SOLAR RESOURCE POTENTIAL MAPPING: COUNTRY STUDY OF THE STATE OF PALESTINE

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Abstrakt

Slnečné žiarenie je palivo pre solárne elektrárne, pričom lokálne geografické a klimatické pomery determinujú efektivitu ich prevádzky. Kľúčovým faktorom výstavby a prevádzky solárnych elektrární je dostupnosť spoľahlivých údajov o slnečnom žiarení ako aj ďalších meteorologických dát. Účelom mapovania potenciálu využitia slnečnej energie je vytvoriť informačnú bázu vo forme GIS dát, mapových výstupov a expertných štúdií vhodných pre strategické rohodovanie vládnych organizácií, investorov, konzultantov, developerov a prevádzkovateľov.

SolarGIS databáza, vyvinutá a prevádzkovaná spoločnosťou GeoModel Solar, je pre takýto účel jedinečným dátovým zdrojom. Obsahuje historické i súčasné dáta o slnečnej radiácii, ktoré v súčasnosti pokrývajú takmer plochu kontinentov medzi rovnobežkami 60°N a 50°S. Okrem slnečného žiarenia, SolarGIS tiež poskytuje meteorologické dáta, odvodené z meteorologických modelov (teplota vzduchu, relatívna vlhkosť, charakteristiky vetra, atď.) a ďalšie geografické dáta (terén, krajinná pokrývka, populácia).

Dôležité vstupy sú poskytované aj z lokálnych zdrojov. Dáta z pozemných meteorologických meraní sú hodnotné pre validáciu a regionálnu adaptáciu modelu SolarGIS a tým na zníženiene určitosti dát.

V predkladanej štúdii prezentujeme metodológiu mapovania slnečného potenciálu a základné výstupy, ktoré boli spracované pre vládne inštitúcie Štátu Palestína. Výstupy obsahujú regionálnu databázu klimatických dát s časovými radmi a agregovanými hodnotami v GIS formáte. Nad databázou boli vytvorené GIS a mapové produkty vybraných charakteristík slnečného potenciálu:

- veľkoformátové posterové mapy a mapy pre Google Earth,
- QGIS a ESRI ArcMap projekty s predpripravenými dátami na riešenie analytických úloh

Súrhn poznatkov bol spracovaný v dvoch štúdiách:

- *Solárny Atlas*, obsahujúci súhrnné informácie predovšetkým pre vládne organizácie, investorov, a širokú verejnosť
- *Technický report*, podávajúci detailnejšie informácie, venovaný cieľovej skupine technických expertov a projektových developerov.

Kľúčové kapitoly štúdií popisujú metodológiu získavania, validácie a mieru neurčitosti poskytnutých dát, hodnotenie slnečného potenciálu a potenciálu výroby elektriny fotovoltickými elektrárňami a odporúčania k aplikáciám spojených so solárnou energetikou.

Kľúčové slová: **slnečné žiarenie, potenciál solárnej energie, solárny atlas, SolarGIS, Štát Palestína**

Keywords: solar resource potential, mapping, solar energy, solar atlas, SolarGIS, State of Palestine

1 INTRODUCTION

Solar resources are fuel to solar power plants and local geography and climate determine effectivity of their operation. Key factor to development and operation of solar power plants is availability of reliable solar and meteorological data. The objective of solar resource potential mapping is to develop such information in the form of GIS data, maps and expert studies for further decision making by governmental agencies, investors, consultants, project developers and operators.

In this study, we present a methodology of solar resource mapping and the key results. The example of the State of Palestine is used. The final products include regional database of climate data, which includes site-specific solar and Meteorological time-series and aggregated characteristics in a GIS data format. The key data layers are organized in a GIS project and also prepared as a series of thematic maps**.**

2 ROLE OF SOLAR AND METEO DATA FOR SOLAR ENERGY

Solar and meteorological data are needed in all phases of development and operation of solar power plants:

1. Prospection, prefeasibility and selection of sites candidate to power plant development
2. Project assessment, engineering, technical design and financial assessment
3. Monitoring and performance assessment of solar power plants and forecasting of solar power
4. Quality control of solar measurements.

Tab.1 provides an overview of data, which are needed in different stages of the project lifetime, and how they are implemented in solar resource analysis and energy simulation. Solar Resource Atlas aims at supporting first two project stages (marked by red box).

Tab. 1 Solar and meteo data needed in development and operation of solar power plants

		Maps and GIS data		**Time series**					**TMY**	
		LTA/monthly	Operational	15' (30')	Hourly	Daily	Monthly	Yearly	P50	P90 and Pxx
1	Prefeasibility	x					x	x		
	Site selection	x					x	x	x	
2	Project first assessment						x	x	x	
	Engineering and project design			x	x				x	x
	Financial modelling			x	x		x	x	x	x
3	Performance assessment	x	x	x	x	x	x			
	Monitoring		x	x	x	x				
	Forecasting		x	x	x					
4	Quality control of solar measurements		x	x	x					

Note: LTA = Longterm averages, P50 = probability of exceedance 50%, P90 = probability of exceedance 90%

2.1 Solar resource data

Solar radiation is the most important parameter for PV power simulation. Two primary solar resource parameters are calculated:

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

Other parameters can be calculated from the above-mentioned primary data:

- Diffuse Horizontal Irradiance (DIF)
- Global Tilted Irradiance (GTI, i.e. irradiance received by tilted surface of PV modules)

Global Horizontal Irradiance (GHI) is the total amount of shortwave radiation received by a horizontal surface of the ground. This value represents the sum of direct (DNI), diffuse (DIF) and ground-reflected irradiance; ground reflected irradiance is usually very low for GHI:

$$GHI = DIF + DNI * \cos (Z),$$ where Z is the solar zenith

Direct Normal Irradiance (DNI) is equal to direct (beam) radiation that comes in a direct line from the sun and is not scattered or absorbed by atmospheric constituents and clouds. Direct radiation can be sometimes obstructed by terrain or any other objects.

