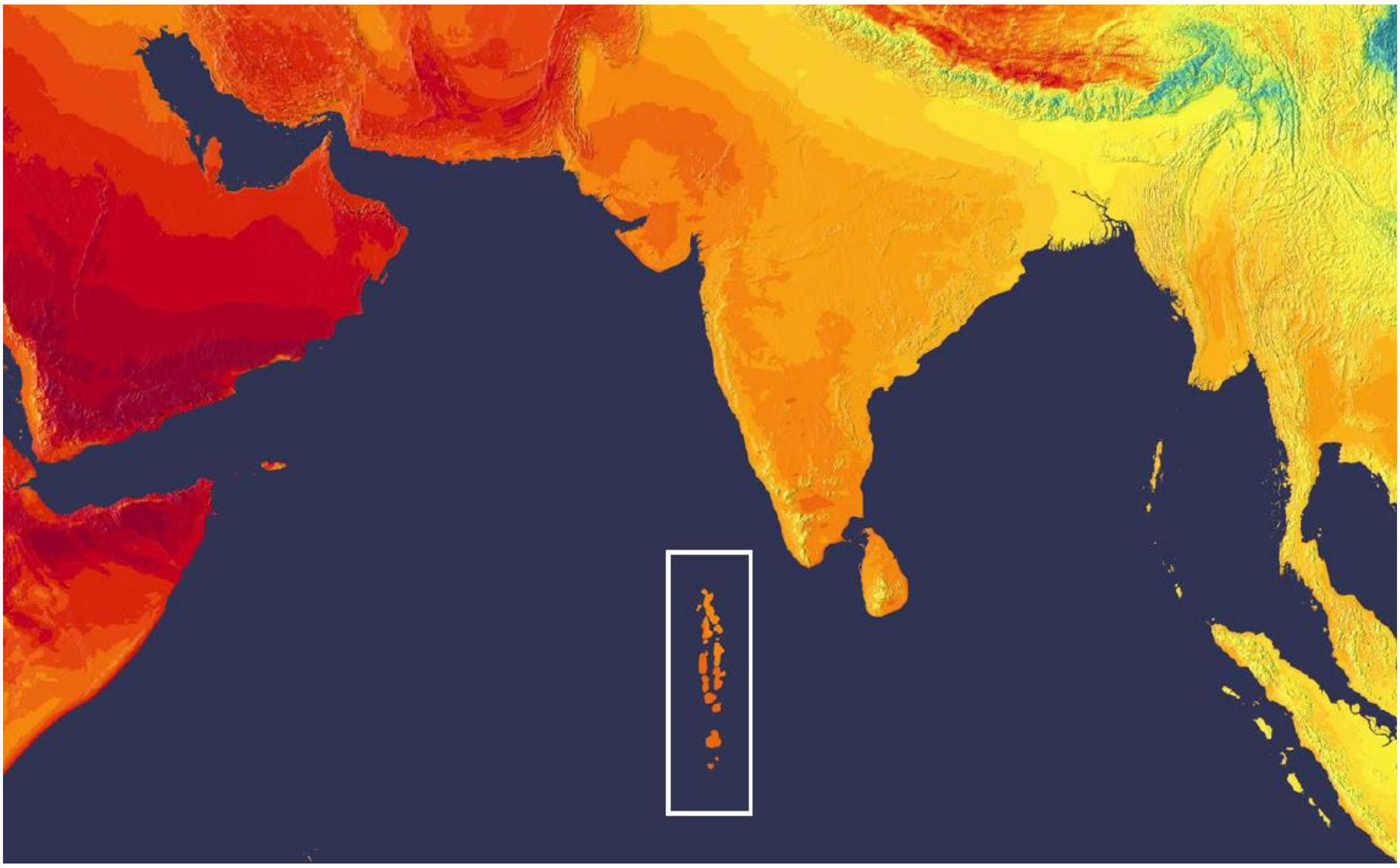

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This document is a **final output** from the above-mentioned project, and the content is the sole responsibility of the consultant authors. Users are strongly advised to exercise caution when utilizing the information and data contained, as this may include preliminary data and/or findings, and the document has not been subject to full peer review. Final outputs from this project will be marked as such, and any improved or validated solar resource data will be incorporated into the Global Solar Atlas.

Solar Resource Atlas

Based on regional adaptation of Solargis model

Republic of Maldives

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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 notabe 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.
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	Meteosat satellite operated by EUMETSAT organization. IODC: Indian Ocean Data Coverage
MERRA	Modern-Era Retrospective Analysis for Research and Applications, a NASA reanalysis for the satellite era using an Earth observing systems
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: $RMSD = \sqrt{\frac{\sum_{k=1}^{n}\left(X^{k}{}_{measured} - X^{k}_{modeled}\right)^{2}}{n}}$ 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 mapping activity undertaken by The World Bank in Maldives, as a part of a broader technical assistance project covering biomass, solar and wind mapping funded by the Energy Sector Management Assistance Program (ESMAP).

The data used in this report is based on the Solargis model. The uncertainty of the solar resource data has been reduced by the regional model adaptation based on the ground measurements collected at four solar meteorological stations across Maldives, commissioned by The World Bank during the years 2015 to 2018 under the same activity. The ground-based solar resource measurements have been supplied by Suntrace GmbH, Germany. The measurement campaign has been technically supported by Renewable Energy Maldives company, based in Maldives.

The report has two objectives:

- To explain the methodologies and outcomes of the solar resource and photovoltaic power potential assessment, based on the combined use of models and measured data. The report documents the uncertainty of solar and meteorological data as key inputs in the technical and financial evaluation of solar energy systems.
- To improve the awareness and knowledge of resources for solar energy technologies by producing a comprehensive countrywide dataset and maps based on the accuracy-enhanced models. 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 compare to interim solar resource validation at the beginning of the project, which were based on the Solargis model, validated by the ground measurements available in a wider region (*ESMAP Solar Resource Mapping for Maldives, Interim Solar Modelling Report, 129-01/2015, February 2015*). The uncertainty of the Solargis model yearly estimates for DNI, has been reduced from the original ±12.0% for yearly values to ±6.0% for the accuracy enhanced values. For yearly GHI, the uncertainty was reduced from the original ±6.0% to ±3.5% for the accuracy enhanced values.

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

- Raster GIS data for the whole territory of the Republic of Maldives, 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 Maldives, yearly sum of global horizontal irradiation is in the range of 2000 to 2050 kWh/m^2. This translates to a specific yearly PV electricity output in the range of 1530 kWh/kWp to 1600 kWh/kWp. The seasonal variability is very low, compared to other countries further away from the equator. This qualifies Maldives as a country with highly feasible potential for PV power generation.

The aggregated data for Maldives 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

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 in remote locations, thus providing development opportunities anywhere.

Access to electricity in Maldives is nearly universal. Power generation in the archipelago (Map 3.1) is based almost exclusively on imported diesel fuel. Installed capacity on the 194 inhabited islands, with more than 440,000 inhabitants, is about 140 megawatts (MW), while an additional 100 resort islands have a generation capacity of about 105 MW, operated independently [5]. Maldives is a middle-income country that remains highly dependent on imported goods and is increasingly vulnerable to the effects of climate change. Based on [1], fuel imports accounted for 31% of GDP in 2013, and electrical energy usage has been rising more than 10% annually.

The end-user tariff is very high (20 to 56 U.S. cents per kWh with fuel surcharge. Providing the energy to the dispersed population is a large undertaking, and a burden on public expenditure.

Land constrains limit the deployment of ground mounted PV and. Rooftop installations are options, as well as installation of solar PV on floating platforms, anchored close to shore and connected to the electricity grid using undersea cables. Battery storage supports high shares of PV and wind; however, the costs needs to be carefully evaluated.

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 instruments installed at meteorological stations.

1.1 Review of studies analysing the solar power generation potential

Adoption of PV systems in the Maldives: A technological review

The study by H. Hameed from the Maldives National University, published in 2015 [1], provides an extensive review of PV history in Maldives and coming opportunities:

- Explains the adoption of PV systems in the Maldives from a historical perspective
- Synthesize information on PV system technology, architecture, reliability, failures and performance
- Identifies research gaps and recommend new research areas for Maldives.

The study elaborates on solar potential evaluation based on the results of the studies by Utrecht University, JICA and NREL [2, 3, 6]. The assessment quoted in the study is made more accurate by this report.

Renewable energy technologies in the Maldives — Realizing the potential

The study authored by K. van Alphena, M.P. Hekkerta and W.G.J.H.M. van Sark from the Utrecht University confirms that the techno-economic potential of renewable energy technologies (RET) in the Maldives is substantial [2]. However, the implementation of these technologies is strongly influenced by social, institutional and political factors.

The study evaluates success of the outcomes of the projects initiated by the Global Environmental Facility, the United Nations Development Program, and the European Commission. The authors show that these programs strengthen most of the key processes necessary in an innovation system conducive to RET transfer. However, as not enough attention is being paid to local entrepreneurial activities and the creation of a domestic market for RET, the process of technology transfer might run the risk of stagnation after completion of these programs.

One of six key components of comprehensive program for development of renewables is resource assessment, where following activities were identified as necessary to be developed:

- Resource assessment methodology
- Resource survey and database
- Capacity building programme on resource assessment

This project addresses them all.

Feasibility study for application of photovoltaic power on Malé and Hulhumalé islands in the Republic of Maldives

The study executed by Japan International Cooperation Agency in 2009. The objectives of the study are [3]:

- Conduct technical and economic/financial feasibility study and confirm the conditions required in order to introduce the grid-connected PV system in Malé and Hulhumalé islands;
- Examine the required legislation, systems, regulations and human resources development plan, etc. and finalize long-term plan and action plan for the introduction and proper operation of the grid-connected PV system.

In addition, the detailed design for the introduction of grid-connected PV system was conducted on five or six potential sites, with a view to building the capacity of the organizations primarily responsible for introducing the PV system. The study includes also solar resource assessment, based on one year of measurements.

Renewable energy roadmap for the Republic of Maldives

The Renewable Energy Roadmap for Maldives, developed by the International Renewable Energy Agency (IRENA) at the request of the Ministry of Environment and Energy of the Republic of Maldives, identifies opportunities and challenges in the country's transition to large-scale renewable energy use [4]. The study authored by P. Journeay-Kaler and E. Taibi analyses and provides recommendations to materialise the opportunities for significant reduction of the dependence on imported fuel and lower the country's high electricity costs.

The roadmap details technologies that would support large-scale renewable energy deployment:

- Interconnection between islands
- Technologies addressing land constraint issues in the Maldives
- Heating and cooling from renewable energy
- Technologies supporting high shares of renewable energy

Challenge is that high investment costs, along with obstacles in the policy and regulatory framework, put limits for renewable energy deployment in the Maldives. The roadmap highlights policy solutions to overcome these barriers and accelerate renewable energy deployment:

- Ambitious but achievable renewable energy targets
- Supporting private renewable energy deployment
- Encouraging use of renewable energy in resort islands
- Improving energy data collection and access

The technical configuration has to be carefully optimised to achieve lowest possible costs. Estimated generation cost for current projects of floating PV, less than USD 0.20 per kilowatt-hour, is below local diesel generation costs, although higher than rooftop. Key drivers are the cost of capital and project scale: utility scale roof-mounted PV generation cost in the Maldives can be USD 0.10 or less if government- guaranteed concessional finance is used to finance the project.

High levels of PV and wind require that diesel generators are properly maintained and operated. New or replacement generators should have low loading and fast response capabilities that support high shares of variable renewable energy. Additional measures such as modern inverters and control systems, solar and wind forecasting and demand side management can provide lower cost alternatives for increasing shares of PV and wind.

The study shows example that even the ambition for 100% renewables backed by storage and intelligent electronics should not increase prices already existing in many islands, while removing the burden of diesel imports and meeting the greenhouse gas emission targets.

Modelling and planning for a large-scale renewable energy deployment requires regularly collected, easily accessible energy data. The study found numerous issues surrounding the quality and availability of energy data in the Maldives, including renewable resource assessment.

Rooftop Solar in Maldives: A World Bank Guarantee and SREP Facilitate Private Investment in Clean and Affordable Energy

This study, authored by S. Kohli and A. Braud, from the World Bank presents the initiative for supporting rooftop PV [5]. The Maldives Ministry of Environment and Energy, with support from the World Bank and from the Scaling Up Renewable Energy Program (SREP), has designed a program focused on solar photovoltaic (PV) rooftop installations to take advantage of high solar resource potential while also coping with the scarcity of land. ASPIRE program was created in 2016 (Accelerating Sustainable Private Investments in Renewable Energy), funded with SREP funds, and support from the Asia Sustainable and Alternative Energy Program. The goal is to scale up solar PV generation from the present level of ~1.5 MW to between 20–40 MW over the next five years by creating a bankable project structure attractive to the private sector.

The project aims to overcome numerous obstacles— among them investor concerns about the risk of non-payment by the publicly owned utility, political risk, currency convertibility issues, and the utility's unfamiliarity with public-private partnerships. The small size of the market, the lack of a national grid, the remoteness of most islands, and the scarcity of land and rooftop space have complicated the process of aggregating investments. Project documents meeting international financing standards, including the power purchase agreement, also had to be developed.

The solar potential expectations quoted in the study are made more accurate by this report.

1.2 Past and on-going solar resource assessment initiatives

Several solar resource assessment initiatives are documented below as publications and online data resources. The works show steadily growing interest and different stages of development of solar resource assessment and energy modelling in the region.

Solar Resource Assessment for Sri Lanka and Maldives, NREL

Extended mapping by NREL team was executed in 2003. The results are available in a set of reports and data downloadable online as a CD ROM package. The package includes GIS data, maps and TMY files [6, 7]. The study shows that ample resources exist throughout the year for virtually all locations in Sri Lanka and the Maldives for PV installations . In the Maldives in particular, the high levels of solar resource throughout the entire country make it well suited for off-grid, island-based photovoltaic installations an alternate to, or supplement to, diesel power generators.

Photovoltaic Geographical Information System (PVGIS), European Commission JRC

Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology. The online tools are accessible from http://re.jrc.ec.europa.eu/pvgis.html. The database is based on Meteosat satellite data calculation [8] and offers solar resource long-term averages as well as hourly data. The database is not validated in this region. The most recent update of the project was in 2017.

NASA Power Project Data Sets, NASA

Monthly and yearly averages are available from the NASA Power Project Data Sets [9]. The data and documentation are updated in 2018. Specific parameters are available at higher time resolution (e.g. daily). The data includes numerous atmospheric and solar radiation parameters, the solar data represents a period from 1983 to 2007, resolution of approx. 55 km. Data is not validated for the region and it can be accessed from https://power.larc.nasa.gov/.

Renewable Energy Resource Mapping for Maldives, World Bank (ESMAP, ASTAE)

This report refers to the outcomes achieved by this project, closed in 2018. A set of data and reports for Maldives has been prepared by Solargis and its subcontractor Suntrace, working on this project until the present. Three areas were addressed, in consecutive phases:

- Preliminary modelling that has been conducted by Solargis
- Installation, operation and data acquisition for four ground-based solar meteorological stations by Suntrace, Germany. All the measured data is accessible via the portal https://energydata.info/
- This report refers to final Phase 3 of the project, and it accompanies the delivery of the final outputs based on the combination of the modelled and the measured data. Solargis provides the final mapping outputs for Maldives. All outputs are accessible from https://globalsolaratlas.info.

Global Solar Atlas, World Bank Group

The World Bank and the International Finance Corporation have provided the Global Solar Atlas to support the scale-up of solar power in their client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank. The Atlas has been prepared by Solargis under a contract to The World Bank. The primary aim is to provide quick and easy access to solar resource data and maps globally [10, 11]. The project is ongoing, and regular updates are planned in the following years https://globalsolaratlas.info.

1.3 Evaluation of the existing data and studies

It has been communicated by all publications that Maldives has considerable potential for solar power generation. The previously developed solar and meteorological data sets (See Chapter 1.1) do not fulfil the requirements for accuracy and reliability needed for commercial development of present times. Table 1.1 compares Solargis results to the previous solar resource assessment initiatives. The main features that differ Solargis database from the above-mentioned data sets, include the following:

- The Solargis models are based on new and advanced algorithms, validated at various climate zones
- Use of modern and systematically updated input data for the models: satellite, atmospheric and meteorological
- Database has global coverage at high resolution

- Historical sub-hourly time series data is updated in real time
- Data can be used for project development but also for monitoring and forecasting
- Data is systematically validated and quality controlled
- There is customer support and supporting consultancy services available

The new data set from Solargis focuses on a systematic supply of data and services for the development and financing of large-scale solar power plants worldwide, including Maldives. The main objective is to systematically supply reliable, validated and high-resolution data to the solar industry with low uncertainty and systematic quality control.

