Estimating Solar Radiation and Photovoltaic System Performance, the PVGIS Approach

Thomas Huld
European Commission, Joint Research Centre
Ispra, Italy

Overview of talk

- Introduction: why solar energy
- Estimates of solar radiation over wide areas, data and methods
- Methods for estimating the performance of photovoltaic systems
- Introduction to PVGIS
- Hands-on experience with PVGIS

Why (sometimes) Solar Energy?

- Rising cost of fossil fuels
- Falling cost of solar energy
- Reduced dependence on energy imports
- Less dependent on extensive grid infrastructure
- Suitable for decentralized deployment
- Climate change!

Of course, most of this goes for other renewables

Comparison Diesel vs. PV minigrids

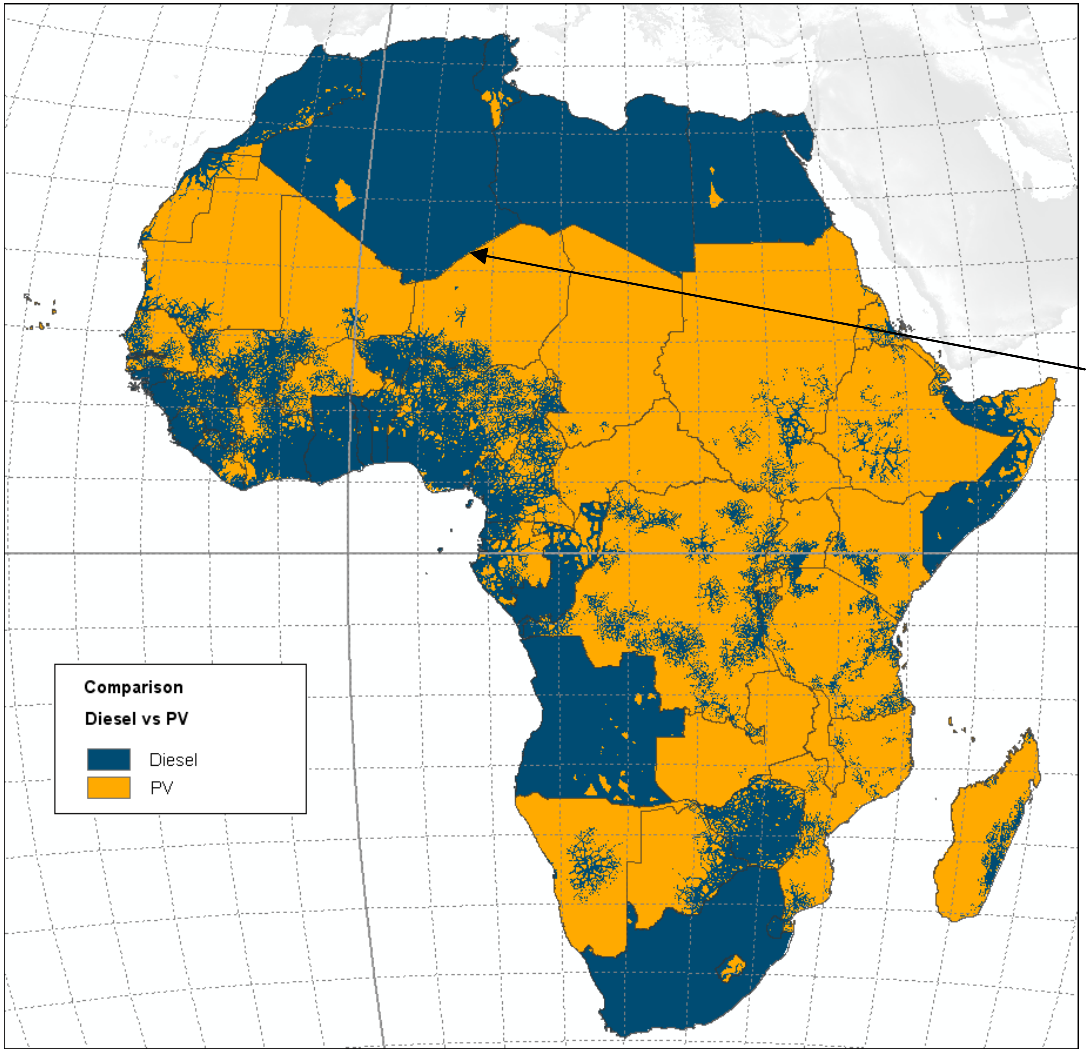
Blue: diesel is cheaper
Yellow: PV is cheaper

Calculation from 2010

Since then:

- Diesel prices increased
- PV prices decreased

Source:
Szabo, Bodis, Huld,
Moner Girona,
Env.Res.Lett. (2011)



Effects of Diesel Subsidies!

Solar radiation estimates

- Solar radiation quantities
- Estimates based on ground station measurements
  - Types of measurements (see also talk by W. Zaaiman)
  - Available data sets
  - Interpolation methods
- Satellite-based estimates
  - Methods

Solar radiation quantities

- Global horizontal irradiation (GHI)
  - All the light that arrives on a horizontal plane, from sun, sky, clouds

- Diffuse horizontal irradiation (DHI)
  - All the light arriving from sky and clouds, but NOT directly from the sun

- Direct normal irradiation (DNI)
  - The light that arrives directly from the sun (and the bright patch around it) onto a plane that is normal to the direction of the sun

Solar radiation measurement databases

- Baseline Surface Radiation Network (BSRN)
  - Generally very high quality
  - Around 40 stations around the world
  - Measurements of GHI, DHI and DNI + other meteorological parameters, including long-wave infrared radiation
  - Data periods not the same for all stations
  - Geographical coverage rather unequal
  - Widely used for validating satellite-based solar radiation estimates

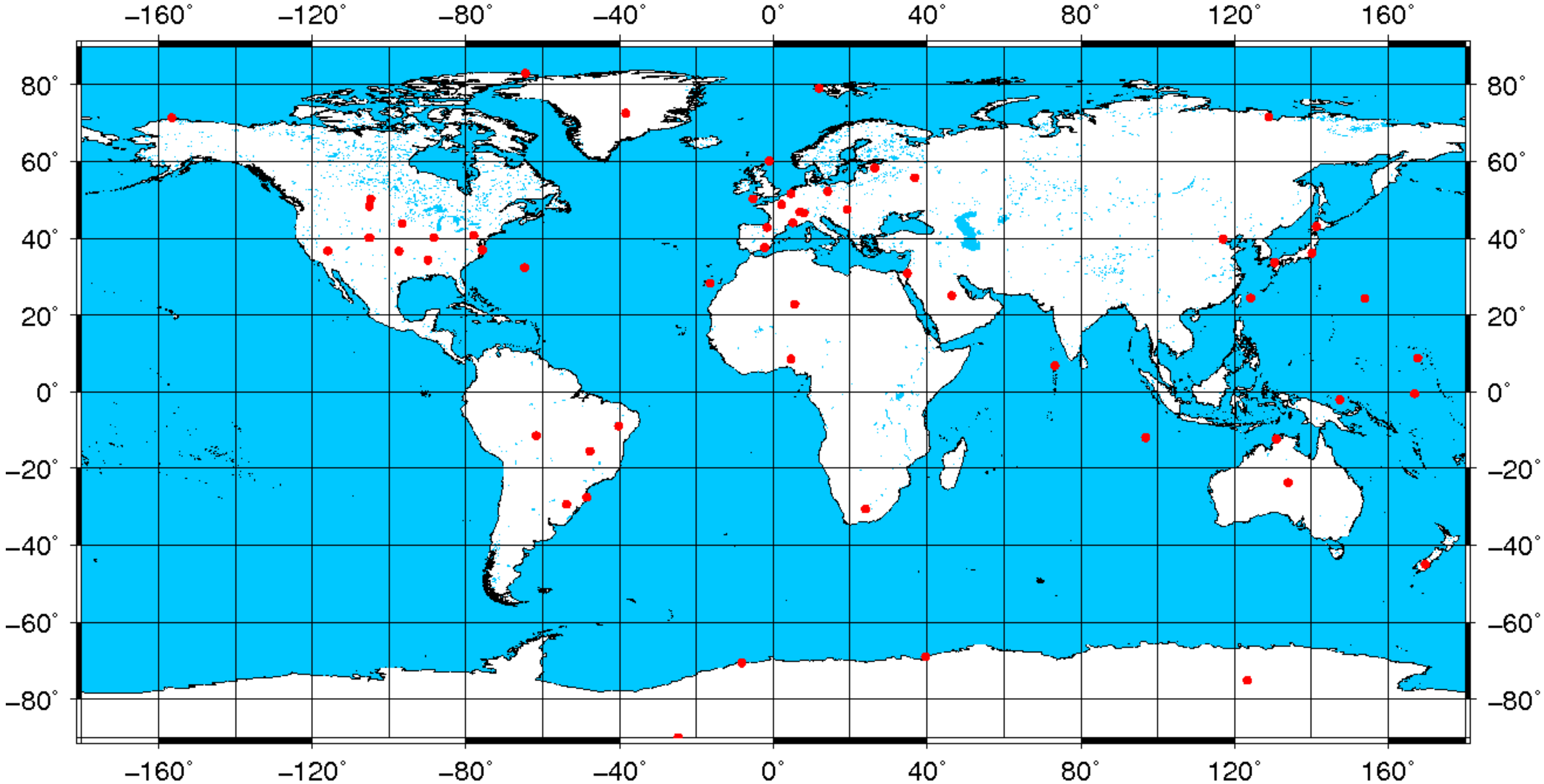
EUROPEAN UNION ENERGY INITIATIVE
for poverty eradication and sustainable development

JRC
EUROPEAN COMMISSION

Institute for Energy and Transport

Fondation 2iE

Running and planned BSRN stations, September 2011



Alfred-Wegener-Institut für Polar- und Meeresforschung in der Helmholtz Gemeinschaft

Solar radiation measurement databases (2)

- World Radiation Data Center
  - Large number of ground stations
  - Normally only GHI available
  - Some stations with decadal time series
  - Quality less certain than BSRN
- European Solar Radiation Atlas
  - Large number of stations ,coverage limited to Europe
  - Data somewhat old, 1981-1990
  - Used for first version of PVGIS (European database)

Ground station interpolation

- Interpolation allows you to estimate the solar radiation in areas lying between the ground station locations. A number of GIS systems can perform such an interpolation (kriging, interpolation by spline functions, etc.)
- Interpolation accuracy decreases with increasing distance between stations, stations must be representative of the climates in the area. Data must be homogeneous (same time period)
- Interpolation used for first European PVGIS version, largely using the open-source GRASS GIS

Satellite-based solar radiation estimates

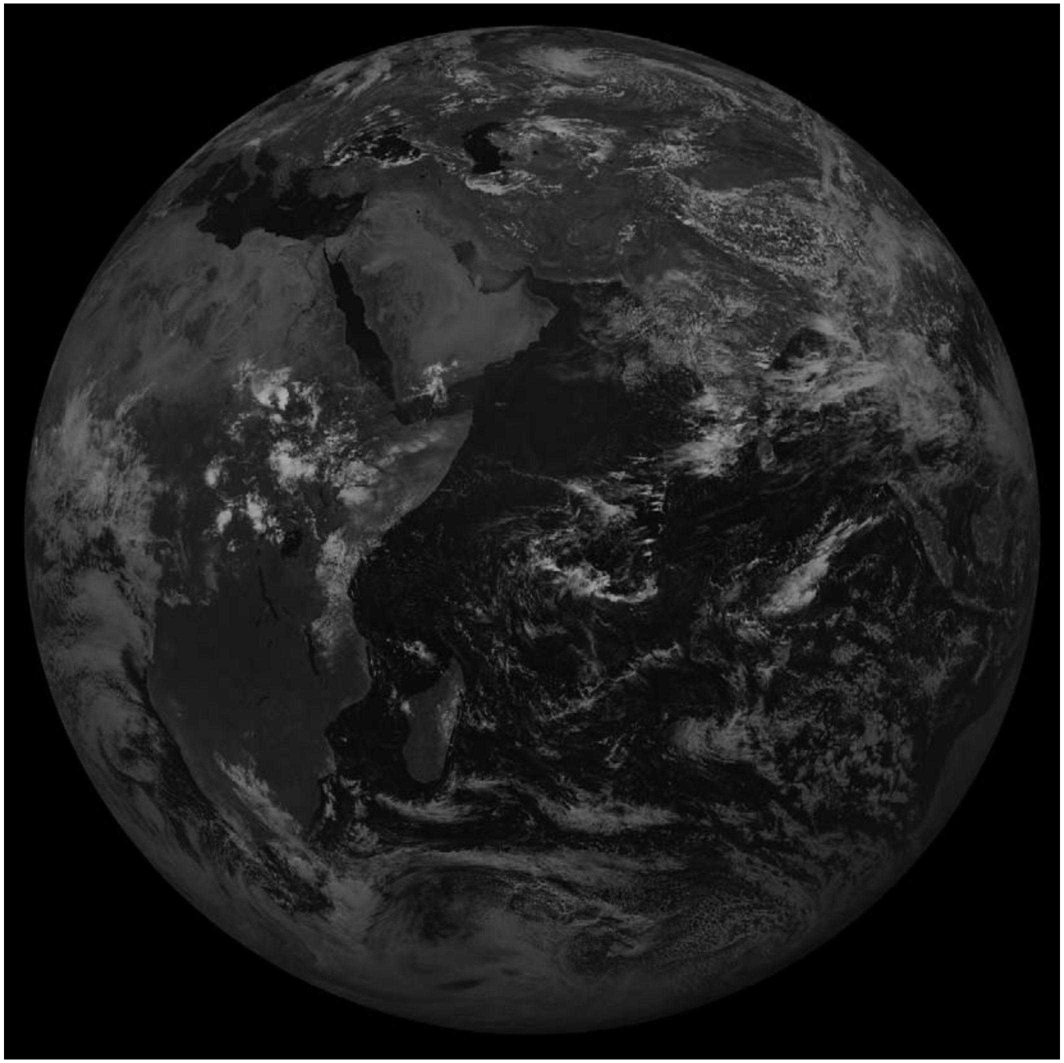
- Advantages:
  - Coverage of large areas with almost uniform resolution
  - Continuous data collection over many years
  - Raw data quality consistency
  - Few sources of data, often free for non-commercial use
- Disadvantages:
  - Not a direct measurement of ground-level radiation
  - Models needed for the calculation of solar radiation
  - Quality of model varies with location
  - Very large amounts of data (terabytes)

Ground stations or satellites?