Global Tilted Irradiance (GTI) received by tilted surface of PV modules is calculated from Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), terrain albedo, and instantaneous sun position within a specified time interval. Reflected irradiance plays more important role for tilted surfaces.

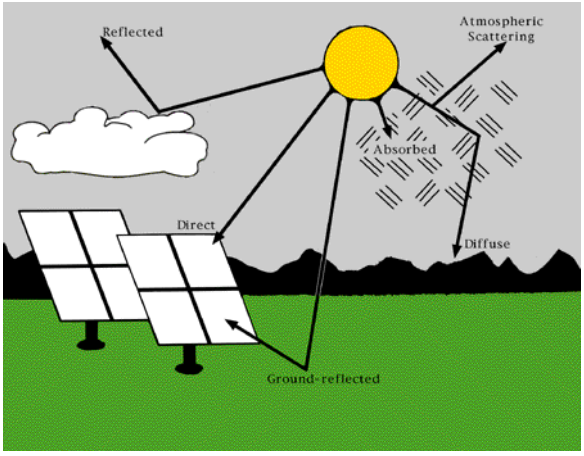

Fig. 1 The sum of the direct (beam), diffuse, and ground-reflected irradiance arriving at the surface is called global irradiance. This can be horizontal or tilted, depending on the surface. Source: NREL

Solar radiation is calculated by numerical models, which are parameterized by a set of inputs characterizing the state of the atmosphere, cloud transmittance and terrain conditions. In this calculation the SolarGIS methodology is used [1], with satellite and atmospheric data used on the input. The output data represent period of years 1994 to 2013 and they include:

- GIS data and digital maps of Global Horizontal Irradiation, Direct Normal Irradiation, Diffuse Horizontal Irradiation, Global Tilted Irradiation, and PV power potential;
- Time series (TS) data and Typical meteorological year (TMY) data.

2.2 Meteorological data

Analysis of meteorological parameters is also important, as they define operating conditions of solar power plants at the site of interest. Best option would be to have data from meteo stations, covering at least 10 recent years (or optimally the same period as satellite data) of continuous measurements. Meteorological equipment is capable of recording automatically weather parameters at good accuracy and high frequency. However, except for sites with long-term meteorological observations, this option is typically not available. Often, the long-term time series are not complete, and there are missing or unreliable data.

Therefore to prepare harmonized and comprehensive meteorological database, the parameters are calculated from the outputs of global weather models; in this case CFSR and CFSv2 [2, 3, 4]. For solar energy projects, the most important characteristics is air temperature, others provide auxiliary information: relative humidity, wind direction, wind speed. Weather model outputs have lower spatial and temporal resolution, thus they do not represent the same accuracy as the solar resource data.

2.3 Geographic data

Geographic information data and maps give additional value to the solar information. Geographic characteristics of a region or particular location create technical and environmental constraints or prerequisites for development of a solar power plant. Among the most important are:

- Terrain, population and accessibility
- Demand centres (energy needs: industry, agriculture, services)
- Electricity grid infrastructure (generation and network)
- Road network

As an example, spatial distribution of settlements refers to the electricity consumption centres, road infrastructure and terrain form physical limitation criteria for project development.

3 SOLAR RESOURCE DATA AND METHODS

SolarGIS includes models and high-resolution global database of solar resource and meteorological parameters, operated by GeoModel Solar. The database is computed and updated on a daily bases from satellite, atmospheric and meteorological inputs. The data are systematically quality controlled in-house. Independent tests [5] identified SolarGIS as the best performing solar resource database.

Advantage of satellite data is their relatively long and continuous record: 20 years of data, with 15-minute and 30-minute frequency, is available in the region.

3.1 SolarGIS model

Solar radiation is calculated by numerical models, which are parameterized by a set of inputs characterizing the cloud transmittance, state of the atmosphere and terrain conditions [1, 6].

In SolarGIS approach, the *clear-sky irradiance* is calculated by the simplified SOLIS model [7]. This model allows fast calculation of clear-sky irradiance from the set of input parameters. Sun position is 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 and delivered at a spatial resolution of about 85 and 125 km. The calculation accuracy of the clear-sky irradiance is especially sensitive to the information about aerosols.

The key factor determining short-term variability of *all-sky irradiance* is clouds. Attenuation effect of clouds is expressed by the means of a parameter called cloud index, which is calculated from the routine observations of meteorological geostationary satellites. To retrieve all-sky irradiance in each time step, the clear-sky global horizontal irradiance is coupled with cloud index. Effect of clouds is calculated from the Meteosat satellite data (© EUMETSAT) in the form of cloud index (cloud transmittance). The cloud index is derived by relating irradiance recorded by the satellite in four spectral channels and surface albedo to the cloud optical properties. Compared to other approaches, a number of improvements have been introduced in SolarGIS, to better cope with specific situations such as high albedo areas (arid zones and deserts), and also with complex terrain.