The solar industry requires models that offer map-based data covering extensive territories at a high level of a detail using both historical and the most recent data. Modern solar measuring stations are used for accuracy enhancement of such models and to gain a better understanding of the local climate. Thus, a combination of the model data with modern solar and meteorological measurements is used to support solar energy development in all stages of its lifecycle.

High accuracy solar resource and meteorological data are 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 are initially used to evaluate the energy yield and assess the performance of the power plants. When the location for commercial project development is selected, a solar meteorological station is installed as the second step. The high accuracy meteorological equipment is used to collect local data for an initial period of at least one year. Such measurements are then used for the site adaptation of solar models and for delivering high accuracy solar resource and meteorological time series that covers a long historical period. At larger power plants, solar measurements are collected over the lifetime of the project.

The solar and meteorological data is used for the following tasks related to solar power generation:

1. Country-level evaluation and strategical assessment
2. Prospection; selection of candidate sites for future power plants, and prefeasibility analysis
3. Project evaluation; solar and energy yield assessment, technical design and financing
4. Monitoring and performance assessment of solar power plants and forecasting of solar power
5. Quality control of solar measurements.

This report addresses the first topic from the list above.

Table 1.1: Comparison of longterm GHI estimate: Solargis vs. previous studies

Source	Citation	Yearly GHI estimate (kWh/m2)	GHI difference to validated Solargis	Uncertainty of yearly value	Year of publication	Data coverage
JICA	[3]	5.15	-6.4 to -8.0%	?	2009	8/2003 - 7/2004
NREL	[6]	5.0 - 5.5	0 to -9.1%	?	2003	1985 - 1991
SREP	[5]	5.4 - 6.4	-1.6 to 14.3%	?	2016	?
PVGIS	[8]	5.8 - 5.9	5.5%	?	2017	2005 - 2016
NASA SSE	[9]	5.8	5.5%	?	2018	1983 - 2005
Solargis/ Global Solar Atlas	This report [10]	5.5 - 5.6	-	±3.5%	2018	1999 - 2017

1.4 Structure of this study

Following an introduction to the activity (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. This chapter documents the role of solar measurements in reducing the uncertainty of solar, meteorological and PV power potential data for the country. Chapter 2.3 explains the relevance of solar resource and meteorological information for the deployment of solar power technologies. An emphasis is given to photovoltaic (PV) technology, which has high potential for developing utility-scale projects close to larger 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 Maldives. Four representative sites are selected to show potential regional differences in Maldives through tables and graphs. Chapter 3.1 introduces ancillary geographical data that influence the performance of solar power plants. Chapter 3.2 to 3.5 summarizes geographical differences and seasonal variability of the solar resource in Maldives, while Chapter 3.6 presents the PV power generation potential of the country. The theoretical specific PV electricity output is calculated from the most commonly used PV technology: a fixed system with crystalline-silicon (c-Si) PV modules, optimally tilted and oriented towards the Equator. Chapter 3.7 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. The interactions of extra-terrestrial solar radiation with the Earth's atmosphere, surface and objects are divided into four groups:

1. Solar geometry, trajectory around the sun and Earth's rotation (declination, latitude, solar angle)
2. Atmospheric attenuation (scattering and absorption) by:
    2.1 Atmospheric gases (air molecules, ozone, NO_2, CO_2 and O_2)
    2.2 Solid and liquid particles (aerosols) and water vapour
    2.3 Clouds (condensed water or ice crystals)
3. Topography (elevation, surface inclination and orientation, horizon)
4. Shadows, reflections from surface or local obstacles (trees, buildings, etc.) and re-diffusion by atmosphere.

The atmosphere attenuates solar radiation selectively: some wavelengths are associated with high attenuation (e.g. UV) and others with a good transmission. Solar radiation called "short wavelength" (in practice, 300 to 4000 nm) is of primary interest to solar power technology and is used as a reference. The component that is neither reflected nor scattered, and which directly reaches the surface, is called *direct radiation*; this is the component that produces shadows. The component scattered by the atmosphere that also reaches the ground is called *diffuse radiation*. A small portion of the radiation reflected by the surface that reaches an inclined plane is called the *reflected radiation*. These three components together create *global radiation*. A proportion of individual component at any time is given by Sun position and by the actual state of atmosphere – mainly the occurrence of clouds, air pollution and humidity.

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 m^2 (unit: W/ m^2).
- **Solar irradiation**, expressed in MJ/ m^2 or Wh/m^2; 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 lager areas. Satellite-models are not capable of producing instantaneous values at the same accuracy as ground sensors, but can provide robust aggregated values.

This Chapter summarizes approaches for measuring and computing these parameters, and the main sources of uncertainty. It also discusses methods for combining data acquired by these two complementary approaches with the aim of maximizing their benefits. The most effective approach is to correlate multiyear satellite time series with data measured locally over short periods of time (at least one year) to reduce uncertainty and achieve more reliable long-term estimates.

2.1.2 ESMAP Solar resource measurements in Maldives

Data from the four ESMAP measuring stations in Maldives was collected and harmonized with the objective of acquiring reference solar radiation data for reducing the uncertainty of the model. The quality data from these meteorological stations were available for this assessment (Tables 2.1 and 2.2, Figure 2.1, Map 2.1). Positions and detailed information about measurement sites is also available on Global Solar Atlas website, http://globalsolaratlas.info/.

More detailed information related to the measurement campaign in Maldives can be found in the report *"Annual Solar Resource Report for solar meteorological stations after completion of 24 months of measurements"*, Ref. Nr. 129-07/2018 (September 2018) [12]. The report presents analysis of ground measured data quality control and results of site adaptation of the Solargis model and data uncertainties.

Table 2.1: Overview information on measurement stations operated in the region

No.	Site name	Latitude [°]	Longitude [°]	Altitude [m a.s.l.]	Measurement station host
1	Hanimaadhoo	6.7482°	73.1696°	2	Hanimaadhoo International Airport
2	Hulhulé	4.1927°	73.5281°	2	Male International Airport
3	Kadhdhoo	1.8599°	73.5203°	2	Kadhdhoo Airport
4	Gan	-0.6911°	73.1599°	2	Gan International Airport

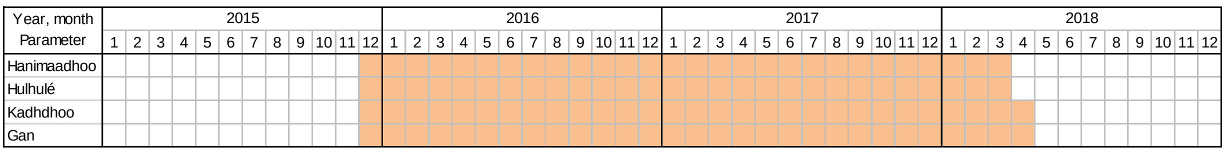
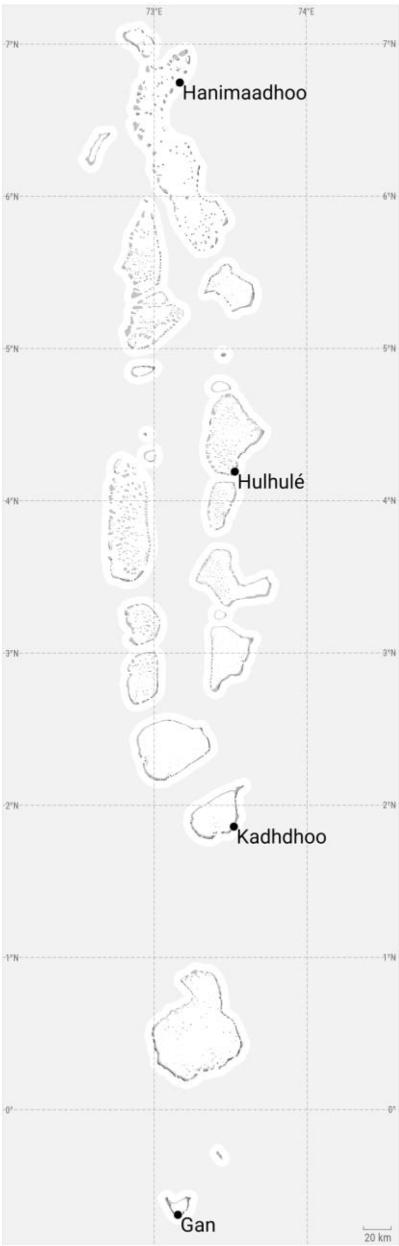


Figure 2.1: Solar resource data availability (GHI, DNI and DIF).

Table 2.2: Overview information on solar meteorological stations operating in the region

No.	Site name	Type	Parameters	Time step	Period of data used in study
1	Hanimaadhoo	TIER2	GHI, GHI2, DNI, DIF	1 min	11 Dec 2015 – 31 Mar 2018
2	Hulhulé	TIER2	GHI, GHI2, DNI, DIF	1 min	09 Dec 2015 – 31 Mar 2018
3	Kadhdhoo	TIER2	GHI, GHI2, DNI, DIF	1 min	15 Dec 2015 – 30 Apr 2018
4	Gan	TIER2	GHI, GHI2, DNI, DIF	1 min	14 Dec 2015 – 30 Apr 2018



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

2.1.3 Solargis satellite-based model

Numerical 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 45° South latitudes. A comprehensive overview of the Solargis model was made available in several publications [13, 14, 15]. The related uncertainty and requirements for bankability are discussed in [16, 17, 18].

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 [19]. 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) [20, 21]. 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 [22, 23]. For years 1999 to 2002, data from the MERRA-2 model (NASA) [24] 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 [25, 26, 27].
- **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 IODC 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 [28]. A number of 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 [29]. Diffuse horizontal irradiance is derived from GHI and DNI according to the following equation:

$$DIF = GHI - DNI * \cos Z \quad (1)$$

Where Z is the zenith angle between the solar position and the Earth's surface.

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 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 [30]. 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 [31]. 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 2.1 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 Maldives

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 (EUMETSAT)	1999 to 2016 2017 to date	30 minutes 15 minutes	2.8 x 3.2 km 3.1 x 3.5 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	30 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 thus adapt the satellite model for the specific site or region.

Within this project, regional model adaptation has been performed using the data from four 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 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 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 context with overall reduction of systematic errors.

The regional-adaptation of satellite-based model data was performed for the whole territory of Maldives and the methodology and results are described in the report *"Solar Model Validation Report; Regional adaptation of Solargis model based on 24 months of solar measurement campaign"*, Ref. Nr. 129-08/2018 [12].

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

	Data from solar measuring stations	Data from satellite-based models
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 45° S. Data covers long period, in Maldives more than 19 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, 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 often 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 few 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 in order to reduce overall model uncertainty in the region. Tables 2.5 to 2.8 show the Solargis model quality indicators for solar primary parameters, DNI and GHI, after the regional model adaptation. The uncertainty is evaluated for the 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 the region, shows overall stability of the Solargis model and of the underlying input data. Locally, a slightly increased bias was identified, which may be the effect of the specific local conditions (e.g. anthropogenic pollution), limited accuracy of the model and its input data, as well as the properties of ground measurements (short period of available data, lower accuracy of instruments). The statistics show that the model uncertainty has been reduced after the regional adaptation, with results comparable to those achieved in other regions [32, 33].

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

Meteo station	Original DNI model data			DNI after regional adaptation		
	Bias [kWh/m²]	Bias [%]	KSI [-]	Bias [kWh/m²]	Bias [%]	KSI [-]
Hanimaadhoo	19	5.3	104	1	0.4	90
Hulhulé	31	8.4	149	4	1.0	107
Kadhdhoo	29	7.5	148	2	0.5	129
Gan	33	8.4	159	-1	-0.2	151
Mean	28.0	7.4	140	1.7	0.4	129
Standard deviation	6.2	1.5		2.5	0.6	

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

Meteo station	Original GHI model data			GHI after regional adaptation		
	Bias [kWh/m²]	Bias [%]	KSI [-]	Bias [kWh/m²]	Bias [%]	KSI [-]
Hanimaadhoo	3	0.7	49	-1	-0.2	45
Hulhulé	0	0.0	50	-6	-1.1	52
Kadhdhoo	3	0.7	52	-2	-0.4	51
Gan	7	1.4	67	1	0.2	55
Mean	3.3	0.7	55	-2.0	-0.3	51
Standard deviation	2.9	0.5		2.9	0.6	

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

Meteo station	RMSD of original DNI data			RMSD of DNI after regional adaptation		
	Hourly [%]	Daily [%]	Monthly [%]	Hourly [%]	Daily [%]	Monthly [%]
Hanimaadhoo	31.8	17.7	6.6	31.3	17.2	3.9
Hulhulé	35.2	20.0	9.1	34.2	18.9	3.9
Kadhdhoo	35.6	19.3	8.1	34.7	18.5	2.7
Gan	35.8	20.1	9.3	35.1	19.4	4.3
Mean	34.6	19.3	8.3	34.7	18.9	3.6

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

Meteo station	RMSD of original GHI data			RMSD of GHI after regional adaptation		
	Hourly [%]	Daily [%]	Monthly [%]	Hourly [%]	Daily [%]	Monthly [%]
Hanimaadhoo	15.3	6.6	2.3	15.2	6.6	2.1
Hulhulé	16.4	7.2	1.8	16.4	7.3	2.0
Kadhdhoo	16.7	7.1	1.3	16.7	7.2	1.2
Gan	16.2	7.2	2.2	16.1	7.1	1.7
Mean	16.2	7.0	1.9	16.1	7.0	1.7

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 [18]:

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 GFS/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 and RMSD (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 Maldives territory has uncertainty of the regionally-adapted model yearly values at the level of ±3.5% for GHI and ±6.0% for DNI. Due to specific monotonous geographical conditions without any topographic barriers, we expect that the four meteorological stations sufficiently represent the territory of Maldives.

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.

Uncertainty of long-term annual values	**Acronym**	**Uncertainty of the original Solargis model**	**Uncertainty of the Solargis model after regional adaptation**	***Theoretical best possible uncertainty***
Global Horizontal Irradiation	GHI	±6.0%	±3.5%	*±2.5%*
Global Tilted Irradiation	GTI	±6.0%	±4.0%	*±3.0%*
Direct Normal Irradiation	DNI	±12.0%	±6.0%	*±3.5%*

The lowest uncertainty in Table 2.9 levels can only be achieved by site-adaptation for a very local region around meteorological stations with site-specific microclimatic conditions recorded in ground measurements. In the case of the regional adaptation used in this study, the uncertainty is usually higher because it describes uncertainty of any selected location in the broader region.

Moreover, a residual discrepancy between ground measurements, and the model data can be found after regional adaptation (Tables 2.5 and 2.6). This adaptation approach is designed to correct only regional discrepancy patterns, not to resolve site-specific issues.

2.2 Meteorological 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 data from meteorological stations and weather models

	Meteorological station data	Data from meteorological models
Availability/ accessibility	Available only for selected sites. Data may cover various periods of time	Data are available for any location Data cover long 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 the local values may be smoothed, especially extreme values.
Original time resolution	From 1 minute to 1 hour	1 hour
Quality	Data needs 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, long-term stability is often a challenge.	In case of reanalysis, long history of data is calculated with one single stable model. Data for operational forecast model 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 high quality local measurements. The data may not exactly represent the local microclimate, but are usually sufficient for solar energy applications.

Several models are available: a good option is to use Climate Forecast System Reanalysis (CFSR) and the Climate Forecast System Version 2 (CFSv2) models (source NOAA, NCEP, USA), which cover a long period of time with continuous data [26, 27]. The results of these models are implemented in Solargis.

The role of meteorological ground measurements in solar energy development has two aspects:

- Measurements are used for the validation and accuracy enhancement of historical data derived from the solar and meteorological models
- The 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 smoothed or well represented.

2.2.2 Method and validation

In this delivery, the air temperature data is derived from the meteorological models: CFSR and CFSv2 (Table 2.11).

It is important to note that 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 but due to very low elevation of the atolls this correction has negligible impact on the final data.

