PVlite

A simulator of PV systems applications

User's manual

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PVlite, version 2.3

https://blogs.upm.es/javiermunoz/

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INDEX

1 Introduction

1-1 Overview

This guide describes how to install, execute and use PVlite. The guide also describes what are the required input data (chapter 2) and simulation results (chapter 3). Chapter 4 includes some simulation exercises for advanced users, which can write their own programs using PVlite scripts. Models and algorithms implemented in PVlite are described in [1]

PVlite is written in standard Matlab language. The source code is essentially a large script, divided in several subscripts. A version for Octave is also available. Previous developed versions of this simulator (IESPRO, SISIFO, and IESPRO2) were very structured, but this light version has few functions to facilitate the reading of the code and the access to nearly all the variables calculated by the program from the workspace.

1-2 Installation and execution

First, download Matlab© or Octave versions of PVlite from https://blogs.upm.es/javiermunoz/ and unzip the file into any folder.

Second, open Matlab© or Octave, select the previous folder in the program path, and run the script *pvlite* from the command line

>> pvlite

The program will ask for selecting an input data file, which contains the required data to perform a simulation. PVlite has not a graphical user interface and the required input data is read from an excel sheet (*.xlsx).

Several examples of input data templates with the name "inputdata_application.xlsx" are available in the unzipped folder, which can be selected for simulation. To save your own projects, just edit one of these files and save it with a different name.

2 Input data

2-1 Introduction

As mentioned above, PVlite has not graphical interfaces and the input data is read from an excel sheet, which has the tabs indicated in Table 1. Next sections detail the input parameters included in each one of these tabs.

Table 1. Tabs of the excel sheet.

Tab	**Input data**
Site	Geographical data of the site
Meteo	Meteorological data
PVgen	Characteristics of the PV generator and mounting structures (static or solar trackers).
Inverter	Characteristics and power efficiency of the inverter.
Wiring	Power losses in both DC and AC wiring.
Battery	Capacity and regulation thresholds of the battery.
Load	Energy consumption and daily load profile.
Genset	Characteristics of the generator set and fuel consumption curve.
Wind	Characteristics of the wind turbine and power curve.
Pumping	Characteristics of the water source and the centrifugal motorpump.
Options	Simulation options.

2-2 Site

This tab contains the geographical data of the location, which is specified by the parameters given in Table 2. Besides the geographical coordinates of latitude and longitude, the altitude of the site is required for calculating the air mass.

The standard longitude is required for calculating the solar hour when typical meteorological years (TMY) are selected for simulation, which use as reference the official (clock) time.

Table 2. Geographical parameters (data for Madrid).

GEOGRAPHICAL DATA

Parameter	Value	Units	Description
Latitude	40,7	*Degree*	Latitude of the location, positive in the Northern Hemisphere and negative in the Southern Hemisphere.
Longitude	-3,7	*Degree*	Longitude of the location, negative towards West and positive towards East.
Altitude	667	*Meter*	Altitude of the location over sea level.
StandardLongitude	0	*Degree*	Standard longitude (multiple of 15º). Negative towards West and positive towards East.

2-3 Meteo

PVlite simulates with time series of horizontal irradiances and temperatures, which are selected using the parameters indicated in Table 3. The $InputData$ parameter allows select between monthly average values or hourly values coming from TMY files. The $TimeSeries$ indicates the mathematical method for generating the synthetic time series when monthly averages are selected ($InputData = 1, 2\ or\ 4$).

Table 3. Selection of the meteorological input data.

METEOROLOGICAL INPUT DATA			
Parameter	**Value**	**Units**	**Description**
InputData	1		Meteorological input data. Options: 1-Monthly averages from the table below. 2-Monthly averages obtained from PVGIS TMY. 3-Hourly values from PVGIS TMY. 4-Monthly averages obtained from USA-TMY3 5-Hourly values from USA-TMY3.
TimeSeries	1		Synthetic method for generating the times series when monthly averages are selected as input data. Options: 1-Mean days 2-Aguiar

Month	Gdm0 [Wh/m²]	Tmm [ºC]	TMm [ºC]
January	2080	3	10
February	3130	3,1	12,7
March	4690	5,3	16,3
April	5600	6,2	17,8
May	6640	10,2	22
June	7670	15,1	29
July	8030	17	31,7
August	7000	16,5	31,2
September	5370	13,3	26,1
October	3700	10,4	20,2
November	2390	6,1	13,3
December	1910	3,4	10