In SolarGIS, the new generation *aerosol* data set representing Atmospheric Optical Depth (AOD) is used; it is derived from the outputs of MACC-II model (© ECMWF) [8, 9]). AOD data capture daily variability of aerosols and allow for simulation of events with extreme atmospheric load of aerosol particles, which improves calculations.

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, [2, 10]) are used in SolarGIS, thus representing the daily variability from 1994 to the present. *Ozone* absorbs solar radiation at wavelengths shorter than 0.3 μm, thus having negligible influence on the broadband solar radiation.

Direct Normal Irradiance (DNI) is calculated from Global Horizontal Irradiance (GHI) using modified Dirindex model [11]. Diffuse irradiance for tilted surfaces is calculated by Perez model [12]. The calculation procedure included also terrain disaggregation model for enhancing spatial representation – from the resolution of satellite (3.5 km) to the resolution of digital terrain model (250 meters) [13].

Technical summary of the input data in the SolarGIS model and output GHI and GTI is shown in Tab. 2.

Tab. 2 Input data used in the SolarGIS solar radiation model and relating GHI and GTI outputs

Inputs into the SolarGIS model	Source of input data	Time representation	Original time step	Approx. grid resolution
Cloud index	Meteosat MFG Meteosat MSG satellites (EUMETSAT)	1994 to 2004 2005 to 2013	30 minutes (MFG) 15 minutes (MSG)	3.5 km
Atmospheric Optical Depth (aerosols)	MACC-II model (ECMWF)	2003 to 2013*	6 hours (monthly averages for a period 1994 to 2002)	85 and 125 km
Water vapor	CFSR and GFS models (NOAA)	1994 to 2013	1 and 3 hours	35 and 55 km
Elevation and horizon	SRTM-3 data (SRTM)	-	-	250 m
SolarGIS primary data outputs (GHI and DNI)	-	1994 to 2013	15 minutes	250 m

Satellite data were validated by ground measurements from the region. To achieve reasonable results, high-quality ground measurements should be available for a period of at least one year, so that all seasons are included.

The uncertainty of the values calculated by the satellite-based solar radiation model depend on the following factors [14, 15]:

- Quality of input parameters describing state of the atmosphere, such as aerosols and water vapour
- Simulation accuracy of the cloud transmittance derived from the satellite data
- Geographical conditions of the site
- Uncertainty of related irradiance numerical models
- Accuracy of ground measurements used for validation.

Uncertainty of the estimates is derived from the validation statistics (bias, RMSD, etc.) and it is considered at 80%occurrence (Tab. 3).

Tab. 3 Uncertainty of the estimate for GHI, GTI and DNI values

	Yearly uncertainty [%]	Monthly uncertainty [%]
Global Horizontal Irradiation (GHI)	±4.0	±4 to ±9
Global Tilted Irradiation (GTI)	±5.0	±5 to ±10
Direct Normal Irradiation (DNI)	±9.0	±10 to ±15

3.2 Photovoltaic potential

Photovoltaic technology will most likely dominate in solar energy applications in Palestine. Therefore, in addition to solar and meteorological data, theoretical photovoltaic (PV) production potential has been calculated for the region.

As for photovoltaic power plants, numerous technical options are available. For calculating map data a typical PV power plant constructed in open space, with PV modules mounted in fixed position was assumed.

PV energy simulation is based on simulation developed by GeoModel Solar. PV algorithms implemented in SolarGIS follow the scientifically proven methods [18 to 22].

4 ATLAS OF SOLAR RESOURCES OF THE STATE OF PALESTINE

Solar Energy Resource Atlas for the State of Palestine [16] is an outcome of a project, where GeoModel Solar was selected, by the state authorities, for delivery of validated data and maps for the State of Palestine. This initiative aims at attracting commercial sector to the development of low carbon energy production and diversity of renewable electricity generation.

Here we provide some examples of the deliveries. The data and maps are supported by a Technical report (not shown in this article) with detailed information on methods and validation of the results.

4.1 Representative Sites

For demonstration of climate diversity, representative sites are selected in the region of interest. For these sites, full time-series and typical meteorological year (TMY) data are provided. Five sites were selected across the country to represent various microclimatic conditions (Fig. 2).

