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Study, Design and Performance Analysis of a Grid-Connected Photovoltaic System

Case study: 5 MW Grid-Connected PV System in Namibia

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The thesis was performed for the wind power consulting company Etha Wind Oy Ab that considers providing consulting services for solar power projects as an expansion of business activity in the nearest future. Hence, the aim of this study was to find the most reliable and robust simulation tool to be used in solar power projects. The focus of interest of this thesis is on the practical side of the matter, although theoretical aspects of a solar photovoltaic system and its operation are covered as well.

The study was conducted by studying, reviewing and testing several simulation tools to be applied in the case of 5 MW solar power plant operation in Namibian region. This system was used as a generic base in each simulation model meaning that its capacity, configuration and geographical location were of the most interest. Simulated performance and energy yield of the system were analysed based on the results from 3 different simulation tools (pvPlanner, PVsyst and PVSOL Premium) operating in a trial mode. In-built solar data, system parameters and losses were studied in each simulation model as well. Since there were no actual solar measured data available, either synthetically generated or average values of solar radiation received on the site were used in the simulation process. A review of the most commonly used meteo databases is also presented. The study proves the inability of a simulation tool to cope with the rather complex and demanding process of simulation a PV system by itself. Every software has its own advantages and disadvantages; thus in order to get the trustworthy model representing the real case scenario, a combination of several simulation tools is typically applied. Out of 3 tested tools, PVsyst, which is sometimes considered as a standard tool for PV installations, delivers the most comprehensive and detailed analysis of the performance of the system.

The choice of a software to be used is based on its availability, solar input data and configuration of the system to be simulated. Further study of available simulation tools is recommended to find tool that might complement PVsyst, hence to reduce uncertainty in the simulation process and provide the most robust results.

Keywords	photovoltaic system, solar radiation, solar resource assessment, simulation model, PV system performance

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Also, I would like to thank my supervisor and principal lecturer from Metropolia UAS, Antti Tohka, for being very acceptive and giving me a free hand to structure and conduct the study independently yet making sure that all the deadlines are met on time and all the requirements are fulfilled.

Notwithstanding all the above-mentioned support for my final thesis project, I take full responsibility over all possible errors and omissions of this work.

Vaasa 6 November 2017

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Abbreviations and Units

AC	Alternate Current
AM	Air Mass
BOS	Balance of System
CO_2	Carbon Dioxide
DC	Direct Current
EMF	Electromagnetic Force
GCR	Ground Cover Ratio
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
P50/90/95	Exceedance Probabilities
PR	Performance Ratio
PSH	Peak Sun Hours
PV	Photovoltaic
RMSE	Root Mean Square Error
SBR	Setback Ratio
SPV	Solar Photovoltaic
STC	Standard Test Conditions (1000 W/m2)
Tamb	Ambient Temperature
TMY	Typical MeteorologicalYear
VAC	Voltage in Alternating Current
VMP	Voltage at Maximum Power

1 Introduction

1.1 Background and Justification

Global environmental concerns about the amount of CO_2 emitted to the atmosphere due to human activities have been boosting the development, investigation and application of renewable energy sources such as wind, solar, hydro or tidal power for over the decades. Moreover, the combination of the renewable sources, known as a hybrid system, is getting more attention in renewable energy applications.

Solar photovoltaic technology is one of the alternatives to conventional energy sources with great potential contribution to solving energy issues. Even the combination of fossil power plants with renewable energy applications, (e.g. photovoltaics system), mitigate the adverse effect of fossil fuels on the environment. The need to reduce CO_2 emissions has affected the price of photovoltaic systems, and solar modules in particular, making application of photovoltaics more profitable.

Since Namibia, the location of the case study, has one of the highest level of solar radiation in the world, the development of solar energy sector including solar thermal, solar photovoltaic and solar water pumps is of a great interest. Additionally, according to The Government of Namibia, development of solar power stations will help to meet the increasing electricity demand in a sustainable and cost-effective way and to decrease the dependency on power imports from neighbouring countries. Thus, prefeasibility studies to investigate the solar potential, its utilization, optimal locations and PV technologies have been actively conducted during the last five years.

Solar is a climate-driven energy source, it varies significantly over the time and the area. Planning and implementation of any SPV system is rather demanding multi-stage process including evaluation of solar potential of a site, assessment of solar source, overall feasibility, design, simulation, optimization of system's yield and log-term performance. Nowadays various tools, databases are available for a PV system design, sizing, modelling, simulation and performance assessment. However, the current issue to be that only one tool by itself cannot execute comprehensive analysis of a PV system due to great complexity of the process. Thus, it is common practice to combine the input data and results from several modelling, sizing and designing tools along with measurements from a site to get the most reliable results. It depends on a location, software availability, and expert experience which tool or combination of tools and datasets to be used in a

PV project. It should be noted that existing software and simulation models are constantly being improved and upgraded. The study is divided into theoretical part, covering the key aspects of solar radiation phenomenon, components, design and performance of a PV system, and comparison analysis of three simulation tools 5 MW PV plant in Namibia as a case study.

1.2 Theoretical Framework

Theoretical part of this work covers key components of a PV installation, their defining features and working principle that is critical for designing process and performance assessment. Rules generally applied for designing and scoping of a PV project as well as potential losses, regardless of a type of a system and its configuration, are discussed. Since energy output of any PV system directly correlated to solar data for a site, nature of solar radiation as a physical phenomenon is to be shortly explained as well. Nowadays solar input data might be bundled in a simulation tool or provided with other meteorological parameters within available meteo databases, the most common of which are reviewed in this study. Prior to practical part of this work, theoretical background of used simulation tools and their comparability was studied.

1.3 Methods and Scope

The objective of this study was to find the most suitable simulation tool for a PV installation by testing the most common of them currently available on the market. Since the case study is a grid-connected 5 MW solar power plant in Namibia, the choice of simulation tools to be tested was based on desired capacity and configuration. To meet the objective, the following steps were to be consecutively taken in this study:

1. to study the key components of the system and its sizing according to the case study;
2. to review availability and quality of solar data sources;
3. to make a brief research on currently available tools;
4. to put on a test several simulation tools;
5. to make a conclusion on the most suitable software to be tested at more detailed scale and applied afterwards.

The above-mentioned steps were to be executed to achieve the objective by doing a research about solar power plants already existing and operating in similar climate conditions, by reviewing various assessments and studies on solar data and simulation tools and by running trial versions of the software. The testing of simulation tools implies that multiple variants can be done within the simulation by the chosen model with predefined or default parameters.

Numerous studies have been done on the operation and performance of grid-tied photovoltaic systems around the world and in Namibian region in particular. However, in this study the case of 5 MW grid-connected photovoltaic power plant project in Namibia was taken to be a generic example of a PV installation to be designed and modelled. In other words, the focus of the study was to evaluate the robustness of a simulation tool to be applied regardless the site rather than the suitability of the tool for implementation of this specific project.

1.4 Limitations

Limitations of the study should be taken into consideration in reviewing and evaluating the results. First of all, trial versions of simulation software were used, meaning that the simulation model would be available over a certain period of time, typically 1 month, or for a certain number of calculations. Trial mode for some of the tools unable some of the features and options, making it not possible to fully evaluate the applicability and robustness of the simulation model and the tool as a whole. Secondly, uncertainties within the simulation model regarding unavailability of measured or synthesized data for initially proposed location were not estimated, which shall be included in evaluation of study's results. Also, the timeframe of the study should be taken into account. This thesis work was done partly during the internship period and partly during the full-time working period, making the hours spent on the study unevenly distributed.

2 Solar Photovoltaic System: Design and Performance

2.1 SPV System Components

Nowadays a great variety of different PV installations is available on the market including on- and off-grid systems with or without battery as a storage system; hybrid systems as combination of a PV system and another energy source (e.g. wind and hydro power) are progressively getting more attention (Figure 1).

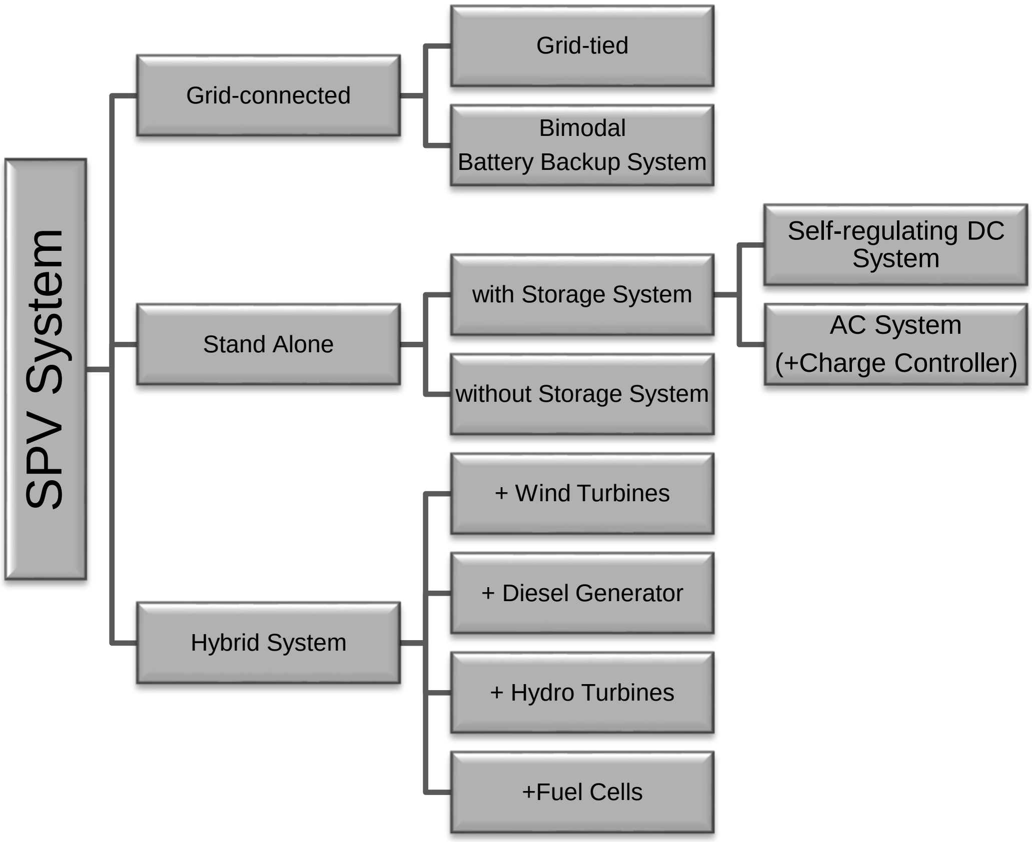


Figure 1. Types of SPV System configurations

Regardless of configuration and capacity, operation of any PV installation requires such key components as photovoltaic solar modules, inverters, transformers, utility meters, performance monitoring system, mounting system. A simplified diagram of a grid-connected PV system can be found in the figure below.

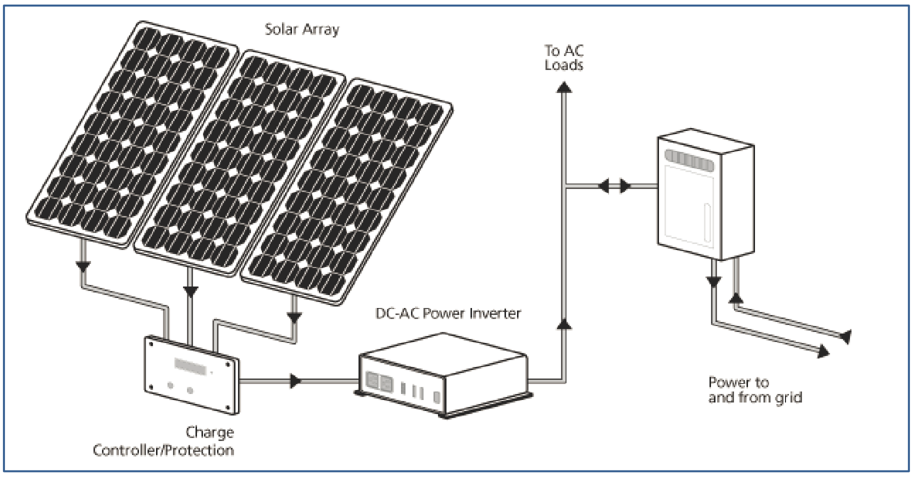


Figure 2. Grid-connected SPV System [1]

Since the objective of the study is a grid-connected, utility-interactive system, all the components with their key characteristics and functions will be briefly discussed in the following subsections.

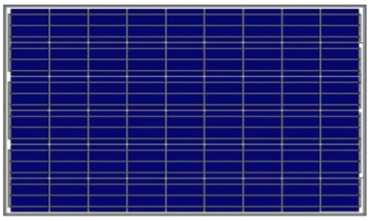
2.1.1 Photovoltaic Solar Modules

Solar photovoltaic modules, as the core of any SPV system, generate electrical energy from incident sun rays based on photovoltaic effect. Multiple solar cells, typically 60 or 72, connected mainly in series in a module comprise 2 adjoining semiconductor layers with separate metal contacts, and thus create a negative “n” layer with surplus of electrons and positive “p” layer with deficiency of electrons. Due to the difference in the concentration, electrons flow from “n” to “p” area creating an electric field or so-called space charge zone. Forced by this built-in electric field free excited electrons travels outside of the space charge zone, into the external electrical load where the excess energy will be dissipated. When an electrical load is connected, the power circuit is closed meaning that the electrons flow across the load to the solar cell’s rear contact and then back to the space charge zone. As a result, solar cells produce direct current (DC), flowing in a single direction only, which later gets converted into alternate current (AC) by an inverter.

Currently single-junction cells with either silicon crystalline or thin-film technology and multiple-junction solar cells are presented on the market. Despite of considerably higher theoretical efficiency of multiple-junction solar cells, about 87 % compared to 33 % of theoretical maximum of single-junction solar cells, they have very limited use due to complex manufacturing process and high price-to performance ratio.

Various single-junction photovoltaic modules are currently available and used in all sorts of PV installations [2, 93-96]. The choice of a PV module technology depends on the complex of factors such as price, efficiency, availability, and site-specific indicators. The most commonly used photovoltaic technologies are silicon crystalline and thin-film sole cells. Summary of key advantages and disadvantages, potential issues of each photovoltaic technology can be found in the table below.

Table 1. Strengths and shortcomings of different photovoltaic technologies

PV Technology	Strengths	Weaknesses
Monocrystalline Silicon (mono-Si) 36 % of market share 	- efficiency: 15-20 % (21.5 % as current maximum) - durability up to 25 years - space-efficient	- the highest price - sensitivity to ambient temperature (performance decrease significantly with an increase of ambient temperature) - sensitivity to shading issues, snow and dirt - wasteful manufacturing process
Polycrystalline Silicon (p-Si or m-Si) 55 % of market share 	- simple, cost-efficient and not wasteful manufacturing process - insignificant intolerance to high ambient temperature	- impurities and efficiency of 13-16 % - not space efficient - energy extensive manufacturing process
Thin-film (TFSC) - Amorphous silicon (a-Si) - Cadmium telluride (CdTe) - Copper indium gallium selenide (CIS/CIGS) 	- cost-efficient and simple manufacturing process - flexible configurations applicable different installations - high tolerance to shading issues and variation of ambient temperature	- low efficiency: 9-12 % - low space efficiency - high degradation rate

As can be seen from Table 1, each photovoltaic technology has its own benefits and intolerances to certain issues. Therefore, it is rather difficult to single out only one technology as the most optimal option for any PV installation by comparing potential efficiencies and prices. For example, despite its low efficiency, thin-film solar cell might be a feasible option if there is no space issue. The choice of suitable PV technology should be based on the site conditions and all possible issue the site might be exposed to.