The program simulates with data of this table when $InputData = 1$ is selected. Where:

$Gdm0$ is the monthly average of daily global horizontal irradiation, Wh/m²

Tmm is the monthly average of minimum daily temperature, ºC

TMm is the monthly average of maximum daily temperature, ºC

2-4 PVgen

This tab contains the characteristics of the PV generator and the type of mounting structure, as described in Table 4. The mounting structure is selected with the parameter Mounting, which allows to choose between two static structures and three sun trackers. Depending on the selected mounting structure, additional parameters should be indicated below.

In the case of the delta static structure, the PV generator is composed by two strings, one oriented toward the Est and the other one oriented toward the West. Each string has its own structure with the same inclination regarding the horizontal and a nominal PV power equal to PVnom/2.

Table 4. Characteristics of the PV generator.

PV GENERATOR			
Parameter	**Value**	**Units**	**Description**
PVnom	5	*kWp*	Nominal PV power.
CVPT	0,5	*%·ºC^{-1}*	Coefficient of Variation of PV module Power with Temperature (absolute value).
NOCT	48	*ºC*	Nominal Operation Cell Temperature
Rth	0,035	*ºC·m^2/W*	Thermal resistance. This parameter is calculated as [NOCT-20]/800, but other values can be chosen depending on the mounting and ventilation of PV modules.
Mounting structure			
Mounting	1		Type of mounting structure. Options: 1-Static: ground or roof. 2-Static: delta. 3-Tracker: One axis N-S horizontal. 4-Tracker: One axis vertical (azimutal). 5-Tracker: Two axis.
***Static ground or roof* (Mounting=1)**			
Inclination	35	*Degree*	Inclination of the modules regarding the horizontal, from 0º to 90º.
Orientation	0	*Degree*	Orientation of the modules towards the Equator. Zero towards the South in the Northern Hemisphere (North in the Southern Hemisphere), negative towards the East, and positive towards the West.

Static delta **(Mounting=2)**			
Inclination	45	*Degree*	Inclination of the modules regarding the horizontal, from 0º to 90º. The same for East and West structrures.
Azimutal tracking **(Mounting=4)**			
Inclination	40	*Degree*	Inclination of the modules regarding the horizontal, from 0º to 90º.

2-5 Inverter

This tab indicates the characteristics of the inverter: nominal power ($PInom$), maximum power ($PImax$), and the power efficiency curve (see Table 5). This inverter is the same for any application simulated by PVlite. Hence, the indicated parameters are those of grid-connected inverter, a stand-alone battery inverter or the variable-frequency drive (VFD) of a water pumping system.

The power efficiency curve can be specified by model parameters k0, k1 and k2, which can be calculated introducing in the script "InverterEfficiency.m" (or "Octave_InverterEfficiency.m" in Octave) the points of the power efficiency curve of the inverter. This script also calculates two yearly energy efficiencies of the inverter, which are usually provided by the manufacturers.

The European η_{EUR} is calculated as

$$\eta_{\mathrm{EUR}} = 0.03\eta_{\mathrm{I}}(0.05) + 0.06\,\eta_{\mathrm{I}}(0.1) + 0.13\,\eta_{\mathrm{I}}(0.2) + 0.1\,\eta_{\mathrm{I}}(0.3) + 0.48\,\eta_{\mathrm{I}}(0.5) + 0.2\,\eta_{\mathrm{I}}(1) \quad (1)$$

Where $\eta_{\mathrm{I}}(p_{\mathrm{ac}})$ is the power efficiency of the inverter at the normalized output power $p_{\mathrm{ac}} = P_{\mathrm{AC}}/P_{\mathrm{I,NOM}}$, where P_{AC} is the output power and $P_{\mathrm{I,NOM}}$ is the nominal power of the inverter (called $PInom$ in the source code).