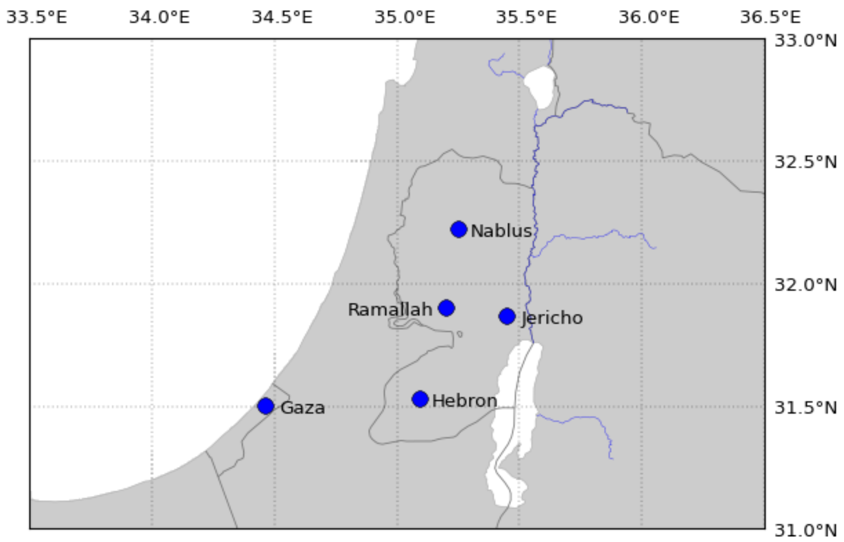

Fig. 2 Localisation of representative sites within the region

Comparison of the solar and meteorological parameters shows geographical differences. The highest values of GHI and GTI (indicators of suitability for PV installations) can be observed in the most southern locations of Hebron and Gaza, followed by Ramallah. From the DNI point of view, these three sites have also the best potential for CPV or CSP installations. However, comparing the five sites within broader region, all of them have very high solar potential.

4.2 Climate

Palestine has Mediterranean climate, with variations given by topography. In the whole area hot, long, dry summers prevail, with cool, short and rainy winter. Rainfall season lasts, in the most of territory, from November to February. The hottest months are July and August. The temperature (Fig 3 and 4) in the summer reaches up to 35°C and in the winter sometimes falls to zero. However, micro-climate conditions are diverse and vary from place to place.

West Bank is quite arid, with about 50% of the land having a rainfall less than 500 mm per year. There is also area with hyper-arid climate with a rainfall less than 100 mm per year. The remaining land has a rainfall in a range of 500-900 mm per year. In the Gaza Strip typical weather pattern is characteristic by hot, dry and sunny summers with virtually no rain. Yearly rainfall in Gaza Strip is about 100-400 mm. From April to mid-June the territory is affected by the annual hot, sandy and dry Khamseen winds, which origin from the Arabian Desert.

The PV technology works the most effectively at mild and cooler air temperature and stable sunny weather, the extremely high air temperature and intermittent weather pattern reduces slightly the power output (lower performance ratio).

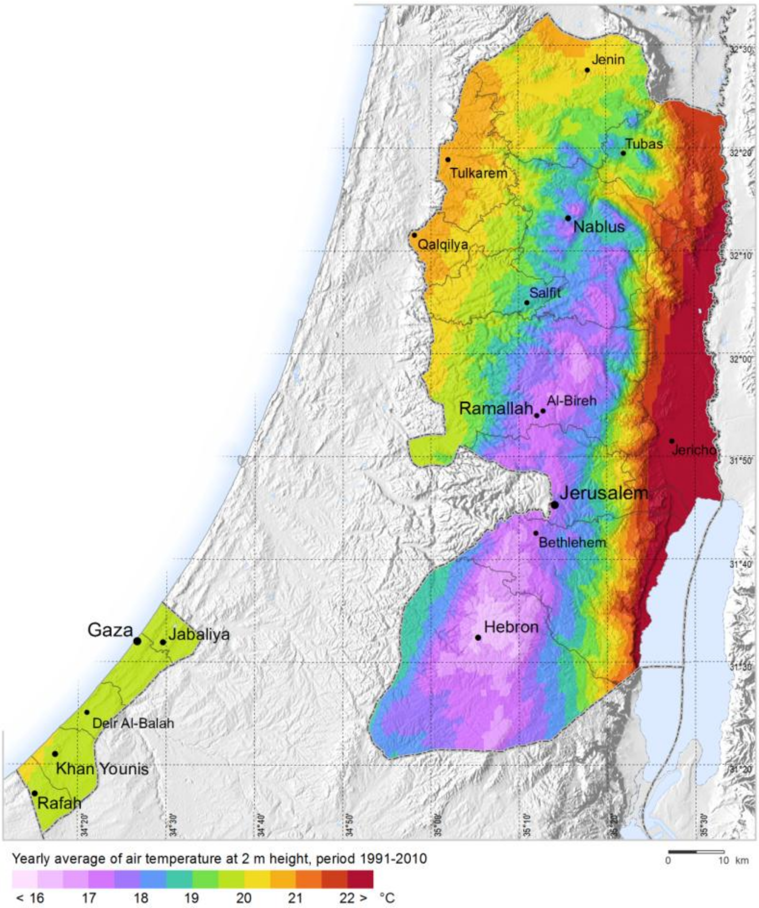

Fig. 3 Long-term yearly average of air-temperature at 2 m.

