iDesignRES

Solar Energy Model: Complementary documentation to the model code

WP1 – Multi-Physics component models: Implementation and development

Task 1.2: Energy sources and conversion

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Work Package	WP1 Multi-Physics component models: Implementation and development
Dissemination Level	Public
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This document has been prepared in the framework of the European project iDesignRES. This project has received funding from the European Union's Horizon Europe programme under grant agreement no. 101095849.

1. Table of Content

1. Solar Energy Model - Purpose of the model

The solar power model provides time-series of annual thermal energy generation in Concentrating Solar Power (CSP) plants and electrical energy generation in large Photovoltaic (PV) plants on hourly basis, for a given NUTS2 region and a specific amount of investment in €, in MWp or in m2 for each of these technologies: CSP and PV. These profiles are provided aggregated at NUTS2 level and disaggregated at NUTS3 level, as well as the annual operational expenditures of both technologies.

2. Model design philosophy

The model firstly establishes the required area to deploy the given investment in each technology. Then, the most suitable available areas in the given region NUTS2 are selected. Once potential areas for each technology in each NUTS3 region are categorized by intervals of 100W/m^2 of Global Horizontal Irradiance (GHI), those with higher GHI are selected until reaching the area, power capacity or investment required by the user at the input.

Since CSP technology requires higher solar radiation, CSP technology is prioritized when selecting the locations. Considering the solar resource on hourly basis of selected areas for each technology, simplified models are used to estimate annual thermal and electrical energy generation. These profiles are obtained at NUTS3 level and they are finally aggregated to provide them at NUTS2 level. The general scheme of CSP and Solar PV components are shown in the figures below.

CSP component

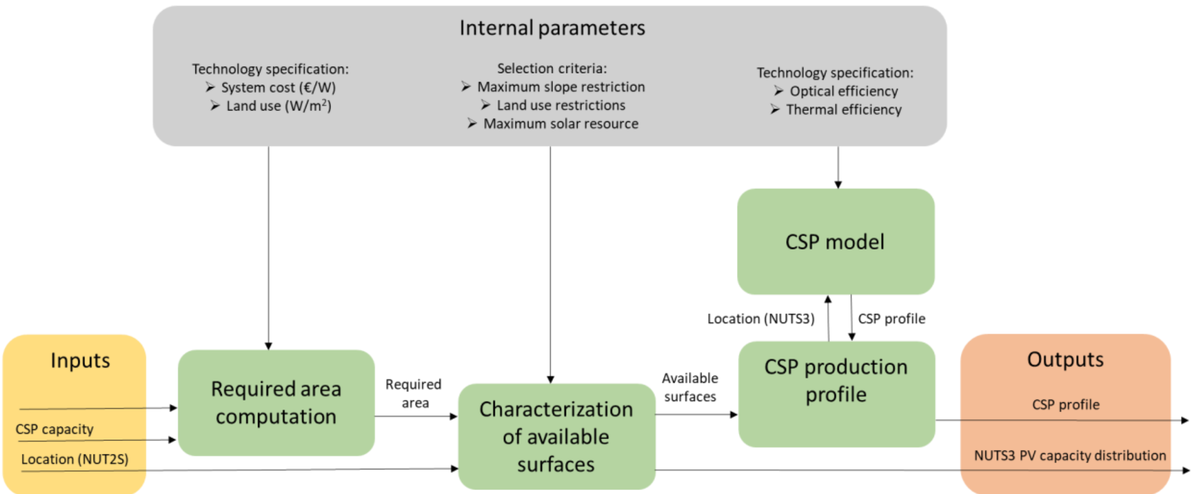

Figure 1. General Scheme of CSP component.