The second parameter is the yearly energy efficiency η_{CEC}, which has been proposed by the California Energy Commission (CEC). It is calculated using weighting coefficients that are more suitable for locations with higher annual irradiation:

$$\eta_{\mathrm{CEC}} = 0.04\eta_{\mathrm{I}}(0.1) + 0.05\eta_{\mathrm{I}}(0.2) + 0.12\,\eta_{\mathrm{I}}(0.3) + 0.21\,\eta_{\mathrm{I}}(0.5) + 0.53\,\eta_{\mathrm{I}}(0.75) + 0.05\eta_{\mathrm{I}}(1) \quad (2)$$

These efficiencies are just informative and PVlite calculates the annual energy efficiency of the inverter $\eta_{\mathrm{I,a}}$ from the simulated power variables as

$$\eta_{I,a} = \frac{E_{ACa}}{E_{DCa}} = \frac{\int_{Year} P_{AC}\,dt}{\int_{Year} P_{DC}\,dt} \quad (3)$$

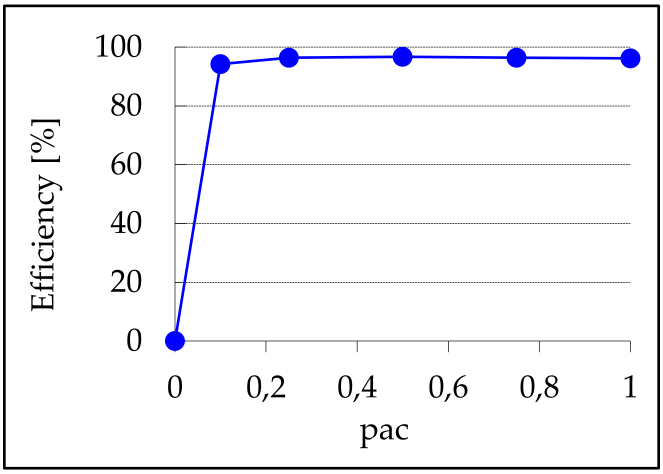
Where E_{ACa} is the annual AC energy at the inverter output and E_{DCa} is the annual DC energy at the inverter input, which are calculated throughout the year, respectively, integrating the simulated AC power P_{AC} and DC power P_{DC} of the inverter.

This tab also allows to introduce the power efficiency points on the bottom table by selecting the option $InverterCurve = 2$. In this case, the program calculates internally the parameters k0, k1 and k2.

Table 5. Characteristics of the inverter.

Inverter				
Parameters		**Value**	**Units**	**Description**
PInom		5	*kW*	Nominal output power of the inverter.
PImax		5	*kW*	Maximum output power of the inverter.
InverterCurve		1	-	Specification of the power efficiency curve. Options: 1. Model parameters (k0, k1 and k2). 2. Points of the power efficiency curve (the program calculates k0, k1 and k2 using the power efficiency points indicated in the table).
Model parameters				
	k0	0,01	-	No-load inverter losses.
	k1	0,05	-	Linear inverter losses.
	k2	0,08	-	Joule inverter losses.

Points of the power efficiency curve	
pac	**Efficiency [%]**
0	0
0,1	94,2
0,25	96,4
0,5	96,7
0,75	96,4
1	96,2



2-6 Wiring

This tab indicates the power wiring losses in DC side (in the PV generator circuit) and AC side (between the inverter and the AC loads).

These losses are specified by the parameters WDC and WAC (Table 6) as a percentage of, respectively, the nominal power of the PV generator, $PVnom$, and the nominal power of the inverter, $PInom$.

Table 6. Specification of wiring losses.

Wiring			
Parameter	**Value**	**Units**	**Description**
WDC	1	%	DC wiring losses
WAC	1	%	AC wiring losses

2-7 Battery

The battery is modelled as an ideal storage (100% efficient) with a given capacity $CBAT$, in kWh. Besides, for stand-alone PV systems, there are two regulation thresholds called $SOCmax$ and $SOCmin$.

$SOCmax$ is the maximum permitted state of charge (SOC). When the SOC reaches this level, the PV generator is disconnected from the system. By default, $SOCmax = 1$ (fully charged battery).

$SOCmin$ is the minimum permitted state of charge. When the SOC decreases until this level, the inverter and the AC loads are disconnected from the system. By default, $SOCmin = 0$ (fully discharged battery).