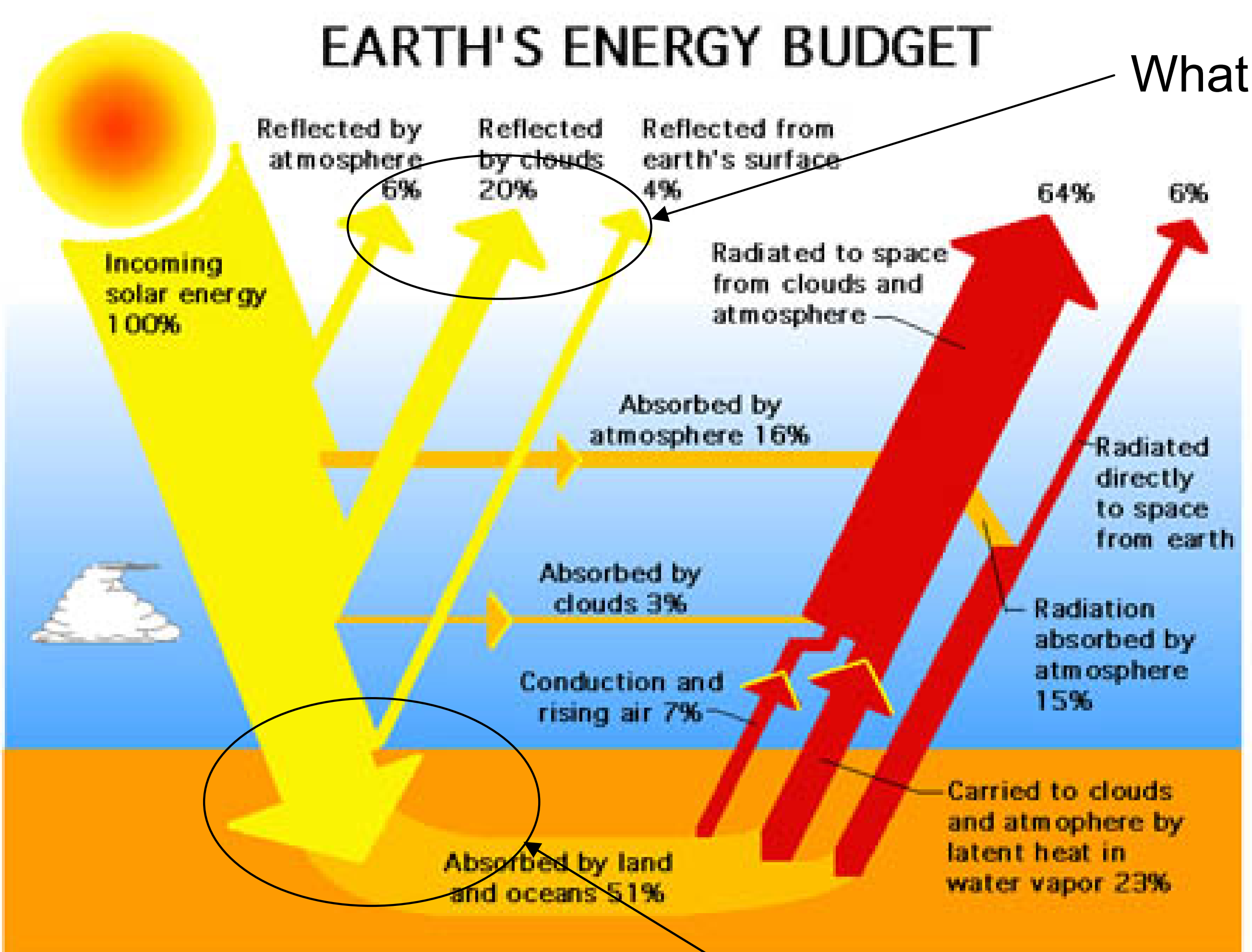
- At the site of the measurement, ground station data are superior to satellite estimates
- More than 30km from station, satellite methods are generally better than station data + interpolation
- Satellite data may have particular problems, for instance in the presence of snow
- Both methods have problems in very complex terrain such as mountains
- Measurements can validate satellite data

Types of satellite data

- Geostationary satellites
  - High time resolution 15-30 minutes
  - Reasonable spatial resolution (few km)
  - Quality of solar radiation estimate varies, lower at the edge of the images
- Polar-orbiting satellites
  - Low time resolution (1-2 images per day)
  - Higher spatial resolution (1km or less)
  - Global coverage
  - Modelling less advanced, still more uncertain



Meteo image example (Meteosat East)



What the satellite sees

What we're trying to calculate

Overview of models used in CMSAF

- The raw data are taken from two different classes of satellites, Meteosat First Generation (MFG) and Meteosat Second Generation (MSG). These have different instruments measuring different types of radiation, so different algorithms must be used for the solar radiation estimates.

Clear-sky radiation calculation

- First step is a calculation of the radiation without the influence of clouds. This gives the *clear-sky* irradiance
- Calculation based on radiative transfer calculations. Very accurate but very time-consuming.
- Requires knowledge of time-varying components of the atmosphere, such as water vapour, aerosols and ozone.
- MAGIC algorithm used for both MFG and MSG (Müller et al., 2009)

Calculation of the effects of clouds (MFG)

- MFG: Heliosat method to estimate the effects of clouds using the actual albedo of a pixel in the image, relative to the “reference albedo” for the given pixel. Reference albedo is assumed to correspond to near-clear-sky conditions. Information from visible channel of MFG instruments

Calculation of the effects of clouds (MSG)

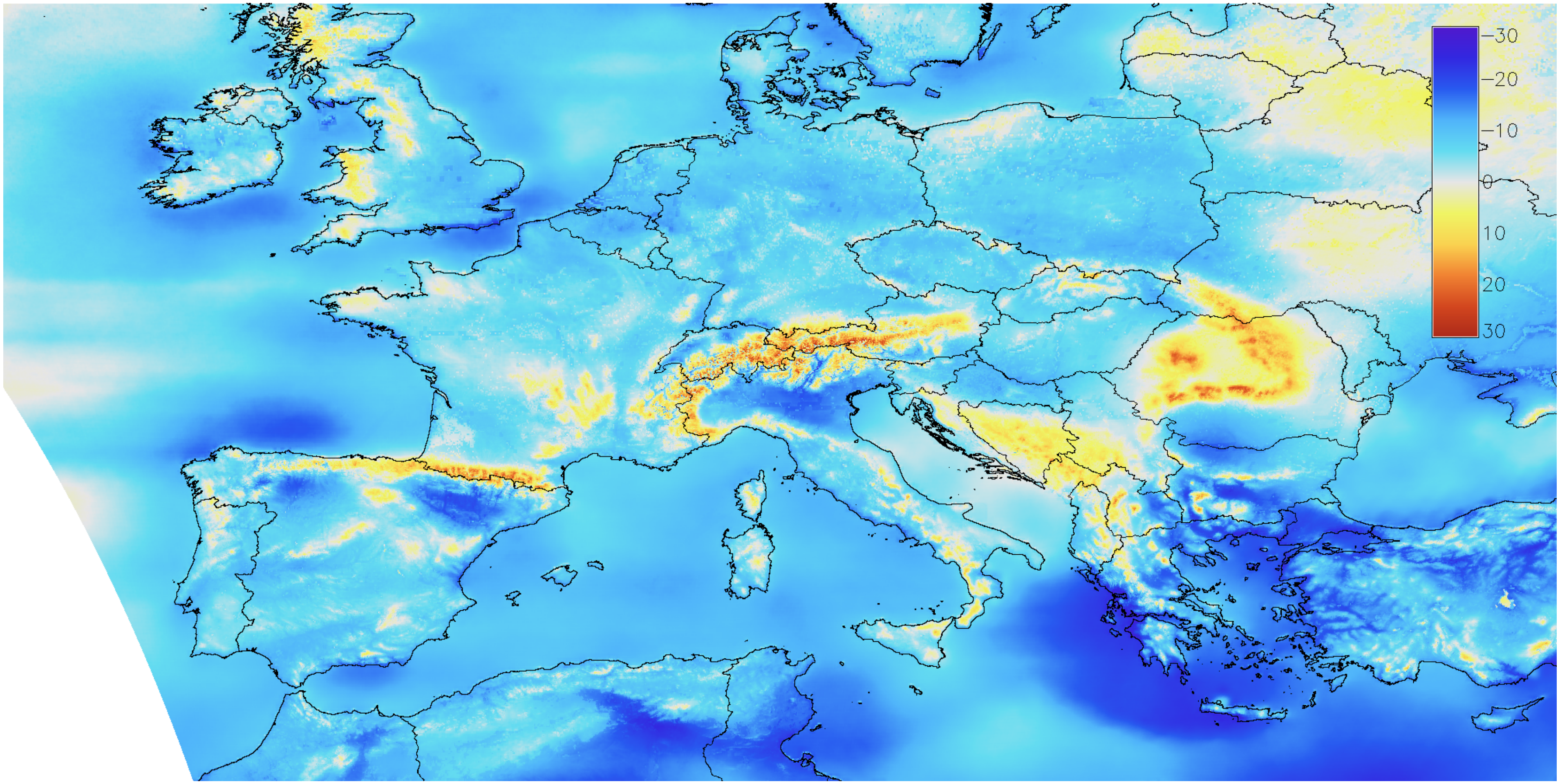
- Use of several instruments on board MSG, such as the Global Earth Radiation Budget (GERB).
- Radiative transfer calculations for improved accuracy.
- Better detection of clouds.
- More accurate treatment of irradiance on very bright ground (deserts).

Validation against ground station measurements

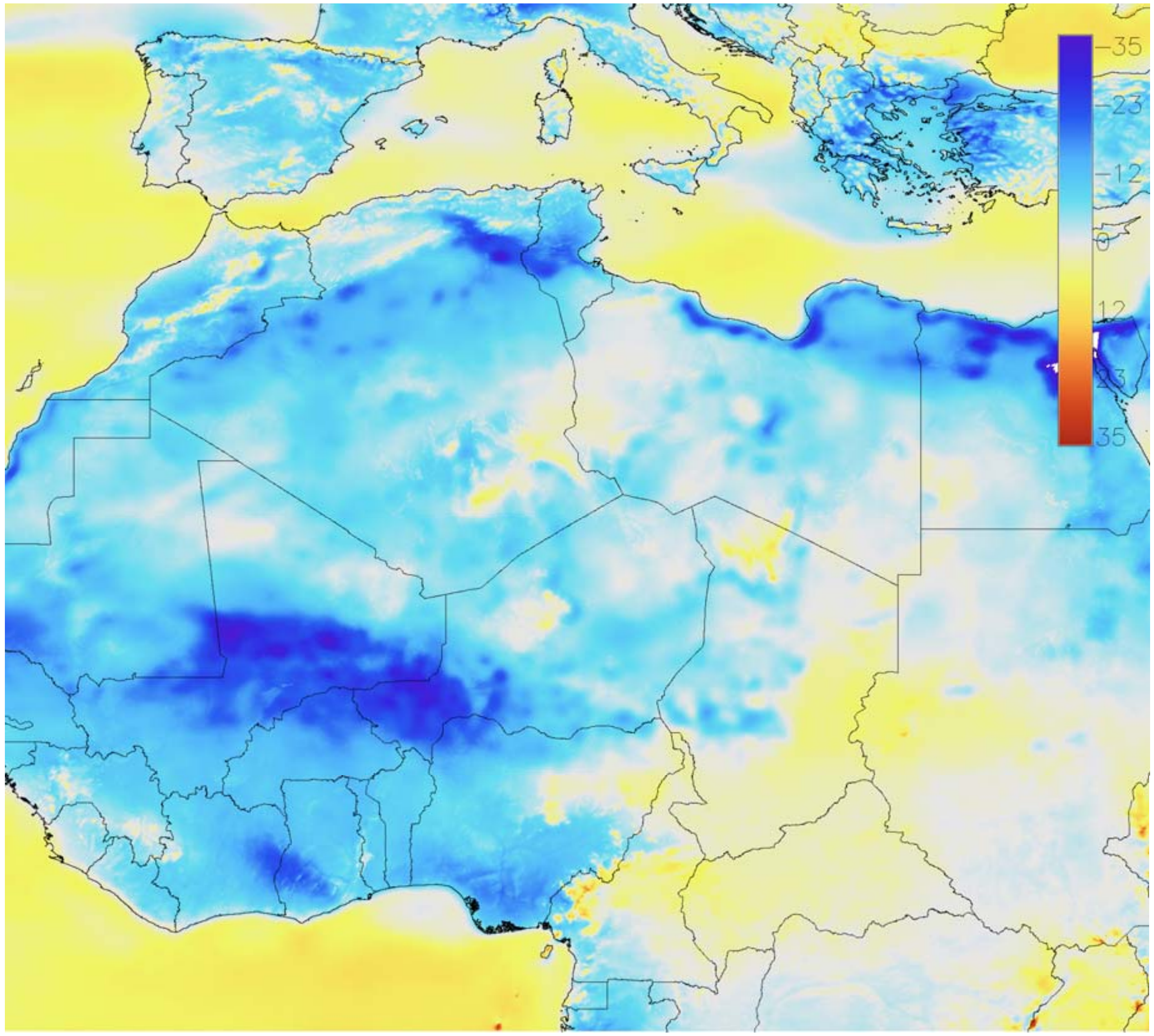
- Full station list in the lecture notes
- MSG results (global horizontal irradiation) have almost no overall bias, MFG shows positive bias of ~2%.
- Standard deviation of individual station bias values give values of 5.3% for MSG and 5.5% for MFG (European stations). The combined value is 4.9%. Excluding high mountains, the value is ~3.8%.
- These uncertainties are larger than that of most other effects influencing PV performance.