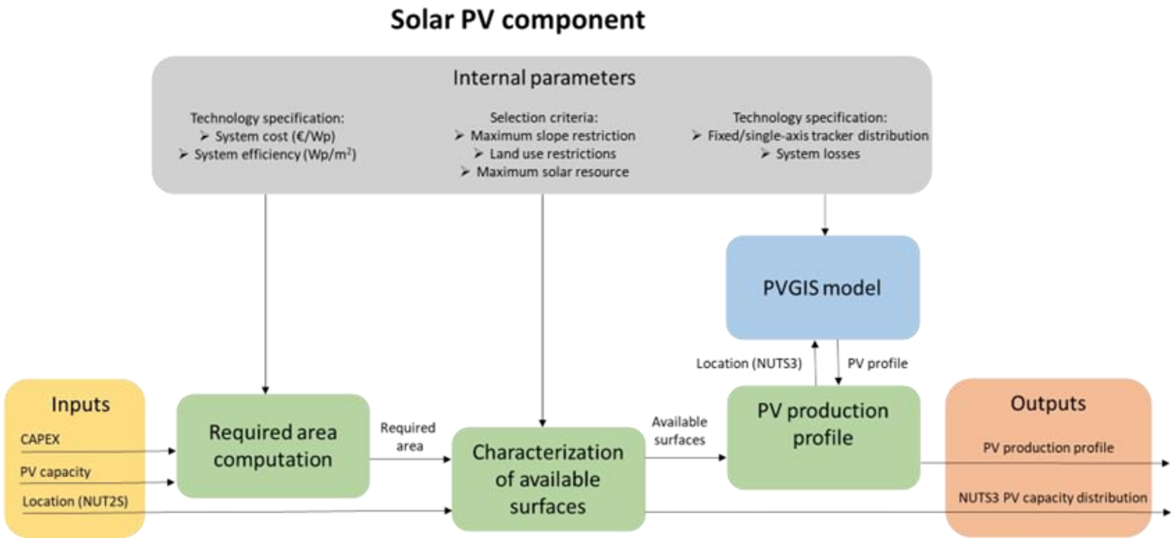

Figure 2. General Scheme of Solar PV component.

3. Input to and output from the model

3.1. Input data

Data to be necessarily filled in by the user

These data are the minimum input data to be provided by the user:

- NUTS2 region code.
- Investment in €, power capacity in MW or area in m^2 to deploy CSP technology in the given NUTS2 region. In case of conflict, area is firstly considered and power capacity secondly. Investment in € is only considered is no other entry is provided.
- Investment in €, power capacity in MWp or area in m^2 to deploy PV plants in the given NUTS2 region. In case of conflict, area is firstly considered and power capacity secondly. Investment in € is only considered is no other entry is provided.

	CSP			**PV**		
	min	default	max	min	default	max
investment (€)	0	-	25e11	0	-	5e11
power capacity (MW)	0	-	5e11	0	-	1e12
area (m2)	0	0	1e10	0	0	1e10

Data to be optionally filled in by the user

Default values are provided by the model, but they can be optionally modified by the user in case more accurate data are available. Please find below the list of parameters with the corresponding default value.

- Configuration parameters of areas selection criteria.
  - Minimum annual Global Horizontal Irradiance (GHI) for CSP technology: 2,000W/m^2.
  - Minimum annual Global Horizontal Irradiance (GHI) for PV technology: 1,000W/m^2.
  - Maximum terrain slope restriction for CSP plants: 5%.
  - Maximum terrain slope restriction for large PV plants: 10%.
- Financial and technical parameters of CSP technologies in the market.

- System cost: 5€/W.
- Operational expenditures: 20,000€/MW.
- Land use: 50W/m^2.
- Thermal efficiency: 45%.
- Optical efficiency: 65%.

- Financial and technical parameters of PV technologies in the market.
  - Single-axis tracker PV percentage: 60%. The rest is considered fixed mounted.
  - System cost: 0.5€/W.
  - Operational expenditures: 15,000€/MW.
  - Land use: 100W/m^2.
  - System losses: 14%.

PV	Min	default	max
min ghi (W/m2)	500	1000	2000
tilt (ºC)	0	30	90
azimuth (ºC)*	0	180	360
losses (%)	8	14	20
single-axis tracker percentage (%)	0	60	100
land use (W/m2)	50	100	200
system cost (€/W)	0.2	0.5	1
operational expenditures (€/MW)	0	15000	30000

**For buildings consider distribution: 60% 180º, 20% 90º, 20% 270º (South 180º)*

CSP	Min	default	Max
min ghi (W/m2)	1500	2000	2500
land use (W/m2)	25	50	100
system cost (€/W)	1	5	10
aperture (%)	25	50	75
operational expenditures (€/MW)	0	20000	40000
thermal efficiency (%)	25	45	65
optical efficiency (%)	45	65	85

<u>Output data:</u>

- Time-series of annual CSP thermal energy generation and PV electrical energy generation in MWh on hourly basis aggregated at NUTS2 level.
- Time-series of annual CSP thermal energy generation and PV electrical energy generation in MWh on hourly basis disaggregated at NUTS3 level.
- Annual operational expenditures of CSP technology and PV technologies in €.