2.1.2 Inverter

An inverter is a critical interface component that deploys feed-in function and converts direct current (DC) from the PV array into alternate current (AC) for the system output to be compatible with a local utility grid in terms of voltage and frequency values (mostly 50 Hz and 60 Hz in the USA). Additionally, inverters function as a control and optimization device, e.g. it might isolate power supply from the grid in case the grid itself is down. Inverters, as any other component of a PV system, should be chosen based on the system and site conditions. Following inverter’s types are most commonly used in different PV systems [3].

1. String inverter: multiple strings get connected to one inverter. A string inverter considered as very reliable, highly sensitive to shading issues, relatively cheap and compatible with power optimizers.
2. Central inverter: multiple strings get connected in a combiner box that runs DC power to the central inverter. Central inverters can support more strings of modules and require less component connections. They are the most suitable for large installations with consistent production across the array.
3. Microinverters: an inverter gets attached to each module individually, i.e. module-level electronics that deploys DC/AC conversion at the panel and monitors its performance. If one of the panels is shaded, performance of other panels will not be jeopardized. Microinverters are more efficient yet more expensive and suitable for installations with major shading issues or systems with various facing directions. A microinverter might get integrated into a module (AC module) resulting in cheaper and easier installation.
4. Battery-based inverters: bidirectional in nature comprising a battery charger and an inverter. These inverters manage energy between the array and the grid while keeping the batteries charged, monitor battery charge status and provide supply for continuous operation of critical loads regardless of the grid.

2.1.3 Transformer

A transformer or a substation is a critical component in power distribution in a grid-connected system as it adjusts the voltage of alternating current from the inverter to the grid voltage. Transformers can either step the voltage up to the grid or step down the utility voltage to individual loads. Working principle of a transformer is based on electromagnetic induction. An electrical current runs through primary windings (input) and produces magnetic field with certain magnetic flux. The magnetic flux goes through the transformer core till secondary windings (output) and electromagnetic force (EMF) which in turn produces voltage. The number of turns in the output relative to the input defines if the voltages gets stepped up or down.

By the configuration substations might be pad-mounted with underground electrical connections, installed indoors or enclosed in fence with overhead wiring. Transformers are either dry-type, which are cooled by air ventilation, or filled with dielectric liquid, mineral or vegetable oil, that insulates the components and transfers extra (waste) heat generated in the core and windings. Pad-mounted liquid substations are typically used in ground grid-tied systems [4].

2.1.4 Optimizer

An optimizer is not essential yet very beneficial component for the system performance. An optimizer is a DC/DC converter connected to each module or inbuilt by the manufacture into the module replacing traditional junction box. By constant tracking the maximum power point (MPPT) of each module, they increase the power output of the entire system. Since optimizers maintain a fixed string voltage, they more feasible for longer strings of panels. Optimizers have rather high efficiency of 98.8 %, mitigate mismatch losses and might be exceptionally useful in extreme environmental conditions.

2.1.5 Utility Meter

Utility meters measure how much power is being used by the system and how much is being fed into the grid. Thus, when the demand exceeds power production, e.g. during the night, the power from the grid is provided automatically. Otherwise, utility meter can spin backwards to sell excess power to the grid.

2.1.6 Mounting System

The type of a mounting system of a PV system depends on a site and area available for installation. To maximize the use of the project area according to site conditions, different configurations of mounting system such as ground mount, pole mount and roof mount with and without roof penetration can be installed. Since the case study is a ground-mounted system, its advantages and disadvantages are of the interest and to be discussed. Ground mount prevents photovoltaic modules from overheat through natural convection by the air. Ground mounted systems are safely installed and are easily accessible for maintenance works. Ground mount structure can be optimized to any tilt angle. However, the system has its disadvantages including space requirement and inter-row shading issues [3].

Additionally, ground mount can be advantaged by the tracking system that makes sure that modules always face the sun and receive the maximum amount of radiation. Single- and dual-axis tracking are the most commonly used. As can be seen from Figure 3, single-axis tracker let the panels follow the sun from east to west whereas dual-axis tracker is able to follow east-west movement of the sun along with its angular height.

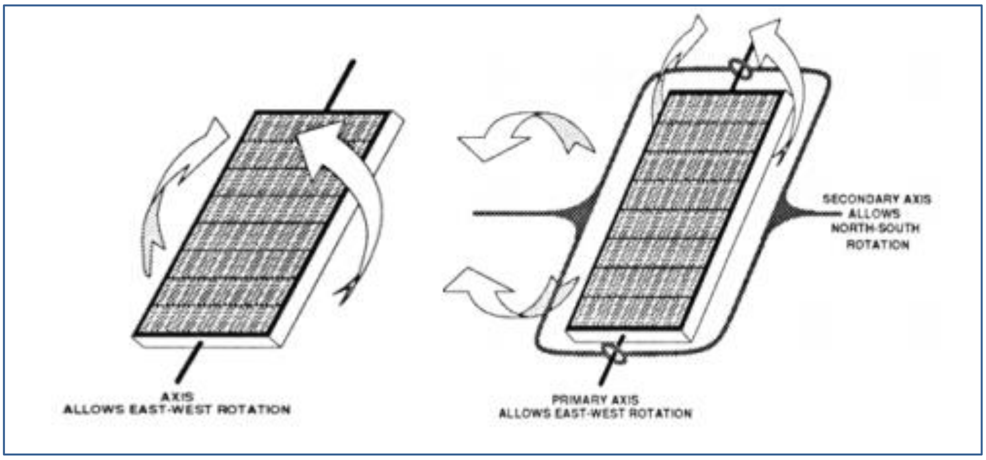


Figure 3. Single- and dual-axis trackers [5]

Floating photovoltaic systems, or floatovoltaics, which might be considered as ground mount as well, are getting more popular around the world. Floatovoltaics are typically installed in limited project area but can be extremely beneficial for the water body by reducing evaporation and algae growth.

All the components of a PV system, except for modules, might be referred as balance of system (BOS). BOS comprises inverters, wiring, MPPT, mounting system, fuses, batteries and charges, switches, and others. In other words, balance-of-system components transfer energy produced by modules (DC) through conversion system into the grid (AC load). Optimization and modernization of a PV system is done through its BOS that makes up most of the costs and maintenance.

2.2 SPV system Designing Parameters

In order to design a PVsystem and reach target output, series of designing steps should be performed including site assessment, selection of components and their integration. The key considerations and parameters of the designing process to be described in the following chapters.

2.2.1 Design Considerations

Since performance and reliability of a PV system are very site-specific, the following factors shall be included in site analysis.

1. Location: the position of the sun, and thus sun paths, peak sun hours and the amount of available solar radiation, are defined by latitude and longitude. The range of ambient temperature on a site, a critical climate variable, define the number of modules in a string based on compatibility of DC voltage of the modules with balance of system.

2. Orientation and tilt: to be applied in a fixed tilt system. As the rule of thumb, the system should face true south with a tilt angle equal to latitude. Optimal orientation and tilt angle also depends on the terrain, microclimate, surroundings and obstacles. This rule, in fact, can be adjusted to the site, for example latitude-tilt can get decreased by 10-15^0 or get increased based on modelled losses with respect to the optimum.

3. Shading: difficult to predict and simulate. Shading analysis shall include near-field shading and far shading or horizon. Near shading (e.g. caused by trees or another row of modules) affects a part pf an array, while far shading (e.g. hills or relatively big buildings) can affect the whole array. Near-shading effect can be considered as a mismatch meaning that shading of one module in a string equals to shading of the entire string that can only carry current of the weakest link. Uniform far shading do not allow any horizontal radiation to reach the array, i.e.

only diffuse radiation gets received by the array. Both shading effects might have a significant impact on a system output, up to 80 %, with the difference that horizon is easily modelled yet not adjustable, while near shading is exceptionally difficult to model but possible to avoid or mitigate. Potential shading loss can be decreased by adjusting such design variables as azimuth and tilt, panel orientation and row spacing. In common practice targeting shading losses would be 2-4 %. To stay within this shading limit, horizontal distance, or setback ration (SBR), should be 2:1 in lower latitudes and 3:1 in mid-latitudes. Figure 4 depicts the relationship between tilt angle, setback and ground cover rations (GCR). Shading analysis in a simulation model let the user set a horizontal gap, tilt and pitch, and thus define the corresponding ratios [6; 861-868].

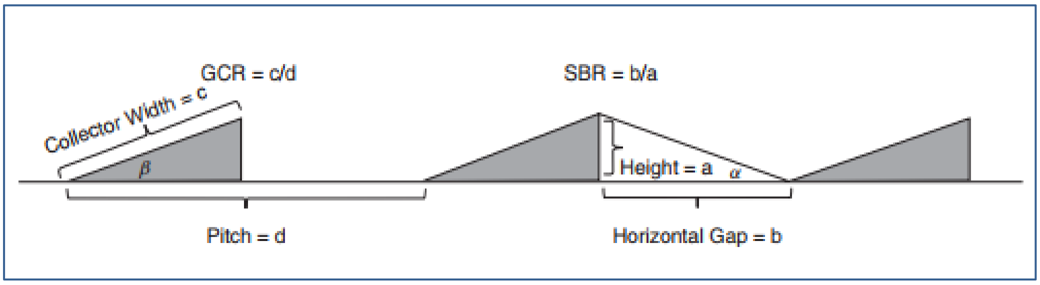


Figure 4. Array geometry

The relationship might be also expressed by the formulas:

$$\alpha = \tan^{-1}(1/SBR) = \tan^{-1}(a/b) \quad (2.2.1.1)$$

$$GCR = c/d = (\cos(\beta) + SBR * \sin(\beta))^{-1} \quad (2.2.1.2)$$

Orientation of a panel is critical with constant row-shading issue. Since PV systems are mainly south-oriented, it is important to take into account the position of the obstacles. East-west shading will go along the lower edge of nearby rows, thus considering the configuration of bypass diodes within a module landscape orientation would benefit to reduce the overall shading effect on the module. Portrait orientation would be advantageous for mitigating shading effect from east- or west-located obstacles, i.e. north-south shading.

4. Dust and Soiling: are season- and climate-dependent. Dust formation is mainly caused by local weather, traffic and agricultural activities. Soling might make up 7% of annual losses but can be reduced in half by regular washings. Roof and ground-mounted installations might also be exposed to snow accumulation resulting in about 2% of annual losses.

5. Ground: soil type, drainage, feasibility of trenching, vegetation, habitats, security and safety to be considered in a ground-mounted installation. A roof system would require more detailed considerations of membrane types, age, accessibility, strengths and loads.

6. Grid availability: electrical infrastructure assessment including PV system ampacity, distance to facility switchgear to adjust wiring losses and costs, utility metering requirements. In case a PV installation is to be a secondary source, such parameters of a main source panel as ampacity, voltage, age and overall condition to be assessed as well.

7. Maintenance access: system accessibility for scheduled inspections and maintenance, replacement of damaged parts to be performed. Storage for spare components, tools and water supply for washing also to be considered.

2.2.2 Components Design

In the designing process the results of site assessment and predefined designing considerations are to be applied to meet the targeting output of the system. Design of a PV system first of all comprises sizing and integration of system components.

Selection of the type and model of a module, which make up to 50% of system's costs, is based on its nominal efficiency, availability, weight, degradation rate, current and voltage compatibility, installation requirements and certification status. Availability is defined by the local supply system and logistics. In case of a constrained project area, high-efficiency modules, mono- or polycrystalline with efficiency over 13 %, are to be used. Thin-film modules in return tend to have lower degradation rate and higher cost efficiency. DC and AC parameters of the chosen module and those of the inverter must be compatible. The variation of power output from module to model is difficult to mitigate; currently average deviation from the nameplate value is about ±2%. Some manufactures might practice unbalanced binning of the modules meaning that modules with higher nameplate power would be considered as a new model with higher nominal power resulting in unpredictable shortfalls in potential production. Eligibility of photovoltaic panels can be proven with a certificate issued by IEC, UL, CE, CSA, TUV Rheinland, and ETL/Intertek. Modules are connected in series forming strings. Voltage of a string, to be the maximum voltage of a system, equals to a sum of voltages of all connected modules, and the current stays the same along the string.

A decrease of power output over the time is caused by modules degradation that commonly accumulate two of the following types:

- Staebler–Wronski degradation (S–W): 15-25 % power reduction in thin-film modules during the first 1000 h, partially reversible through the annealing process;
- Light-induced degradation (LID): 1-3 % power reduction in wafer silicon modules, irreversible loss due to oxygen impurities;
- long-term degradation: not clearly defined 0-2 % power reduction at module and system level including for example module failure, increase of series resistance, wiring corrosion.

The chief criteria for an inverter selection is its compatibility with a PV array and the local grid. Voltage output (DC) of a PV array must fall within DC voltage range of an inverter. As a rule of thumb, voltage at maximum power (VMP) of an array output should be within operating range of an inverter. Since electrical grid parameters, standards ad codes may vary from country to country, the grounding system of the local grid shall be takin into account for safe operation. Also, an inverter's voltage and frequency must match the utility grid. These values are usually 220 VAC at 50 Hz in European electrical grids and 120/240 VAC at 60 Hz in North America. Power rating of an inverter shall be adjusted to an array's power rating, as in case of such mismatch; for example if the power from an array exceeds the power of the inverter, the inverter will clip the power and limit output. Since nameplate output of an array is commonly overestimated, power rating of an array might be larger than inverter's one with common outputs ratio 1.2:1 to be applied in the design process [15; 6, 869-872].

The rest components of BOS, for example wiring, switches, fuses, also need to be defined according to current and voltage parameters of selected modules and inverter as well as to local electrical grid and codes [24].

3 Solar Radiation and Solar Data Sources

Solar radiation was previously mentioned among other factors affecting a PV system performance due to the fact that energy yield of the system and the amount of radiation received on a site are strongly correlated. Available solar radiation of a site is determined by its geographical location and climate conditions. As any other climate-driven renewable energy source, solar radiation varies considerably over the time and the area. Thus, solar resource assessment regarding data availability, credibility and variability is information of vital importance in any PV project, its potential energy output and profitability. The basics of solar radiation as a physical phenomenon with its key components and geometry is outlined in this chapter. Since any simulation model requires not solar radiation alone but a set of such meteorological parameters as wind speed, ambient temperature, and atmospheric pressure available meteo databases either integrated into simulation tool or importable are discussed in this chapter as well.