PVGIS solar radiation databases

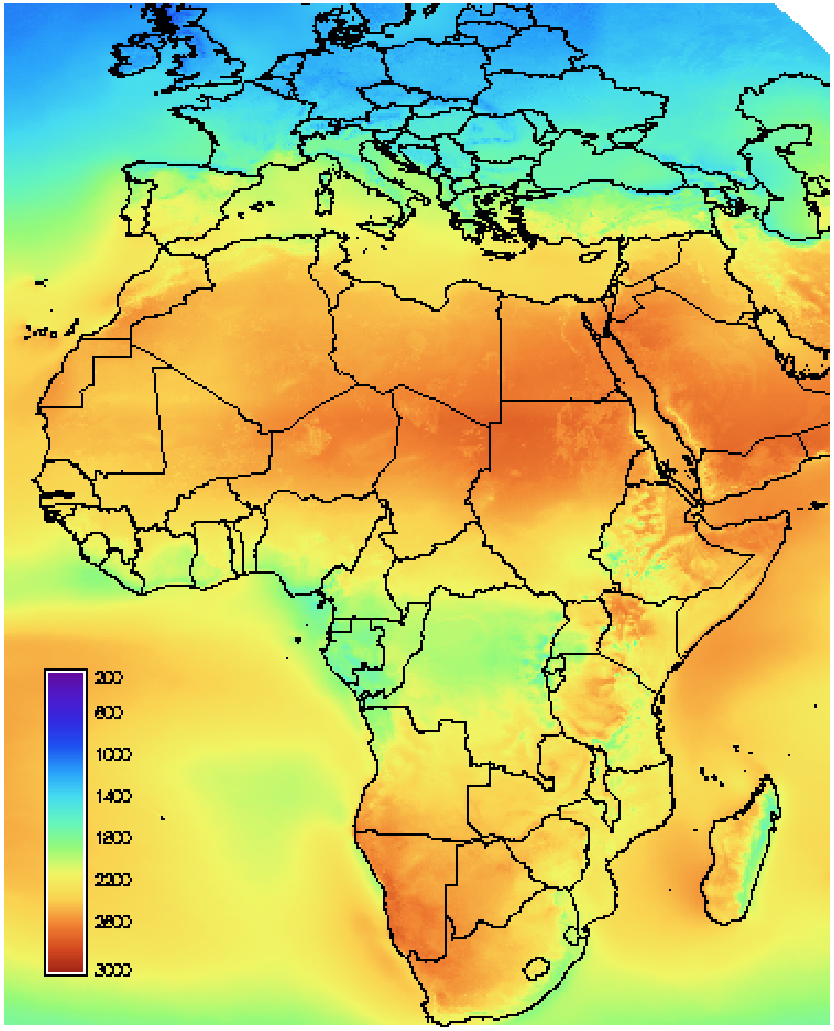
- Europe: “Classic” database from ESRA ground station data and interpolation, 1km resolution over Europe to the Urals.
- Africa: “Helioclim” database,based on MFG satellite data 1985-2004, original resolution 15’≈30km, downscaled to 2km
- Most of Europe and Northern Africa: new CM-SAF database from CM-SAF –based calculations of solar radiation from MFG and MSG. Spatial resolution of 1’30’’ ≈2.5km



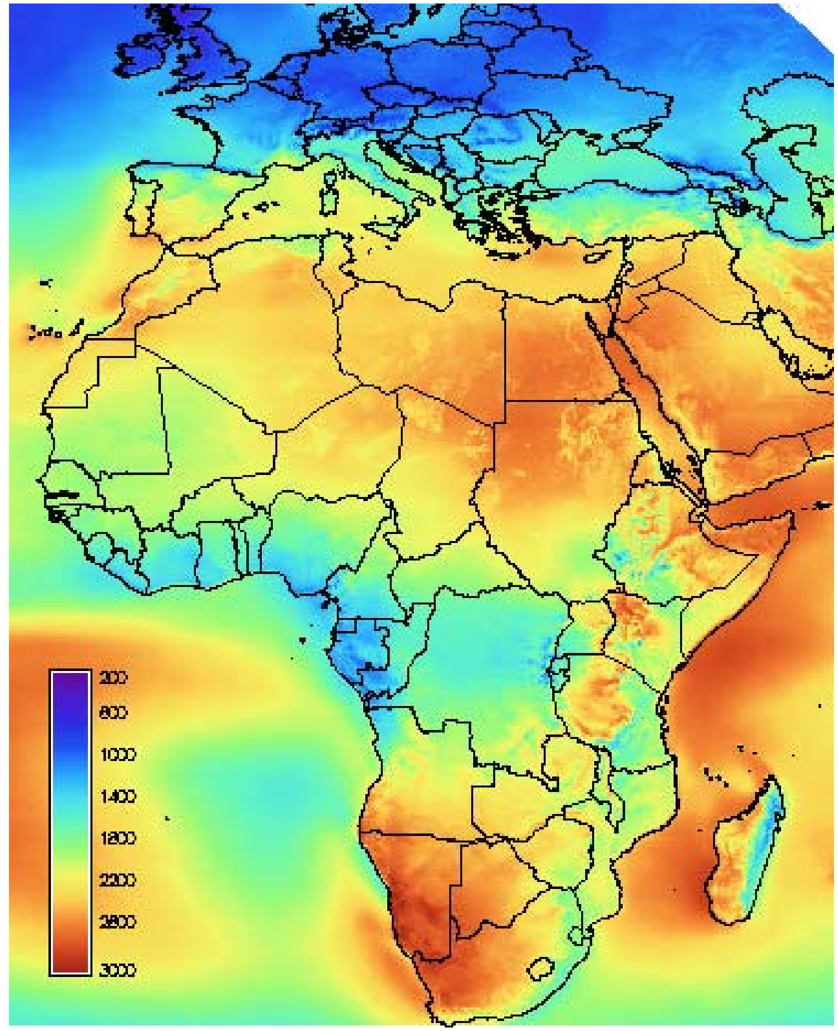
Relative difference (%), PVGIS-classic – PVGIS-CMSAF



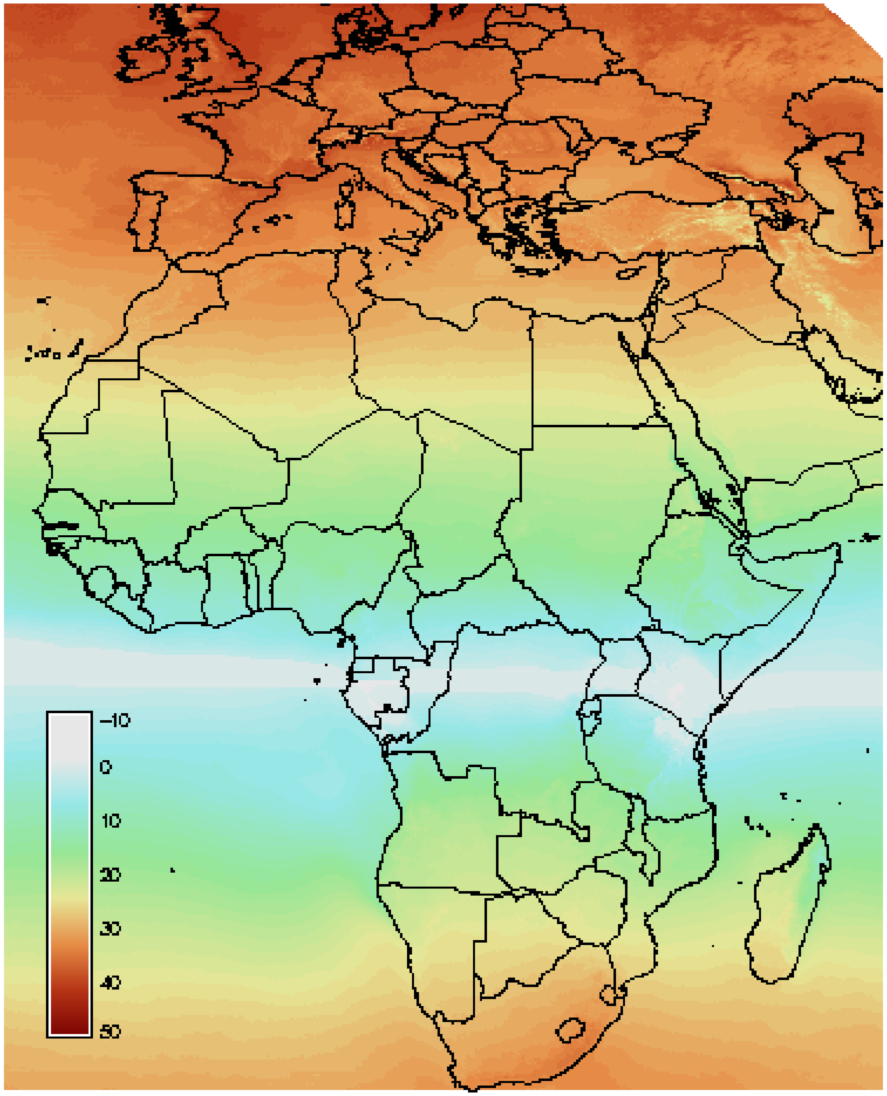
Relative difference (%), PVGIS-classic – PVGIS-CMSAF



Global optimum angle irradiation



Direct normal irradiation

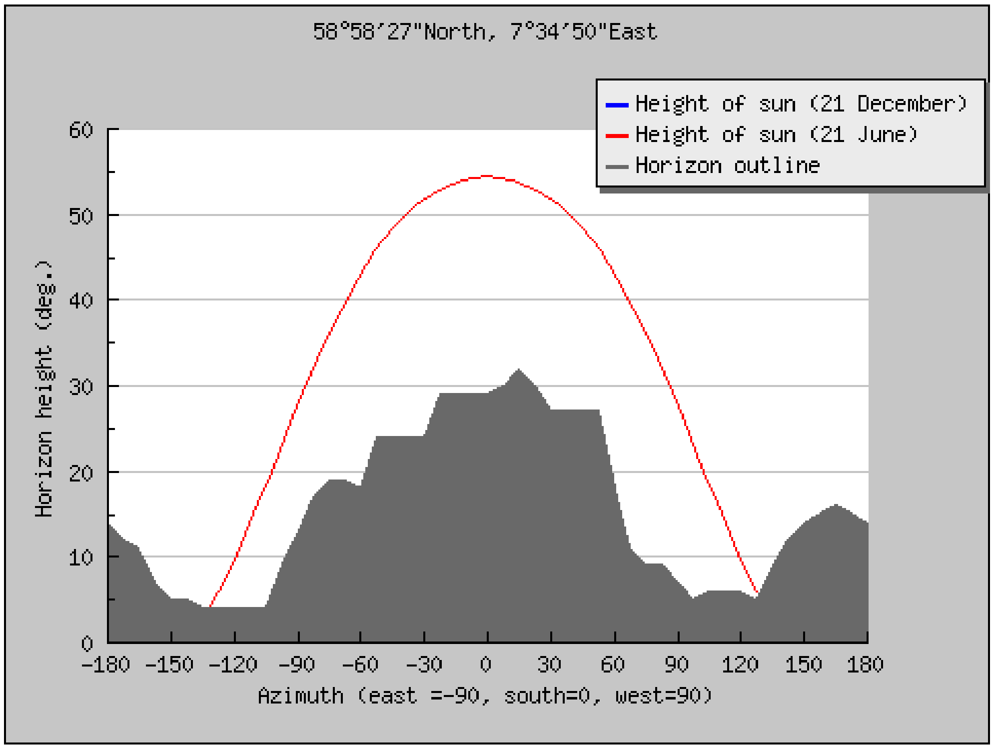


Optimum angle for solar irradiation

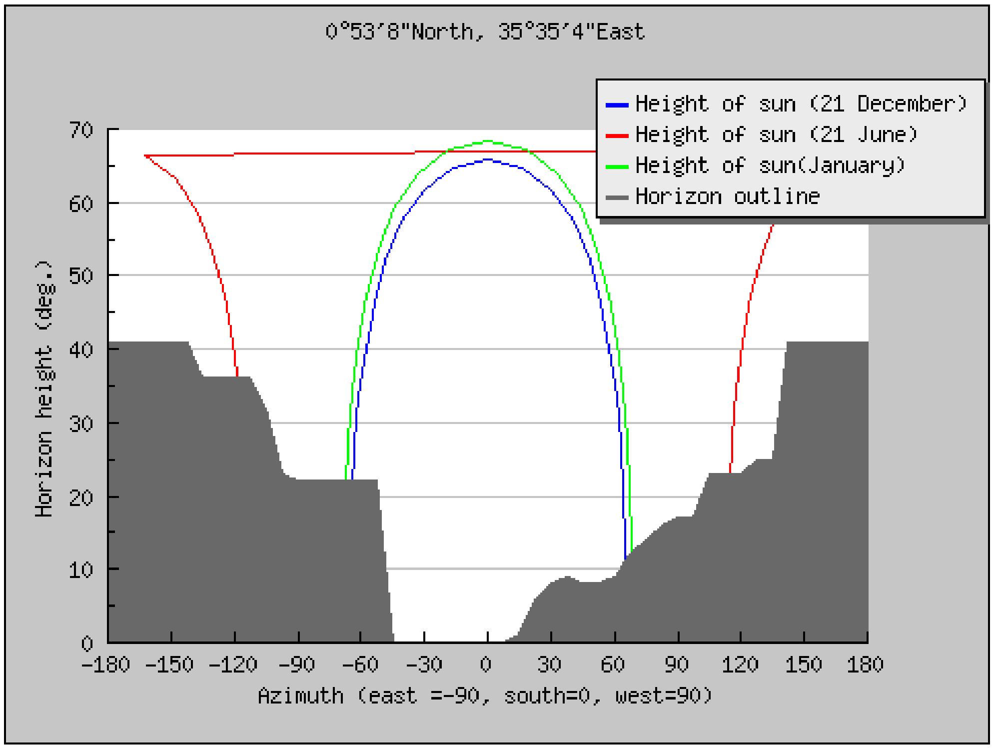
Note: optimum angle for solar radiation and grid-connected PV, not for off-grid applications