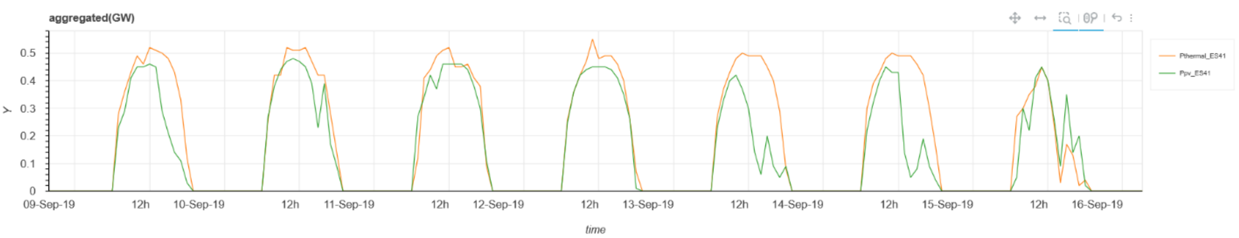

Figure 3. CSP and PV generation profile.

4. Implemented features

- The model estimates the required area to deploy given investment or power capacity of CSP and PV technologies.
- The model categorizes available areas in intervals of 100W/m^2 of annual global horizontal irradiation (GHI) for each NUTS3 region complying with selection criteria (maximum slope and land use restriction) for each technology.
- The model selects areas with the highest annual GHI until reaching all the required area, prioritizing CSP and relegating PV in case of conflicts.
- For the selected areas in each NUTS 3 region, the model determines the location with the median of annual GHI and estimates annual CSP thermal and/or PV electrical energy generation profiles on hourly basis, making use of simplified model of CSP and Solar PV generators and the Typical Meteorological Year (TMY) corresponding to this location.
- The model aggregates estimated generation profiles at NUTS3 level to compute generation profile at NUTS2 level, with the variability due to spatial distribution.

5. Core assumptions

5.1. General assumptions

- The model does not allow optimization. It is a simulation model that allows the evaluation of prospective exploratory scenarios characterized by a given amount of investment on each of the potential solar technologies: CSP and PV.
- The most relevant aspect at the output of the model is obtaining realistic solar generation profiles for each technology representing their variability, as result of solar resource availability and spatial distribution.
- For CSP generation, only Parabolic Trough technology is considered, as this stands for more than 75% of the market, it requires less annual Direct Normal Irradiance (DNI) presenting a bit higher overall efficiency and lower LCOE than Power Tower technology. Furthermore, it is important to remark that generation profiles of both technologies (Parabolic Trough and Power Tower) are directly dependent on DNI availability on the considered locations, so a technology disaggregation would not make a big difference in the results.
- For PV generation, fixed-mounted and single-axis tracking systems are separately considered, mainly because generation profiles of both technologies are quite different, with a wider shape during daylight for single-axis tracking than for fixed-mounted systems.
- In case of conflict of available areas for CSP and PV technologies, the former is prioritized, relegating PV to those areas with lower GHI.

5.2. Mathematical description

The most relevant aspects of the mathematical description of the generation models are detailed below. It should be noted that proposed models are quite simple and general, since more precise models would require a level of detail unknown for each NUTS3 region and proposed scenario.

This section is composed of different subsections, each of them focused on the description of the most relevant methodological and mathematical aspects of each of the large blocks described in the model design philosophy section.

Required area computation.

In case the input from the user is not directly the area to be used for CSP and PV technologies, the investment in € will be translated into power capacities to be installed through systems costs reported above and these into required area through land use ratios also previously reported.

Characterization of available surfaces.