Table 2.11: Original source of Solargis meteorological data for Maldives: models CFSR and CFSv2.

	Climate Forecast System Reanalysis (CFSR)	Climate Forecast System (CFSv2)
Time period	1999 to 2010	2011 to the present time
Original spatial resolution	30 x 35 km	19 x 22 km
Original time resolution	1 hour	1 hour

For the purpose of validating the meteorological models in Maldives, we have utilized the data collected at four meteorological stations (Table 2.1, Map. 2.1). The summary of basic statistical parameters is presented in Table 2.12.

The main issue identified is strongly reduced daily temperature amplitude. This is caused by relatively small land mass of the islands (in comparison to the pixel size of the meteorological model). Model air temperature is driven mainly by the air temperature over the ocean, where the daily amplitude is much lower than temperature amplitude seen in the islands. Yet, the insufficiency of meteorological models may have limited importance, as air temperature is changing only a little across the seasons and day time.

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

Meteorological station	Validation period	Bias mean	RMSD hourly	RMSD daily	RMSD monthly
Hanimaadhoo	12/2015 – 03/2018	-0.9	1.9	1.3	1.0
Hulhulé	12/2015 – 03/2018	-0.9	1.5	1.1	0.9
Kadhdhoo	12/2015 – 04/2018	-0.5	1.8	1.0	0.6
Gan	12/2015 – 04/2018	-0.4	1.4	0.8	0.5

2.2.3 Uncertainty of air temperature

In general, the data from the meteorological models represent larger area, and it is not capable to represent accurately the microclimate created by small land mass of the islands. The main issue identified in air temperature model data is strongly reduced daily amplitude.

The uncertainty of the model estimate for air temperature is summarised in Table 2.13.

Table 2.13: Expected uncertainty of air temperature in Maldives.

	Unit	Annual	Monthly	Hourly
Air temperature at 2 m	°C	±1.0	±1.5	±2.5

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 Maldives, and this technology is discussed in this Chapter. CSP technology is not expected to be implemented in Maldives.

Photovoltaics exploit global horizontal or tilted irradiation, which is the sum of direct and diffuse components (see equation (1) in Chapter 2.1.3). To simulate power production from a PV system, global irradiance received by a flat surface of PV modules must be correctly 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 Maldives:

- 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 in the islands.

Off-grid PV systems are small 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 PV modules**, considered here as the mainstream technology. 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 3.6, 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)	250 m (9 arc-sec)
Time resolution	30-minute
Geographical extent (this study)	Republic of Maldives
Period covered by data (this study)	01/1999 to 12/2017

The PV software implemented by Solargis has scientifically proven methods [34 to 39] 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 (this issue is not relevant for Maldives)**.** 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 [30]. The performance ageing of PV modules is not considered in this study.

The calculation results of PV power potential for Maldives are shown in Chapter 3.6.

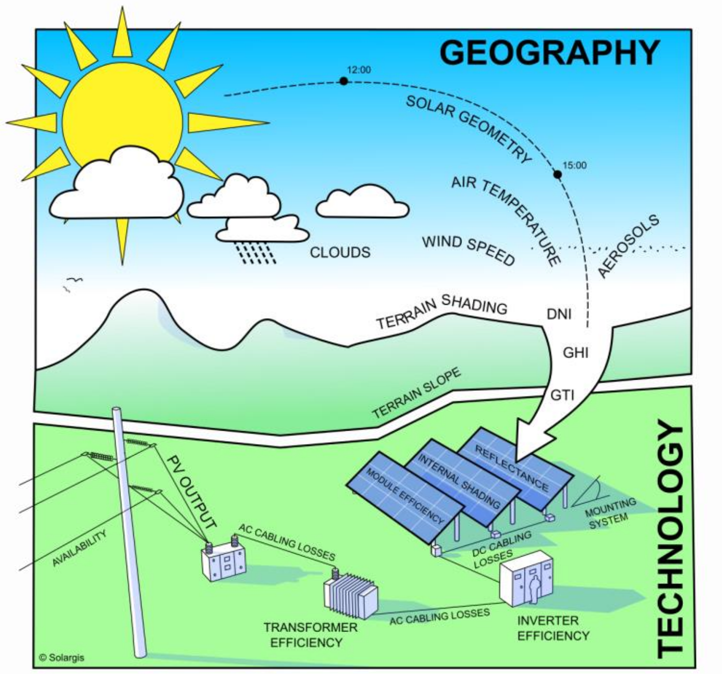


Figure 2.2: Simplified Solargis PV simulation chain

2.3.2 Technical configuration of a reference PV system

Theoretical photovoltaic power production in Maldives has been calculated using numerical models developed and implemented in-house by Solargis. As introduced in Chapter 2.1, 30-minute **time series of solar radiation and air temperature**, representing last 19 years, are used as an input to the simulation. The models are developed based on the advanced algorithms, expert knowledge and recommendations given in [40] and tested using monitoring results from existing PV power plants. Table 2.16 summarizes losses and related uncertainty throughout the PV computing chain.

In this study, the following configuration of a PV power plant is considered: small ground mounted power plant with PV modules oriented towards the Equator (modules on Gan island are oriented towards North, modules on Hanimaadhoo, Hulhulé and Kadhdhoo island oriented towards South). The modules are fixed-mounted (non-tracking) with a tilt angle of 7° and configured so that there is no shading caused by adjacent rows. The optimum tilt angle for Maldives is in the range between 3° and 10° depending on the geographic location, but due to minimum effect on differences in GTI a one tilt of 7° has been chosen for all sites. Keeping the modules tilted to some extent helps cleaning their surface by rainfall.

Map 3.16 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.

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.

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 10 kWp 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) 45°C and temperature coefficient of the Pmax -0.44 %/K
Inverters	String inverter with declared datasheet efficiency (Euro efficiency) 97.0%
Mounting of PV modules	Ground mounted PV modules, facing towards the equator with 7° tilt, assuming no shading between rows
Transformer	No transformer: only direct connection into the grid is assumed

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

	Simulation step	Losses	Uncertainty	Notes
		[%]	[± %]	
1	Global Tilted Irradiation (model estimate with terrain shading)	N/A	4.0	Annual Global Irradiation falling on the surface of PV modules
2	Module surface angular reflectivity (numerical model)	-3.0 to -3.5	1.0	Slightly polluted surface is assumed in the calculation of the module surface reflectivity
	Conversion in modules relative to STC (numerical model)	-11.0 to -12.0	3.5	Depends on the temperature and irradiance. NOCT of 45°C is considered
3	Polluted surface of modules (empirical estimate)	-1.5	1.5	Losses due to 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)	0.0	0.0	No 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)	-1.5	1.5	This value can be calculated from the electrical design
4	Conversion in the inverter (value from the technical data sheet)	-3.0	0.5	Given by the Euro efficiency of the inverter, which is considered at 97.0%
	AC cable losses (empirical estimate)	-1.0	0.5	AC connection is assumed without transformer
5	Availability	0.0	1.5	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	-20.0 to -21.3	6.1	These values are indicative and do not consider project specific features and performance degradation of a PV system over its lifetime

3 Solar resource and PV potential of Maldives

3.1 Geography

This report analyses solar and meteorological data for Maldives, 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.

Maldives is located in South Asia, approximately between latitudes 8° North and 1° South and longitudes 70° and 75° 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 **four selected sites** that, to a large extent, represent the variability of the climate and solar power (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 four sites.

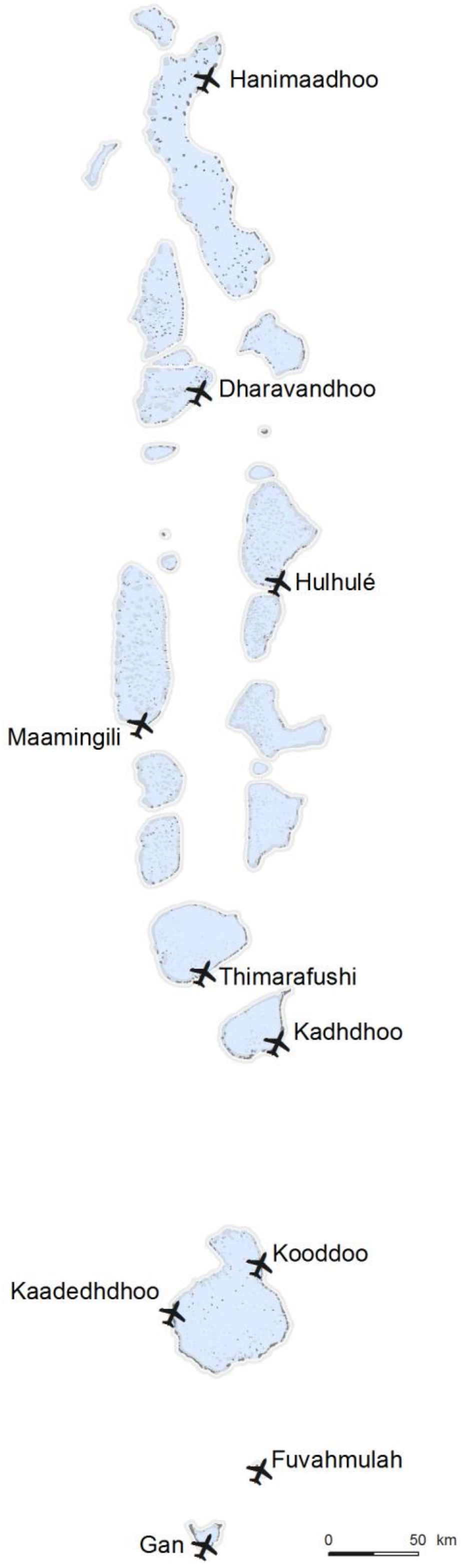
Geographic information and maps bring additional value to the solar data. Geographical characteristics of the country from a regional to local scale may represent technical and environmental prerequisites, as well as constraints, for solar energy development.

In this report, we integrated into GIS project the following data:

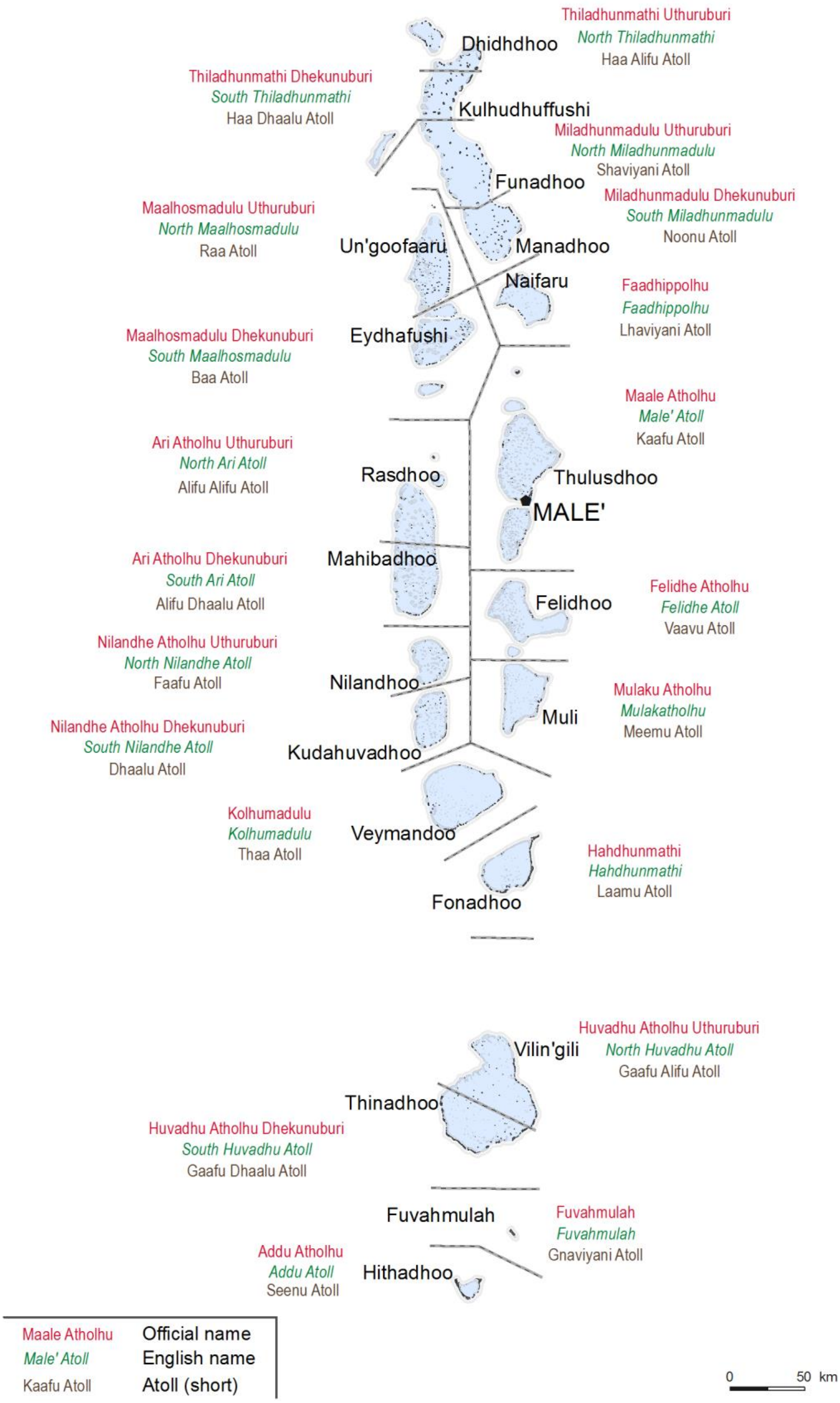
- Population of islands (Map 3.1)
- Air transport infrastructure/accessibility of the power plant sites (Map 3.2)
- Administrative division and towns (Map 3.3)

The population of the islands provides an indication of spatial distribution of energy demand.

Map 3.1: Populated islands
Source: Maldivian Ministry of Planning and National Development. Cartography: Solargis



Map 3.2: Air transport infrastructure
Source: Maldivian Ministry of Planning and National Development. Cartography: Solargis



Map 3.3: Administrative division, towns and cities in Maldives.
Source: Government of Maldives, adapted by Solargis

3.2 Air temperature

Air temperature determines the operating environment and performance efficiency of the solar power systems. Air temperature is used as one of the inputs in the energy simulation models. In this report, the yearly and monthly average maps are shown. Map 3.4 and Map 3.5 show the yearly and monthly averages.

The long-term averages of air temperature are derived from the CFSR and CFSv2 models (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.).

Table 3.1: Monthly averages and average minima and maxima of air-temperature at 2 m at 4 sites

Month	Temperature [°C]							
	Hanimaadhoo		Hulhulé		Kadhdhoo		Gan	
	Average	Min Max	Average	Min Max	Average	Min Max	Average	Min Max
January	**27.3**	26.8 27.6	**27.5**	27.1 27.8	**27.7**	27.3 27.9	**27.7**	27.3 28.0
February	**27.5**	27.0 27.8	**27.6**	27.2 27.9	**27.9**	27.4 28.2	**28.0**	27.6 28.3
March	**28.2**	27.7 28.5	**28.2**	27.7 28.5	**28.3**	27.8 28.6	**28.3**	27.9 28.7
April	**28.9**	28.5 29.2	**28.7**	28.3 29.0	**28.6**	28.1 28.9	**28.7**	28.2 29.0
May	**29.0**	28.5 29.3	**28.7**	28.2 29.1	**28.6**	28.2 29.0	**28.7**	28.2 29.0
June	**28.4**	27.9 28.8	**28.4**	27.9 28.7	**28.4**	28.0 28.7	**28.3**	27.9 28.7
July	**28.0**	27.5 28.4	**28.2**	27.7 28.5	**28.2**	27.7 28.5	**28.1**	27.6 28.4
August	**27.9**	27.4 28.3	**28.0**	27.5 28.3	**28.0**	27.5 28.3	**27.9**	27.5 28.3
September	**27.8**	27.4 28.2	**27.9**	27.4 28.3	**28.0**	27.5 28.4	**27.9**	27.4 28.3
October	**27.9**	27.5 28.2	**27.9**	27.5 28.3	**27.9**	27.4 28.3	**27.9**	27.4 28.3
November	**27.8**	27.3 28.1	**27.7**	27.3 28.1	**27.8**	27.3 28.2	**27.8**	27.3 28.2
December	**27.5**	27.1 27.9	**27.5**	27.1 27.9	**27.6**	27.2 28.0	**27.8**	27.3 28.1
YEAR	**28.0**		**28.0**		**28.1**		**28.1**	

Table 3.1 shows monthly characteristics of air temperature at four selected sites; they represent statistics calculated over a 24-hour diurnal cycle. Minimum and maximum air temperatures are calculated as an average of minimum and maximum values of temperature during each day (assuming full diurnal cycle - 24 hours) of the given month.