3.1 Solar Radiation

Prior to the discussion of geometric and atmospheric aspects of solar radiation and its application in meteorological databases, the difference between solar radiation, solar irradiance, solar irradiation and solar insolation should be clearly stated.

Solar radiation is electromagnetic in nature radiant energy emitted from the sun. The electromagnetic radiation from the sun ranges in wavelength between 0.25 and 4.5 µm, thus the frequency spectrum of solar radiation includes both visible short-wave light, or near ultraviolet radiation, and near-infrared radiation. Insignificantly small, compared to the total amount of radiation produced by the sun, fraction of near ultraviolet radiation reaches and get utilized by the earth, while near-infrared radiation is mostly dismissed by the atmosphere.

Solar irradiance is the radiant flux or power of the sun received by the surface per unit area; solar irradiance conventionally expressed in the units of W/m^2 or kW/m^2 [7]. Typical peak value of solar irradiance received by 1 m^2 of a terrestrial surface facing the sun on a clear day in solar noon at sea level equals to 1000 W that is rated as standard test conditions (STC) in PV applications.

The total amount of shortwave radiation received by a horizontal surface, global horizontal irradiance (GHI), consists of direct normal irradiance (DNI), diffuse horizontal irradiance (DIF or DHI) and additional irradiance component for a tilted plane. Additional irradiance stands for the amount of radiation reflected from the ground by water bodies (lakes, seas, rivers) and corresponds to approximately 20 % of global horizontal radiation as a whole. Global horizontal irradiance can be either measured on the site (e.g. with a pyranometer) or computed from direct normal and diffuse horizonal irradiance values by the formula below:

$$GHI= DNI^* \cos (ZSA)+ DIF, \quad (3.1.1)$$

where ZSA stand for zenith solar angle, i.e. angle between direction of the interest (the sun) and the zenith.

Additional reflected irradiance is considered to be an insignificant component; thus its value can be neglected in global irradiance computation. For example, in the ground power plants albedo has an impact only on the first row as the shading factor on the albedo equals to (n-1)/n with n to be the number of rows. Alternatively, the fraction of ground reflected irradiance (albedo) might be included into diffuse irradiance. In simulation model albedo values can be adjusted for each month based on the measurement data from the site, or general default value can be applied instead. Conventional value of the albedo factor in urban areas ranges between 0.14 and 0.22. Some typical values of the albedo factor are listed in the table below [8].

Table 2. Common values of albedo coefficient

Surface	**Albedo Factor**
Very dirty galvanized	0.08
Dry asphalt	0.09-0.15
Urban environment	0.14-0.22
Grass	0.15-0.25
Wet Asphalt	0.18
Concrete	0.25-0.35
Fresh grass	0.26
Red tiles	0.33
New galvanized steel	0.35
Wet snow	0.55-0.75
Copper	0.74
Fresh snow	0.82
Aluminum	0.85
Black body	1

The amount of reflected irradiance can be calculated by using the following equation:

$$Irradiance_{ref} = (DNI+DIF)*albedo \quad (3.1.2)$$

Direct normal (beam) irradiance is the component of total global radiation received by a surface normal to the sun rays that come in a straight line from the direction of the sun at its current position. Thus, as a rule of sum the amount of annually received radiation can be maximized by keeping a surface perpendicular to incoming sun beams.

Diffuse horizontal irradiance is the amount of radiation received per unit area by a surface that is not a subject to any shade or shadow and is not arrived directly from the sun. DIF gets scattered by molecules and particles in the atmosphere and comes equally from all directions.

The ratio between DNI and DIF irradiance in the atmosphere depends on the following factors [9]:

1. atmospheric conditions including air pollution, cloudiness and water vapor content; for example, on a clear sky day the total irradiance by the rough estimation contains 85 % of DNI and 15 % of DIF.

2. latitude and season: the higher the latitude and the lower the temperature, the more irradiance is reflected; for example, in wet and mild climate in London (51^0) 50 % of irradiance gets scattered in the atmosphere during the summer, and almost all the irradiance is diffused in the winter time, while in dry and hot climate in Aden (19.5^0) only 30 % and 35 % of the irradiance is diffused in summer and winter time respectively.

3. terrain: the amount of solar radiation gain on the site significantly depends on its terrain disregarding optimal orientation and tilt angle of the system; major shading issues caused by the obstacles, roughness and vegetation might considerably reduce available radiation.

4. time of the day: the lower the sun goes, the higher the DIF gets (e.g. when the sun is 10^0 above the horizon the ration of DNI to DIF equals to 60%/40%).

5. tilt of the modules: maximum irradiance is received by the panels if an incidence angle of the sun beams equals to 90^0, whereas diffuse irradiance is gathered by the panels the most at horizontal position. The larger the tilt angle, the less of the sky the panels are facing meaning that the more diffuse irradiance is missed. However, DNI is more intense than DIF, thus the amount of radiation gained by the tilted panels is more considerable than potential extra gain of diffuse radiation at horizontal position.

Figure 5 summarises the effect of atmospheric factors on solar radiation followed by its breakdown into several components.

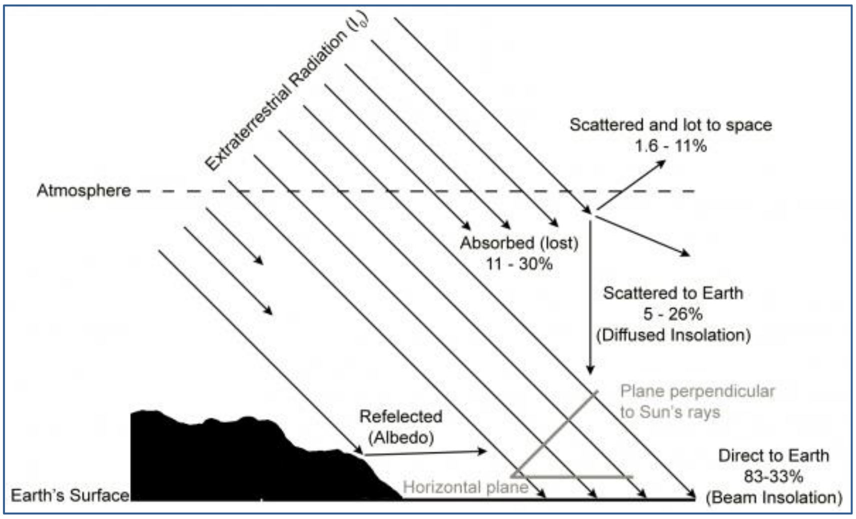


Figure 5. Atmospheric effect on the amount of solar radiation received by the Earth's surface [10]

Solar irradiation accounts for the amount of sun energy in the form of electromagnetic radiation received by a surface on unit area over a period of time (expressed in kWh/m^2). Solar irradiation might be also referred to as solar insolation, solar power or peak sun hours (PSH). Interrelation between solar irradiance and irradiation on the course of a day, as between power and energy in general, is illustrated in the figure below.

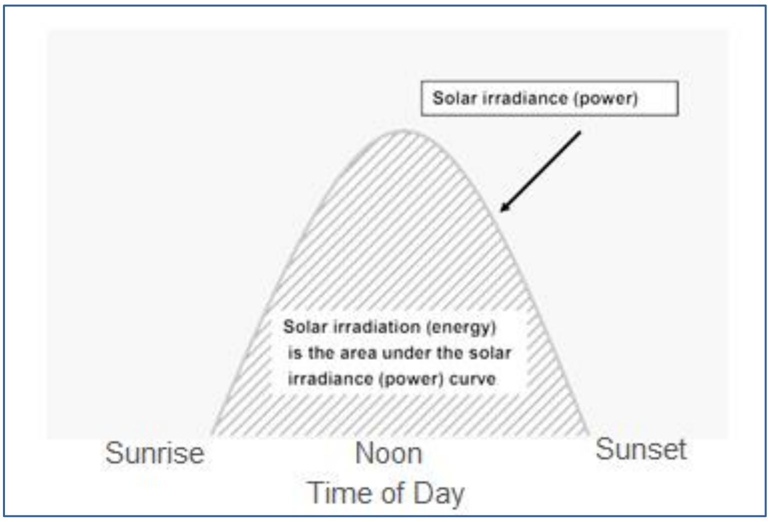


Figure 6. Daily variation of solar energy and power [7]

PSH, as an average amount of solar energy accumulated on a surface daily, correspond to the number of hours when solar irradiance reaches a peak level of 1 kW/m^2. PSH show how many hours per day a PV system can operate at peak rated output at rated temperature. The figure below depicts how solar irradiance and solar insolation get distributed during the day.

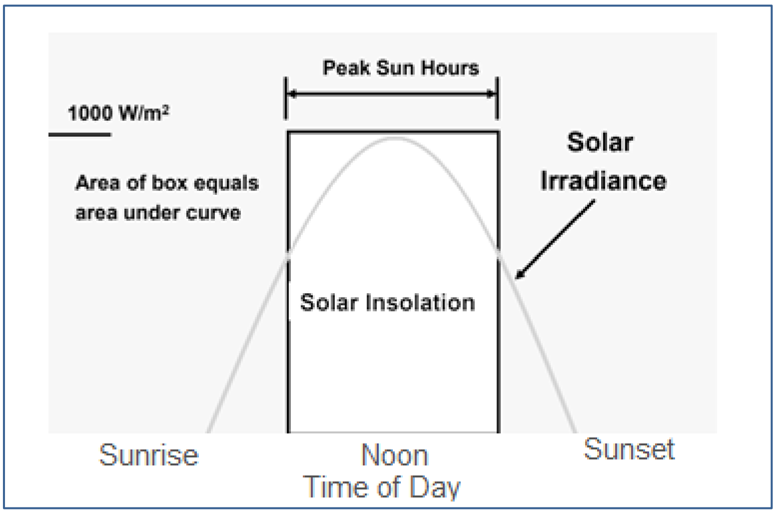


Figure 7. Daly distribution of solar irradiance and Peak Sun Hours [7]

3.2 Solar Geometry

Even though the key parameters of solar geometry are included in a simulation model, it is critical to understand how the position of the sun might affect the performance of a PV system. The position of the sun is defined mainly by the angles illustrated in Figure 8.

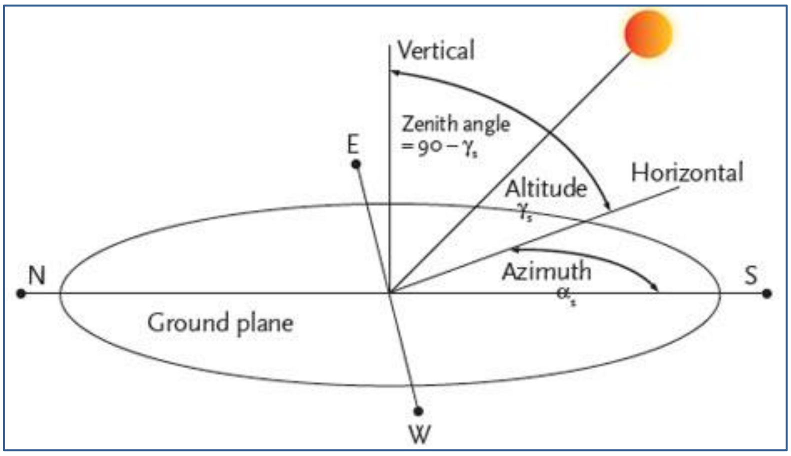


Figure 8. Relative position of the Sun to a point on the surface [11]

Solar azimuth angle, α_S*,* is the angle between the position of the sun and the south (north-south axis).

Solar elevation angle or the altitude of the sun, γ_S*,* is the angle between the horizon and the center of the disk of the sun. The altitude might be expressed through declination angle and the local altitude as following:

$$\gamma_S = 90^0 - \text{declination angle} + \text{latitude}, \quad (3.2.1)$$

where declination angle stands for the angle between the sun and the equator. Depending on the day of the year, the value of declination angle varies within [-23.45^0, 23.45^0].

Solar zenith angle is the angle between the sun and the vertical, the zenith. Zenith angle also depends on the declination angle and the latitude.

Position of the sun and rotation of the Earth define solar local time that is conventionally used in PV applications. Local solar time differs from the Coordinated Universal Time (UTC) by +/- 45 min depending on the day of the year, longitude and whether the day-light-saving shift is applied.

The depth or the distance travelled by the sun beam through the atmosphere is also defined by the position of the sun. The depth in that case affects the amount of radiation to be scattered, absorbed and reflected in the atmosphere. The effective atmospheric depth gets affected by the angle between the sun beams and the ground (see Figure 8), while actual path length can be described by *relative air mass* (AM). AM is the path length of solar direct radiation that might be expressed as the ratio between path length travelled and vertical depth of the atmosphere. AM defines the amount and the spectrum of radiation received by the surface. AM depends on the solar zenith angle and the height above the sea level, i.e. when zenith angle increases, the travelled path gets longer, and thus air mass increases as well; when elevation increases, the thickness of the atmosphere decrease, and thus air mass decreases as well. For the zenith angle, θ_z, to be < 70^0, AM might be simply calculated as a sec ($\theta_{z)}$, otherwise more complex model should be applied:

$$AM= \frac{e^{-0.0001184*alt}}{\cos(\theta z)+0.5057(96.06-\theta z)^\wedge(-1.634)}\ , \qquad (3.2.2)$$

where alt stands for the altitude of the site [6].
The default value of AM on a clear day is typically set to 1.5, this value is included in simulation and used for solar cells and modules testing and calibration.

3.3 Solar Data Sources

The importance of solar radiation data quality and its assessment in any kind of PV installation is indisputable, since it significantly affects the expected output of the system. Solar radiation measurement data, either from a satellite or a ground station, from the site is considered to be the most reliable source; however annual average measurement campaign is not sufficient to predict accurate annual irradiance and potential production value. The studies have shown that the annual mean value can differ from long-term by 5-20 % (for GHI and DNI respectively). Hence, long-term data for solar irradiance to be applied to estimate the variance of the production [12].

Nowadays many various meteorological databases, either in-built into a simulation tool or importable, are available. It is rather difficult to evaluate which database represents the actual amount of radiation received by the surface since it is very site-dependent parameter. Additionally, databases might have different input parameters, time steps, methodology and spatial resolution of either measured or synthesized data. Measurement data can be obtained from a ground observation station or from a satellite. Since surface observations have short-term observation period (several months to several years) and might contain measurement errors, satellite measurement values are considered to be more accurate, especially if the distance between observation station and the site is over 25 km. As might be seen from the summary table below, meteo data bases might contain monthly or hourly data from terrestrial observations, satellites, or be synthetically generated. Datasets cover different areas and time periods with global horizontal irradiance to be the one common parameter and ambient temperature as the second one.