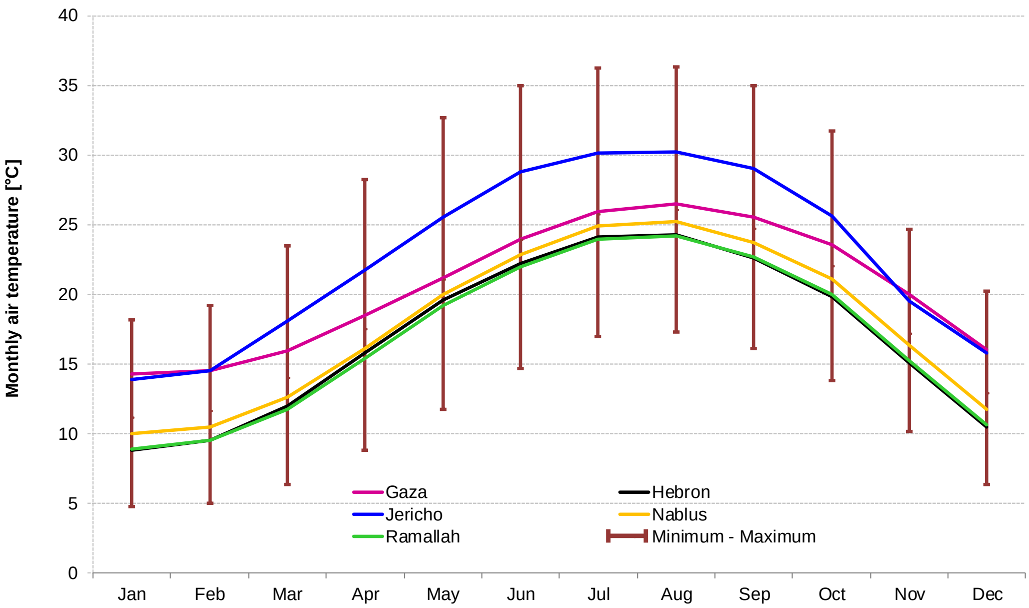

Fig. 4 Monthly averages, minima and maxima of air-temperature at 2 m for selected sites.

4.3 Solar Resource

Global Horizontal Irradiation (GHI) is considered as solar climate reference (Fig. 5). Diffuse and direct components of GTI (or GHI) indicate how different types of PV technology may perform. The most important parameter for PV potential evaluation is Global Tilted Irradiation (GTI), i.e. sum of direct and diffuse solar radiation falling at the surface of PV modules. Direct Normal Irradiation (DNI) is relevant for solar concentrating technologies (CPV and CSP).

The highest GHI is identified in the Gaza region and in southern and central hilly parts of the West Bank, where values can reach up to 2100 and more kWh/km2.

Fig. 6 compares monthly values of Global horizontal irradiation (GHI). Sunny season lasts relatively long (from April to September). Less stable weather is from November to May, highest variability of GHI between sites is observed from January to April. Small variability of values is determined by similar geographical characteristics, and this indicates that all sites will experience similar PV power performance.

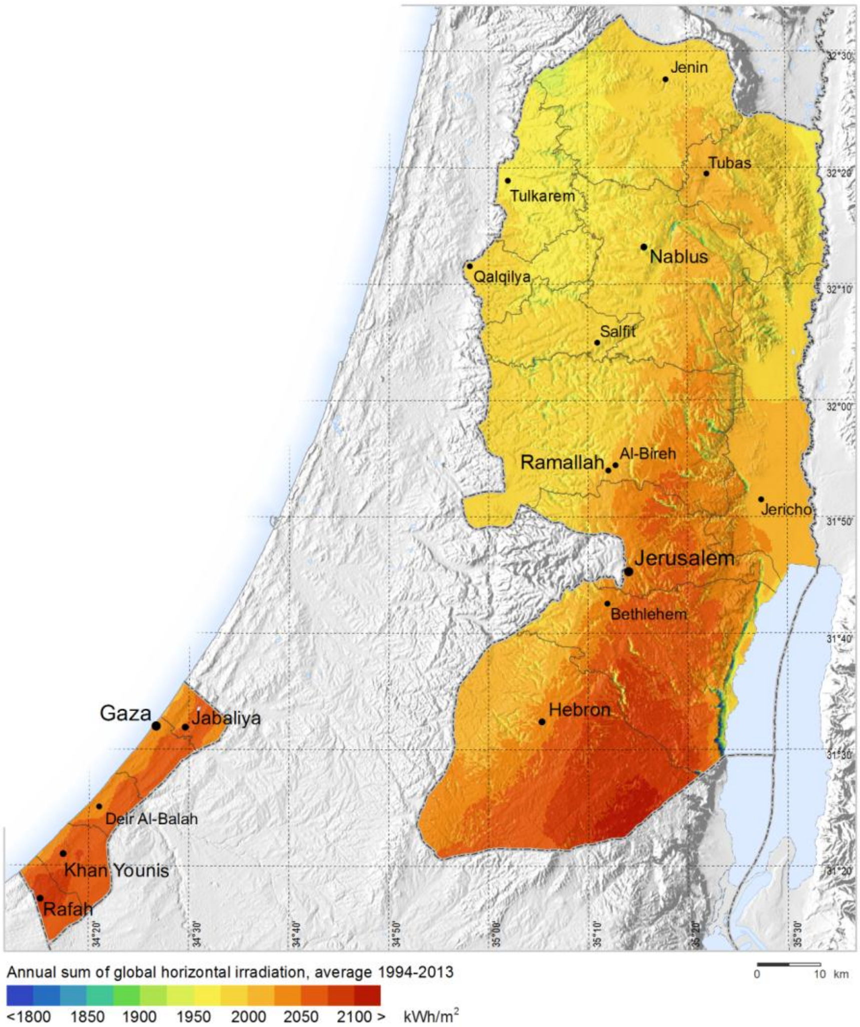

Fig. 5 Global Horizontal Irradiation - long-term yearly average. Period 1994-2013