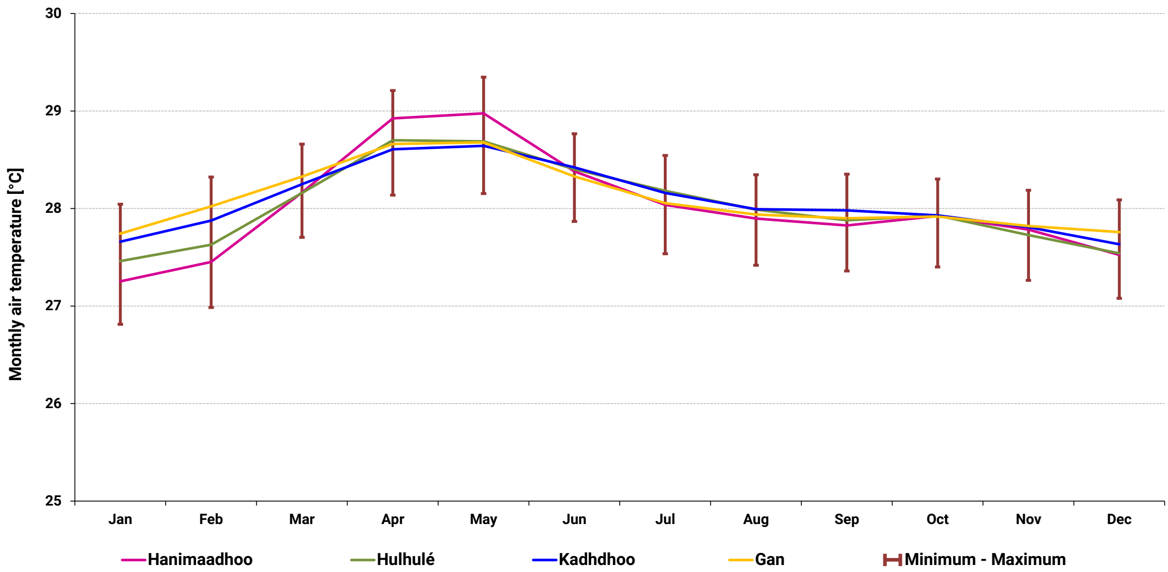
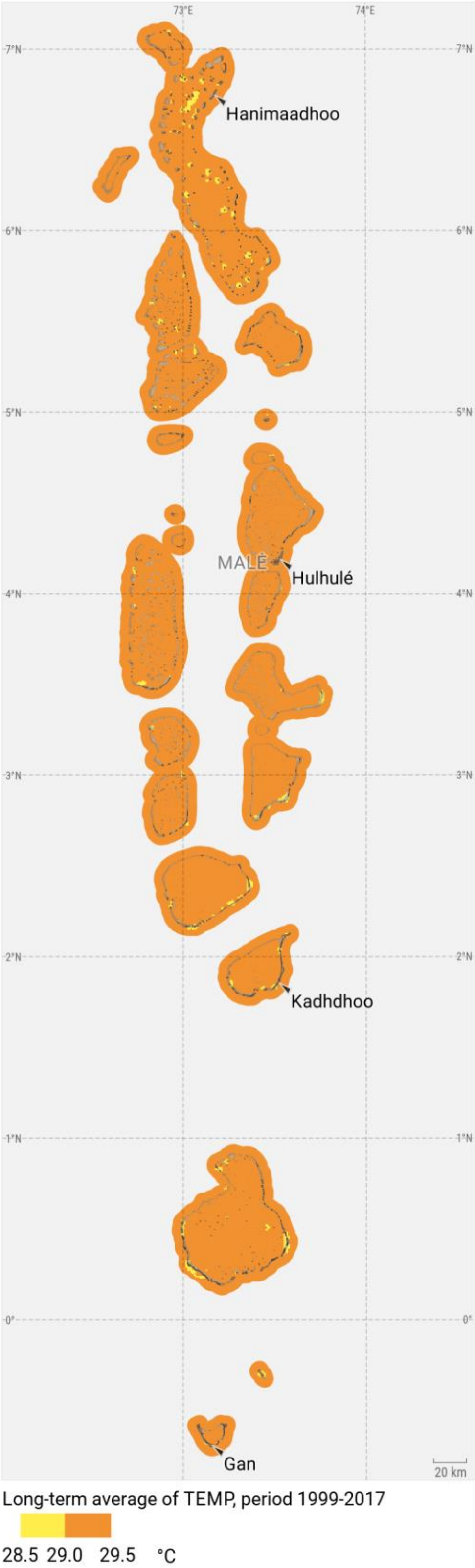


Figure 3.1: Monthly averages, minima and maxima of air-temperature at 2 m for selected sites.

Monthly averages of minimum and maximum daily values show their typical daily amplitude in each month (Figure 3.1). See Chapter 2.2 discussing the uncertainty of the air temperature model estimates.



Map 3.4: Long-term yearly average of air temperature at 2 metres, period 1999-2017.
Source: Models CFSR and CFSv2, post-processed by Solargis

Map 3.5: Long-term monthly average of air temperature at 2 metres, period 1999-2017.
Source: Models CFSR and CFSv2, NOAA, post-processed by Solargis

3.3 Global Horizontal Irradiation

Global Horizontal Irradiation (GHI) 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, and average minima and maxima of daily totals of Global Horizontal Irradiation (GHI) for a period 1999 to 2017 for four 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 most stable weather with highest GHI values is observed in March. Some variability of GHI between sites is observed in November and December. These months show also the highest range of minimum and maximum values of GHI. Very small variability of values is determined by similar geographical characteristics, and Figure. 3.2 indicates that all sites will experience similar PV power performance.

Table 3.2: Daily averages and average minima and maxima of Global Horizontal Irradiation at 4 sites

Month	Global Horizontal Irradiation [kWh/m^2]								Variability between sites [%]
	Hanimaadhoo		Hulhulé		Kadhdhoo		Gan		
	Average	Min / Max	Average	Min / Max	Average	Min / Max	Average	Min / Max	
January	**5.62**	5.11 / 5.96	**5.68**	4.84 / 6.15	**5.75**	5.01 / 6.35	**5.76**	4.82 / 6.54	**1.1**
February	**6.16**	5.34 / 6.59	**6.36**	5.93 / 6.79	**6.28**	5.61 / 6.79	**6.33**	5.70 / 6.79	**1.4**
March	**6.59**	5.49 / 6.93	**6.59**	5.74 / 7.12	**6.56**	5.91 / 7.05	**6.49**	5.55 / 7.05	**0.7**
April	**6.20**	5.74 / 6.79	**6.06**	5.48 / 6.66	**5.91**	5.35 / 6.62	**5.90**	5.32 / 6.52	**2.4**
May	**5.22**	4.43 / 6.15	**5.29**	4.40 / 5.80	**5.36**	4.82 / 5.81	**5.40**	5.01 / 5.92	**1.5**
June	**4.89**	4.16 / 5.75	**5.14**	4.38 / 5.75	**5.27**	4.63 / 6.05	**5.13**	4.13 / 5.96	**3.1**
July	**5.02**	4.32 / 5.75	**5.10**	4.50 / 5.59	**5.08**	4.53 / 5.60	**4.92**	4.36 / 5.68	**1.6**
August	**5.37**	4.72 / 6.02	**5.40**	4.54 / 5.99	**5.27**	4.61 / 5.75	**5.26**	4.53 / 5.83	**1.4**
September	**5.54**	4.90 / 6.53	**5.39**	4.73 / 6.57	**5.56**	5.07 / 6.43	**5.59**	4.72 / 6.08	**1.6**
October	**5.53**	4.60 / 6.30	**5.65**	5.07 / 6.44	**5.58**	4.88 / 6.20	**5.64**	4.92 / 6.63	**1.0**
November	**4.97**	3.90 / 5.75	**5.02**	4.07 / 5.86	**5.19**	4.21 / 6.45	**5.50**	4.63 / 6.59	**4.6**
December	**5.02**	4.25 / 5.84	**4.95**	3.69 / 5.79	**5.11**	3.97 / 5.87	**5.55**	4.55 / 6.31	**5.2**
YEAR	**5.51**	**5.32 / 5.63**	**5.55**	**5.33 / 5.67**	**5.57**	**5.30 / 5.74**	**5.62**	**5.31 / 5.75**	**0.8**

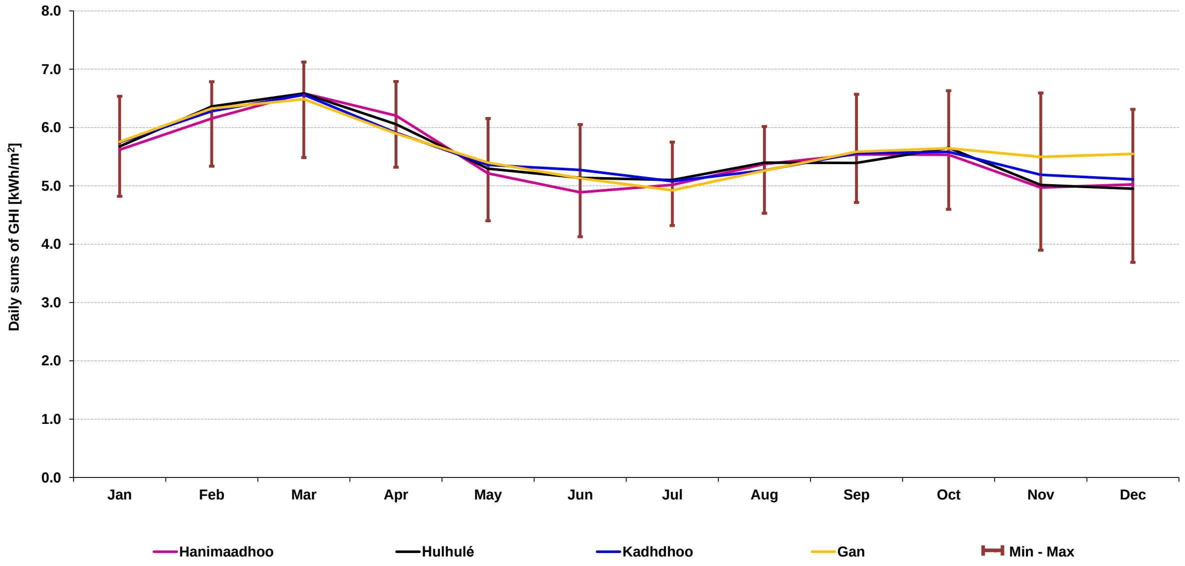


Figure 3.2: Long-term monthly averages, minima and maxima of Global Horizontal Irradiation.

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.

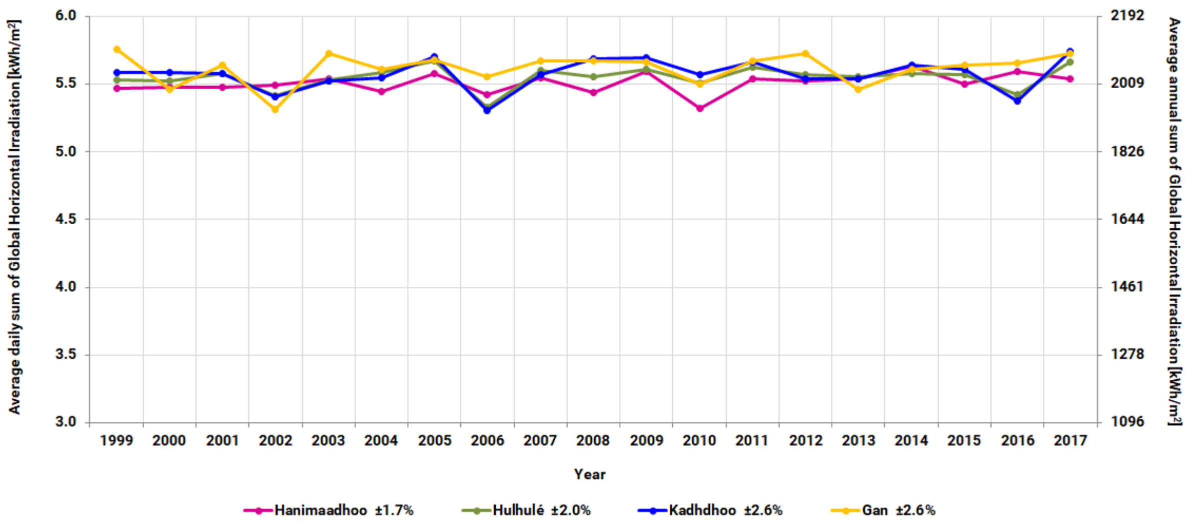
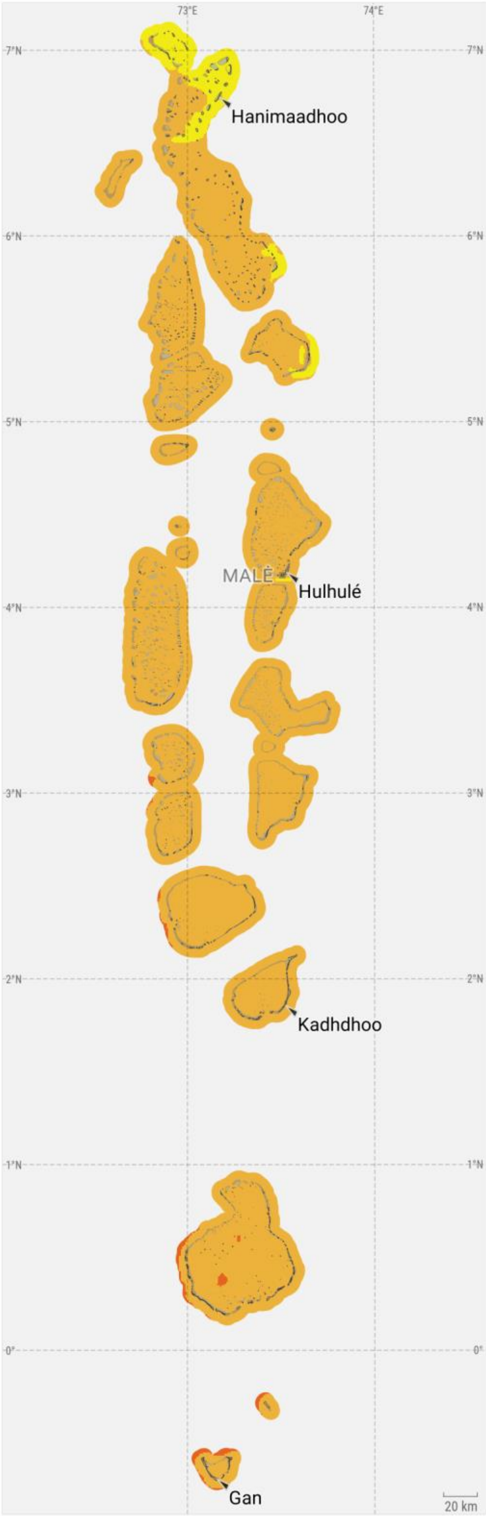


Figure 3.3: Interannual variability of Global Horizontal Irradiation for selected sites.

The interannual variability of GHI for the representative sites is calculated from the unbiased standard deviation of GHI over 19 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) and extremes for all sites (minimum and maximum) are reached almost in the same years. More stable GHI (the smallest interannual variability) is observed in Hanimaadhoo and Hulhulé. Higher variability is observed at the sites Gan and Kadhdhoo (both 2.6%); Gan has also the highest GHI values.