Table 3. Meteorological Databases

Database	Region	Source	Period	Time base	Parameters
Meteonorm	Worldwide	Synthetic Generation	1960-1991 (averages) 1995-2005 (average)	Hour	GH,DH, Tamb,WindVel
Meteonorm	Worldwide	1700 Terrestrial Stations Interpolations	1960-1991 (average) 1995-2005 (average)	Month	GH, Tamb, WindVel
Database	Region	Source	Period	Time base	Parameters
Satel-light	Europe	Meteostat	1996-2000	Hour	GH
Helioclim-1 (SoDa)	Europe Africa	Meteostat 50 x 50 km^2	1985-2005 each year	Hour	GH
NASSA-SSE	Worldwide	Satellite 1^0 x 1^0	1983-1993 (averages)	Month	GH, Tamb
PVGIS-ESRA	Europe, Africa	566 stations, Interpolations 1 x 1 km^2 Meteostat (Helioclim-1 database)	1981-1990 (averages) 1985-2004	Month	GH, Tamb, Linke Turbidity
RETScreen	Worldwide	20 Sources Compiled	1961-1990 (averages)	Month	GH, Tamb, WindVel
SolarGIS	Europe, Africa,Asia, Brazil, Australia	Meteostat 4 x 5 km^2	from 1994	Hour	GH, DH, Tamb

Even though it is not feasible to validate a solar data source without actual measurement data from the location, PVsyst experts performed comparison analysis for the most commonly used meteo data sources. Annual available radiation [kWh/m²/an] was defined as the reference parameter which is relevant for grid-connected PV systems. The comparison was done between 7 meteo data sources for 12 European locations. Instead of real amount of radiation received on each site, the average value of all datasets without any weighting was applied. The graph below illustrates how global horizontal irradiance deviates from the average value at every location (%) .

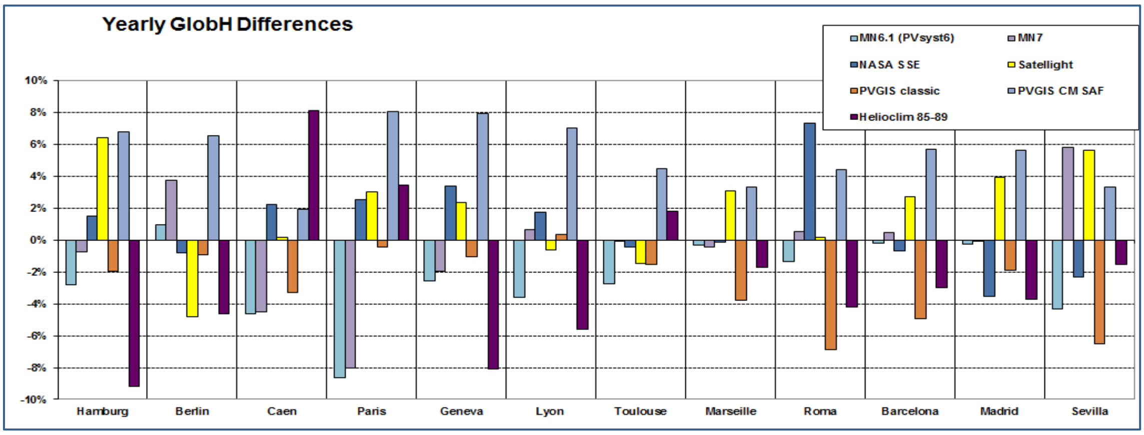


Figure 9. Annual deviation of GHI from the average, 12 European sites [13]

It might be concluded from the diagram that compared solar data sources agree with one another within 10 % deviation. It is rather problematic to make a definite conclusion on which dataset is the most representative and the most reliable due to noticeable variations from site to site, but some common trends can be seen. Satellite-derived values from the most recent PVGIS (CM SAF) show the tendency to outreach the average value systematically, while the previous, older version of PVGIS consistently gives lower values. Similarly to PVGIS (CM SAF), values from Satel-light exceed the average systematically but to lesser extent. Meteonorm, which is used as a default solar source in PVsyst simulation model, show a clear underestimation meaning that the results for a PV system output would be on more conservative side.

In order to illustrate and even more so to prove the dependency of a solar data source validation on a site, another comparison study can be referenced. The study was performed based on the measurement data from 75 MW Kalkbult PV power plant, SA. The comparison and validation of 7 different meteo databases were carried out based on the averaged measured values from 4 ground weather station on Kalkbult site (see Table 4).

Table 4. Validation of solar databases based on the terrestrial measurement data, Kalkbult, SA

Database	Source	Annual GHI, kW/m^2	Deviation, %
Measured (Kalkbult,SA)	terrestrial	2117	0
Meteonorm 6.1	terrestrial+ satellite	2179.5	2.95
Meteonoirm 7.1	terrestrial+ satellite	2203.8	4.10
Helioclim-3 (SoDa)	satellite	2145.16	1.33
NASSA-SSE	satellite+model	2099.3	-0.84
PVGIS Helioclim	terrestrial+ satellite	2196.1	3.74
Climate-SAF PVGIS	terrestrial+ satellite	2110	-0.33

The comparison shows that percentage of deviation of GHI from chosen datasets from the measured average lies within 5% range. Based on the annual GHI values, Climate-SAF is to be the most reliable source for this site with deviation of 0.33%. However, the validation shall be performed on monthly basis as well to refine the results according to monthly metric errors (RMSE, MAD, MAPE and MBE). Root mean square error (RMSE), as the standard deviation of prediction values and the most commonly used measure to validate the difference between modelled and measured values, can be considered for this comparison [14].

Table 5. Monthly metric error analysis (RMSE) for GHI, 2014

Database	RMSE
Meteonorm 6.1	9.97
Meteonoirm 7.1	12.20
Helioclim-3 (SoDa)	4.01
NASSA-SSE	9.26
PVGIS Helioclim	10.50
Climate-SAF PVGIS	8.77

As can be seen from Table 5, solar data from Helioclim-3 represents the actual amount received by Kalkbult site the most accurately, whereas Meteonorm 7.1 shows the highest overestimation for both annual and monthly analysis.

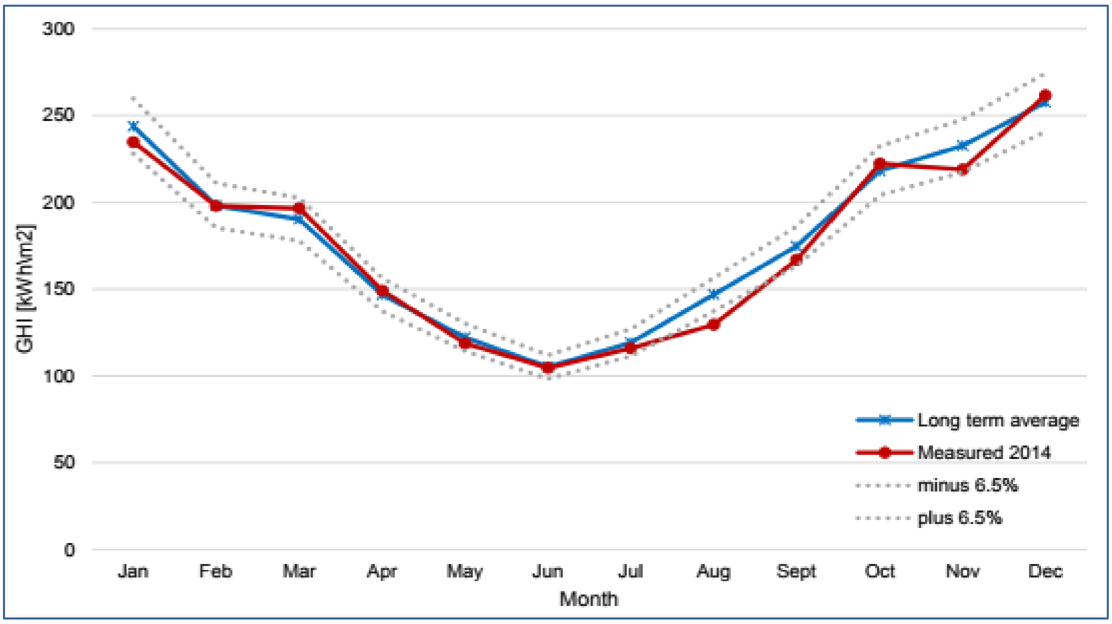


Figure 10. Measured (Kalkbult, 2014) and averaged long-term GHI data

Even though the difference between measured and averaged long-term data from 6 different databases is within the acceptable range of ± 6.5 % (for South Africa region), and annual comparison analysis shows relatively small deviations, it is not advisable to use databases with differently scale meteorological parameters [14; 16]. As might be seen from Table 2, meteo databases have different terrestrial resolutions, measurement periods and time base which might bring an undefined uncertainty to the validation. Thus, in order to get realistic output figures for a PV system, meteorological and solar radiation measurement campaigns shall be conducted on a site, and consequently a long-term solar radiation data is to be applied for normalization over the expected operation period.

4 Solar PV Design and Simulation Software

Nowadays a wide variety of design, simulation and optimization tools and software are available on the market. The choice of the best available option depends mainly on the desired output and which parameters are the most critical for the project. For example, some tools might be used for sizing, optimization, prefeasibility calculations, shading analysis and so on, while more comprehensive studying of solar PV system requires more complex software package that comprises a set of interacting tools. In this chapter simulation tools that were put to the test and used in the case study for 5 MW PV system will be reviewed. Since the case study is done for a grid-connected, ground-mounted system, all the programs were tested considering only this type of PV system and corresponding settings.

4.1 pvPlanner

PvPlanner is a cloud based software provided by solar resource database (SolarGIS). The main idea is that solar data from SolarGIs is used on a ‘software as a service’ platform meaning that no installation is required, and all calculations and maps are available online. Typically, pvPlanner can be used as a preliminary evaluation tool for a solar project performing time- and resource-saving assessment of PV electricity potential. SolarGIS provides satellite data on a monthly and an annual (long-term) basis including:

- Global horizontal irradiation (GHI)
- Diffuse horizontal irradiation (DIF)
- Global tilted irradiation (GTI)
- Air temperature at 2 m (TEMP) [21].

Solar radiation in 15-minute time series and air temperature are used as an input or site parameters, while technical parameters, including system capacity and its availability, module type, inverter efficiency, DC to AC conversion losses and mounting system, are provided by the user as a manual input, or default values can be used instead. It is, nevertheless, not possible to import any data from other databases (e.g. Meteonorm, NASA). Site data includes the horizon of the location that can be modified manually or with a site photo meaning that far shading are taken into consideration in the calculation. Near shading analysis, on the other side, with surrounding buildings and obstacle is not available.

PvPlanner does not have bundled module and inverter databases, instead generic crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) or copper indium selenide (CIS) module and generic module with manually defined efficiency can be chosen. According to pvPlanner, there is no need to specify a type of a module or an inverter simply because the variation between different types is not significant and less than variation in solar radiation.

PvPlanner is suitable for small or medium-size PV systems. If large scale project planning and financing need to be performed in pvPlanner, additional information such as statistical distribution and uncertainty of solar radiation, detailed specifications of the system, variability and P90 uncertainty of PV production and performance degradation of PV components is required. PvPlanner is available in 14 languages, and pricing depends on locations and map availability, for example one or multiple locations and with or without map functions.

4.2 PVSOL Premium

PVSOL Premium is a dynamic simulation program with detailed shading analysis of a roof- or a ground-mounted, a grid-connected or a stand-alone PV system. Simulation might be performed in a 2D or a 3D mode based on the shadow cast information from surrounding 3D objects, meaning that shadowing effect at different time of the year and the day is taken into account in power optimization and consequently in evaluation of the system yield.

Meteonorm 7.1, an integrated database, provides monthly climatic data from over 8000 global data sets with averaging period 1991-2010. For Germany specifically another integrated database, MeteoSyn, with over 450 data between 1981-2010 from German Weather Service can be used. An interactive map let the user select the climate data, new climate data is also can be created by interpolation from existing measurement values of global horizontal and diffused horizontal irradiance and ambient temperature or by applying own monthly mean values [22].

Detailed shading analysis, as the key feature and the main advantage of the tool, includes near and far shading definitions. Horizon line of the site can be set by default or drawn manually. Near shadings including such nearby obstacles as building, trees, masts and others can be created by free hand or defined by extruding according to the actual height of the object based on floor plan drawings or satellite maps.
PVSOL Premium has an extensive built-in database comprising over 7500 modules and over 1500 inverters. Moreover, the data is updated and extended by the manufactures on a regular basis so that the users get access to information about currently available components. Module configuration in optimization process might be done automatically by the program according to individual strings or defined by the user considering shading effect. The number of modules can also be automatically defined by the software based

on the available area or manually set by the user. Optionally, a power optimizer can be added to a yield simulation of the system. Prior to yield simulation detailed circuit diagram in a standardized form can be drawn and exported, and dimensioning of AC and DC cabling and its losses can be defined. Values of cable length and cross section can be entered by the user, and thus let the software calculate total losses from the array output under STC conditions. Total losses can also be predefined in planning phase by the user.

PVSOL Premium can also perform financial analysis based on user-defined cost of modules, inverters and mounting systems. Financial analysis allows the user to take into account loans, depreciations, discounts, tax payments and operational time of the system. PVSOL provides calculation for capital value, electricity production costs and amortization period according to VDI Guideline 2067 (VDI: Association of German Engineers) [22]. Furthermore, multiple feed-in tariffs can be applied in the analysis parallelly, consecutively or with an offset. Results of the analysis are summarized in a table in the balance of the costs.

Regarding suitability of the simulation tool to PV systems of different sizes, a limit to the system output should be taken into consideration. If a PV system is simulated as a single 3D project, a 5000 modules limit is applied. In case of larger project to be simulated, there is a possibility to sub-divide the project into several 3D projects to perform layout and shade analysis. Hence, for overall financial and yield analysis the configuration from separate 3D projects can be manually duplicated into 2D mode with a module limit of 100 000 per one array. The results of inter-row shading analysis from 3D accounting for indirect radiation loss might be manually added to the total percentage loss or depicted in a sun-path diagram of each array. PVSOL is available in 7 languages in Premium with 3D visualization and detailed shading analysis and standard version.

4.3 PVsyst 6.6.3

PVsyst is a software package that allows the user to employ full-featured study and analysis of a PV project. PVsyst integrates simulation of a PV system with evaluation of its pre-feasibility, sizing and financial analysis, no matter whether it is a grid-connected, stand-alone, pumping or DC grid system.

Meteorological data is provided by Meteonorm 7.1 for about 1200 geographical sites. Meteonorm 7.1 contains monthly measured and hourly synthesized data. Monthly irradiance values are averages of irradiance measurements during the period of 1960-1991. Mainly meteorological stations in PVsyst are referenced to the actual ones, otherwise the data is interpolated between 3 nearest stations.

To obtain hourly values, PVsyst applies synthetic generation to monthly measured data. Monthly meteo data from Metetonorm 7.1 includes global and diffuse irradiation, temperature and wind velocity. Hourly data can be also constructed by using another data source in PVsyst directly, however it is claimed that Meteonerm gives more realistic and reliable results due to its improved model for temperature and wind velocity values. Similarly to Meteonerm 7.1, various measured, interpolated or synthesized meteorological data from such sources as Satellight, SolarGIS, US TMY2/3 NASA-SSE, and others are available for simulation in PVsyst. It is also possible to import user defined data including set of parameters listed in the table below [23].