The process determines for each selected region whether or not each zone is suitable for the potential implementation of solar technology. Different criteria (layers of information) are used, as well as a series of extra-limiting criteria that overlap each other to determine the suitability of each zone.

More specifically, in a first step, potential areas for the installation of solar systems are calculated based on a combination of information layers that consider global incipient solar irradiation (GHI), environmental protection (protected areas), land use and terrain slope. With all this information, a new layer is generated with a final image of each point in the region based on its suitability to these criteria.

On the other hand, for each region a raster file is generated with the areas of potential radiation differentiated by different radiation ranges or thresholds. This is intended to obtain more criteria to determine which are the most interesting areas in which to start deploying solar technology once the alternative scenarios are being generate.

As output of this process, the results obtained in terms of the region ID (NUTS Level 3 and NUTS Leve 2), the coordinates of the region centroid, the total area, the maximum radiation, the average radiation, and the area corresponding to each of the zones corresponding to each radiation threshold measured above are stored.

This information is used in later phases to calculate solar generation, taking as inputs data with a high degree of disaggregation.

The different layers of information used in the process described above are listed in more detail below.

- Slope terrain inclination map: 25x25m and classifies them from 0 to 90º (It is only inclination)[1].
- Global solar radiation atlas GHI at 200x200m resolution[2].
- Land use map: 100x100m. Selected from this layer the uses corresponding to; pastures (2310, 3210), shrubs and heaths (3220, 3240), and sparsely vegetated areas (3330)[3].
- Several layers of protected areas[4]:
    - Emerald network The Emerald Network is an ecological network made up of Areas of Special Conservation Interest. The objective of the Emerald Network is the long-term survival of the species and habitats. The Emerald Network consists of the Areas of Special Conservation Interest (ASCI)[5].

[1] https://ec.europa.eu/eurostat/web/gisco/geodata/digital-elevation-model/eu-dem#Slope

[2] https://globalsolaratlas.info/download/world

[3] https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/LUISA/EUROPE/Basemaps/LandUse/2018/LATEST/

[4] https://www.eea.europa.eu/en/analysis/maps-and-charts/european-protected-areas-1

[5] https://www.eea.europa.eu/en/datahub/datahubitem-view/4c4c8086-c940-400b-9064-29063143b2de

- Natura 2000: Natura 2000 is an ecological network of protected areas, set up to ensure the survival of Europe's most valuable species and habitats. Natura 2000 is based on the 1979 Birds Directive and the 1992 Habitats Directive[6].
- Nationally designated areas The European inventory of Nationally designated areas holds information about designated areas and their designation types, which directly or indirectly create protected areas. The Nationally designated areas is the official source of protected area information from the 38 European member countries to the World Database of Protected Areas (WDPA)[7].

The following is a more detailed description of the preprocessing process according to its logic and processing sequence.

Data Preparation and Clipping

- Clip the NUTS (Nomenclature of Territorial Units for Statistics) regions layer to the selected NUTS 2 or NUTS 3 region.
- Clip the following layers to the selected region: (Slope, Land use, Protected areas, Solar radiation)

Slope Layer Filtering

The slope layer is filtered to create a binary map indicating areas where the slope exceeds a specified threshold angle. This process involves:

- Converting the threshold angle to radians.
- Applying a cosine function and multiplying by 250 to calculate the slope threshold value.
- Creating a new raster image where pixels exceeding the threshold are set to 1, and others to 0.

Land Use Layer Filtering

The land use layer is filtered to identify specific land cover types suitable for solar installation:

- User-defined codes for suitable land types (e.g., pastures, shrubs, heathlands, and sparsely vegetated areas) are used to filter the layer.
- Pixels corresponding to the specified land use codes are set to 1, while all others are set to 0.

Raster Alignment and Standardization

All layers are aligned and adjusted to ensure consistent resolution, projection system, and size across datasets.

Potential Area Calculation

The code calculates potential areas for solar infrastructure installation by combining multiple factors: (Global Horizontal Irradiance (GHI), Environmental protection status, Land use, Slope)

These factors are represented as raster images and are multiplied together to generate a new composite image identifying the most suitable areas for installation.