Effects of shadows from terrain

- By calculating the height of the horizon around your location it is possible to estimate the effect this has on the total solar irradiation (and hence PV output)
- PVGIS uses the SRTM-3 digital elevation model, with 3 arc-second (~90m) resolution between 60°S and 60°N.
- Importance of shadows depends also on the latitude, generally less important near equator



Example from Norway (59°N)



Example from Kenya (1°N)

Other solar radiation databases

The free

- **NASA-SSE**, global coverage, long-term averages of global horizontal irradiation, low resolution (1° lat/lon)
- **ECMWF**, global coverage, weather model reanalysis, 3-hourly values of global horizontal irradiance, freely available version has low resolution (1.5 ° lat/lon)
- **SWERA**, coverage for selected regions and countries, generally long-term average values, varying spatial resolution.
- **CMSAF**: daily or hourly irradiance maps free for download, at least for non-commercial use. Full Meteosat resolution (~3km)

Other solar radiation databases

Selected commercial products

- **Meteonorm**, global coverage, generally long-term averages, runs as a PC software
- **SOLEMI**, data available from Meteosat satellites (Europe and Africa), maps and time series available, global and direct irradiance
- **SolarGIS**, data from Meteosat satellites (Europe, Africa and India), maps and time series, global and direct irradiance, downscaling to very high spatial resolution.

Summary of this presentation

- Solar radiation is (by far) the most important factor in estimating the performance of solar energy systems
- Maps of solar radiation may be made using ground station data or with satellite data. Generally, for large geographical areas, the satellite data are better
- PVGIS offers a free database of solar radiation data for Europe and Africa, based on satellite data.
- Uncertainty in solar radiation estimates is probably the largest source of uncertainty in solar energy.

PV systems and their performance

- Types of PV systems
  - Grid-connected PV systems
  - Off-grid PV systems
- Models for performance of grid-connected PV systems
- Models for performance of off-grid systems

PV systems come in different sizes

Large

Medium

Small

11 orders of magnitude range in power

Grid-connected PV systems

- PV systems with inverters that convert DC current from the PV modules into AC current for the grid
- Inverter optimizes the power output of the PV modules
- Dependent on the presence of the grid current (usually)
- Power that is not used locally is sent to the grid
- Normally no local electrical energy storage
- Fixed mounting or tracking systems
- Could also use concentrating PV

Off-grid PV systems

- Independent of the electricity grid
- Mostly small installations (<1kWp)
- Often has local battery storage
- May have an inverter but could also have just a simple charge controller, output normally DC
- Used for telecommunications, street lighting, power for single households or buildings, water pumping, etc.

A half-way house: minigrids

- Independent of the general electricity grid but serves a small local grid
- Size from a few kWp to a few tens of kWp
- Normally has an inverter, nearly always has battery storage, output normally AC
- May be made in combination with diesel generators or other renewable energy sources (wind, small hydro)

PV system performance

The output of a PV system is of course mainly influenced by the amount of solar radiation that arrives at the surface of the PV modules of the system. But there are a number of other effects that can be important.

The amount of solar radiation itself depends on the way the system is made.

For fixed PV systems the incident solar radiation depends on inclination and orientation

PV systems can also be mounted on a tracking system. The incident solar radiation depends on type of tracker

Concentrating PV systems make use only of the direct normal irradiation

PV power, a few definitions

The power of a PV module/array is given as the *nominal* or *peak* power, defined as the maximum output power under the following conditions:

- In-plane irradiance of $1000 W/m^2$
- Module temperature T=25°C

Peak power is measured in W_p (watt-peak), kWp or MWp for larger systems

The theoretical power is then:

$$P = P_{nom} G / 1000$$

where G is the received solar irradiance (W/m^2) and P_{nom} is the peak power, in kW$_p$.

The ratio between actual power and the theoretical power is called *Performance Ratio* (PR). We can talk of module PR (PR_m) or system PR (PR_s).

Effects that influence PV performance (1)

- Shadows, also partial, reduce the PV performance(*)
- Dust, dirt, frost and snow on modules. Depends on location and also on rainfall and module inclination
- Reflectance of module surface. Depends on module type and inclination (and geographical location) (*)
- PV conversion efficiency depends on temperature and irradiance (more about this later) (*)
- For some PV technologies, efficiency depends on the sunlight spectrum

Effects that influence PV performance (2)

Grid-connected systems

- Losses in the DC/AC conversion by the inverter (may depend on the power level)
- Losses in cables, connecters etc.
- Grid outage, causing the PV system to shut off

Effects that influence PV performance (3)

Off-grid systems

- Mismatch between PV module and battery voltages, or
- Mismatch between PV module and load voltages
- Losses in charging and discharging battery
- Losses in cables, connectors etc.
- Losses when battery is full and not all power can be used (*)

Effects that influence PV performance (4)

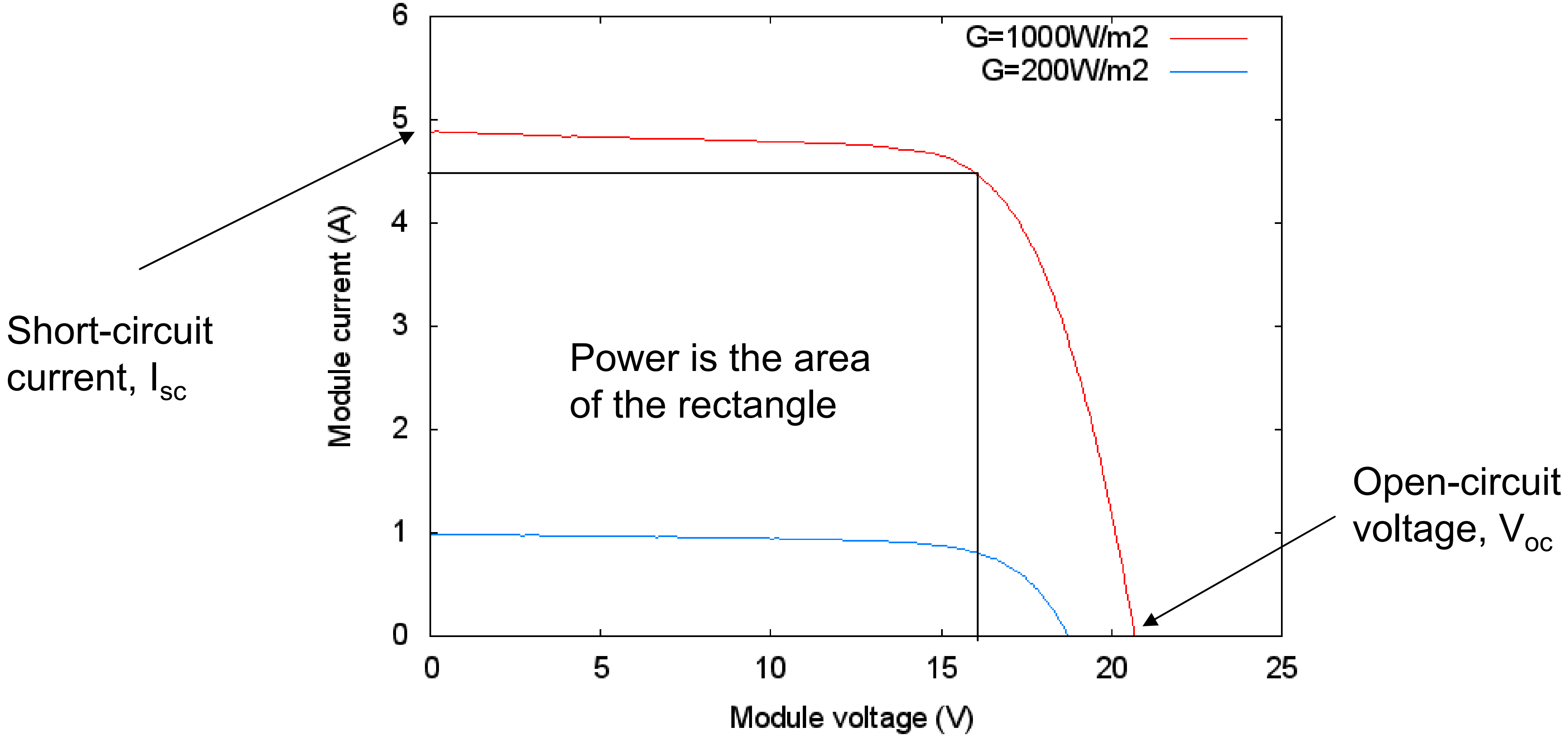
Minigrid systems

- Losses in the DC/AC conversion by the inverter (may depend on the power level)
- Losses in cables, connecters etc.
- Losses in charging and discharging battery
- Losses when battery is full and not all power can be used (*)

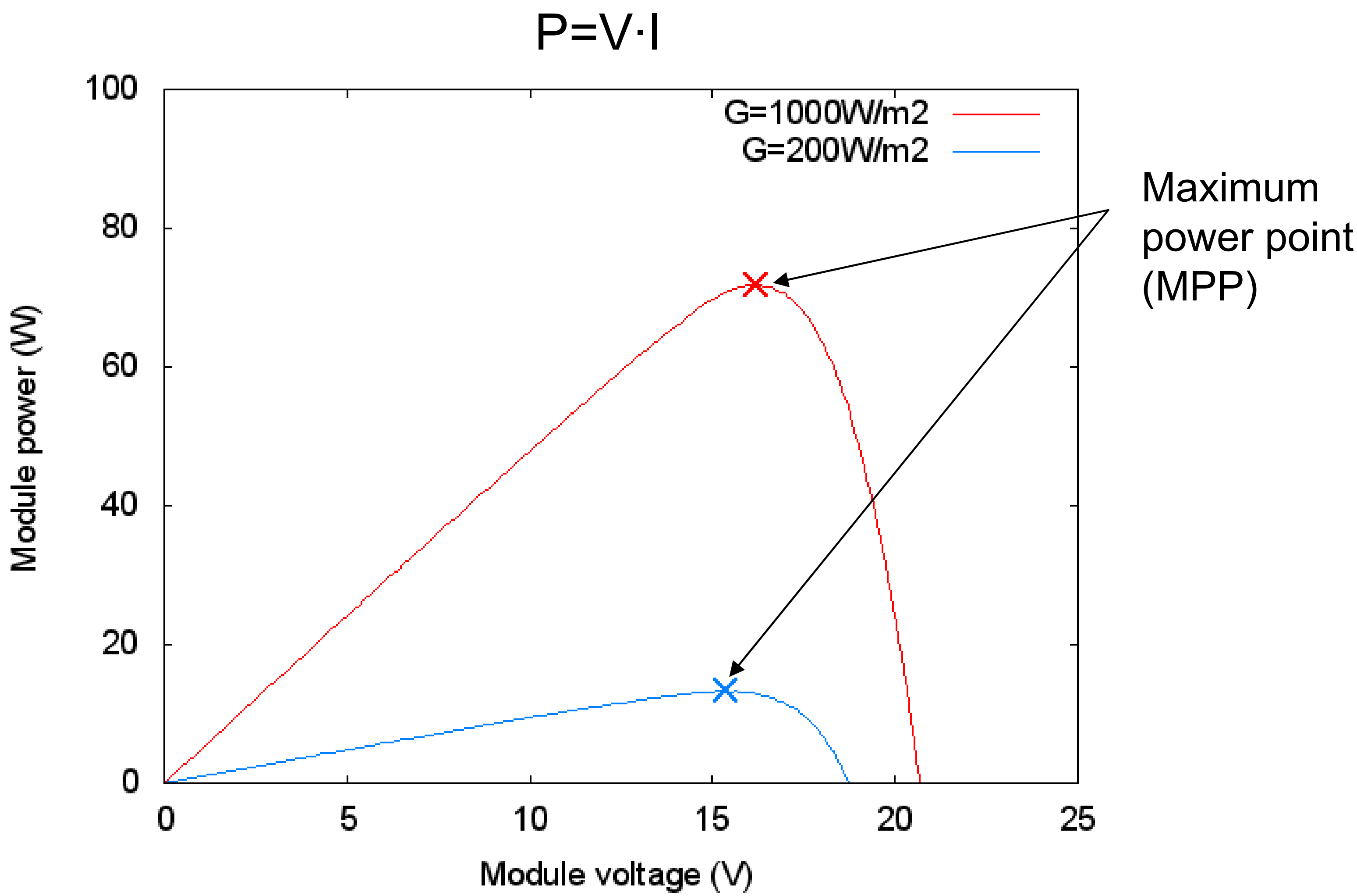
A bit of PV cell theory

(not too much, promise!)