Table 6. Pvsyst meteorological data input

Mandatory data	
Header = GHI	Horizontal global irradiation [W/m2]
Header = Tamb	Ambient (dry bulb) air temperature [deg.C]
Additional data	
Header = DHI	Diffuse horizontal irradiance [W/m2]
Header = DNI	Direct normal irradiance [W/m2]
Header = GPI	Plane of Array irradiance [W/m2]
Header = WindVel	Wind velocity (at 10m altitude) [m/sec]

Missing data in the imported data set shall be labeled properly (e.g. -99) so that the missing values could be replaced by an average of the corresponding hour either from previous or next day.

PVsyst has a bundled data base of PV system components including currently available and generic modules, inverters and optimizers. Manually defined components can be used in simulation as well.

Configuration of the system is done by the software automatically as soon as the user defines a project area or desired installed capacity and chooses a module and an inverter. Based on these inputs PVsyst proposes a system configuration, and thus preliminary simulation can be run. The optimal sizing is done according to acceptable overload loss during the year, i.e. the ration of an array nominal power to nominal AC power of an inverter. The optimal sizing typically implies an over-size of power ration by a factor of 1.2. PVsyst allows the user to define and control various factors and losses such as wiring losses, mismatch between modules, losses due to temperature, soiling and many others according to the mounting system, site conditions, unavailability. Shading losses, as one of the most critical parameter affecting system performance, can be defined with 3D editor. Far shading can be set by PVsyst automatically based on horizon shading from geographical data, imported from another database or a site picture or drawn manually by the user.

Near shading analysis perform by PVsyst is constantly being improved due to its unstable and unreliable performance. The user can define nearby obstacles either by freehand or by using objects form 3D tool, run and save a shading scene to be used in simulation. Near shading construction is rather complex and demanding, thus some phenomena are not accurately calculated and based on the assumptions (e.g. fraction for electrical effect).

After all required and desired parameters are set, the simulation calculates energy distribution throughout the year. Thus, the evaluation of the system profitability and quality can be done based on total energy production (MWh/y), performance ratio (%) and specific energy (kWh/kWp) as a correlation between the production figure and irradiation available at the site with given orientation. The potential improvement of the system performance can be based on figures from detailed loss diagram that contains main energies and gain or losses in the simulation process. Multiple simulation variants can be performed and compared within the project.

Economic evaluation of the system can be employed by setting investment, financing and loan parameters. In other words, the user shall define the cost of the components, (i.e. PV modules, inverters, wiring, mounting system), taxes, subsidies and loan term and interest rate. Carbon balance, as a performance characteristic of the system, can be evaluated within financial analysis tool. The Carbon Balance estimates the CO_2 emissions saved thanks to the PV system operation. The calculation is based on Life Cycle

Emissions (LCE) as CO_2 emissions (tons) associated to energy amount or a component throughout the total life cycle including production, production, operation, maintenance, disposal [24].

PVsyst is developed by Geneva University, Switzerland. English is the main installation language of the software, however simulations can be done and reports can be exported in French, Italian, German and Spanish as well. The pricing is based on how many licenses was previously purchased by the company and on installation capacity (PVsyst PRO30 has a limit up to 30 kW installed capacity, PVsyst Premium is unlimited).

5 Case Study: 5 MW Solar Power Plant in Walvis Bay, Namibia

5.1 Input Parameters and Specifications

Regardless of software to be tested the parameters of simulation model were defined based on the case study input information. Simulation process and its results performed with three simulation tools are discussed in the following chapters. Initially the system with 5 MW installed capacity would be located in Walvis Bay, Namibia (22° 59' S, 14° 29' E). Based on preliminary simulations and data availability input parameters were adjusted accordingly. Summary of the system to be simulated are presented in the table below. The reports of simulations for each tool are presented in the Appendixes.

Table 7. Input parameters of the SPV system for the case study

Geographical location	22° 57' S, 17° 10' E Windhoek, Namibia
Nominal capacity	5000 kWp
Presizing	capacity-based
Azimuth	0^0 (north)
Inclination	25^0
Mounting system	fixed
Module	310 Wp, Si-poly
Inverter	800 kW, 50/60 Hz, 530-850 V Sunny Central, SMA

As can be seen from the summary table, geographical location of the site was changed to Windhoek, about 275 km and 310 km away from Walvis Bay towards the East. Solar data for Walvis Bay is not available in any of the simulation tools; thus modelling was done based on the data from Windhoek site.

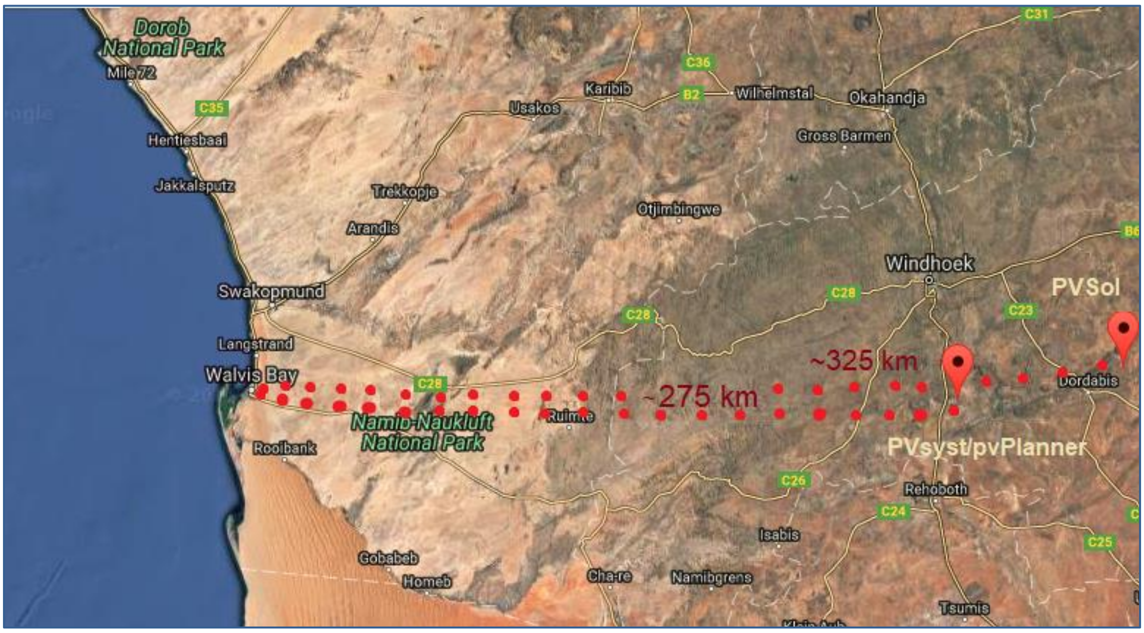


Figure 11. Geographical location of the site

In the simulation model, the size of the system is based on desired installed capacity assuming that area available for the project is not constrained. The system faces true south, i.e. azimuth of 0^0 or north. According to the rule of thumb, tilt angle should equal to latitude, i.e. 23^0, however modeling variants has shown that inclination of 25^0 would give 0 losses with respect to optimum. Fixed tilted mounting plane was chosen to make the configurations between the tools comparable. Polycrystalline module with nameplate power of 310 Wp/31 V was paired with 800 kW/530-850 inverter.

5.2 pvPlanner Simulation

PvPlanner to be the least detailed tool out of three tested let the user define only key parameters for system sizing and simulation. Since the user cannot see and adjust every step of simulation process, and modules and inverters are generic, it is rather difficult to evaluate the simulation process and the model itself. The input parameters defined manually are based on the parameters from PVsyst simulation model, e.g. inverter's efficiency and DC/AC losses. Geographical coordinates for Windhoek meteo station are defined on the interactive map. The summary of pvPlanner simulation can be found from the table below.

Table 8. pvPlanner Simulation Results, Windhoek site

Parameter	Result
Geographical location	22° 57' S, 17° 10' E Windhoek, Namibia
Nominal capacity, kWp	5 000
Azimuth/inclination, ^{0}	0 (north)/ 25
Module	c-Si, generic
Inverter	generic, 98.5 % efficiency
Elevation, m	1671
Annual ambient temperature (at 2m), ^{0}C	18.4
Annual global in-plane radiation, kWh/m^2	2492
Annual average electricity production, GWh	10.24
DC/AC losses, %	0.8/0.6
Average performance ratio, %	80.5

Annual global in-plane radiation value takes into account terrain shading losses, with other losses (e.g. reflectivity, cables losses, DC conversion in the modules) in-plane radiation equal to 2040 kWh/m2. Far shading on the site can be defined manually, horizon line from PVsyst simulation model was applied (see Figure 12).

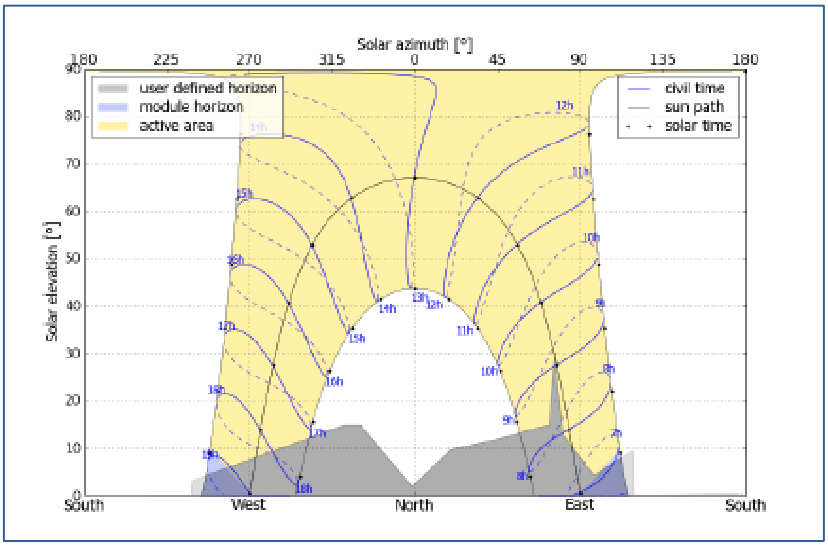


Figure 12. Terrain horizon and day length at Windhoek site

Unlike PVsyst and PVSol Premium, pvPlanner can perform simulation for the exact location. Thus, the simulation for initially defined site at Walvis Bay was also run. The results can be seen from the table below.

Table 9. pvPlanner Simulation Results, Walvis Bay site

Parameter	Result
Geographical location	22° 59' S, 14° 29' E Walvis Bay, Namibia
Nominal capacity, kWp	5 000
Azimuth/inclination, ^{0}	0 (north)/ 25
Module	c-Si, generic
Inverter	generic, 98.5 % efficiency
Elevation, m	7
Annual ambient temperature (at 2m), ^{0}C	18.0
Annual global in-plane radiation, kWh/m^2	2160
Annual average electricity production, GWh	9.13
DC/AC losses, %	0.8/0.6
Average performance ratio, %	84.4

Clear difference between sites conditions and systems outputs can be seen from the results. Due to and restricted access to the simulation model, it is difficult to estimate and evaluate inaccuracy and uncertainties of the process. However, we can suppose that significant difference in elevation and geographical location, Walvis bay is much closer to the coastline, and thus wind speeds, not defined horizon line affects the annual output. Lower electricity production at Walvis Bay can also be explained by smaller amount of solar radiation available, however performance ratio is about 4% higher.

5.3 PVSOL Premium Simulation

Since PVSol premium has a limit of 5000 modules in 3D mode with detailed far and near shading analysis, simulation variant in 2D was performed using meterorlical data from Windhoek site.

Table 10. PVSol Premium Simulation Results, 2D

Parameter	Result
Geographical location	22° 48' S, 17° 47' E J.G. Strijdom Airport, Windhoek, Namibia
Nominal capacity, kWp	5 000
Azimuth/inclination, ^{0}	0 (north)/ 25
Module	310 Wp, Si-poly, Suntech Power
Inverter	800 kW, 50/60 Hz, 530-850 V Sunny Central, SMA
Elevation, m	1674
Annual ambient temperature (at 2m), ^{0}C	20.4
Annual global in-plane radiation, kWh/m^2	2481
Annual average electricity production, GWh	10.35
Specific energy yield, kWh/kWp	2049
Average performance ratio, %	83.3

The fact that 2D mode of PVSol does not include near-shading analysis makes the results comparable with pvPlanner results from Windhoek site in terms of shading losses. It might be seen that geographical location and ambient temperature differ slightly while solar radiation data match very good. Electrical energy outputs are of the same order regarding oversizing of the system in PVSol simulation. The reported results include detailed loss diagram (see Appendix 2). Soiling losses were set to average value of 2 %, while mismatch loss and STC conversion, i.e. rated module efficiency, were defined automatically from manufacture information. The most contributive loss to be due to deviation from the nominal module temperature, 7.14 %. DC/AC conversion and cable total losses make up 1.75% and 0.5% respectively.

5.4 PVsyst 6.6.3 Simulation

PVsyst to be the most comprehensive out of the tools tested for the case study, thus simulations run in pvPlanner and PVSol are to some extent based on simulation results of PVsyst model. To be able to run simulation in PVsyst, series of steps to be performed with preliminary defined project location and available solar data (see Figure 13).

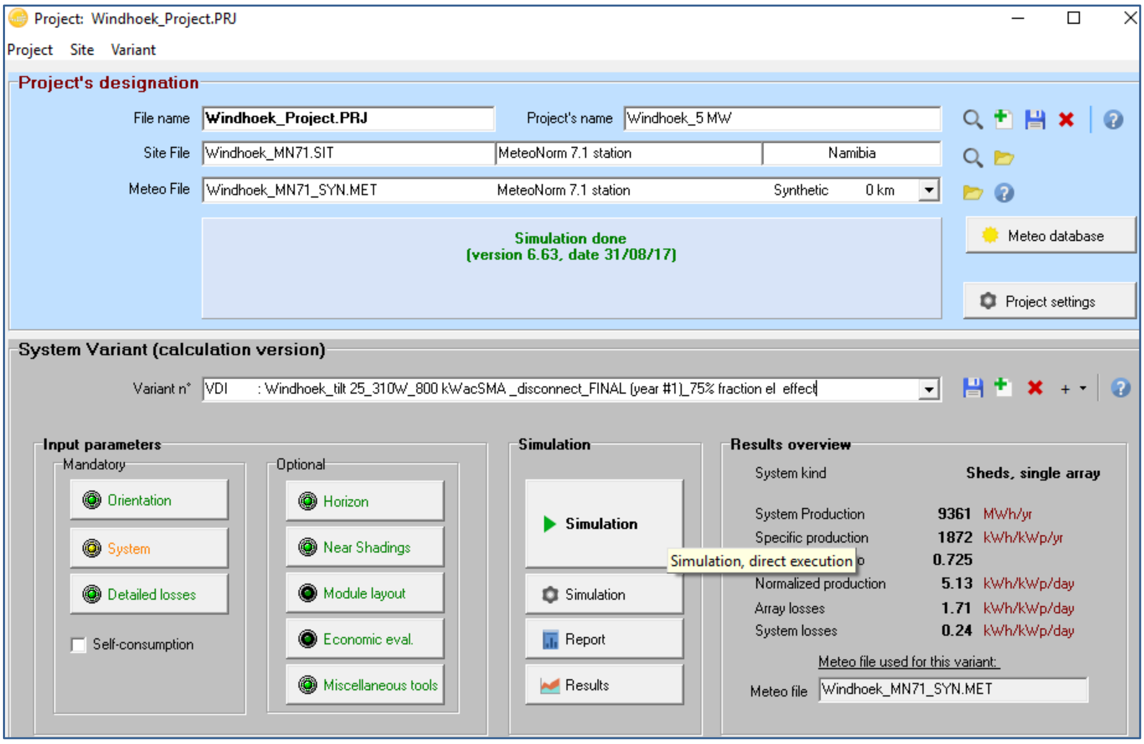


Figure 13. PVsyst project set-up

Orientation including fixed mounting system, tilt angle of 25^0 and azimuth of 0^0 is determined so that the loss by respect to optimum is to be 0.0 %. Than modules without optimizer, to make them comparable with modules used in other simulations, selected and 18 modules put automatically in series (strings). Number and type of inverters are defined based on 1.2:1 ratio between modules nominal power and inverter power rating resulting in slight undersize of the inverter [17; 18]. Loss analysis includes thermal parameters, Ohmic losses, aging factors, mismatch, module quality and LID degradation, soiling losses, efficiency of incidence angle and unavailability.