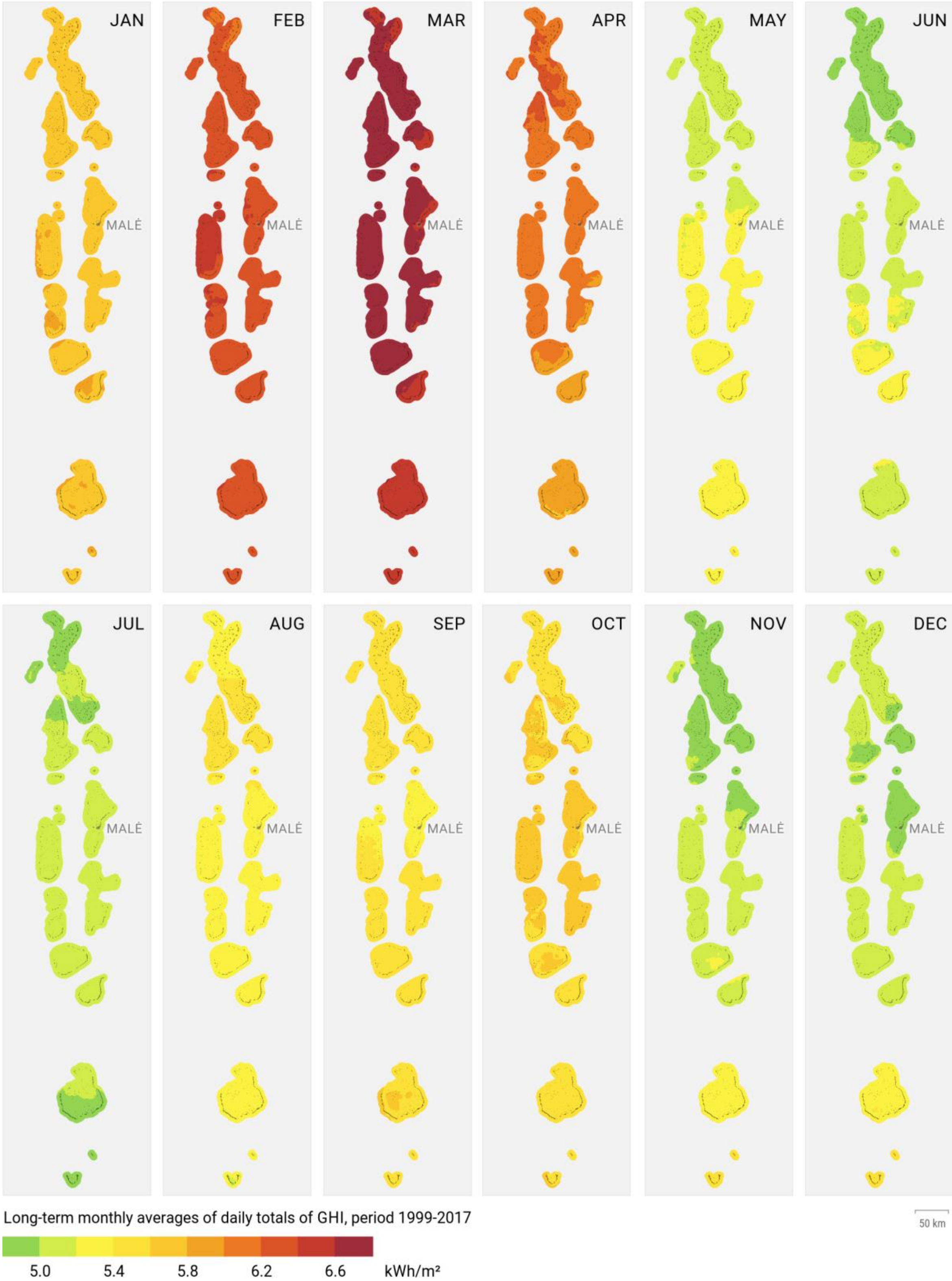
Long-term average of GHI, period 1999-2017

Daily totals: 5.5 5.6

kWh/m²

Yearly totals: 2008 2045

Map 3.6: Global Horizontal Irradiation – long-term average of daily and yearly totals.
Source: Solargis



Map 3.7: Global Horizontal Irradiation – long-term monthly average of daily totals.
Source: Solargis

The highest GHI is identified in the South of the archipelago, where average daily sums exceed 5.6 kWh/m^2 (yearly sum about 2050 kWh/m^2) and more (Map 3.6). The season of highest irradiation with daily sums above 6.2 kWh/km^2 lasts three months (from February to April, Map 3.7). Second season of higher solar radiation, with daily sums from 5.3 to 5.6 kWh/m^2, is found in a period from August to October.

Map 3.8 delineates the ratio of diffuse to global horizontal irradiation. This ratio is important for the performance of PV systems.

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. The lowest DIF/GHI values are identified in South of archipelago, where the yearly average ratio falls to 36%. During the season from June to September all sites show stable, but relatively high DIF/GHI ratio (up to 55%). The best conditions with clear sky and low aerosols typically occur from February to April in all Maldives, however this period is very short (Figure 3.4). This indicates that the potential for concentrator technologies (CSP, CPV) in Maldives is limited.

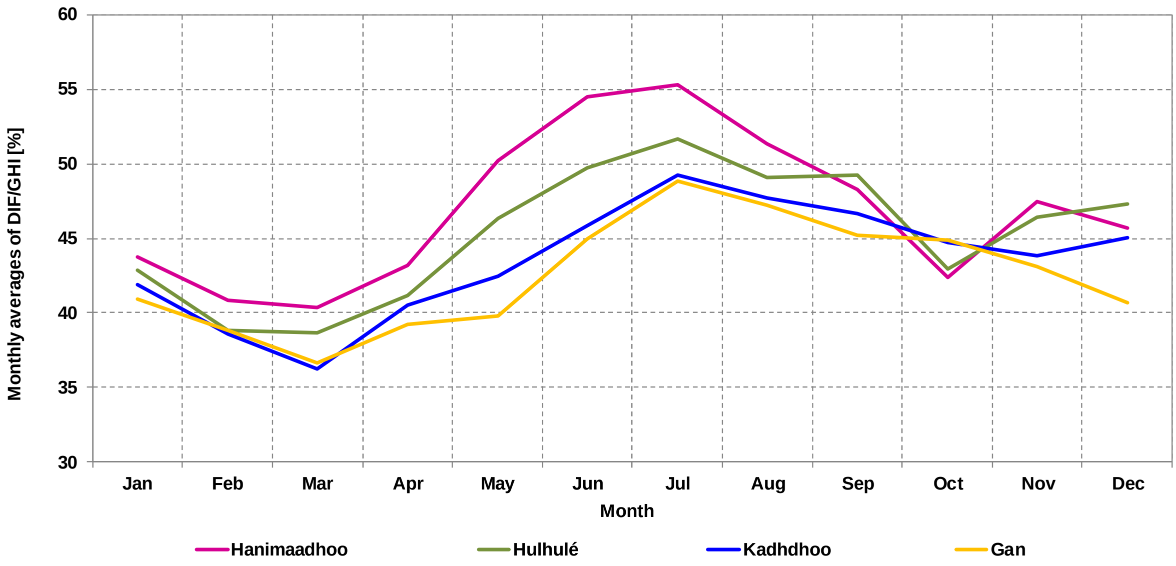
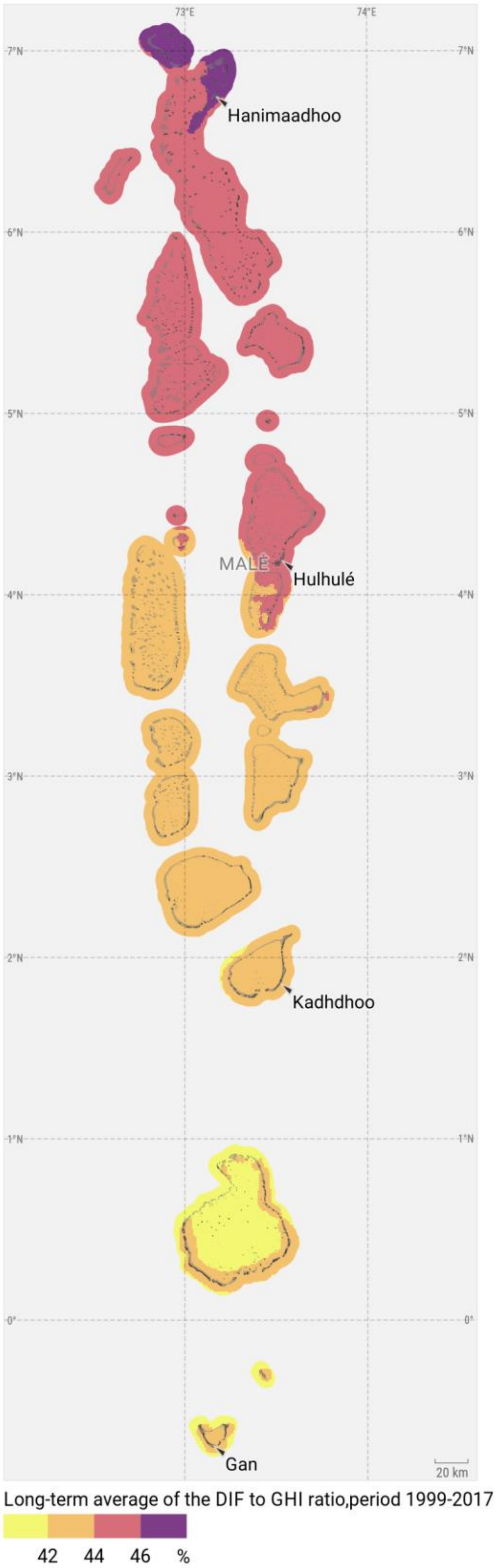


Figure 3.4: Monthly averages of DIF/GHI.



Map 3.8: Long-term average for ratio of diffuse and global irradiation (DIF/GHI).
Source: Solargis

3.4 Direct Normal Irradiation

Direct Normal Irradiation (DNI) is one of the primary solar resource parameters needed for the computation of Global Tilted Irradiation (GTI) (Chapter 3.5).

Table 3.3 and Figure 3.5 show long-term average daily totals and average daily minimum and maximum of DNI for the four selected sites, during the period from 1999 to 2017. The highest DNI is reached in Gan and Kadhdhoo, the lowest on Hanimaadhoo.

Table 3.3: Daily averages and average minima and maxima of Direct Normal Irradiation at 4 sites

Month	Direct Normal Irradiation [kWh/m²]								Variability between sites [%]
	Hanimaadhoo		Hulhulé		Kadhdhoo		Gan		
	Average	Min / Max	Average	Min / Max	Average	Min / Max	Average	Min / Max	
January	**4.58**	3.57 / 5.35	**4.61**	3.68 / 5.38	**4.73**	3.48 / 5.68	**4.73**	3.31 / 5.94	**1.7**
February	**5.02**	3.66 / 5.89	**5.30**	4.15 / 6.21	**5.22**	3.76 / 5.93	**5.19**	4.39 / 5.98	**2.3**
March	**5.12**	4.15 / 5.67	**5.29**	4.39 / 6.40	**5.49**	4.40 / 6.33	**5.43**	4.16 / 6.43	**3.1**
April	**4.55**	3.62 / 5.46	**4.70**	3.80 / 5.80	**4.74**	4.06 / 5.59	**4.89**	4.01 / 5.76	**3.0**
May	**3.41**	2.38 / 4.43	**3.80**	2.76 / 4.69	**4.21**	3.49 / 5.13	**4.49**	3.66 / 5.19	**11.9**
June	**2.92**	2.21 / 4.71	**3.45**	2.72 / 4.38	**3.90**	2.94 / 5.28	**3.96**	2.67 / 5.52	**13.6**
July	**2.86**	1.93 / 3.64	**3.23**	2.59 / 3.93	**3.46**	2.65 / 4.44	**3.46**	2.97 / 4.60	**8.7**
August	**3.33**	2.56 / 4.06	**3.55**	2.76 / 4.26	**3.60**	2.89 / 4.22	**3.67**	2.85 / 4.49	**4.2**
September	**3.70**	2.78 / 5.24	**3.53**	2.74 / 5.16	**3.83**	3.14 / 5.11	**3.95**	2.84 / 4.78	**4.8**
October	**4.30**	2.91 / 5.32	**4.32**	3.38 / 5.79	**4.15**	3.30 / 5.06	**4.18**	3.18 / 5.78	**2.1**
November	**3.73**	2.61 / 5.45	**3.77**	2.40 / 5.10	**4.07**	2.84 / 5.96	**4.32**	3.03 / 6.07	**7.0**
December	**4.05**	2.79 / 5.58	**3.79**	2.06 / 5.12	**4.04**	2.41 / 5.17	**4.67**	3.23 / 5.86	**9.1**
YEAR	**3.96**	**3.72 / 4.16**	**4.11**	**3.78 / 4.31**	**4.28**	**3.93 / 4.59**	**4.41**	**4.05 / 4.68**	**4.7**

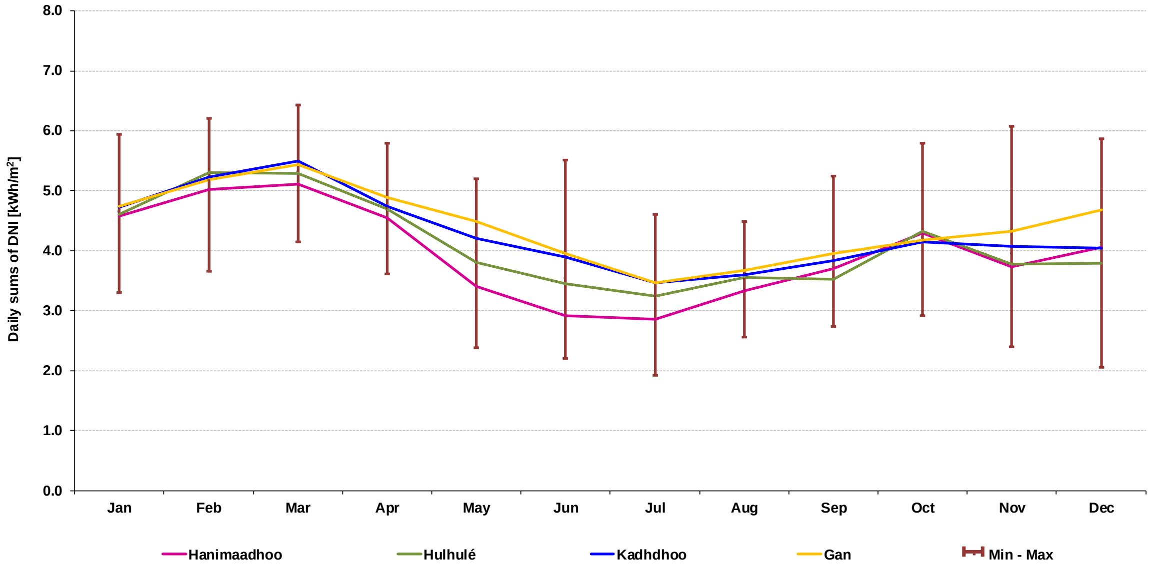


Figure 3.5: Daily averages of Direct Normal Irradiation at selected sites.

Interannual variability of DNI for selected sites (Figure 3.6) is calculated from the unbiased standard deviation of yearly DNI over 19 years and it is based on a simplified assumption of normal distribution of the yearly sums. Three sites show similar patterns of DNI changes over recorded period. The most stable DNI (the lowest interannual variability) is observed in Hanimaadhoo.

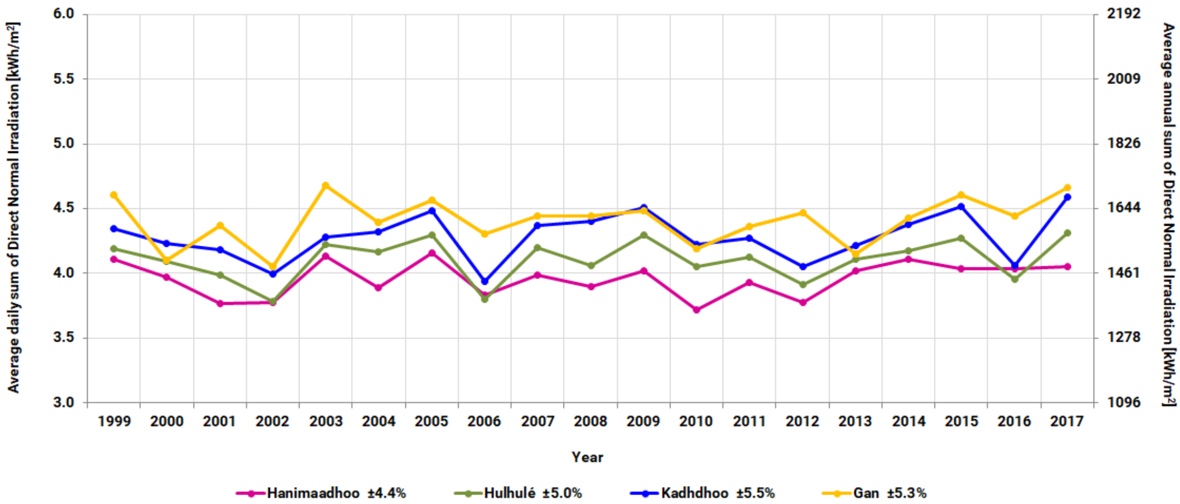


Figure 3.6: Interannual variability of Direct Normal Irradiation at representative sites

Daily totals in a particular year can be displayed for a better visual presentation of DNI in relation to GHI. Figure 3.7 shows daily totals for year 2017 in Hulhulé. The blue pattern, representing GHI sums, is transparent in order to make the lower values of the DNI pattern (yellow) visible.