Electrical characteristics of a PV module

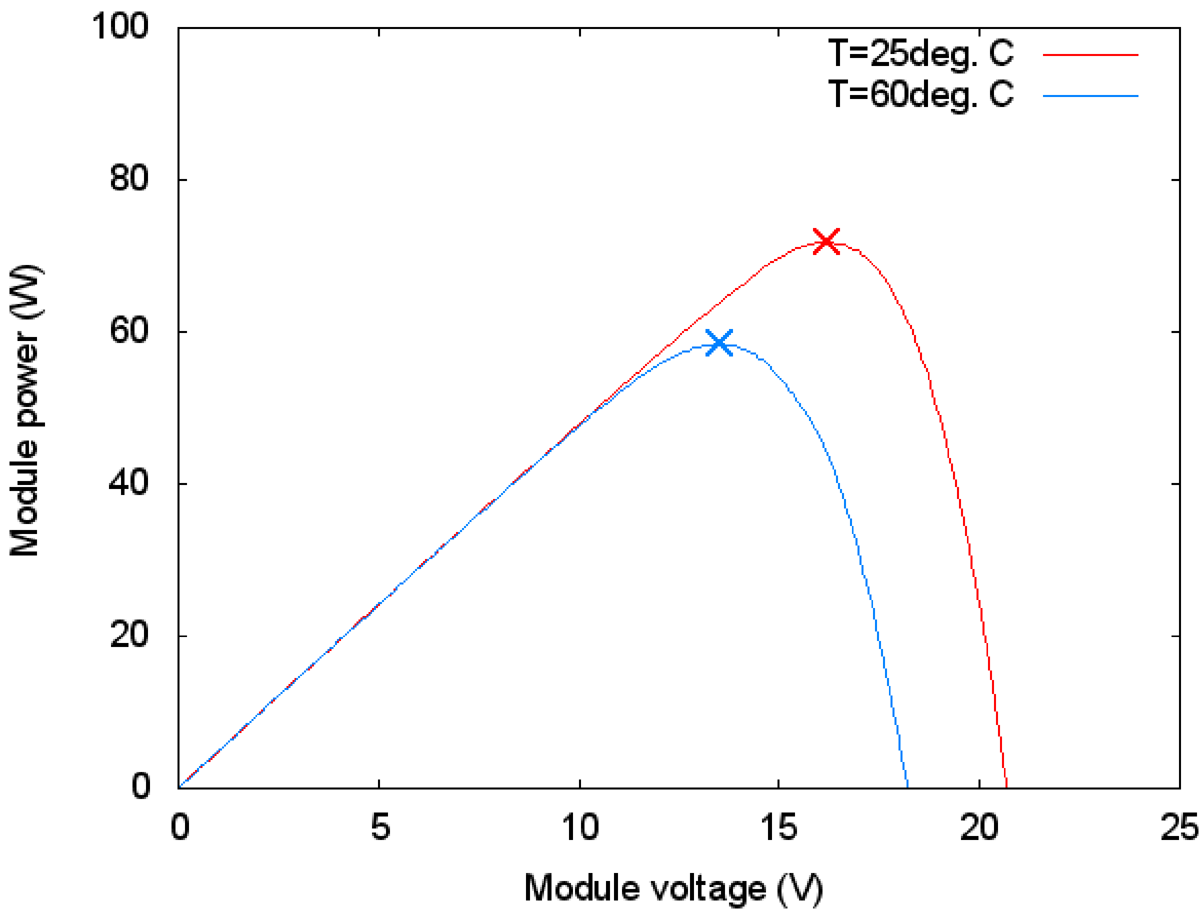


Electrical characteristics, contd.



PV power depends on module temperature

Temperature coefficient is normally negative



Model for PV performance at MPP

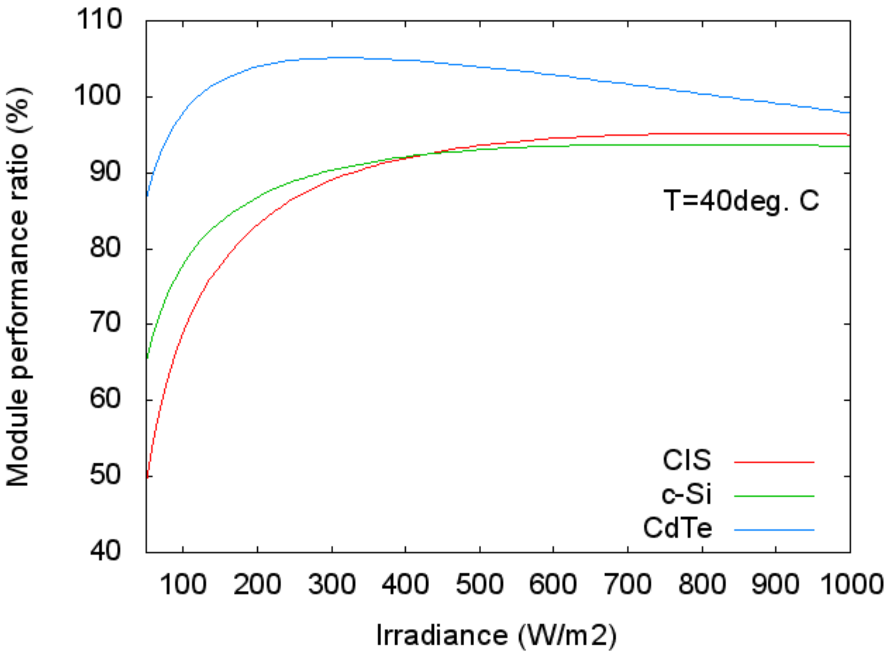
Instantaneous PV power is described as

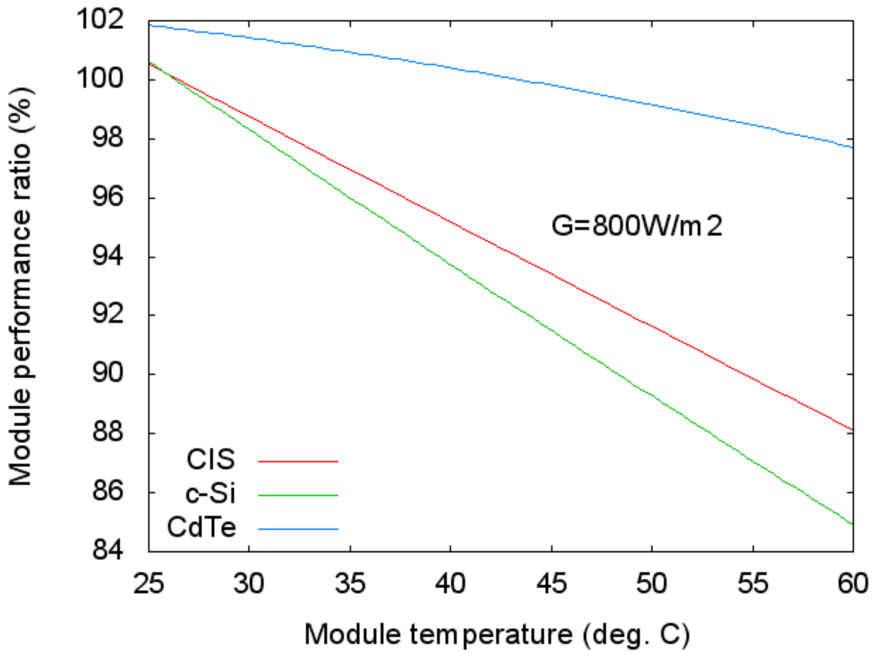
$$P = P(G, T_{\mathrm{mod}})$$

where *G* is the received irradiance and T_{mod} is the module temperature:

$$T_{\mathrm{mod}} = T_{air} + k_T G$$

Module performance for different PV types





Models included in PVGIS

PVGIS calculations of grid-connected PV

- Shadows from hills and mountains
- Model for shallow-angle reflectivity at module surface
- Model for PV power as function of irradiance and temperature (as just described)
- All other losses are lumped in a single user-defined “system loss”.

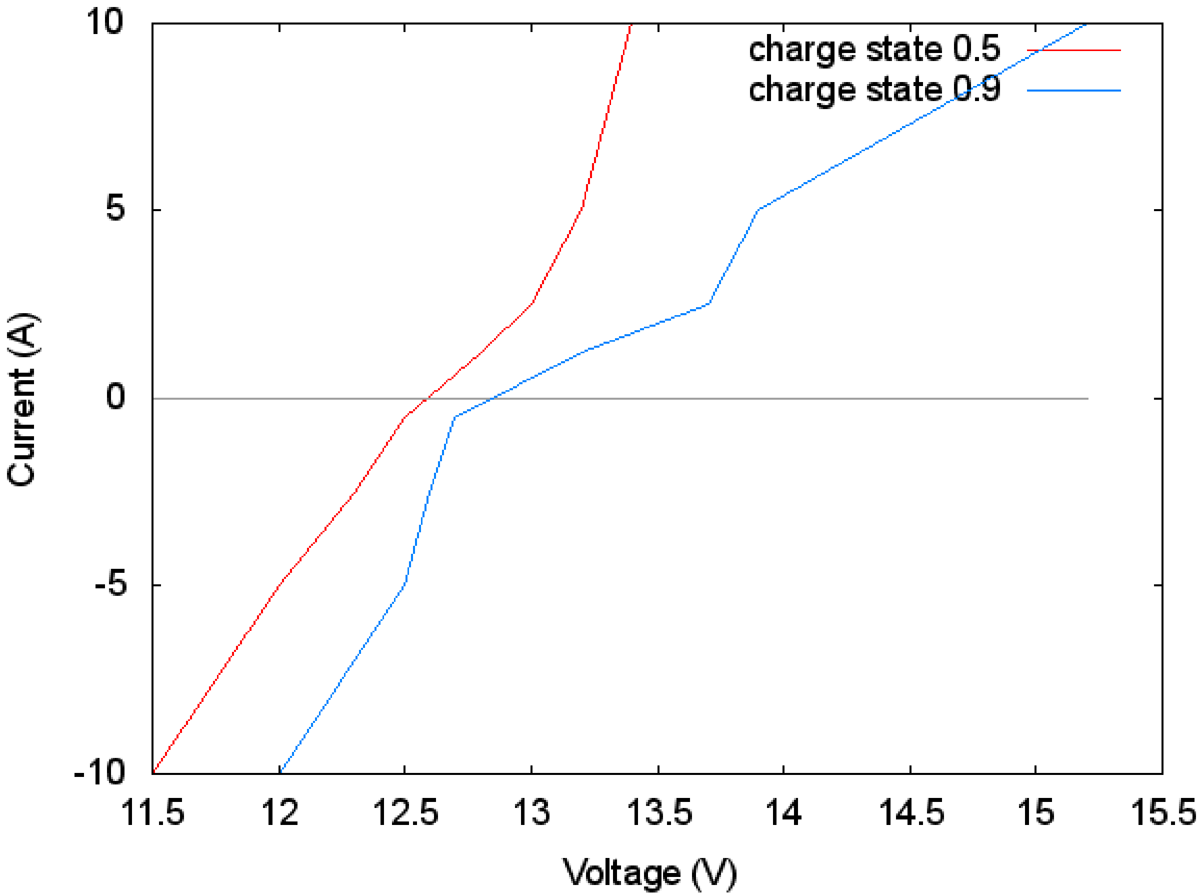
Performance of off-grid PV systems

For small PV systems that are connected directly to a battery with a simple charge controller but no inverter, the interaction between the module and the battery becomes important. If there is a mismatch between the module voltage and the battery voltage, the system performance may suffer.