For free-standing systems with air circulation in the absence of reliable measurement data, no wind speed measurements, thermal loss factor is based on a default value of 29 $W/m^2 \cdot k$ for constant loss factor. Losses of external transformer with ‘night disconnect’ mode on include iron losses of 0.1 % and resistive to inductive losses of 1.0% at STC. The efficiency loss of the chosen module equals to -2.5% where negative value signifies tendency to overperformance. LID factor loss, 1.0 %, refers to degradation of crystalline silicon in first operating hours with respect to the flash test at STC. Soiling loss of 2% was applied. Unavailability of the system, 2% or 7.3 days, was also defined automatically based on the synthesized data from Meteonorm 7.1 database.

Far shading effect was estimated in the model according to the horizon line at Windhoek site. Near shading analysis was performed based on the positioned 3D shading scene including nearby trees with average height of 20 m and wind turbine generator. The actual layout of the site and nearby obstacles was not known, thus the shading scene should be considered as an assumption. To be able use the shading scene, the programme needs to check the compatibility of the 3D layout with other parameters of the system. The check includes 2 consecutive steps: linear shading and shadings according to the module strings. The linear shading was done to calculate shading factor for all positions on the sky seen by the modules, and thus to calculate the shading factor for diffuse and albedo. The simulation model interpolated the calculation results to evaluate shading factor on normal component as well. Then shading according to the strings can be performed with electrical effect. Fraction for electrical effect, i.e. how much the string will be affected by the shading, is very critical factor of rather complex phenomenon with no mean value available. Rough estimate for fraction for electrical effect is 60-80% but this value shall be defined foe each system individually. One way to evaluate the fraction for the system is to figure out the relation between electrical losses from the simulation according to the module string and detailed simulation according to the layout. In this case, the fraction for electrical effect resulted in 75 % with 4% electrical loss from ‘according to the module string’ option and 3% from ‘module layout’. In other words, 75 % of a string will be considered by the model as electrically inactive when it gets hit by shade. The result of shading analysis according to the strings with fraction for electrical effect of 75 % was applied in the simulation process. Annual variability of Meteonerm 7.1 equals to 7.5 % with 0.2 % climate change. Module layout was define based on previously set mechanical, electrical and shading effects. With all the above-mentioned steps, the simulation was run. Simulation results can be found in the table below.

Table 11. PVsyst simulation results, Windhoek site

Parameter	Result
Geographical location	22° 57' S, 17° 10' E Windhoek, Namibia
Nominal capacity, kWp	5 000
Azimuth/inclination, ^{0}	0 (north)/ 25
Module	310 Wp, Si-poly, Suntech Power
Inverter	800 kW, 50/60 Hz, 530-850 V Sunny Central, SMA

Parameter	Result
Elevation, m	1674
Annual ambient temperature, ^{0}C	20.5
Annual global in-plane radiation, kWh/m^2	2303
Annual average electricity production, P50, GWh	9.36
Specific energy yield, kWh/kWp	1872
Average performance ratio, %	72.45

Simulation of the system performance was also performed with the meteo data from PVSol Premium. Since wind speed measurements were missing in the PVSol data, default values from simulation for Windhoek site were used in the simulation. Results of the simulation can be seen from in the table below.

Table 12. Pvsyst simulation results with PVSol solar data, Windhoek site

Parameter	Result
Geographical location	22° 48' S, 17° 47' E J.G. Strijdom Airport, Windhoek, Namibia
Nominal capacity, kWp	5 000
Azimuth/inclination, ^{0}	0 (north)/ 25
Module	310 Wp, Si-poly, Suntech Power
Inverter	800 kW, 50/60 Hz, 530-850 V, Sunny Central, SMA
Elevation, m	1674
Annual ambient temperature, ^{0}C	20.5
Annual global in-plane radiation, kWh/m^2	2263
Annual average electricity production, P50, GWh	9.49
Specific energy yield, kWh/kWp	1897
Average performance ratio, %	73.52

It should be noted that annual production in the summary table corresponds to P50, i.e. annual electricity production with probability of 50 %. P90 and P95 are provided by the PVsyst as well. Both simulation variants were done with Perez-Ineichen model. As can be seen from the summary tables, there is minor difference between the measured data

(2000-2009) from PVSol and synthesized data from PVsyst due to bigger diffuse component in the PVSol data. However, production value and specific energy yield of the system with PVSol input data increased.

6 Discussion and Conclusions

Solar, as any other energy source driven by climate, depends to a great extent on a site conditions and varies significantly over the time and the area. Hence, it is crucial to simulate model for a PV installation considering site-specific conditions including not only geographical location and related solar geometry, but also such parameters as site's availability, surrounding obstacles, local restrictions. Typically, site's specifications might be predefined in the simulation tool by the coordinates and by manually adjusted parameters (e.g. orientation, tilt angle, altitude, albedo). Variation of solar radiation received on the site and inconsistent availability can be resolved by applying simulation model to predict the potential output of the system over the desired operation period. Nowadays, numerous tools with various bundled meteorological datasets, rather extensive databases for system's components, different simulation models and shading and financial analysis are available. The major issue to be that existing simulation tools are unable to cope with the complexity of the process comprising sizing, modelling, assessment of solar data and its uncertainty, energy yield simulation of a SPV system. Therefore, a simulation tool is commonly supported by another one that can advantage simulation and optimization process and increase the overall robustness of the main tool.

Since this study was performed for the company whose current activities do not include solar power applications, the results and their potential application might make a valuable contribution to the business portfolio. The study provides substantial amount of information on currently existing simulation tools and performance of a PV system in general and gives beneficial insights of the matter. The study includes testing and evaluation of three simulation tools: pvPlanner, PVSol Premium and Pvsyst. The same initial conditions for the simulation in each tool were defined based on the case study: installed of capacity of 5 MW at Walvis Bay, Namibia with azimuth angle of 0^0(orientation to the north) and inclination of 25^0. Meteo databases inbuilt into PVsyst and PVSol do not provide solar data for the desired location; thus simulation was performed for available data at Windhoek site, whereas pvPanner let the user run simulation with exact coordinates of the site. However, to make the results more comparable, all simulations were run with the same geographical coordinates. Additionally, simulation of a PV system in initially desired location was performed in pvPlanner. Since PVsyst allows the user to import the data, simulation models based on the solar data from PVSOL Premium and pvPlanner were run in PVsyst to identify the difference between the models. Missing input data from pvPlanner and PVSOl Premium (e.g. wind speeds) required by PVsyst simulation model was filled with default values.

It is important to note that simulation process, models and tools itself have a numerous limitations and uncertainties which to undefined extent affect the simulation and evaluation process. First of all, the trial versions of the software disable some features and simplify the simulation process, in pvPlanner model in particular. Secondly, difference between solar datasets bundled within the tools make them less comparable. That is why the comparison and validation of simulation tools to one another is generally not recommended. Also, easily noticeable difference between simulation steps and number of specification parameters in PVsyst and PVSol Premium models compared to just few manually defined inputs in pvPlaner, increases the incomparability.

Even though it is difficult evaluate the accuracy of simulation models based on the synthesized data without actual measurements from the site, PVsyst was found to deliver more conservative simulation results for the system output. It should be noted that PVSol Premium simulation model was not properly estimated due to the capacity limitation up to 5000 modules in 3D mode. Instead, simulation in 2D mode exclude the shading analysis, the most critical step, and deliver less realistic results of overestimated output. Energy yield according to PVsyst simulation model is 9.4% less than pvPlanner results and 10.6 % than PVSol Premium results. However, simulation results from PVsyst with PVSol data and with inbuilt meteo data base show 1.4 % difference with 9.49 GWh and 9.36 GWh of annual electricity production respectively, that reaffirms the significance of shading analysis in simulation model and, as a result, in the system output. Additionally, PVsyst solar data (Metonorm 7.1) gives the lowest value of global in-plane radiation resulting in the most conservative output. Performance ration over 80 % also indicates the overestimation of the system output in pvPlanner and PVSol simulation, while the typical value would be within the range of 72-80 %. Table 13 summarises the results of simulations run by the software in Windhoek and Walvis Bay site. The results let us conclude that PVsyst should be considered as the most robust simulation tool with the most accurate model out of three tested ones.

Table 13. Simulation results, 5 MW PV plant, Namibia

Simulation Tool / Parameter	pvPlanner	pvPlanner (Walvis Bay)	PVSol	Pvsyst(PVSol)	Pvsyst
Annual ambient temperature (at 2m), ^0C	18.4	18.0	20.4	20.5	20.5
Annual global in-plane radiation, kWh/m2	2492	2160	2481	2263	2303
Annual average electricity production, GWh	10.24	9.13	10.35	9.49	9.36
Specific energy yield, kWh/kWp	2048	1826	2049	1897	1872
Specific energy yield, kWh/kWp/day	5.61	5.00	5.61	5.20	5.13
Average performance ratio, %	80.5	84.4	83.3	72.5	73.5

Prior to application of the tested simulation tools, further study and investigation of uncertainty of the simulation process and inaccuracies in the model are recommended. As stated before, the software should not be used on its own, rather combination of at least two simulation tools can significantly increase the reliability of the results.

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pvPlanner Simulation Results

SOLARGIS pvPlanner

YIELD ASSESSMENT OF THE PHOTOVOLTAIC POWER PLANT

Report number: PV-42794-1710-9
Issued: 06 October 2017 15:22 (UTC)

1. Site info

Site name:	Windhoek_22'57/17'10, Namibia
Coordinates:	**22° 57' 0.06" S, 17° 09' 59.8" E**
Elevation a.s.l.:	1671 m
Slope inclination:	2°
Slope azimuth:	180° south

Annual global in-plane irradiation: **2492 kWh/m²**
Annual air temperature at 2 m: **18.4 °C**

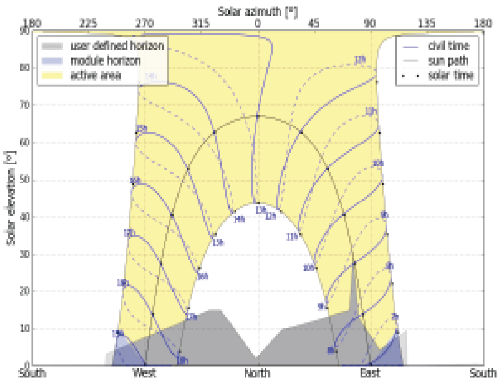
2. PV system info

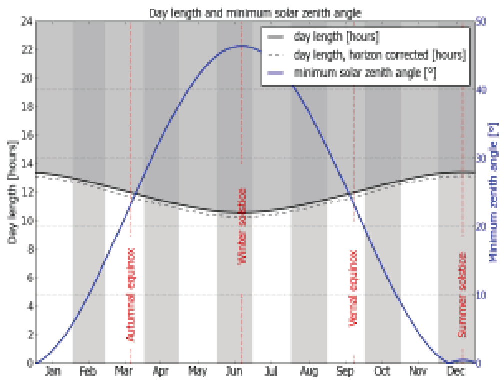
Installed power:	**5000.0 kWp**
Type of modules:	crystalline silicon **(c-Si)**
Mounting system:	**fixed mounting, free standing**
Azimuth/inclination:	**0° (north) / 25°**
Inverter Euro eff.:	98.5%
DC / AC losses:	0.8% / 0.6%
Availability:	98.0%

Annual average electricity production: **10.24 GWh**
Average performance ratio: **80.5%**

Location on the map: http://solargis.info/imaps/#tl=Google:satellite&loc=-22.9500156775,17.166097641&z=14

4. Terrain horizon and day length





Left: Path of the Sun over a year. Terrain horizon (drawn by grey filling) and module horizon (blue filling) may have shading effect on solar radiation. Black dots show True Solar Time. Blue labels show Local Clock Time.

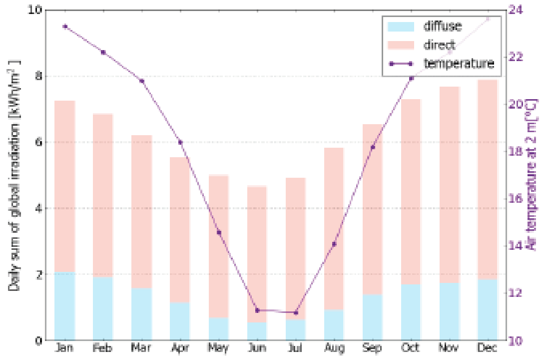
Right: Change of the day length and solar zenith angle during a year. The local day length (time when the Sun is above the horizon) is shorter compared to the astronomical day length, if obstructed by higher terrain horizon.