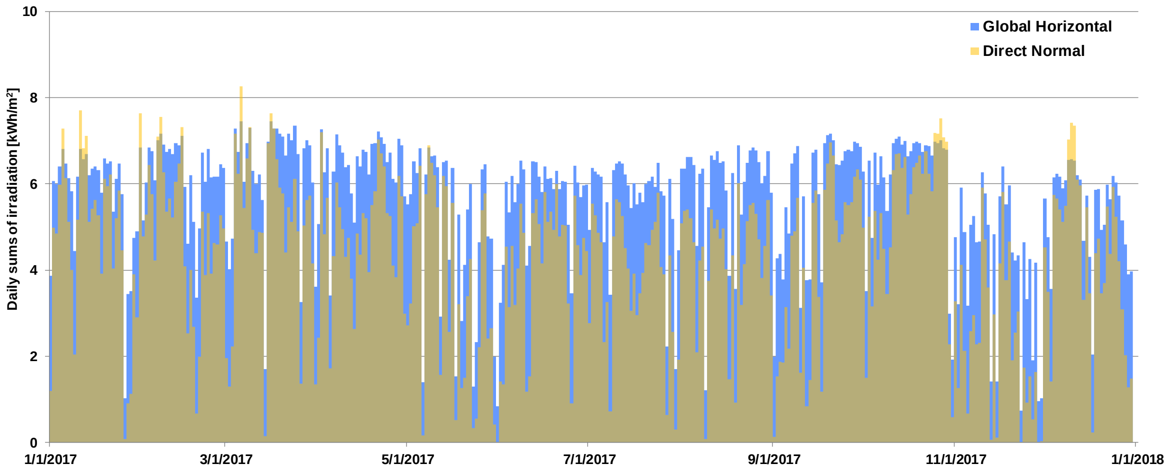
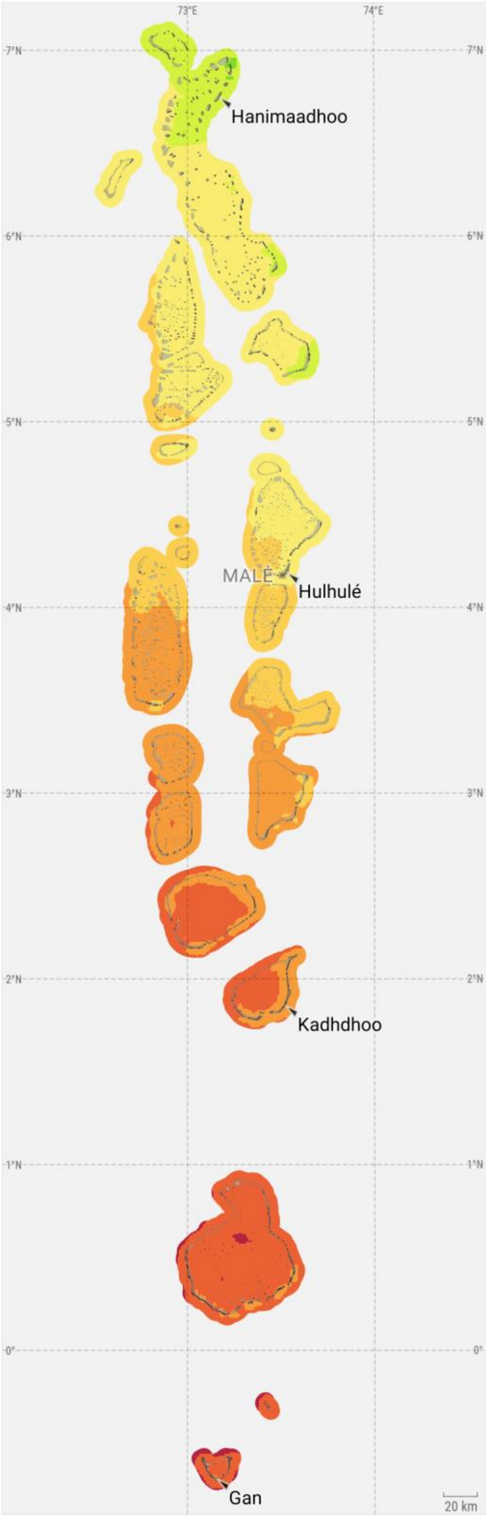


Figure 3.7: Daily totals of GHI (blue) and DNI (yellow) in Hulhulé, year 2017
Source: Solargis

The highest DNI in the South region of archipelago represents average daily totals of up to 4.4 kWh/m^2 (equal to yearly sum of about 1610 kWh/m^2, Map 3.9). The season of high DNI with daily sums above 4.6 kWh/m^2 lasts from January to April (Map 3.10). When comparing monthly values of DNI with GHI it is apparent that there is just one season with high DNI yields – from January to April.

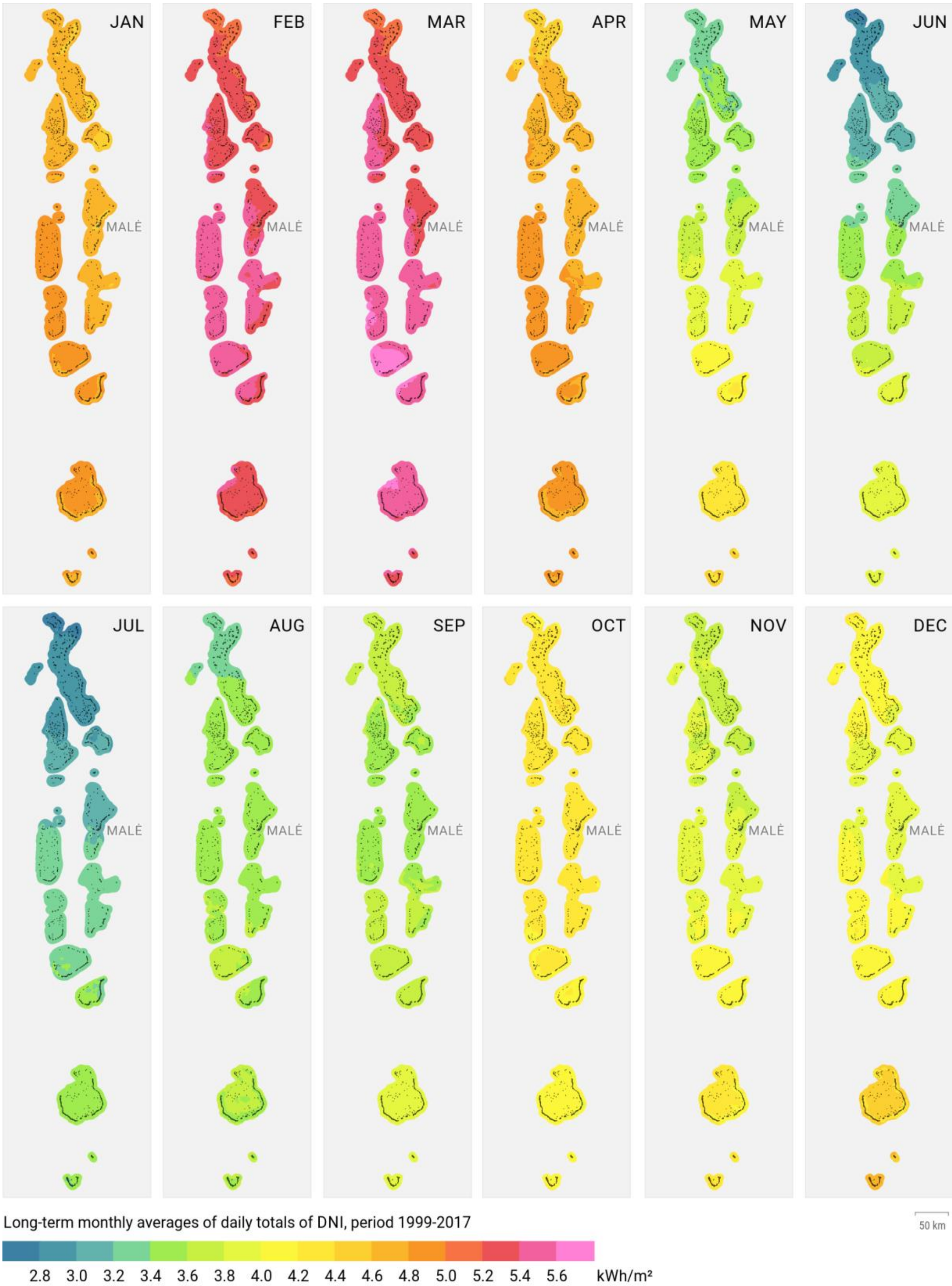


Long-term average of DNI, period 1999-2017

Daily totals: 3.9 4.0 4.1 4.2 4.3 4.4 kWh/m²

Yearly totals: 1424 1461 1497 1534 1570 1607

Map 3.9: Direct Normal Irradiation – long-term average of daily and yearly totals.
Source: Solargis



Map 3.10: Direct Normal Irradiation – long-term monthly average of daily totals.
Source: Solargis

3.5 Global Tilted Irradiation

Global Tilted Irradiation (GTI) is the key source of energy for flat-plate photovoltaic (PV) technologies (Chapter 3.6). In this study GTI is calculated for the tilt angle of 7° oriented towards the Equator. The optimum tilt angle for Maldives is in the range between 3° and 10° depending on the geographic location, but due to minimum effect on differences in GTI a one tilt of 7° has been chosen for all sites. Keeping the modules tilted to some extent helps cleaning their surface by rainfall.

Table 3.4 shows the long-term averages of average daily total Global Tilted Irradiation (GTI) for selected sites. It is assumed that solar radiation is received by PV modules with surface inclined at 7° tilt towards equator.

Table 3.4: Daily averages and average minima and maxima of Global Tilted Irradiation at 4 sites

Month	Global Tilted Irradiation [kWh/m^2]								Variability between sites [%]
	Hanimaadhoo		Hulhulé		Kadhdhoo		Gan		
	Average	Min Max	Average	Min Max	Average	Min Max	Average	Min Max	
January	**5.94**	5.37 6.32	**5.97**	5.08 6.49	**6.02**	5.22 6.67	**5.48**	4.62 6.21	**4.3**
February	**6.39**	5.52 6.85	**6.58**	6.12 7.04	**6.47**	5.76 7.00	**6.14**	5.54 6.59	**2.9**
March	**6.68**	5.54 7.02	**6.65**	5.78 7.19	**6.60**	5.93 7.09	**6.46**	5.53 7.02	**1.5**
April	**6.13**	5.68 6.71	**5.96**	5.40 6.54	**5.79**	5.25 6.48	**6.03**	5.42 6.67	**2.4**
May	**5.07**	4.32 5.97	**5.11**	4.26 5.58	**5.15**	4.63 5.57	**5.62**	5.21 6.18	**4.9**
June	**4.72**	4.02 5.53	**4.93**	4.21 5.50	**5.02**	4.42 5.74	**5.38**	4.30 6.29	**5.5**
July	**4.86**	4.20 5.57	**4.92**	4.35 5.38	**4.87**	4.36 5.36	**5.13**	4.53 5.94	**2.5**
August	**5.28**	4.64 5.90	**5.28**	4.44 5.86	**5.13**	4.49 5.60	**5.40**	4.64 6.00	**2.1**
September	**5.56**	4.92 6.55	**5.39**	4.72 6.57	**5.53**	5.05 6.40	**5.61**	4.73 6.11	**1.7**
October	**5.69**	4.72 6.49	**5.79**	5.18 6.60	**5.69**	4.97 6.35	**5.53**	4.83 6.49	**1.8**
November	**5.21**	4.06 6.06	**5.23**	4.21 6.14	**5.40**	4.36 6.74	**5.27**	4.47 6.29	**1.6**
December	**5.33**	4.47 6.24	**5.22**	3.84 6.14	**5.37**	4.13 6.20	**5.25**	4.34 5.96	**1.3**
YEAR	**5.57**	**5.39** **5.68**	**5.58**	**5.35** **5.71**	**5.58**	**5.30** **5.74**	**5.61**	**5.30** **5.75**	**0.3**

Figure 3.8 compares long-term daily averages at selected sites. Stable weather with high GTI values is seen from January to April. Variability of GTI in all selected sites is very small. Lower daily averages in period from September to December are very similar for all sites, which are related to the rainy season.

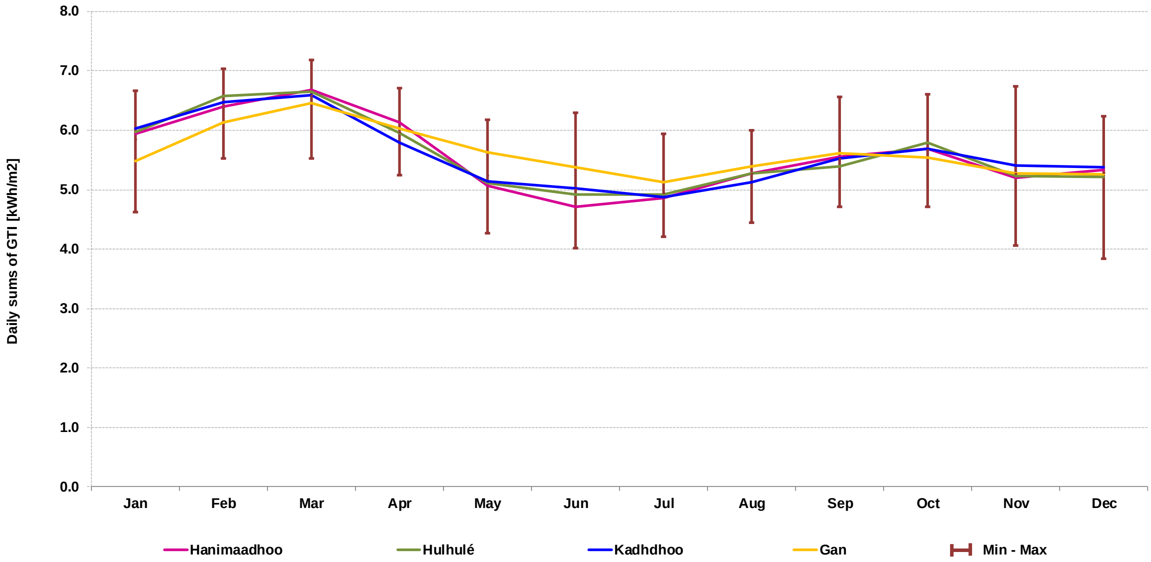


Figure 3.8: Global Tilted Irradiation – long-term daily averages, minima and maxima.

A surface inclined at an optimum angle (tilt) gains more yearly irradiation than a horizontal surface (depending on the latitude of a site). In Maldives, where optimum tilt is close to horizontal position (ranging from 3° to 10°), the yearly gains of GTI are very low in comparison to GHI. This is documented on Figure 3.9, where a positive gain of GTI is about 5% to 6% (in October-March for sites located on Northern hemisphere), but this gain is reduced with almost similar losses during second half of the year (April-September). At Gan, located in the Southern hemisphere, the periods of gains and losses are reversed compared to the other selected sites. The annual gain of a tilted plane is only slightly above the yield of a horizontally mounted plane for all representative sites.