PV batteries in a nutshell

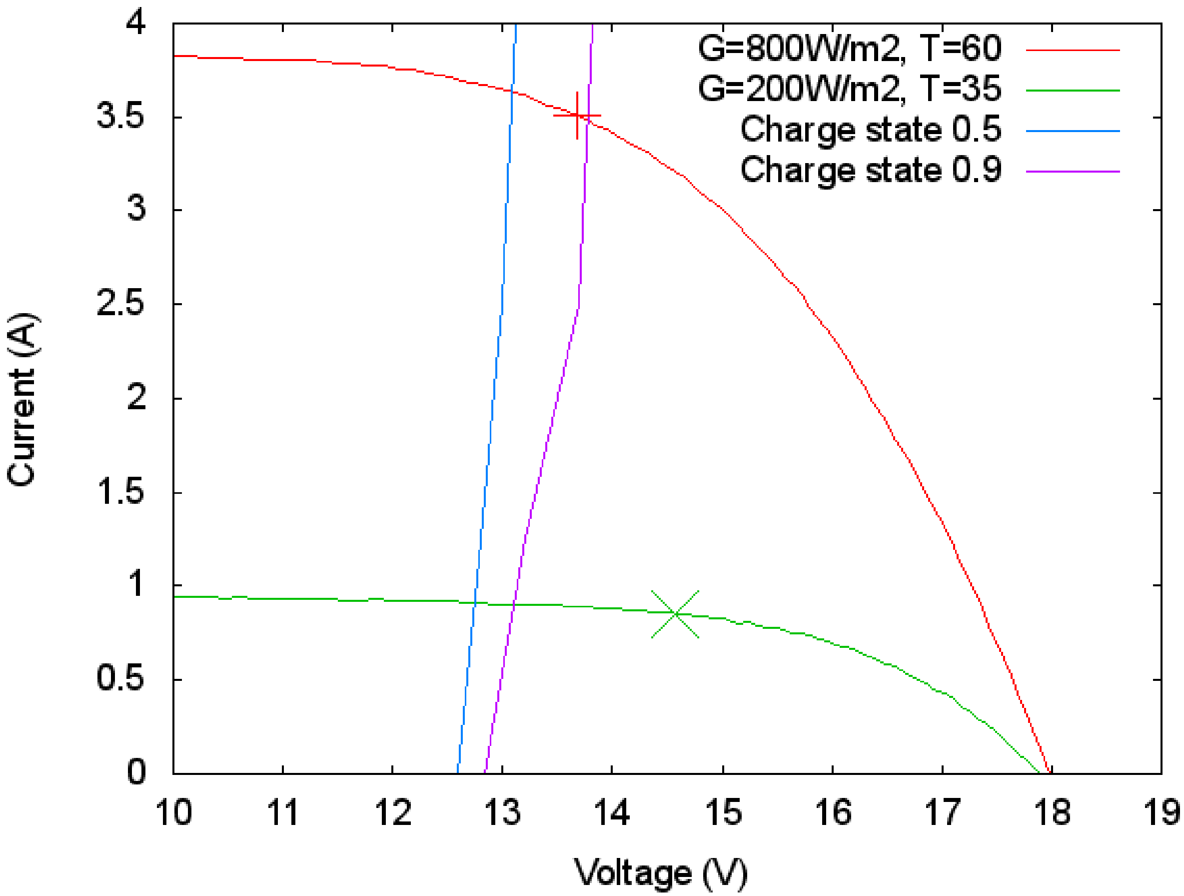
- Batteries for PV systems are normally lead-acid batteries like car batteries
- Special construction for improved deep discharging
- Full discharge damages the battery, good solar batteries can be ~70% discharged
- Typical battery voltage 12V or multiples (24, 48…)
- Size normally measured in Ampere-hours (Ah) for a given voltage

Battery electrical characteristics



12V battery
Capacity 50Ah

Electrical characteristics of PV-battery systems



Module: c-Si 36 cells

P_{nom}=72W

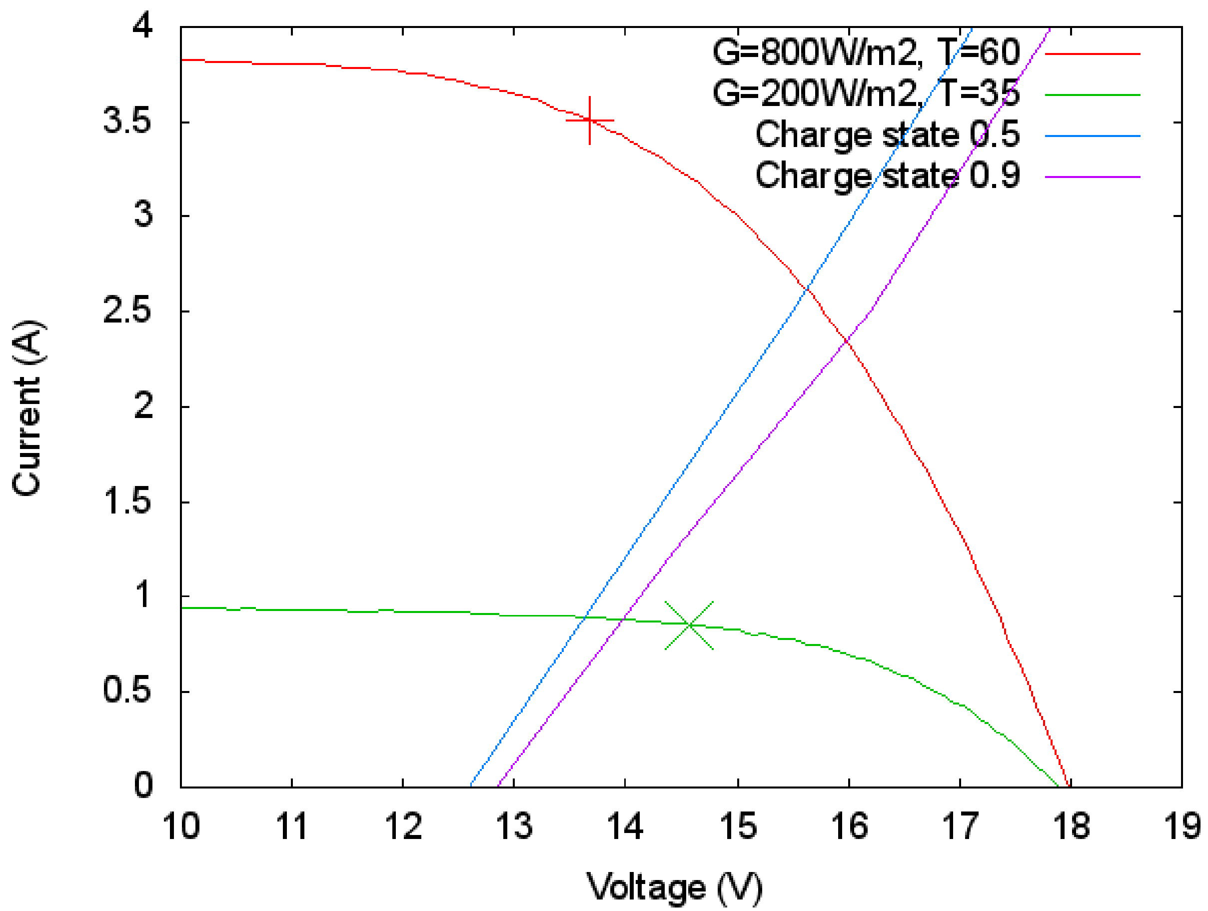
Battery: 12V 50Ah

Effect of cable resistance

If there is a non-zero resistance between the module and battery, the relation between module and battery voltage is:

$$V_{\mathrm{mod}} = V_{bat} + RI$$

This can seriously affect the performance of the system.



Effect of a 1Ohm resistance

Models for off-grid PV system performance

To estimate the actual performance of an off-grid PV system, real time series of solar radiation and power consumption values should be used. The actual simulation of the system state can be done with varying level of complexity.

General model outline

- For each time interval (hour or day):
  - Add energy produced by PV module
  - Subtract energy consumed
  - If battery becomes full, cut off PV power production
  - If battery becomes empty (lower charge state limit), cut off consumption

Different model features

1. Hourly data for production and consumption. Detailed model for PV-battery interaction.

2. Hourly data for production and consumption. Simple model for PV-battery interaction.

3. Daily data for production. Consumption divided into day and night. Simple model for PV-battery interaction. This is the model used in PVGIS.

Model comparison

Model output results given in the lecture notes

Conclusion: daily model gives reasonable results with an overall performance ratio of ~65% considering other system losses (cable losses, dirt on modules, etc.)

This conclusion is for a well-designed system with a good good balance between PV module and battery, and not too high resistive losses.

Effect of resistive losses

- If there is a significant resistance between module and battery, there will be losses in the resistor (cable, connectors), but also a loss due to non-optimal performance of the module

- Example: Location in Algeria, 75W PV, 50Ah battery, 300Wh daily consumption, simulation with full model for 360 days. Total desired consumption: 108kWh

R (Ohm)	E (kWh)
0	116.0
0.5	107.5
1.0	99.5

- Apart from the resistive losses themselves, the total energy output decreases with increasing series resistance

Summary of this presentation

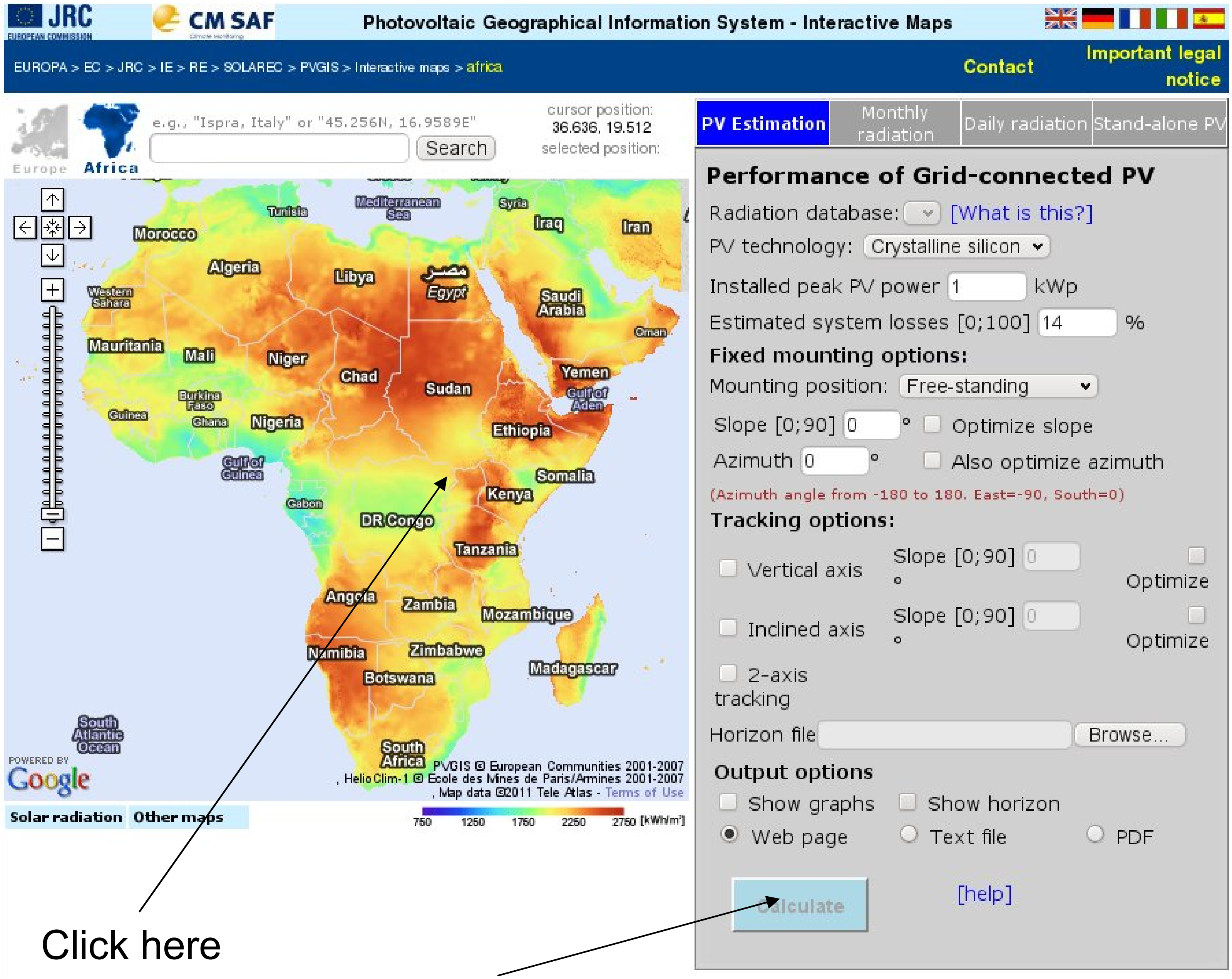
- PV energy output depends on a number of different factors.
- Methods for estimating PV output are different for grid-connected and off-grid systems
- PVGIS contains models for a number of different factors affecting grid-connected PV performance
- Simple off-grid model can be tuned for good performance by comparison with more detailed models (but experimental data would be nice)

The PVGIS web application

- What is it?
- What can it do (and not do)?
- How is it used?