Regional Analysis and Reporting

The code performs a regional analysis based on the potential radiation areas:

[6] https://www.eea.europa.eu/en/datahub/datahubitem-view/6fc8ad2d-195d-40f4-bdec-576e7d1268e4

[7] https://www.eea.europa.eu/en/datahub/datahubitem-view/f60cec02-6494-4d08-b12d-17a37012cb2

- Radiation thresholds are defined from a starting value to the maximum raster value, incrementing by 100W/m^2.
- A Data Frame is created to store results corresponding to each radiation threshold, including: region ID, centroid coordinates, total area, maximum radiation, average radiation, median radiation and coordinates for this median radiation.
- The code iterates over each NUTS 3 region, calculating values for each radiation threshold.
- Results are saved as a CSV file in the same directory as the input raster file.

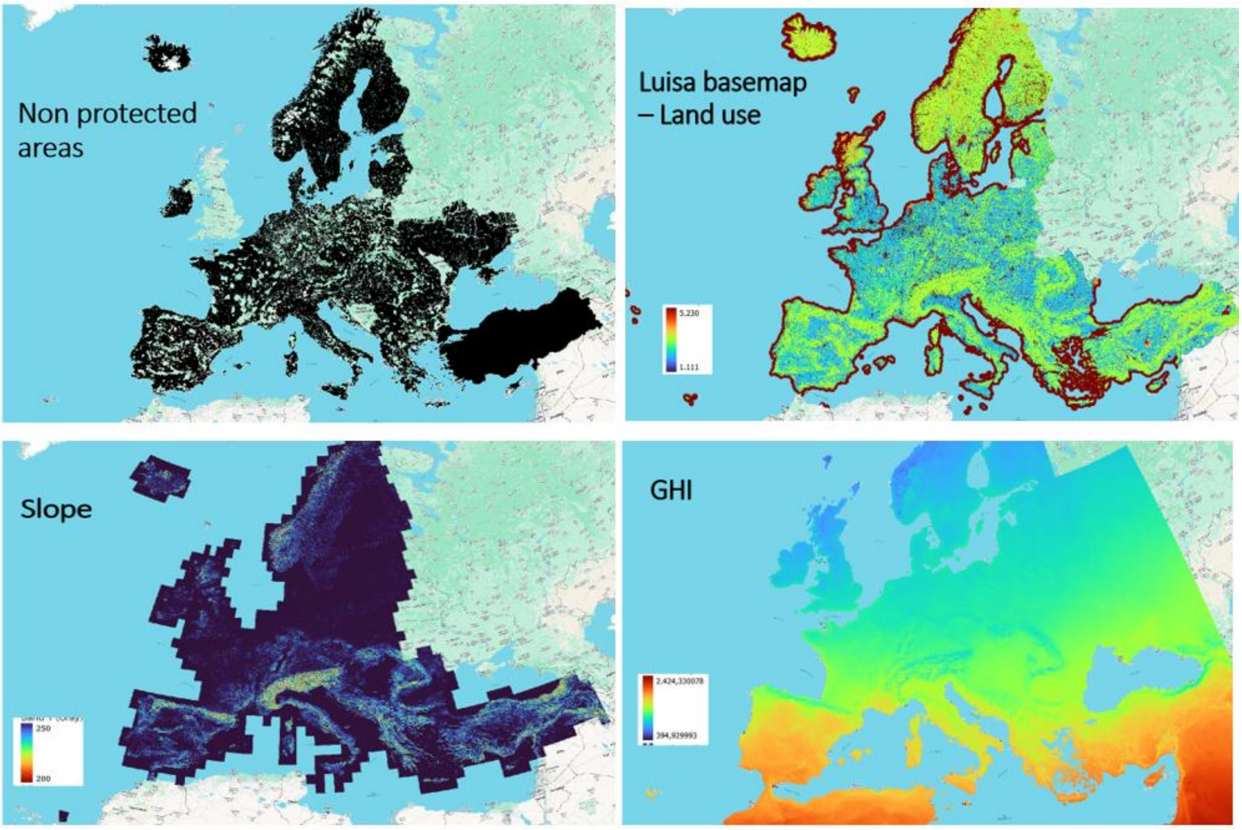

Figure 4. Visual example of different information layers that are used in the process.