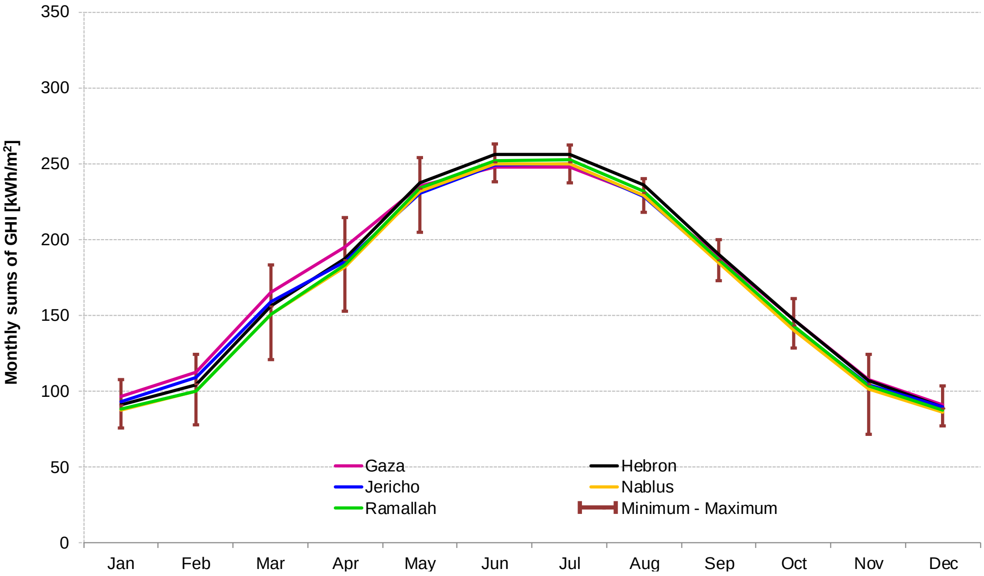

Fig. 6 Global Horizontal Irradiation - long-term monthly averages, minima and maxima at selected sites. Source: SolarGIS

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. This analysis is based on the data representing a history of year 1994 to 2013. This report may not reflect possible man-induced climate change or occurrence of extreme events such as large volcano eruptions in the future.

The interannual variability of GHI for the representative sites is calculated from the unbiased standard deviation of GHI over 20 years and considering the long-term, normal distribution of the annual sums. All sites show similar patterns of GHI changes over recorded period (Fig. 7) and extremes for all sites (minimum and maximum) or values close to extremes are reached almost in the same years. The most stable GHI values (the smallest interannual variability) are observed in Jericho.

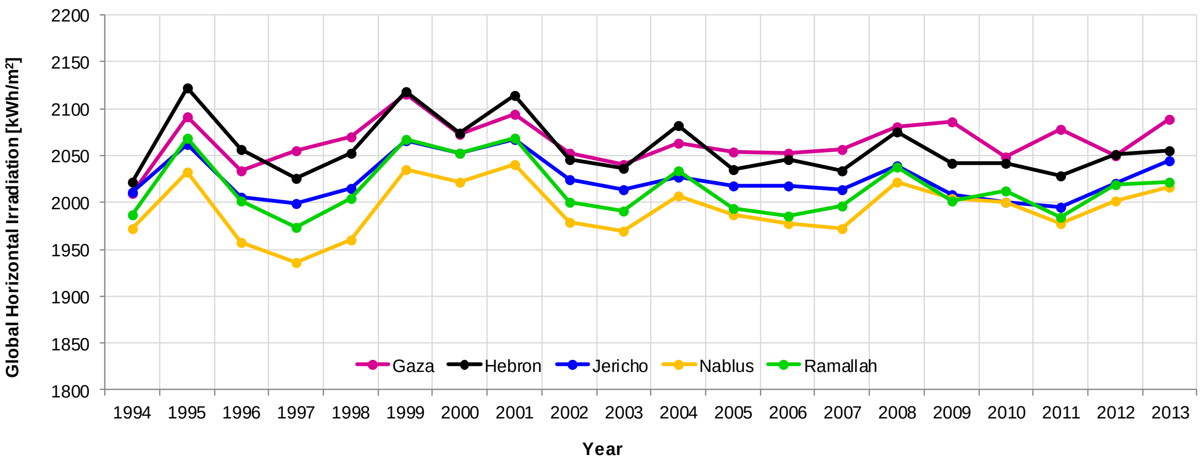

Fig. 7 Interannual variability of GHI for selected sites.

GTI represents the global irradiation that falls on a tilted surface. Unlike a horizontal surface, a tilted surface also receives small amount of ground-reflected radiation. The highest electricity gains from tilted PV modules can be obtained when modules are oriented in optimum angle (assuming maximising the yearly power production).

The main parameter influencing optimum angle is latitude. For this region the optimum tilt angle is 26°to 28°. Detailed comparison of monthly GTI and GHI values for Ramallah is shown in Fig. 8.