SOLARGIS **pvPlanner**

Site: Windhoek_22'57/17'10, Namibia, lat/lon: -22.9500°/17.1666°
PV system: 5000.0 kWp, crystalline silicon, fixed free, azim. 0° (north), inclination 25°

5. Global horizontal irradiation and air temperature - climate reference

Month	Gh_m	Gh_d	Dh_d	T_{24}
Jan	225	7.26	2.08	23.3
Feb	192	6.86	1.92	22.2
Mar	192	6.20	1.59	21.0
Apr	166	5.53	1.14	18.4
May	155	5.00	0.68	14.6
Jun	140	4.67	0.56	11.3
Jul	153	4.93	0.63	11.2
Aug	181	5.83	0.92	14.1
Sep	196	6.53	1.38	18.2
Oct	226	7.29	1.71	21.1
Nov	231	7.69	1.74	22.2
Dec	244	7.88	1.86	23.6
Year	**2300**	**6.30**	**1.35**	**18.4**



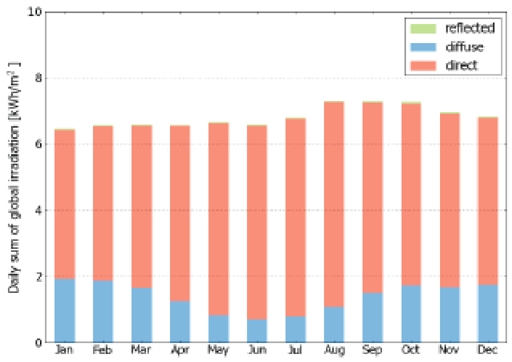
Long-term monthly averages:

Gh_m Monthly sum of global irradiation [kWh/m^2]
Gh_d Daily sum of global irradiation [kWh/m^2]
Dh_d Daily sum of diffuse irradiation [kWh/m^2]
T_{24} Daily (diurnal) air temperature [°C]

6. Global in-plane irradiation

Fixed surface, azimuth 0° (north), inclination. 25°

Month	Gi_m	Gi_d	Di_d	Ri_d	Sh_{loss}
Jan	200	6.46	1.94	0.04	1.2
Feb	184	6.58	1.87	0.04	1.1
Mar	204	6.59	1.64	0.04	1.0
Apr	198	6.58	1.26	0.03	2.0
May	207	6.66	0.83	0.03	3.3
Jun	197	6.59	0.71	0.03	4.1
Jul	210	6.79	0.80	0.03	3.2
Aug	227	7.30	1.08	0.03	1.9
Sep	219	7.30	1.50	0.04	3.6
Oct	225	7.27	1.72	0.04	0.8
Nov	209	6.97	1.66	0.05	0.9
Dec	212	6.84	1.74	0.05	0.9
Year	**2492**	**6.83**	**1.39**	**0.04**	**2.0**



Long-term monthly averages:

Gi_m Monthly sum of global irradiation [kWh/m^2]
Gi_d Daily sum of global irradiation [kWh/m^2]
Di_d Daily sum of diffuse irradiation [kWh/m^2]
Ri_d Daily sum of reflected irradiation [kWh/m^2]

Sh_{loss} Losses of global irradiation by terrain shading [%]

Average yearly sum of global irradiation for different types of surface:

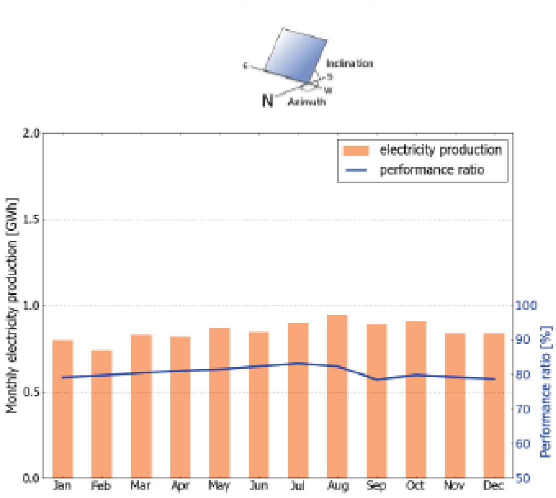
	kWh/m^2	relative to optimally inclined
Horizontal	2300	92.3%
Optimally inclined (24°)	2493	100.0%
2-axis tracking	3340	134.0%
Your option	**2492**	**100.0%**

SOLARGIS pvPlanner

Site: Windhoek_22'57/17'10, Namibia, lat/lon: -22.9500°/17.1666°
PV system: 5000.0 kWp, crystalline silicon, fixed free, azim. 0° (north), inclination 25°

7. PV electricity production in the start-up

Month	Es_m	Es_d	Et_m	E_{share}	PR
Jan	160	5.17	0.80	7.8	79.1
Feb	148	5.30	0.74	7.2	79.7
Mar	166	5.35	0.83	8.1	80.4
Apr	164	5.45	0.82	8.0	81.1
May	174	5.62	0.87	8.5	81.5
Jun	170	5.66	0.85	8.3	82.4
Jul	181	5.83	0.90	8.8	83.2
Aug	190	6.13	0.95	9.3	82.4
Sep	178	5.94	0.89	8.7	78.5
Oct	181	5.85	0.91	8.9	79.8
Nov	167	5.57	0.84	8.2	79.2
Dec	168	5.43	0.84	8.2	78.7
Year	**2048**	**5.61**	**10.24**	**100.0**	**80.5**



Long-term monthly averages:

Es_m Monthly sum of specific electricity prod. [kWh/kWp]
Es_d Daily sum of specific electricity prod. [kWh/kWp]
Et_m Monthly sum of total electricity prod. [GWh]
E_{share} Percentual share of monthly electricity prod. [%]
PR Performance ratio [%]

8. System losses and performance ratio

Energy conversion step	Energy output [kWh/kWp]	Energy loss [kWh/kWp]	Energy loss [%]	Performance ratio [partial %]	Performance ratio [cumul. %]
1. Global in-plane irradiation (input)	2543	-	-	100.0	100.0
2. Global irradiation reduced by terrain shading	2492	-51	-2.0	98.0	98.0
3. Global irradiation reduced by reflectivity	2437	-56	-2.2	97.8	95.8
4. Conversion to DC in the modules	2151	-285	-11.7	88.3	84.6
5. Other DC losses	2134	-17	-0.8	99.2	83.9
6. Inverters (DC/AC conversion)	2102	-32	-1.5	98.5	82.6
7. Transformer and AC cabling losses	2089	-13	-0.6	99.4	82.2
8. Reduced availability	2048	-42	-2.0	98.0	80.5
Total system performance	**2048**	**-496**	**-19.5**	**-**	**80.5**

Energy conversion steps and losses:

1. Initial production at Standard Test Conditions (STC) is assumed,
2. Reduction of global in-plane irradiation due to obstruction of terrain horizon and PV modules,
3. Proportion of global irradiation that is reflected by surface of PV modules (typically glass),
4. Losses in PV modules due to conversion of solar radiation to DC electricity; deviation of module efficiency from STC,
5. DC losses: this step assumes integrated effect of mismatch between PV modules, heat losses in interconnections and cables, losses due to dirt, snow, icing and soiling, and self-shading of PV modules,
6. This step considers euro efficiency to approximate average losses in the inverter,
7. Losses in AC section and transformer (where applicable) depend on the system architecture,
8. Availability parameter assumes losses due to downtime caused by maintenance or failures.

Losses at steps 2 to 4 are numerically modeled by pvPlanner. Losses at steps 5 to 8 are to be assessed by a user. The simulation models have inherent uncertainties that are not discussed in this report. Read more about simulation methods and related uncertainties to evaluate possible risks at http://solargis.com/products/pvplanner/.

PVSol Premium Simulation Results

Project Number: 002 5MW PV-system_2D-Namibia_Windhoek/Walvis
Date of Offer: 2.10.2017

Project Designer:
Company: Etha Wind Oy

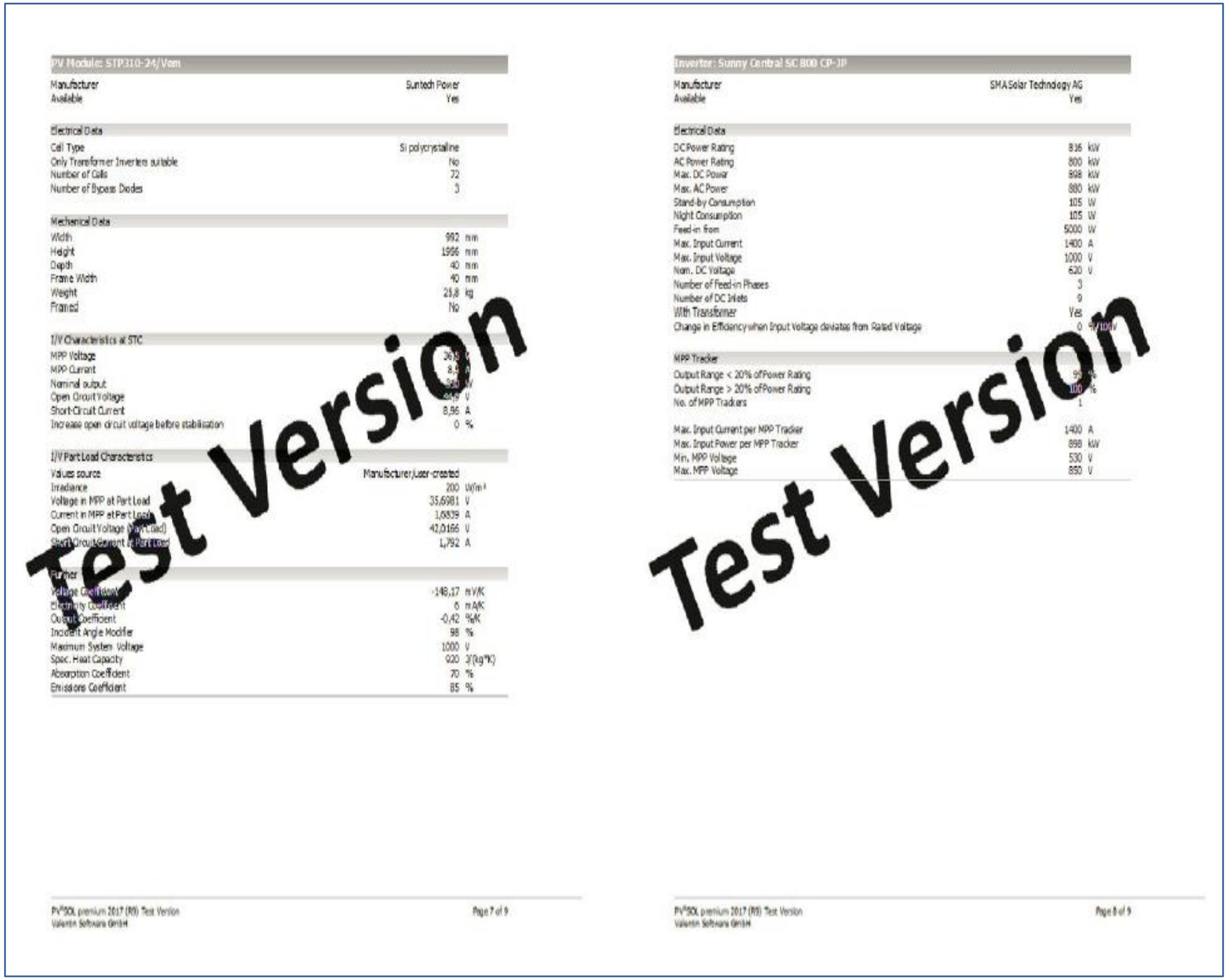
Set-up of the system	
Climate Data	J. G. Strijdom
Type of System	Grid Connected PV System
PV Generator Module Area	
Name	Module Area 1
PV Modules*	17000 x STP310-24/Vem
Manufacturer	Suntech Power
Inclination	25 °
Orientation	North 0 °
Installation Type	Mounted - Open Space
PV Generator Surface	32 986,0 m²
Shading	0 %
Inverter	
Module Area	**Module Area 1**
Inverter 1*	6 x Sunny Central SC 800 CP-JP
Manufacturer	SMA Solar Technology AG
Configuration	MPP 1: 188 x 18
Inverter 2*	2 x Sunny Central SC 800 CP-JP
Manufacturer	SMA Solar Technology AG
Configuration	MPP 1: 112 x 19
AC Mains	
Number of Phases	3
Mains Voltage (1-phase)	230 V
Displacement Power Factor (cos phi)	+/- 1

* The guarantee provisions of the respective manufacturer apply

Project Number: 002 5MW PV-system_2D-Namibia_Windhoek/Walvis
Date of Offer: 2.10.2017

Project Designer:
Company: Etha Wind Oy

PV System Energy Balance			
Global radiation - horizontal	**2 363,6**	**kWh/m²**	
Deviation from standard spectrum	-47,27	kWh/m²	-2,00 %
Ground Reflection (Albedo)	21,70	kWh/m²	0,94 %
Orientation and inclination of the module surface	143,62	kWh/m²	6,14 %
Shading	0,00	kWh/m²	0,00 %
Reflection on the Module Interface	-41,24	kWh/m²	-1,66 %
Global Radiation at the Module	**2 440,4**	**kWh/m²**	
	2 440,4	kWh/m²	
	x 32985,98	m²	
	= 80 500 447,0	kWh	
Global PV Radiation	**80 500 447,0**	**kWh**	
Soiling	-1 610 008,94	kWh	[illegible]
STC Conversion (Rated Efficiency of Module 15,99 %)	-66 276 356,45	kWh	[illegible]
Rated PV Energy	**12 014 0[illegible]**	**kWh**	
Low-light performance	-229 23[illegible]	kWh	[illegible]
Deviation from the nominal module temperature	[illegible]	kWh	-7,14 %
Diodes	[illegible]	kWh	-1,40 %
Mismatch (Manufacturer Information)	[illegible]	kWh	-1,00 %
Mismatch (Configuration/Shading)	0,00	kWh	0,00 %
PV Energy (DC) without inverter regulation	**11 226 312,8**	**kWh**	
Regulation on account of the MPP Voltage Range	-63,68	kWh	0,00 %
Regulation on account of the max. DC Current	0,00	kWh	0,00 %
Regulation on account of the max. DC Power	0,00	kWh	0,00 %
Regulation on account of the max. AC Power/cos phi	-66 147,22	kWh	-0,59 %
MPP Matching	-3 978,10	kWh	-0,04 %
PV energy (DC)	**11 156 123,8**	**kWh**	
Energy at the Inverter Input	**11 156 123,8**	**kWh**	
Input voltage deviates from rated voltage	0,00	kWh	0,00 %
DC/AC Conversion	-195 466,10	kWh	-1,75 %
Stand-by Consumption	-3 851,40	kWh	-0,04 %
Total Cable Losses	-54 784,03	kWh	-0,50 %
PV energy (AC) minus standby use	**10 902 022,3**	**kWh**	
Grid Feed-in	**10 905 632,1**	**kWh**	



PV Module: STP310-24/Vem

Manufacturer	Suntech Power
Available	Yes

Electrical Data

Cell Type	Si polycrystalline
Only Transformer Inverters suitable	No
Number of Cells	72
Number of Bypass Diodes	3

Mechanical Data

Width	992 mm
Height	1956 mm
Depth	40 mm
Frame Width	40 mm
Weight	25,8 kg
Framed	No

I/V Characteristics at STC

MPP Voltage	36,[illegible] V
MPP Current	8,5[illegible] A
Nominal output	[illegible] W
Open Circuit Voltage	44,9 V
Short-Circuit Current	8,96 A
Increase open circuit voltage before stabilisation	0 %

I/V Part Load Characteristics

Values source	Manufacturer/user-created
Irradiance	200 W/m²
Voltage in MPP at Part Load	35,6981 V
Current in MPP at Part Load	1,6839 A
Open Circuit Voltage (Part Load)	42,0166 V
Short Circuit Current at Part Load	1,792 A

Further

Voltage Coefficient	-148,17 mV/K
Electricity Coefficient	6 mA/K
Output Coefficient	-0,42 %/K
Incident Angle Modifier	98 %
Maximum System Voltage	1000 V
Spec. Heat Capacity	920 J/(kg*K)
Absorption Coefficient	70 %
Emissions Coefficient	85 %