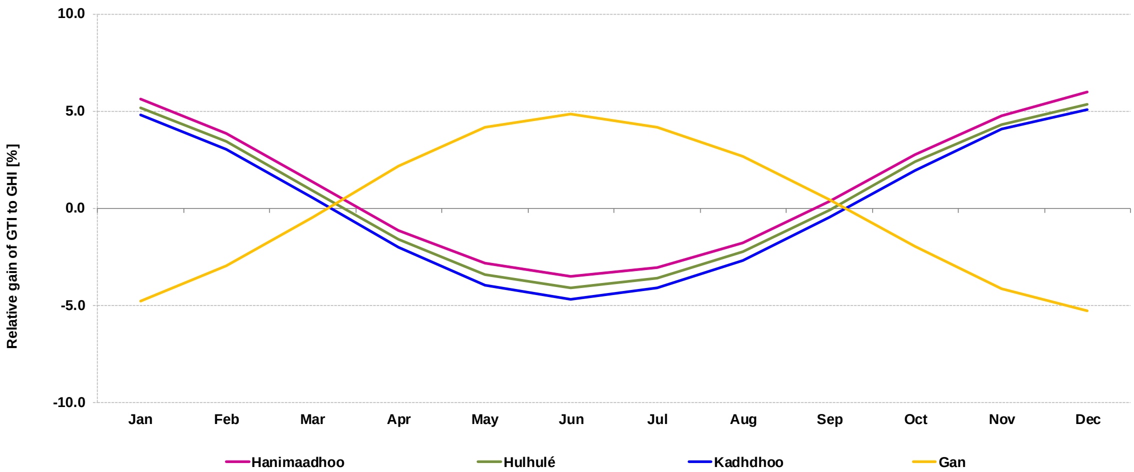
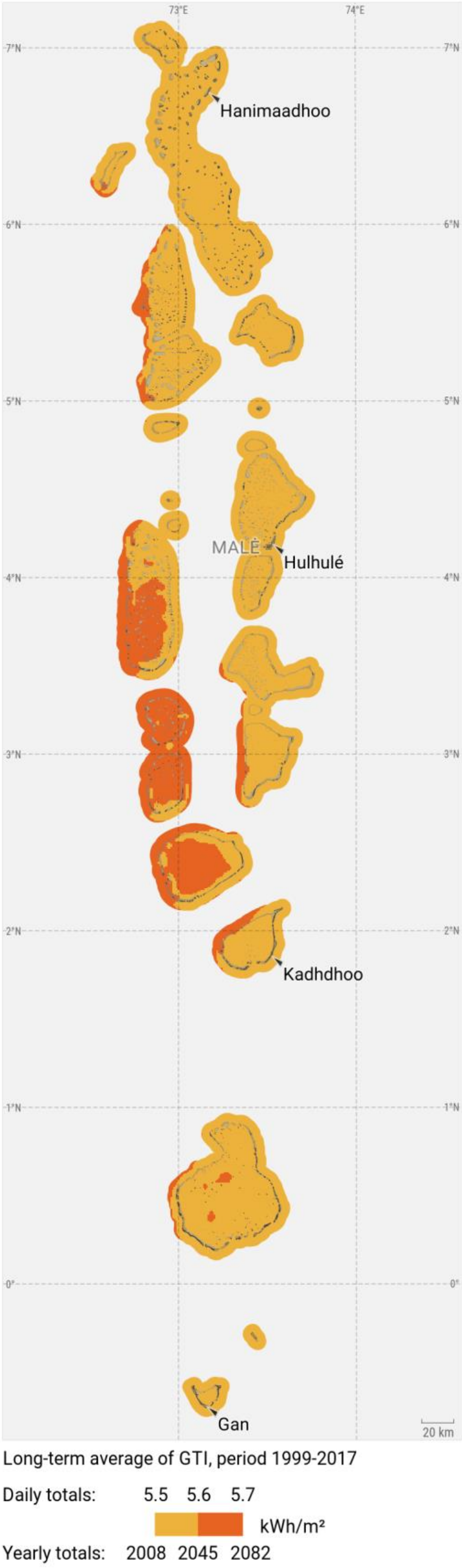
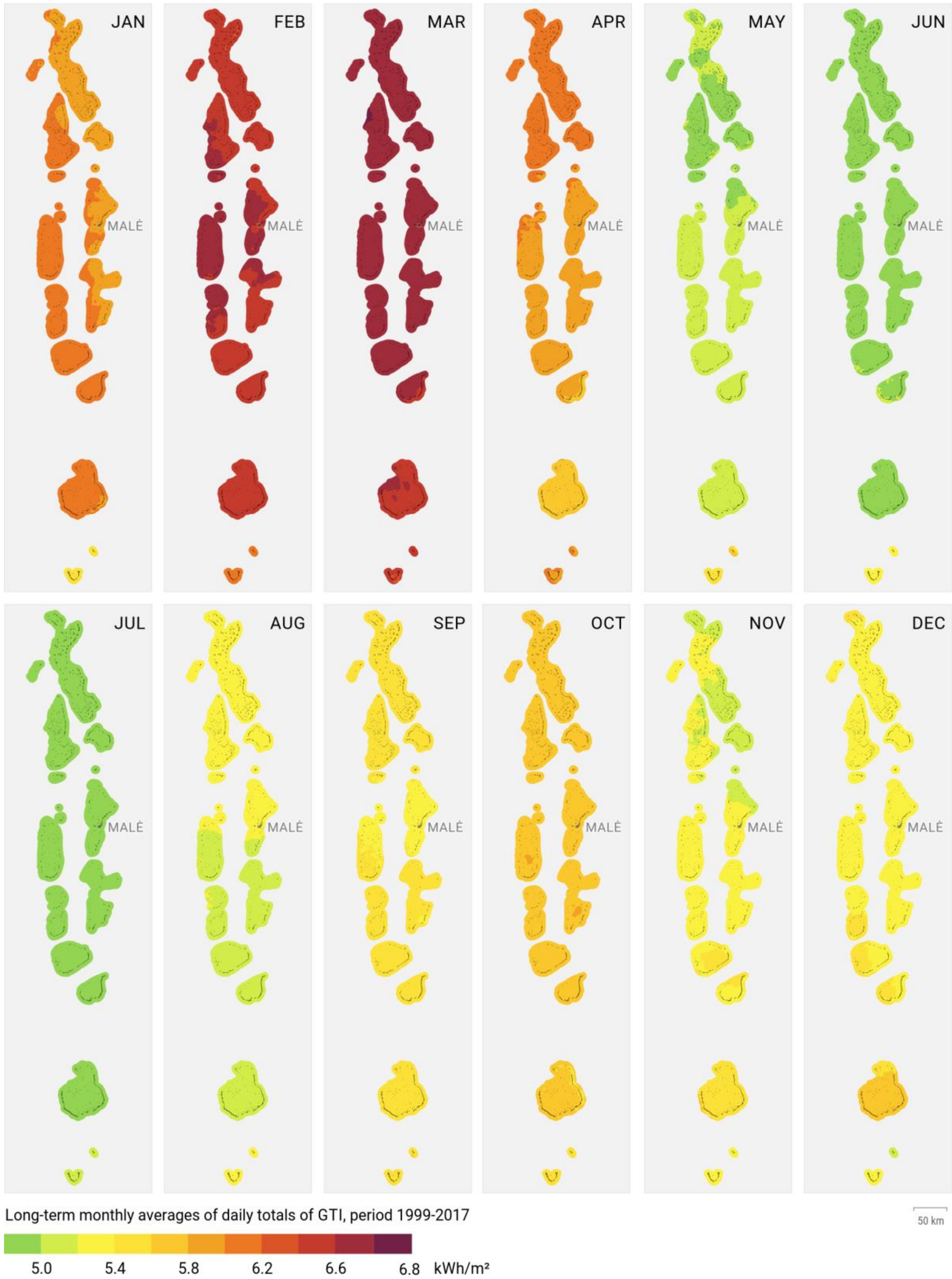


Figure 3.9: Monthly relative gain of GTI relative to GHI at selected sites.

The regional and seasonal trend of GTI is similar to GHI (Map 3.11 and 3.12). Installing PV modules at the tilt 7° (inclination) and orientated toward the Equator can result in annual average daily sum of GTI energy input up to 5.6 kWh/m^2 (yearly sum about 2045 kWh/m^2), almost in all territory of Maldives.



Map 3.11: Global Tilted Irradiation at 7° tilt towards equator – long-term average of daily and yearly totals.
Source: Solargis



Map 3.12: Global Tilted Irradiation at 7° tilt towards equator – long-term monthly average of daily totals.
Source: Solargis

3.6 Photovoltaic power potential

The PV potential from a reference system for four representative sites is shown in Table 3.5. Despite the geographic distribution of selected sites, electricity production form a PV power system is similar for all sites and follows a combined pattern of global irradiation and air temperature. The difference between production from the "best" site (Gan, 4.40 kWh/kWp) and "the least productive" site (Hanimaadhoo, 4.37 kWh/kWp) is only 0.7%. Also, monthly power production profiles are very similar for all sites. The highest seasonal production occurs from January to April (Table 3.6).

Table 3.5: Annual performance parameters of a PV system with modules fixed at 7° tilt towards equator

	Hanimaadhoo	Hulhulé	Kadhdhoo	Gan
PVOUT Average daily total [kWh/kWp]	4.37	4.38	4.38	4.40
PVOUT Yearly total [kWh/kWp]	1595	1598	1599	1606
Annual ratio of DIF/GHI	46.6%	45.1%	43.3%	42.3%
System PR	78.4%	78.4%	78.4%	78.4%

PVOUT - PV electricity yield for fixed-mounted modules at 7° tilt towards equator; DIF/GHI – Ratio of Diffuse/Global horizontal irradiation; PR - Performance ratio for fixed-mounted PV

Table 3.6: Average daily sums of PV electricity output from an open-space 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	
Hanimaadhoo	4.68	5.02	5.21	4.78	3.96	3.70	3.82	4.15	4.36	4.45	4.09	4.20	4.37
Hulhulé	4.69	5.15	5.19	4.66	4.01	3.87	3.87	4.15	4.23	4.53	4.11	4.10	4.38
Kadhdhoo	4.73	5.06	5.15	4.53	4.04	3.95	3.83	4.03	4.34	4.46	4.23	4.22	4.38
Gan	4.30	4.81	5.04	4.71	4.41	4.23	4.04	4.24	4.40	4.34	4.14	4.13	4.40

Map 3.14 shows monthly production from a PV power system, and Figure 3.10 breaks down the values for the four 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, it is recommended to install modules close to an 7° 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.

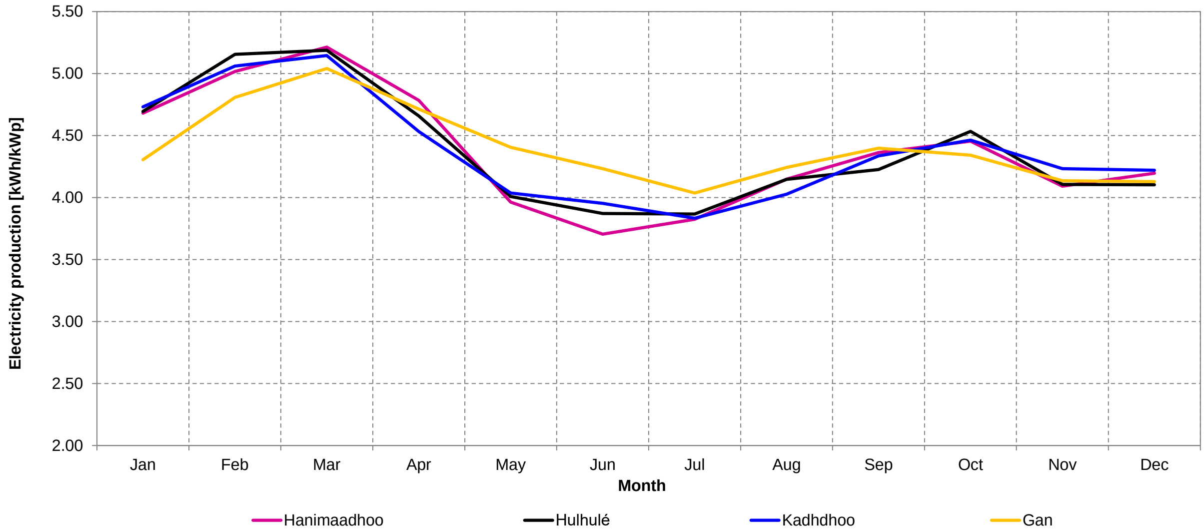


Figure 3.10: Monthly averages of daily totals of power production from the fixed tilted PV systems with a nominal peak power of 1 kW at four sites [kWh/kWp]

The monthly and yearly performance ratios (PR) of a reference installation for the selected sites are shown in Table 3.7 and Figure 3.11. The range of yearly PR for the selected sites is the same for all four sites: 78.4%. The only difference being the monthly variations, which falls in a very narrow range of ±0.4%.

Table 3.7: 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	
Hanimaadhoo	78.8	78.5	78.1	78.0	78.2	78.5	78.6	78.6	78.5	78.3	78.6	78.8	78.4
Hulhulé	78.6	78.3	78.1	78.1	78.4	78.6	78.6	78.6	78.4	78.3	78.5	78.7	78.4
Kadhdhoo	78.5	78.2	78.0	78.3	78.4	78.7	78.7	78.6	78.4	78.4	78.4	78.6	78.4
Gan	78.5	78.3	78.1	78.2	78.3	78.7	78.7	78.6	78.4	78.5	78.5	78.6	78.4

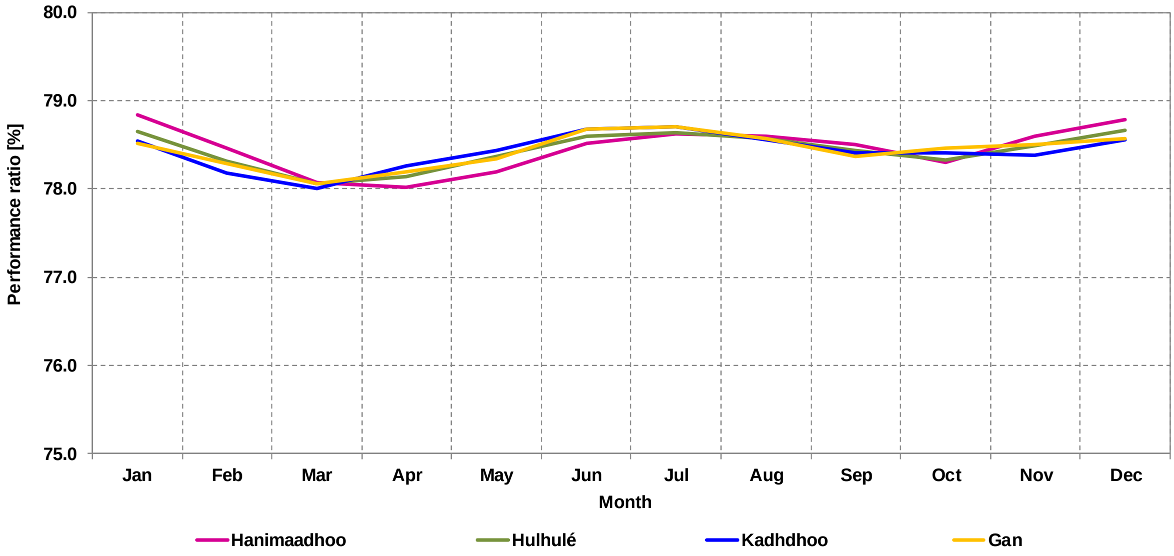
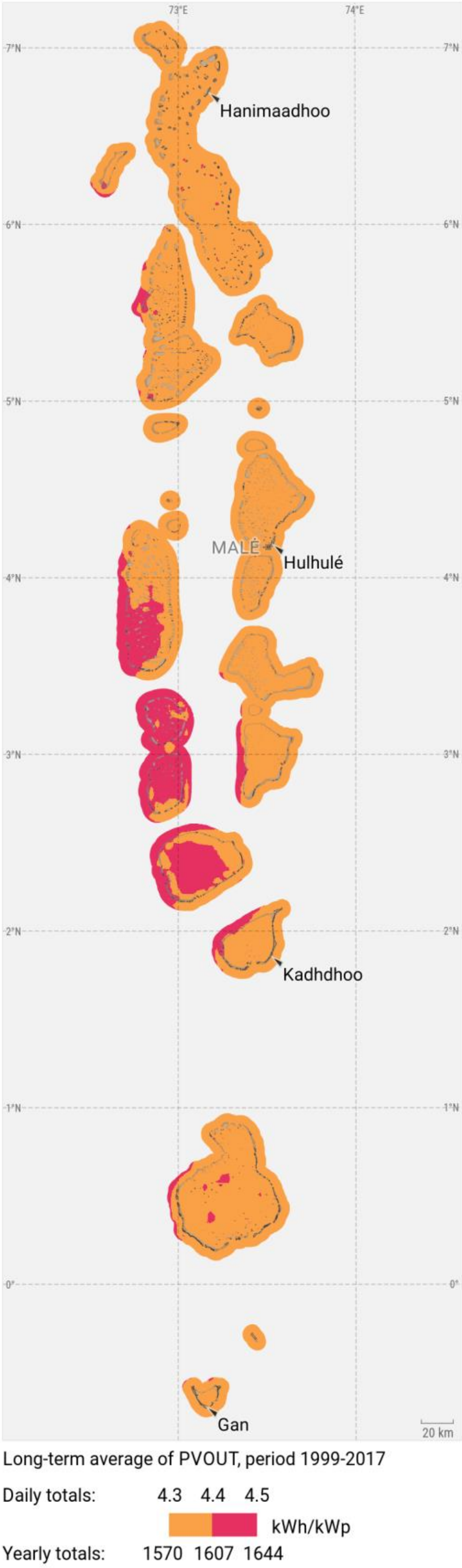