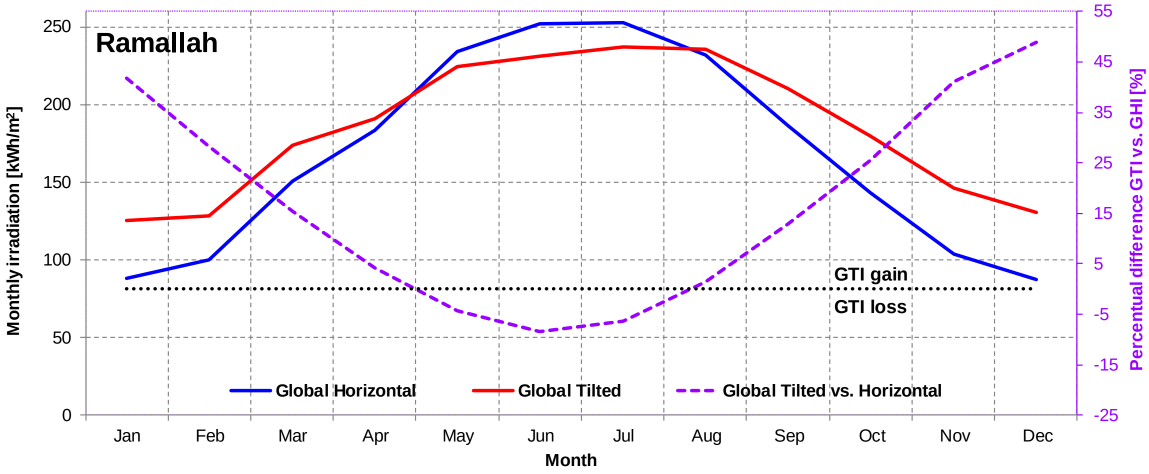

Fig. 8 Monthly GHI, GTI and Relative gain of monthly Global Tilted Irradiation relative to Global Horizontal Irradiation in Ramallah.

Daily sums for each particular year can be displayed for better visual presentation of portion DNI in relation to GHI. Fig. 9 shows daily sums for year 2013 in Ramallah. Blue pattern, representing GHI sums is transparent in order to make visible lower values of orange, DNI pattern.

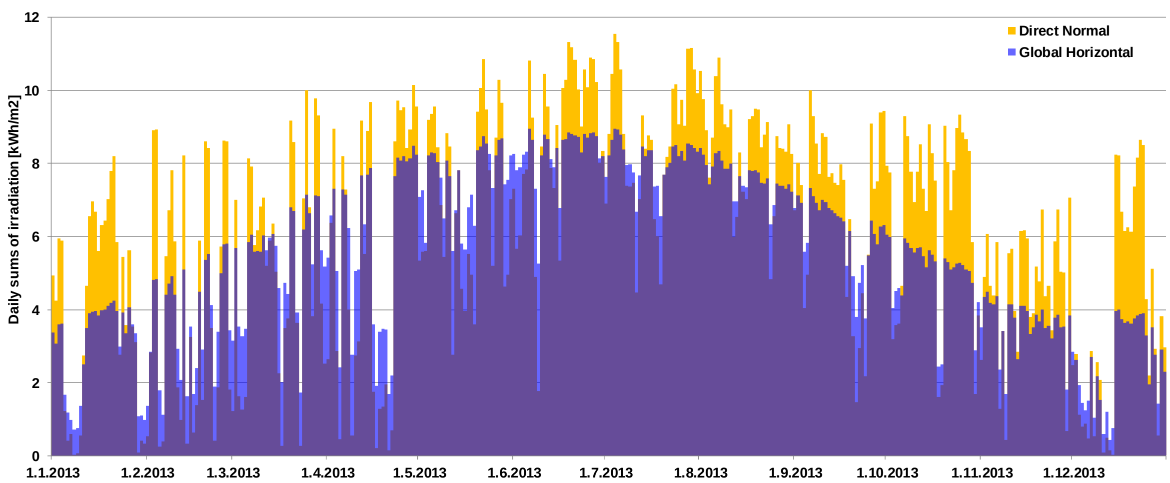

Fig. 9 Daily values of GHI and DNI for Ramallah, year 2013.

4.4 PV electricity potential

Fig. 10 shows the specific PV electricity output per year from a typical open-space PV system with a nominal peak power of 1 kWp system, i.e. the values are in kWh/kWp. Calculating PV output for 1 kWp of installed power makes it possible to scale the estimate of PV power production power plant of any size. The power production strongly depends on geographical position of the PV power plant.