PV*SOL premium 2017 (R9) Test Version
Valentin Software GmbH
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Inverter: Sunny Central SC 800 CP-JP

Manufacturer	SMA Solar Technology AG
Available	Yes

Electrical Data

DC Power Rating	816 kW
AC Power Rating	800 kW
Max. DC Power	898 kW
Max. AC Power	880 kW
Stand-by Consumption	105 W
Night Consumption	105 W
Feed-in from	5000 W
Max. Input Current	1400 A
Max. Input Voltage	1000 V
Nom. DC Voltage	620 V
Number of Feed-in Phases	3
Number of DC Inlets	9
With Transformer	Yes
Change in Efficiency when Input Voltage deviates from Rated Voltage	0 %/100V

MPP Tracker

Output Range < 20% of Power Rating	9[illegible] %
Output Range > 20% of Power Rating	100 %
No. of MPP Trackers	1
Max. Input Current per MPP Tracker	1400 A
Max. Input Power per MPP Tracker	898 kW
Min. MPP Voltage	530 V
Max. MPP Voltage	850 V

PV*SOL premium 2017 (R9) Test Version
Valentin Software GmbH
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PVsyst Simulation Results

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Grid-Connected System: Simulation parameters

Project :	**Windhoek_5 MW**			
Geographical Site		**Windhoek**	Country	**Namibia**
Situation	Latitude	-22.57° S	Longitude	17.10° E
Time defined as	Legal Time	Time zone UT+1	Altitude	1674 m
	Albedo	0.20		
Meteo data:	**Windhoek**	MeteoNorm 7.1 station - Synthetic		

Simulation variant :	**Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect**	
	Simulation date	31/08/17 19h09
	Simulation for the	**first year of operation**

Simulation parameters

Collector Plane Orientation	Tilt	25°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Average Height	9.7°		
Near Shadings	According to strings		Electrical effect	75 %

PV Array Characteristics

PV module Si-poly	Model	**STP 310-24/Ve**		
Original PVsyst database	Manufacturer	Suntech		
Number of PV modules	In series	18 modules	In parallel	896 strings
Total number of PV modules	Nb. modules	16128	Unit Nom. Power	310 Wp
Array global power	Nominal (STC)	**5000 kWp**	At operating cond.	4465 kWp (50°C)
Array operating characteristics (50°C)	U mpp	585 V	I mpp	7634 A
Total area	Module area	**31294 m²**		

Inverter	Model	**Sunny Central 800CP-JP**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	530-850 V	Unit Nom. Power	800 kWac
			Max. power (=>25°C)	880 kWac
Inverter pack	Nb. of inverters	5 units	Total Power	4000 kWac

PV Array loss factors

Array Soiling Losses			Loss Fraction	2.0 %
Thermal Loss factor	Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.53 mOhm	Loss Fraction	0.6 % at STC
LID - Light Induced Degradation			Loss Fraction	1.0 %
Module Quality Loss			Loss Fraction	-2.5 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Module average degradation	Year no	1	Loss factor	0.4 %/year
Mismatch due to degradation	Imp dispersion RMS	0.4 %/year	Voc dispersion RMS	0.4 %/year
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

System loss factors

AC wire loss inverter to transfo	Inverter voltage	360 Vac tri		
	Wires: 3x5000.0 mm²	28 m	Loss Fraction	0.4 % at STC
External transformer	Iron loss (Night disconnect)	4913 W	Loss Fraction	0.1 % at STC
	Resistive/Inductive losses	0.3 mOhm	Loss Fraction	1.0 % at STC
Unavailability of the system	7.3 days, 3 periods		Time fraction	2.0 %

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Grid-Connected System: Horizon definition

Project : **Windhoek_5 MW**

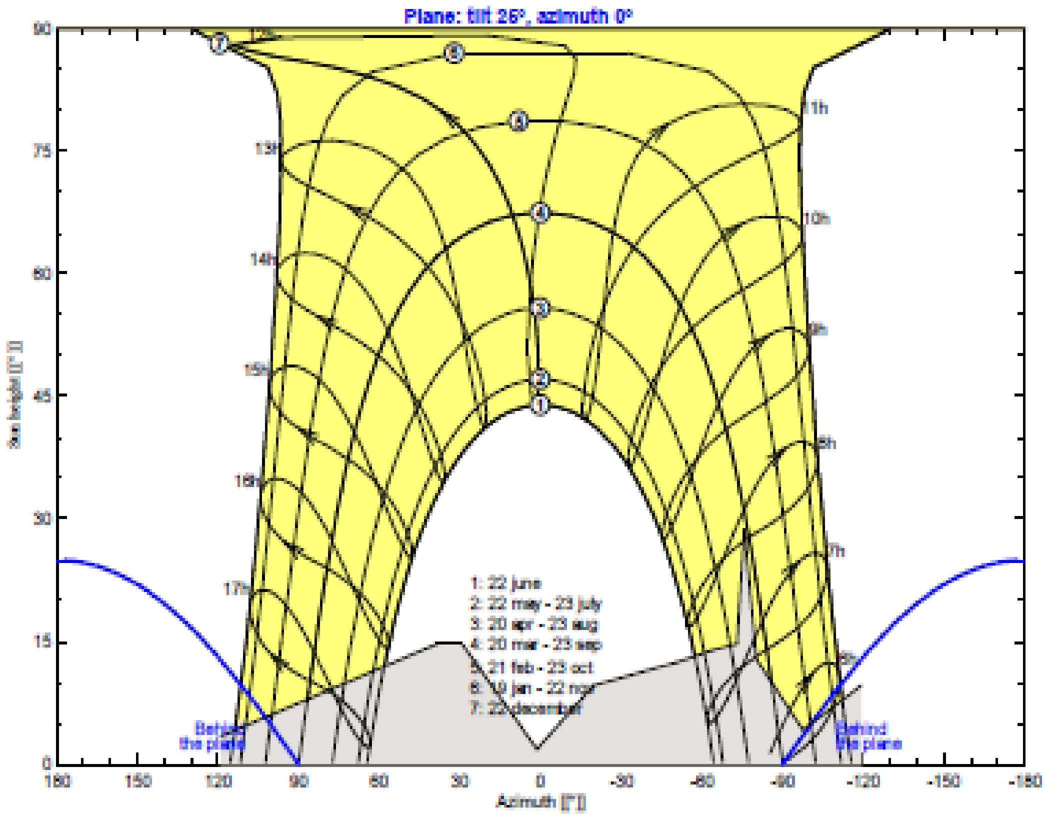
Simulation variant : **Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect**
Simulation for the first year of operation

Main system parameters	System type	**Grid-Connected**		
Horizon	Average Height	9.7°		
Near Shadings	According to strings		Electrical effect	75 %
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	STP 310-24/Ve	Pnom	310 Wp
PV Array	Nb. of modules	16128	Pnom total	**5000 kWp**
Inverter	Model	Sunny Central 800CP-JP	Pnom	800 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**4000 kW ac**
User's needs	Unlimited load (grid)			

Horizon	Average Height	9.7°	Diffuse Factor	0.93
	Albedo Factor	100 %	Albedo Fraction	0.52

Height [°]	9.6	4.2	12.8	28.8	14.7	13.9	12.4	9.6	1.8	14.7	14.7	3.4
Azimuth [°]	-119	-98	-80	-76	-73	-64	-50	-20	1	29	38	119

Horizon line at Windhoek



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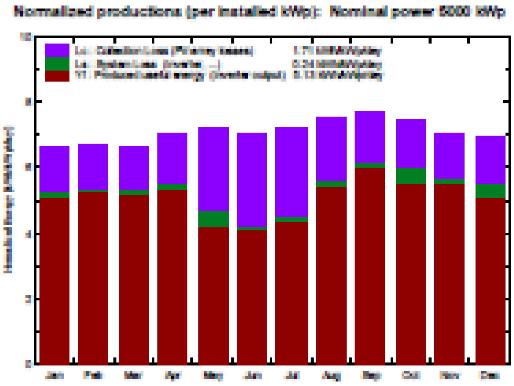
Grid-Connected System: Main results

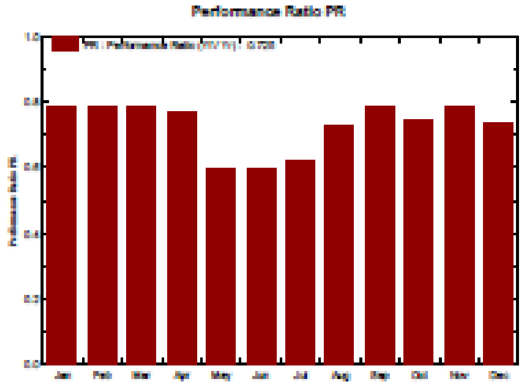
Project : **Windhoek_5 MW**

Simulation variant : **Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect**
Simulation for the first year of operation

Main system parameters	System type	**Grid-Connected**			
Horizon	Average Height	9.7°			
Near Shadings	According to strings			Electrical effect	75 %
PV Field Orientation	tilt	25°		azimuth	0°
PV modules	Model	STP 310-24/Ve		Pnom	310 Wp
PV Array	Nb. of modules	16128		Pnom total	**5000 kWp**
Inverter	Model	Sunny Central 800CP-JP		Pnom	800 kW ac
Inverter pack	Nb. of units	5.0		Pnom total	**4000 kW ac**
User's needs	Unlimited load (grid)				

Main simulation results				
System Production	**Produced Energy**	**9361 MWh/year**	Specific prod.	1872 kWh/kWp/year
	Performance Ratio PR	72.45 %		





Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	227.7	73.10	24.49	205.1	184.0	824.5	800.9	0.781
February	194.3	72.80	23.11	187.2	167.3	758.9	737.8	0.788
March	192.0	61.90	23.28	204.5	185.4	830.3	805.9	0.788
April	176.7	41.50	20.15	211.1	191.5	833.6	809.9	0.768
May	166.3	30.10	17.00	221.9	192.5	735.7	661.2	0.596
June	147.9	22.60	13.82	209.8	174.1	639.5	622.6	0.594
July	161.1	26.10	13.52	222.7	188.4	707.3	688.2	0.618
August	185.6	29.10	17.13	233.1	210.9	870.6	845.2	0.725
September	206.6	40.10	20.94	231.2	212.1	934.6	906.8	0.785
October	230.3	52.70	24.59	231.1	212.5	898.8	863.8	0.748
November	231.7	61.60	24.35	211.3	191.8	855.1	829.9	0.786
December	245.5	74.60	24.98	215.2	193.3	802.4	789.8	0.734
Year	2365.7	586.19	20.51	2584.2	2303.8	9791.3	9361.0	0.725

Legends:

GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

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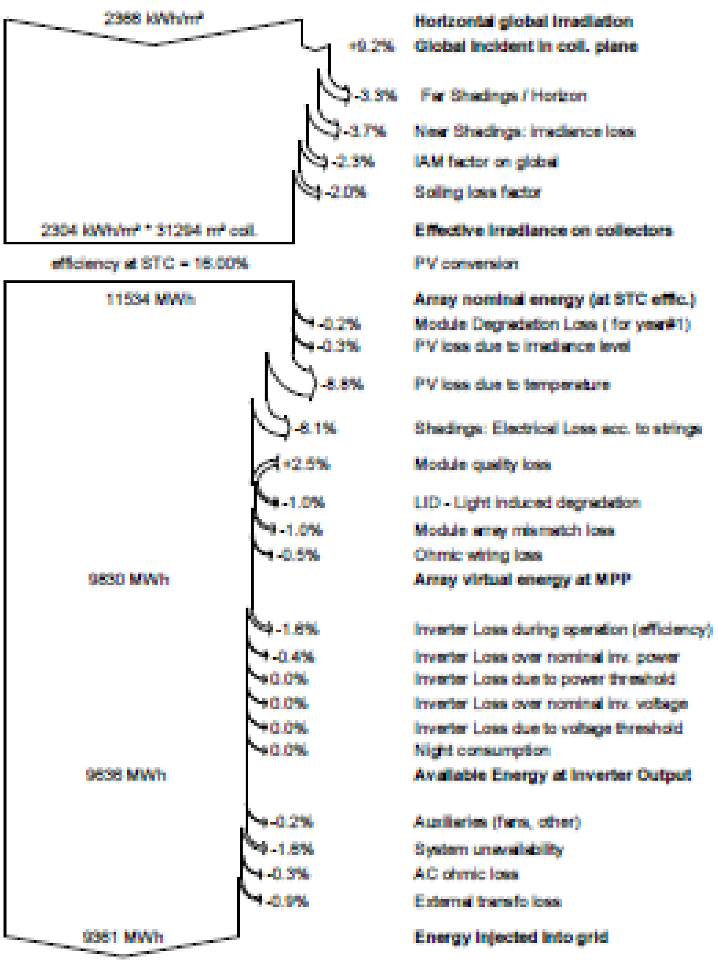
Grid-Connected System: Loss diagram

Project : **Windhoek_5 MW**

Simulation variant : **Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect**
Simulation for the first year of operation

Main system parameters	System type	**Grid-Connected**		
Horizon	Average Height	9.7°		
Near Shadings	According to strings		Electrical effect	75 %
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	STP 310-24/Ve	Pnom	310 Wp
PV Array	Nb. of modules	16128	Pnom total	**5000 kWp**
Inverter	Model	Sunny Central 800CP-JP	Pnom	800 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**4000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: P50 - P90 evaluation

Project : **Windhoek_5 MW**

Simulation variant : **Windhoek_tilt 25_310W_800 kWacSMA _disconnect_FINAL (year #1)_75% fraction el effect**
Simulation for the first year of operation

Main system parameters	System type	**Grid-Connected**			
Horizon	Average Height	9.7°			
Near Shadings	According to strings			Electrical effect	75 %
PV Field Orientation	tilt	25°		azimuth	0°
PV modules	Model	STP 310-24/Ve		Pnom	310 Wp
PV Array	Nb. of modules	16128		Pnom total	**5000 kWp**
Inverter	Model	Sunny Central 800CP-JP		Pnom	800 kW ac
Inverter pack	Nb. of units	5.0		Pnom total	**4000 kW ac**
User's needs	Unlimited load (grid)				

Evaluation of the Production probability forecast

The probability distribution of the system production forecast for different years is mainly dependent on the meteo data used for the simulation, and depends on the following choices:

Meteo data source		MeteoNorm 7.1 station	
Meteo data	Kind	TMY, multi-year	
Specified Deviation	Climate change	0.2 %	
Year-to-year variability	Variance	7.5 %	

The probability distribution variance is also depending on some system parameters uncertainties

Specified Deviation	PV module modelling/parameters	2.0 %	
	Inverter efficiency uncertainty	0.5 %	
	Soiling and mismatch uncertainties	1.0 %	
	Degradation uncertainty	1.0 %	
Global variability (meteo + system)	Variance	7.9 %	(quadratic sum)

Annual production probability	**Variability**	**742 MWh**
	P50	**9380 MWh**
	P90	**8429 MWh**
	P95	**8161 MWh**