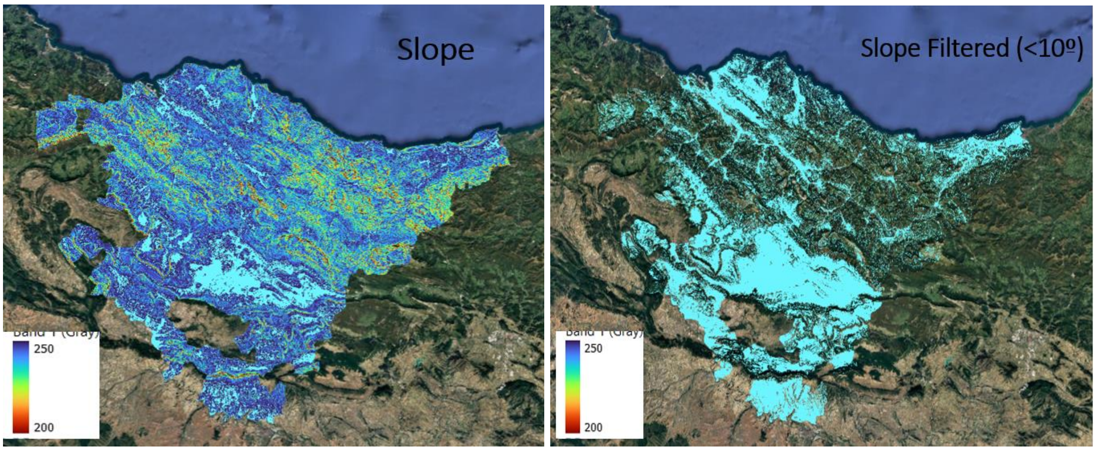

Figure 5. Visual example of one of the information layers (slope) before and after applying the necessary filters as part of the data processing.

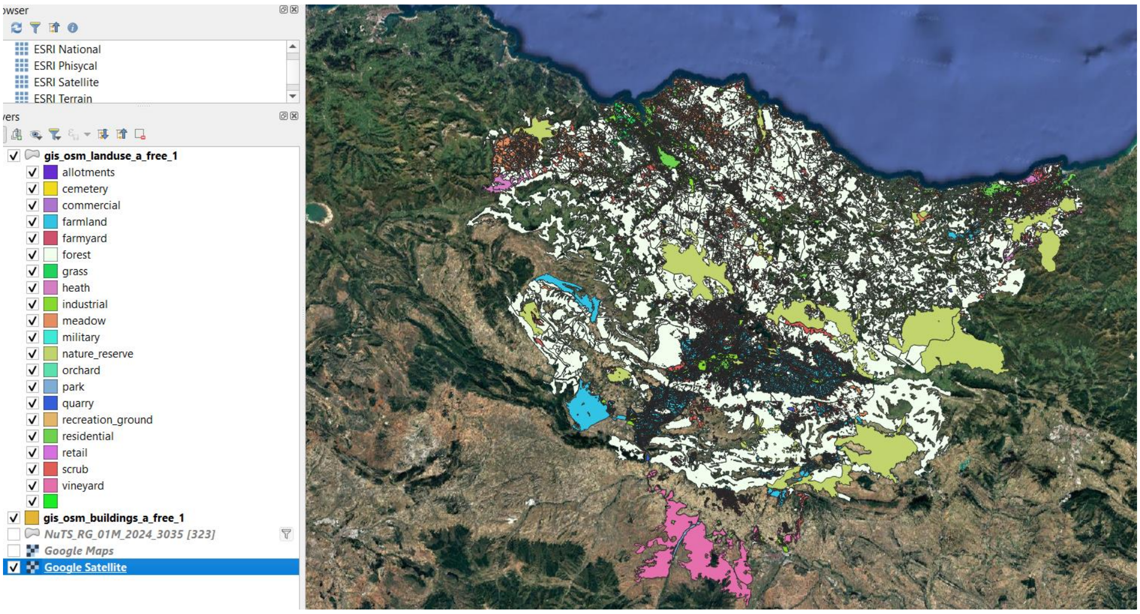

Figure 6. Visual example of the processing of the Geofabrik land use layer for a specific region.