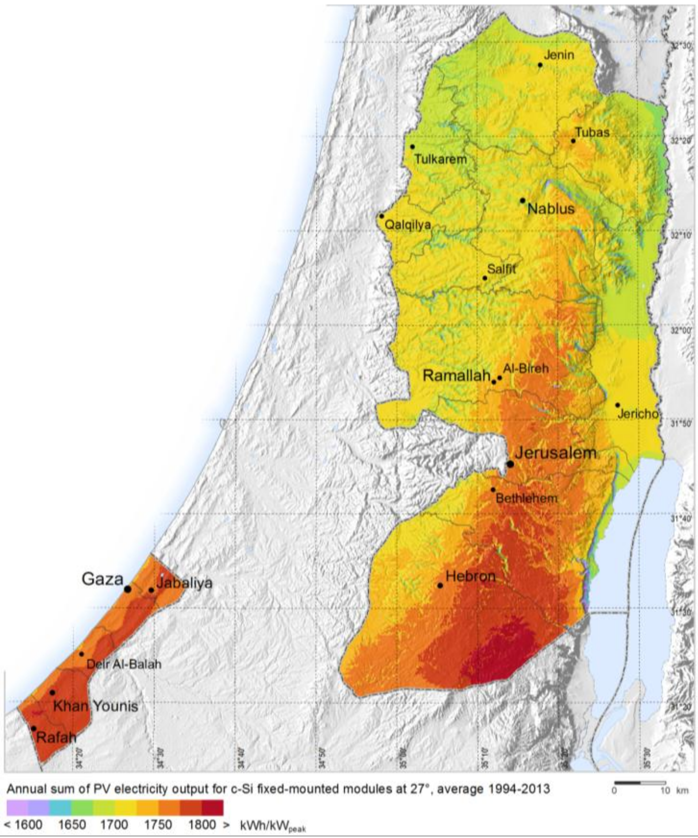

Fig. 10 Annual PV electricity output from an open-space fixed PV system with a nominal peak power of 1 kW [kWh/kWp].

Monthly and yearly performance ratio (PR) of reference installation for selected sites is shown in Fig. 11. Yearly PR of reference installation for selected sites is in range between 76.5% (Jericho) and 78.3% (Ramallah). Monthly changes in PR may be up to 5% in both positive and negative direction and depends on specific climatic conditions of the site, especially of temperature. Performance ratio is higher in winter season, when PV output of modules is not influenced by high daily temperatures. Impact of temperatures to performance of power plants is clearly visible when comparing monthly temperature profiles with monthly PR profiles.

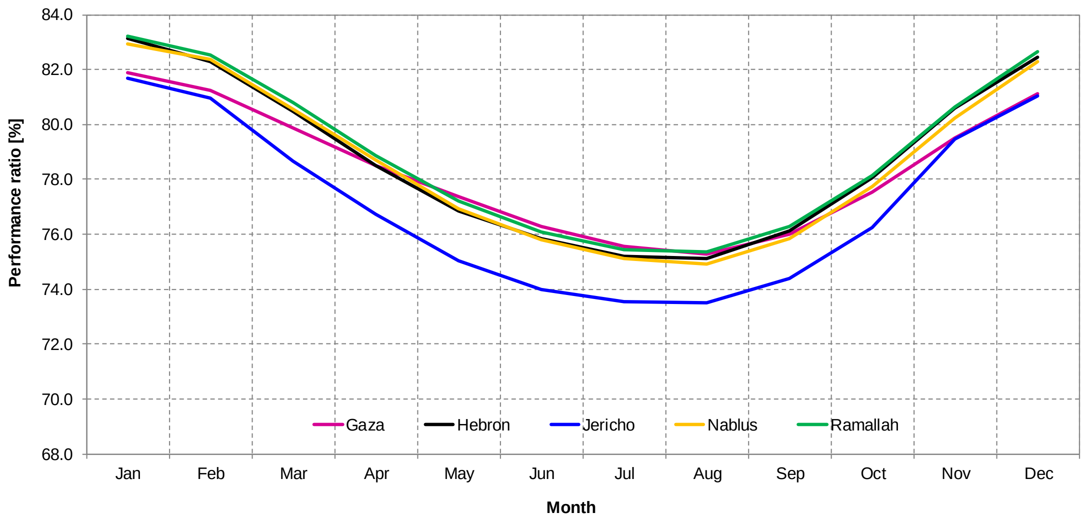

Fig. 11 Monthly power production from the fixed tilted PV systems at five sites with a nominal peak power of 1 kW [kWh/kWp].

CONCLUSIONS

The Solar Atlas of the State of Palestine is designed to help develop and operate solar energy projects effectively and with low uncertainty. The key feature of the delivered data and maps are:

- Harmonized solar, meteorological and geographical data are available, based on the best available methods and input data sources.
- Historical data for 20 years are available at high spatial and temporal resolution for any location.
- SolarGIS database and energy simulation software is extensively validated by GeoModel Solar, and also by external organizations. They are also verified within monitoring of numerous commercial PV power plants and solar measuring stations worldwide.
- As follow up, SolarGIS online tools offer real-time updated data and operational data services for monitoring of solar power plants, their regular performance assessment and for solar power forecasting. These data are harmonized with historical data to create a seamless flow of information.
- Additional data can be accessed online (http://solargis.info) and they are also available through PV electricity simulation tools for planning and performance assessment.

The data and maps delivered with the atlas create inevitable knowledge-base for decision makers, governments, financers, developers or designers in project development. The same type of solar, meteo and PV data can be further used in solar monitoring, performance assessment and forecasting.

In this study we presented only selected results, focusing on Solar Energy Resource Atlas. The list of data products, delivered with the Solar Resource Atlas [16] included:

1. GIS data and digital maps for the whole territory of West Bank and Gaza, representing long-term monthly and yearly averages
   - Raster and vector digital data layers for Geographical Information System (GIS)
   - High resolution digital maps for poster printing
   - Medium resolution digital maps for presentations
   - Image maps for Google Earth and GIS data projects for QGIS and Esri ArcMap
2. Comprehensive Site specific data for 5 locations (Hebron, Ramallah, Jericho, Nablus and Gaza)
   - Hourly Time Series for a period of 1994 to 2013
   - Typical Meteorological Year data for P50 and P90 representing period 1994 to 2013
3. Expert reports
   - Solar Atlas of the State of Palestine
   - Technical Report for Solar Atlas

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