The PVGIS web application (2)

PVGIS is a web application (runs in a web browser) which allows users to get information about solar radiation and PV system performance at any place in Europe and Africa



Click here

Then click here

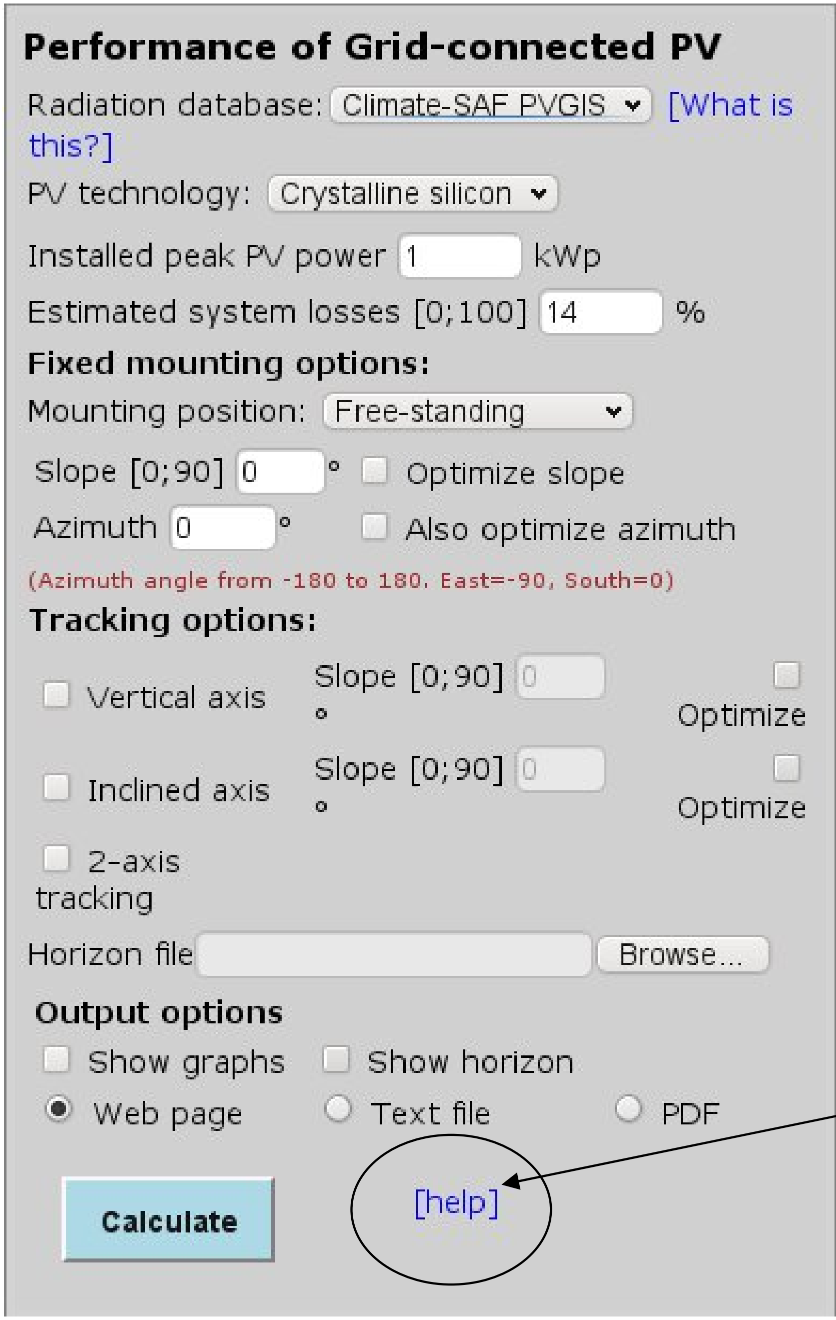
PVGIS features overview

- Calculation of grid-connected PV energy yield
- Monthly solar radiation and ancillary data values
- Average daily profile of solar radiation
- Calculation of off-grid PV system performance

- All solar radiation estimates (and solar radiation used for PV estimates) downscaled using horizon information with 30'' ≈90m resolution.

Grid-connected PV energy yield

- Calculation takes into account shadows from hills and mountains
- Calculation for arbitrary slope and orientation
- Finds optimum slope and orientation
- Calculation for fixed systems and various tracking options
- Models for effects of reflection, temperature and low irradiance, for a number of PV technologies
- Output as tables and graphs

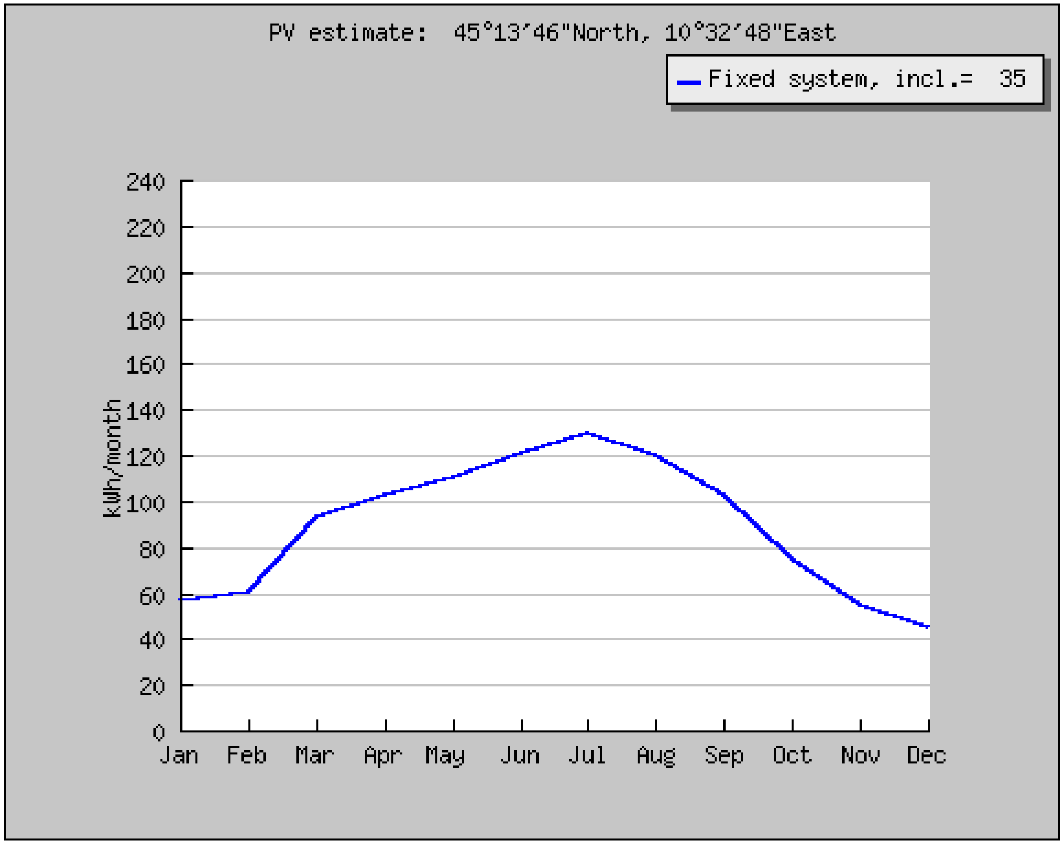


Interface for grid-connected PV energy yield estimation

Useful help link!

Grid-connected PV estimator, sample output

Fixed system: inclination=35°, orientation=0°				
Month	E_d	E_m	H_d	H_m
Jan	1.83	56.6	2.21	68.4
Feb	2.15	60.2	2.65	74.2
Mar	3.01	93.2	3.86	120
Apr	3.42	103	4.50	135
May	3.56	110	4.83	150
Jun	4.03	121	5.58	167
Jul	4.19	130	5.84	181
Aug	3.86	120	5.38	167
Sep	3.42	103	4.63	139
Oct	2.43	75.3	3.15	97.8
Nov	1.81	54.4	2.26	67.9
Dec	1.45	45.0	1.76	54.6
Yearly average	**2.93**	**89.2**	**3.89**	**118**
Total for year		**1070**		**1420**

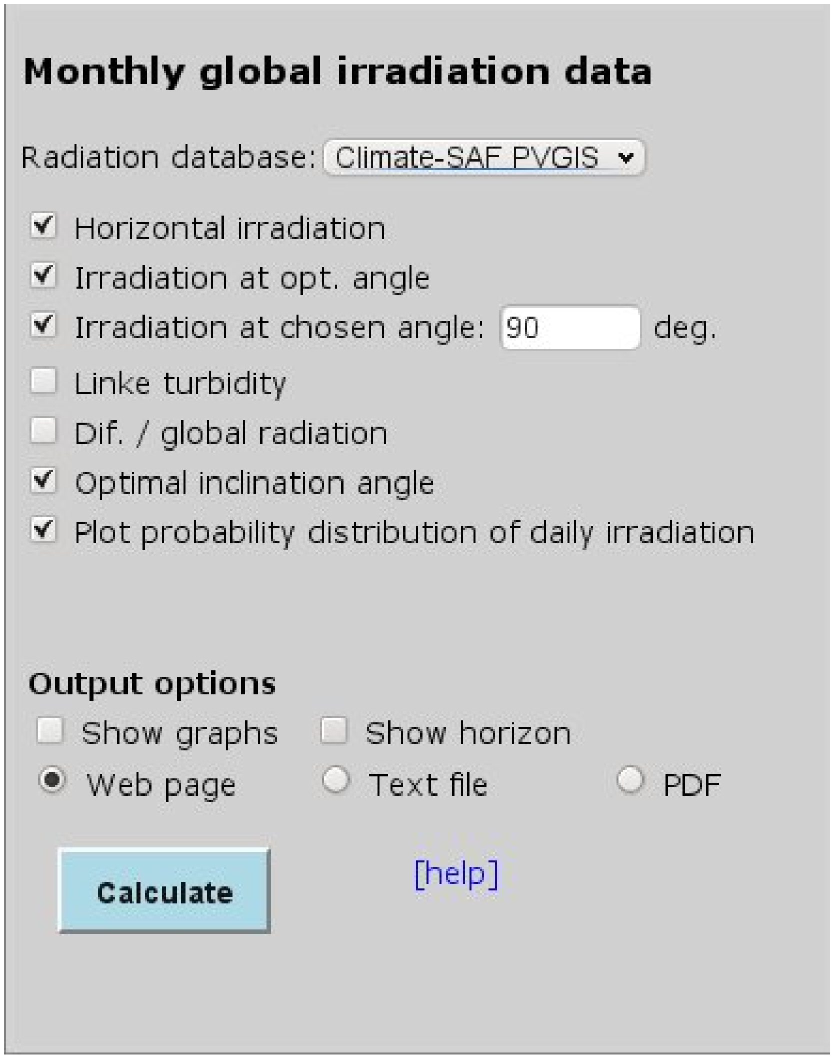


As table values

As a graph

Monthly average of solar radiation

- Values of radiation are long-term monthly averages, given in $Wh/m^2/day$
- Other values of interest can be chosen as well:
  - Diffuse to global ratio, showing the importance of the diffuse light at the chosen location
  - Linke turbidity, an indication of the clearness of the atmosphere
  - Monthly optimum angle
  - (Europe only so far): monthly averages of temperature



Interface for monthly radiation estimates (Africa). Temperatures are not available here.

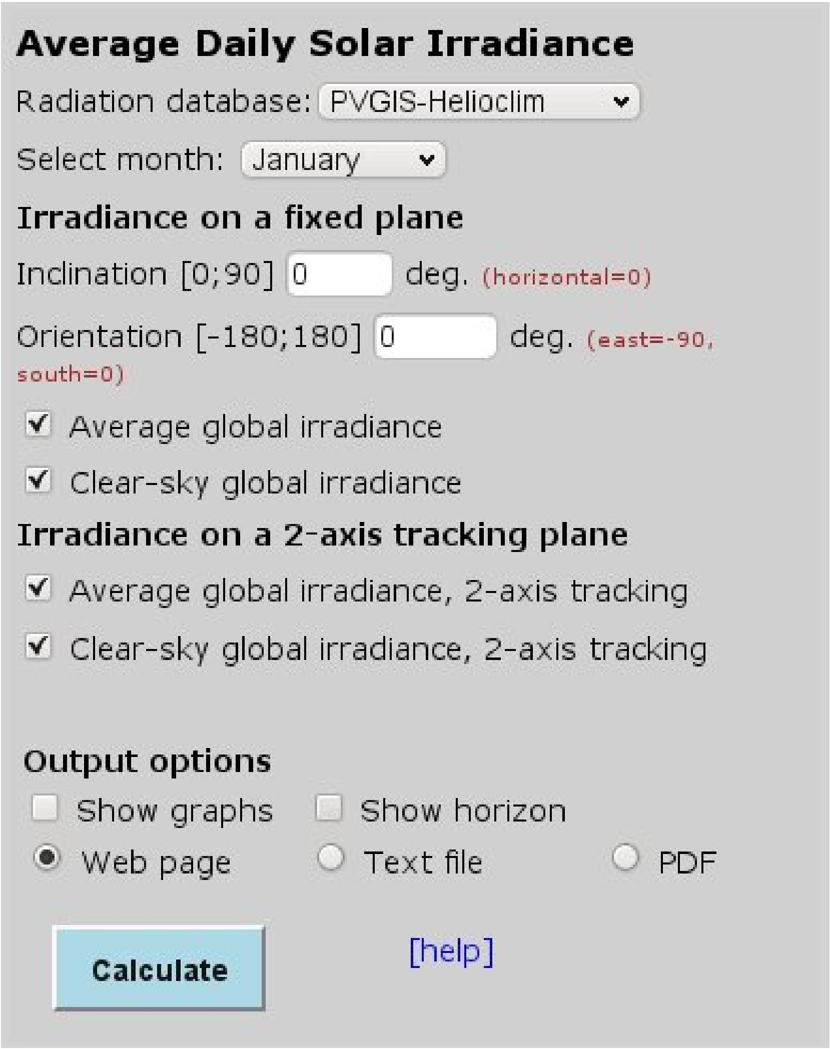
Month	H_h	H_{opt}	$H(25)$	I_{opt}
Jan	5850	6010	6500	31
Feb	5980	6080	6260	21
Mar	5940	5960	5730	6
Apr	5790	5730	5070	-12
May	5630	5500	4510	-25
Jun	4880	4750	3860	-30
Jul	4720	4620	3860	-26
Aug	4700	4640	4090	-16
Sep	5120	5110	4780	-1
Oct	5110	5160	5180	15
Nov	5350	5480	5850	28
Dec	5530	5690	6230	33
Year	5380	5390	5150	4

Negative optimum angle means north-facing!