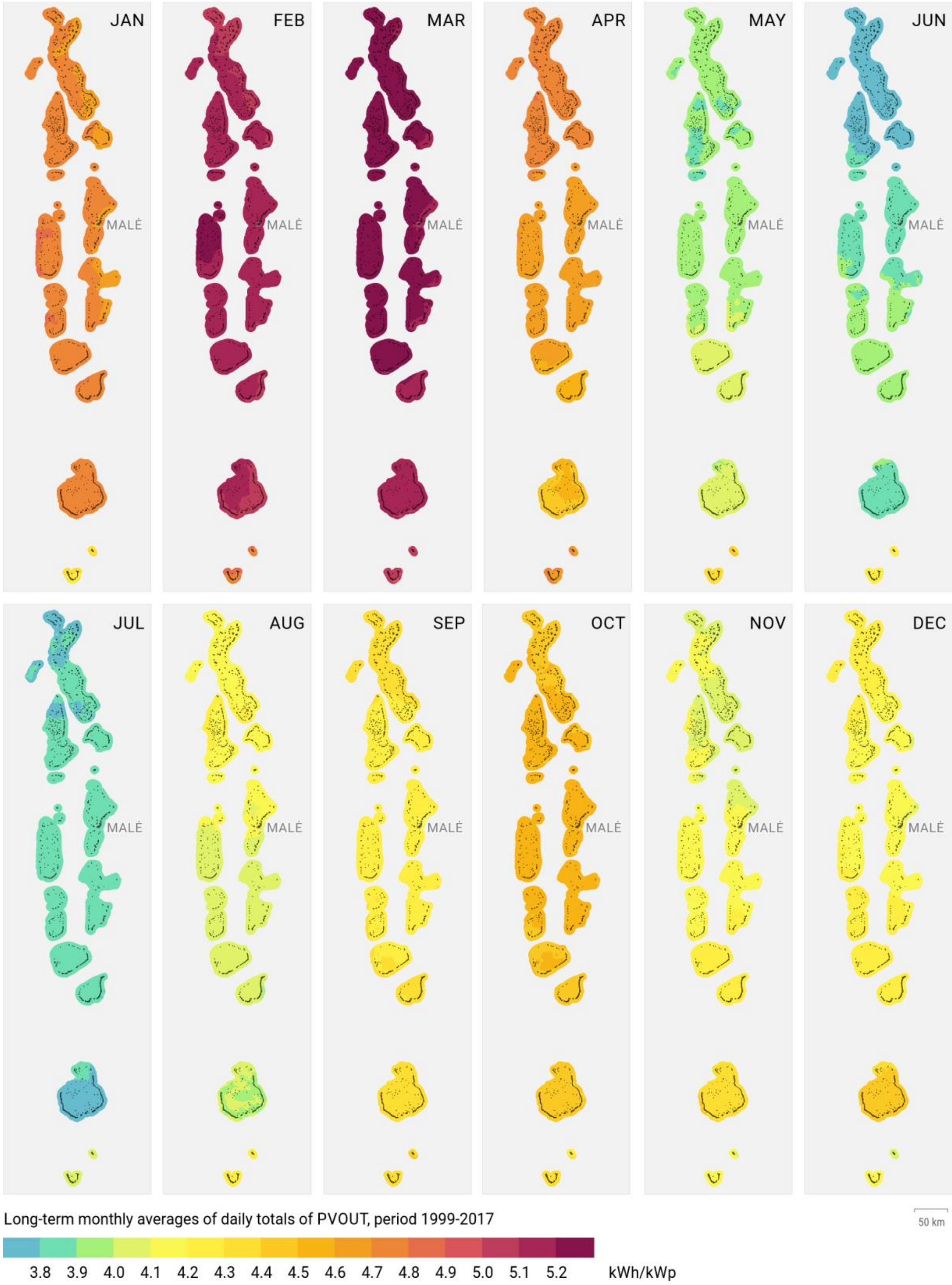
Figure 3.11: Monthly performance ratio of a PV system at selected sites.
Fixed mounted modules at 7° tilt towards equator are considered

Map 3.13 shows the average daily total of specific PV electricity output from a typical open-space PV system with a nominal peak power of 1 kW, i.e. 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.

In Maldives, the average daily sums of specific PV power production from a reference system vary between 4.3 kWh/kWp (equals to yearly sum of about 1570 kWh/kWp) and 4.5 kWh/kWp (about 1640 kWh/kWp yearly). Average daily totals for the year are very uniform throughout all of Maldives. The best season for PV power production is from January to April, with extreme values in March, when they reach more than 5.2 kWh/kWp.



Map 3.13: PV electricity output from an open space fixed-mounted PV system with PV modules mounted at 7° tilt towards equator and a nominal peak power of 1 kWp. Long-term averages of daily and yearly totals.



Map 3.14: PV power generation potential for an open-space fixed-mounted PV system.
Long-term monthly averages of daily totals.

Source: Solargis

3.7 Evaluation

The chapters above describe various aspects of PV power generation potential in Maldives, and its relevance for the development and operation of photovoltaic systems. A large extent of the country has specific PV electricity output within a range of 1570 kWh/kWp and 1607 kWh/kWp (equals to average daily totals between 4.3 and 4.4 kWh/kWp). **This places Maldives into the category of countries with very feasible potential for PV power generation.**

Additionally, the seasonal variability in the country is low, when compared to other regions further away from the equator. The ratio between months with maximum and minimum GHI is about 1.33 in Hulhulé, which is better than the ratio for Upington, South Africa (2.29) and Sevilla, Spain (3.54) (Figure 3.12).

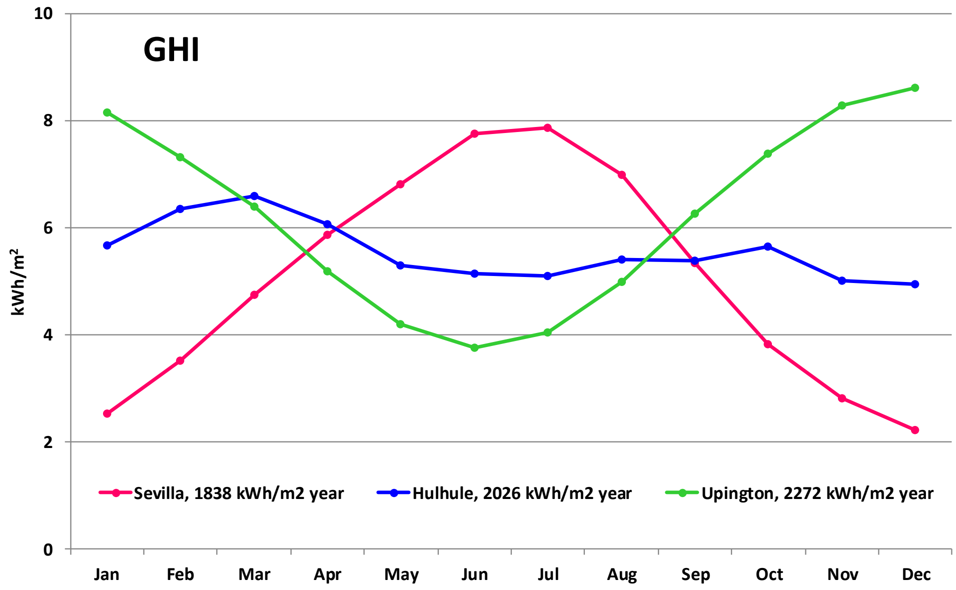


Figure 3.12: Comparing seasonal variability in three locations for GHI

4 Data delivered for Maldives

The key features of the delivered data and maps for Maldives are:

- Harmonized solar, meteorological and geographical data based on the best available methods and input data sources.
- Historical long-term averages representing 19 years at high spatial and temporal resolution, available for any location.
- Regionally adapted solar resource data - improved data accuracy based on two years of measurements on four solar meteorological stations, located across the country
- The Solargis database and energy simulation software is extensively validated by company Solargis, as well as by independent organizations. They are also verified within monitoring of commercial PV power plants and solar measuring stations worldwide.
- The aggregated data for the whole country can be accessed as downloadable files and maps through an online map-based application http://globalsolaratlas.info/.

The delivered data and maps offer a good basis for knowledge-based decision making and project development. These data are updated in real time and can be further used in solar monitoring, performance assessment and forecasting.

4.1 Spatial data products

High-resolution Solargis data have been delivered in the format suitable for common GIS software. The *Primary data* represent solar radiation, meteorological data and PV power potential. The *Supporting data* include various vector data, such as islands, cities, etc.

Tables 4.1 and 4.2 show information about the data layers and the 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	Land, including the intra-reef area with buffer approximately 15 km towards the open ocean) between 8°N and 1°S, 72°W and 74°E, covering the Republic of Maldives
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 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 7° tilt towards equator	kWh/m^2	Assessment of solar resource for PV technologies	Long-term yearly and monthly average of daily totals
PVOUT	Photovoltaic power potential	kWh/kWp	Assessment of power production potential for a PV power plant with free-standing fixed-mounted c-Si modules, mounted at 7° tilt 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	72:00:00E – 74:00:00E
North – South	8:00:00N – 1:00:00S
Resolution (GHI, DNI, GTI, DIF, PVOUT)	00:00:09 (800 columns x 3600 rows)
Resolution (TEMP)	00:00:30 (240 columns x 1080 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. 275 x 275 m)	1999 – 2017	12+1
DNI	Direct Normal Irradiation	Raster	9 arc-sec. (approx. 275 x 275 m)	1999 – 2017	12+1
DIF	Diffuse Horizontal Irradiation	Raster	9 arc-sec. (approx. 275 x 275 m)	1999 – 2017	12+1
GTI	Global Irradiation at 7° tilt towards equator	Raster	9 arc-sec. (approx. 275 x 275 m)	1999 – 2017	12+1
PVOUT	Photovoltaic power potential	Raster	9 arc-sec. (approx. 275 x 275 m)	1999 – 2017	12+1
TEMP	Air Temperature at 2 m above ground level	Raster	30 arc-sec. (approx. 930x930 m)	1999 – 2017	12+1

Explanation:

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

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) complement ESRI ASCII grid files (*.asc)

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	Size (approx.)
GHI	Global Horizontal Irradiation, long-term yearly average of daily totals	GHI.*ext*	1+1	17 MB
GHI	Global Horizontal Irradiation, long-term monthly averages of daily totals	GHI_*MM.ext*	12+12	190 MB
DNI	Direct Normal Irradiation, long-term yearly average of daily totals	DNI.*ext*	1+1	17 MB
DNI	Direct Normal Irradiation, long-term monthly averages of daily totals	DNI_*MM.ext*	12+12	190 MB
DIF	Diffuse Horizontal Irradiation, long-term yearly average of daily totals	DIF.*ext*	1+1	17 MB
DIF	Diffuse Horizontal Irradiation, long-term monthly averages of daily totals	DIF_*MM.ext*	12+12	190 MB
GTI	Global Irradiation at 7° tilt towards equator, long-term yearly average of daily totals	GTI.*ext*	1+1	17 MB
GTI	Global Irradiation at 7° tilt towards equator, long-term monthly averages of daily totals	GTI_*MM.ext*	12+12	190 MB
PVOUT	Photovoltaic power potential , long-term yearly average of daily totals	PVOUT.*ext*	1+1	17 MB
PVOUT	Photovoltaic power potential , long-term monthly averages of daily totals	PVOUT_MM.*ext*	12+12	190 MB
TEMP	Air Temperature at 2 m above ground, long-term yearly average	TEMP.*ext*	1+1	2 MB
TEMP	Air Temperature at 2 m above ground, long-term monthly averages	TEMP_*MM.ext*	12+12	18 MB

Table 4.6: Support GIS data

Data type	Source	Data format
City location	OpenStreetMap.org contributors, GeoNames.org, adapted by Solargis	Point shapefile
Islands	Cartography Unit, GSDPM, World Bank Group	Polyline shapefile
Solar meteorological stations	Solargis	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 Quantum GIS (QGIS) project files with colour schemes and annotation (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.

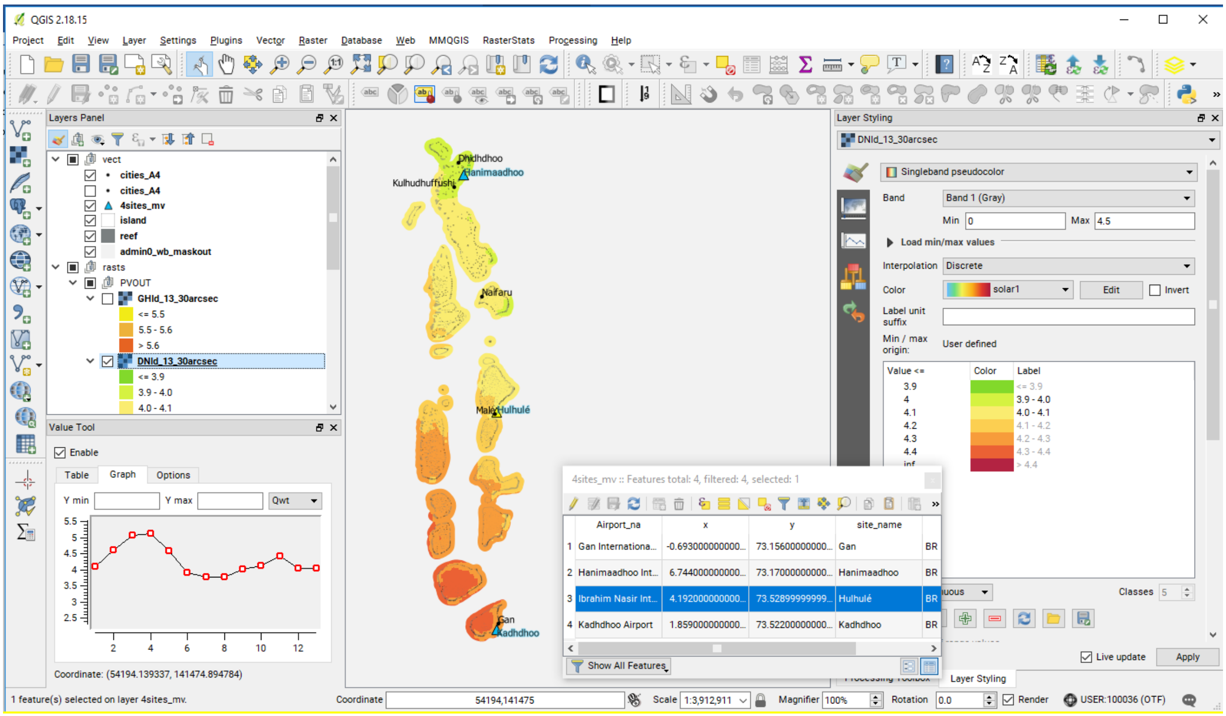


Figure 4.1: Screenshot of the map and data in the QGIS environment

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: http://globalsolaratlas.info/downloads/maldives.

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8 References

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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 more than 18 years. We develop and operate a new generation 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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