PVGIS model and PV production profile.

The tool used to estimate the Photovoltaic generation in buildings is PVGIS[8], a free web application that allows the user to get data on solar radiation and photovoltaic system energy production. This is automatedly accessible via API.

Firs of all, PVGIS makes use of reanalysis-based solar radiation data sets to estimate the solar radiation arriving at the earth surface. Data. Reanalysis data are calculated using numerical weather forecast models, re-running the models for the past and making corrections using the known meteorological measurements. The output of the models is a large number of meteorological quantities, often including the solar irradiance at ground level. More concretely, ECMWF ERA-5, produced by the European Centre for Medium-range Weather Forecast (ECMWF), has global coverage at a resolution of about 30km, and includes both global and direct solar irradiance. At the time of writing, only the time period 2005-2020 has been in PVGIS along with global coverage.

The satellite-based calculation described above produces values of global and beam irradiance on a horizontal plane.

However, modules and PV systems are generally installed at an inclined angle with regard to the horizontal plane or on tracking systems, so as to maximize the received in-plane irradiance. Therefore, the satellite retrieved irradiance values are not representative of the solar radiation available at the module surface, and it becomes necessary to estimate the in-plane irradiance.

There are several models in the scientific bibliography which use as input data the irradiance values on the horizontal plane of global and diffuse and/or beam irradiance components, to estimate the values of the beam and diffuse components on tilted surfaces. A comparison of some of these models can be found

[8]PVGIS data sources & calculation methods - European Commission

in *Gracia Amillo and Huld, 2013*. The estimation model implemented in PVGIS is the one developed by Muneer T. (1990) *,* which can be classified as anisotropic of two components.

In the case of large PV plants, fixed-mounted and single-axis tracking systems are considered. The distribution between these two technologies is set as an input parameter.

On the other hand, PVGIS uses information about the elevation of the terrain with a resolution of 3 arc-seconds (about 90m). This means that for every 90m we have a value for the ground elevation. From these data the height of the horizon around each geographical location is calculated. These data are then used to calculate the times when the sun is shadowed by hills or mountains. When this happens, the solar radiation is then calculated using only the diffuse part of the radiation. Please notice that with a resolution of ~90m the calculations in PVGIS cannot take into account the effects of shadows from nearby objects.

Indeed, once the amount of solar radiation that arrives at the PV modules is computed, the different effects that influence PV output and how they are calculated in PVGIS.

- Shallow-angle reflection. This is calculated using a mathematical model described in (*Martin&Ruiz, 2001, Martin&Ruiz, 2013*). Generally, this effect causes a loss of 2-4% of the sunlight, though this will be lower for sun-tracking PV systems (*Huld et al., 2015*).
- Effects of changes in the solar spectrum. PVGIS has used solar radiation data from satellite that have been calculated for different spectral bands (*Mueller et al., 2012*) to calculate the effect of spectrum changes on the PV energy output.
- PV power dependence on irradiance and module temperature. PVGIS calculates the effects of irradiance and module temperature using a model described in (*Huld et al., 2011*). Module temperature is treated in PVGIS using a model suggested by Faiman (*Faiman, 2008*) and the BIPV/BAPV configuration is selected in this case.
- System losses and degradation. Considering the system losses and the losses due to ageing PVGIS recommends a value of 14% for the "system loss" that the user gives as input to the model.

CSP model and CSP production profile.

The CSP Parabolic Trough generation model is quite simplified by the following equation including: (1) the available Direct Normal Irradiance (DNI) on the location in W/m^2, (2) the aperture area of the Parabolic Trough solar field in m^2, (3) optical efficiency in %, and (4) thermal efficiency in %.

$$CSP_{generation} = efficiency_{optical} * efficiency_{thermal} * aperture\_area * DNI$$

The DNI is directly obtained from PVGIS reanalysis-based solar radiation data sets.

The aperture area is estimated as a half of the total area for CSP technology, considering that each collector loop of a Parabolic Trough System typically has an aperture area of 5,000 to 7,000m^2 and it requires about 10,000 to 15,000m^2 of land.

The optical and thermal efficiencies are input parameters for CSP technology that can be modified by the user.

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