Sample output from monthly radiation estimates

Average daily irradiance profile

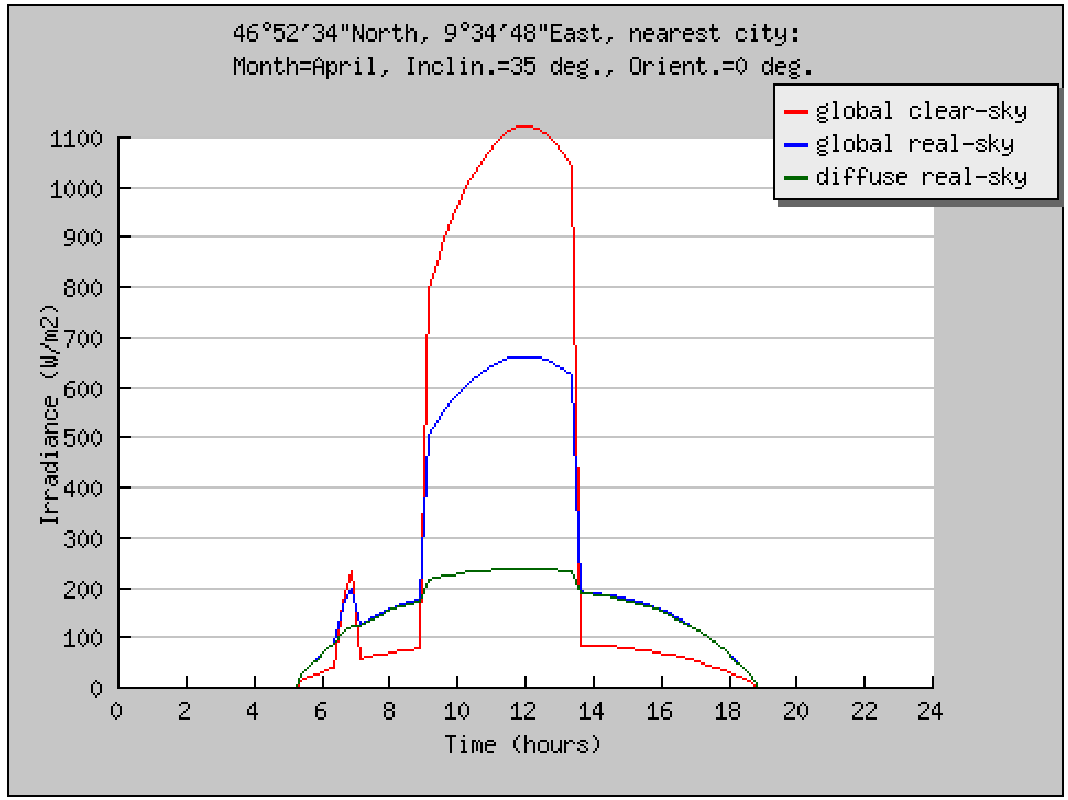
- Options to get values for the **average** irradiance during a typical day in each month
- Fixed angle or 2-axis tracking
- Shows also average temperature variation during the day (for Europe)
- Includes the effects of shadows



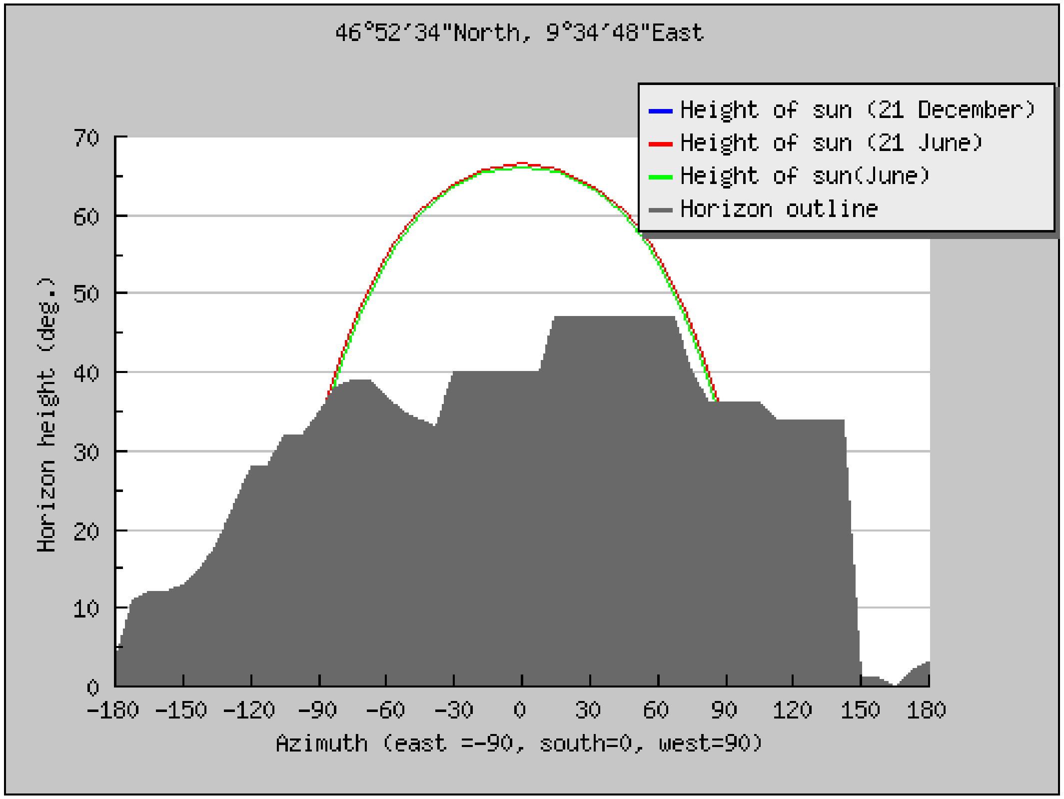
Interface for daily irradiance profile. Version for Africa without temperatures

Time	G	G_d	G_c	A	A_d	A_c
05:37	44	44	20	23	20	10
05:52	60	59	27	33	28	15
06:07	75	74	33	43	37	19
06:22	89	88	40	53	47	24
06:37	162	108	173	444	166	775
06:52	200	124	234	478	177	833
07:07	125	123	56	84	76	37
07:22	135	133	60	94	86	42
07:37	145	142	64	103	96	46
07:52	153	150	68	113	106	50
08:07	160	157	71	122	115	54
08:22	166	164	74	131	124	58
08:37	172	169	76	139	132	62
08:52	176	174	78	147	140	65
09:07	507	214	797	632	230	1080
09:22	533	219	849	639	232	1090

Output as table (part)



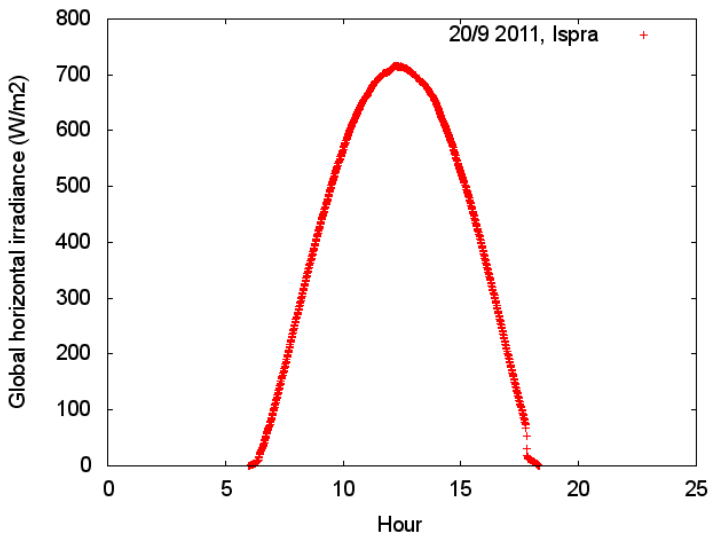
Output as graph



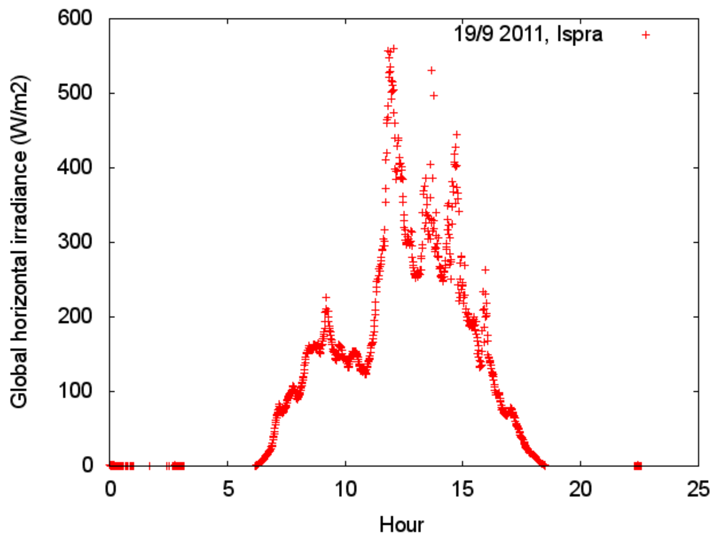
Horizon output from daily irradiance option

Real vs. average daily profile

The average clear-sky profile from PVGIS is similar to the irradiance on a clear day. But the average real-sky profile looks nothing like a real day!



Clear day



Not so clear day!

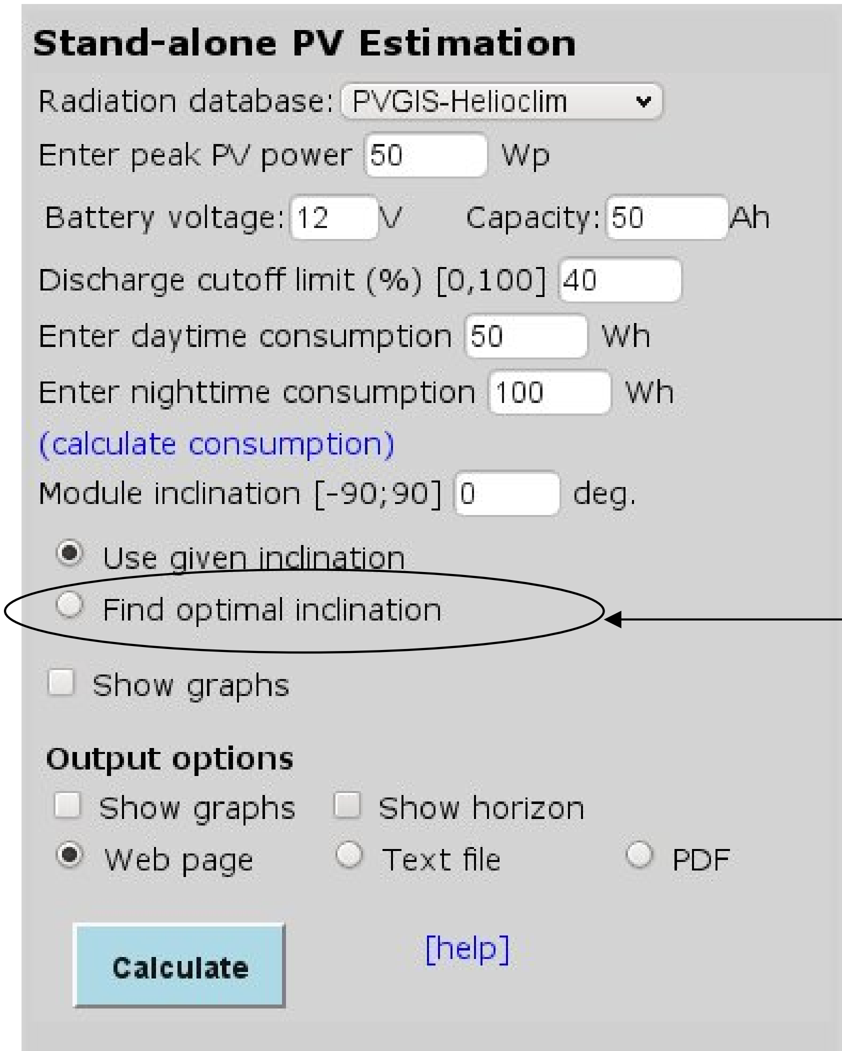
Off-grid PV system estimation

- Calculations for simple off-grid PV systems with battery but no inverter (simple charge controller)
- Uses daily irradiation data and assumes a constant daytime and nighttime consumption (entered by the user)
- Gives average monthly energy output
- Gives occurrence of battery full (so no further charging possible) and battery empty (so no power available)

Estimating PV minigrid performance

…. is not available yet ☹

(but I'm working on it)



Optimal inclination is for annual irradiation, not necessarily for off-grid output!

Off-grid output tables

Month	E_d	F_f	F_e
Jan	200.0	98	0
Feb	199.0	100	0
Mar	200.0	93	0
Apr	199.0	77	0
May	192.0	23	10
Jun	181.0	2	50
Jul	166.0	0	70
Aug	171.0	0	61
Sep	194.0	5	26
Oct	201.0	51	2
Nov	200.0	91	0
Dec	199.0	98	0
Year	**192.3**		

Energy output, battery full/empty

C_s	C_b
40-46	0
46-52	2
52-58	4
58-64	8
64-70	11
70-76	4
76-82	3
82-88	3
88-94	3
94-100	58

Battery charge statistics

Other PV system design tools (selected)

- PVSyst, PC application for designing grid-connected PV systems (www.pvsyst.com)
- RetSCREEN, PV design tool that runs in Excel, free (www.retscreen.net)
- HOMER, PC application to design minigrid systems, including PV, wind, hydro, diesel generators, etc. (homerenergy.com)
- SolarGIS, online tool like PVGIS, but with extra bells and whistles, commercial (solargis.info)

Quick comparison with PVGIS

- Advantages of other tools:
  - Generally have lots more options, for instance HOMER can combine PV with other electricity generators
  - Some cover geographical areas that PVGIS don't
  - Let you calculate costs of PV systems
  - Should definitely be consulted when designing larger systems
- Disadvantages:
  - More complicated to use, could be overkill for simple systems
  - Data quality uncertain for Africa in particular
  - Some are not free

Summary of this presentation

- PVGIS allows you to perform estimates of PV system performance with your web browser
- Grid-connected system estimates include a number of effects influencing performance, including temperature and terrain shadowing
- Solar radiation data available for Europe and Africa
- Off-grid calculator for design of small stand-alone PV systems, with simulation using long time-series of solar radiation data.