Using these parameters, the useful capacity of the battery C_{U} is given by:

$$C_{\mathrm{U}} = (SOC_{\mathrm{max}} - SOC_{\mathrm{min}})C_{\mathrm{BAT}} \quad (4)$$

Table 7. Battery model.

Battery (Stand-alone PV systems)			
Parameter	**Value**	**Units**	**Description**
CBAT	150	*kWh*	Battery capacity
SOCmax	1	-	Maximum state of charge.
SOCmin	0	-	Minimum state of charge.

2-8 Load

The energy consumption monthly average of daily consumption is indicated by the parameter *Ldm*, in kWh, which can be different for each month (see Table 8).

The daily variation of the power consumption is assumed to be the same for all the days of the year, and it is specified by 24 hourly load factors $F(h)$, see Table 9, which indicates the fraction of *Ldm* consumed during each hour:

$$P_{LOAD}(h) = F(h) \cdot L_{dm} \qquad (h = 1, 2, \ldots 24) \tag{5}$$

A warning message appears if the sum of these 24 hourly factors is not the unity. Besides, the user must ensure that the maximum power of the inverter ($PImax$) is higher than the peak load demand, which is given by

$$P_{I,max} \geq max\ (F(h)) \cdot L_{dm} \tag{6}$$

If the last condition is not fulfilled the simulation will be stopped.

Table 8. Monthly energy consumption.

Load profiles

Monthly average of daily energy consumption, Ldm [kWh/day]		
Month	**Ldm**	
January	50	
February	50	
March	50	
April	50	
Mayo	50	
June	50	
July	50	
August	50	
September	50	
October	50	
November	50	
December	50	
Total	18250	Total yearly energy consumption [kWh/year]

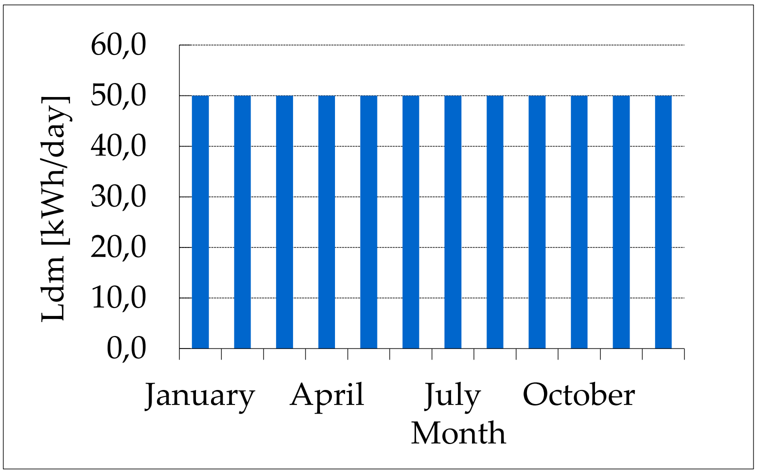
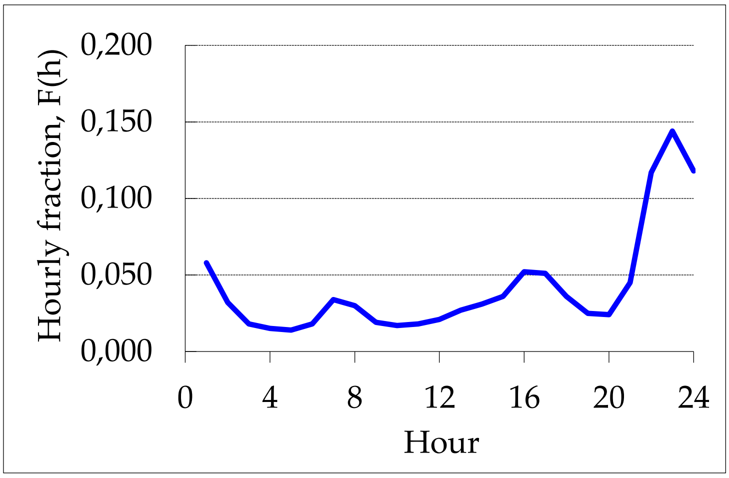


Table 9. Daily load profile.

Normalised daily load profile

Hour, h	F(h)
1	0,058
2	0,032
3	0,018
4	0,015
5	0,014
6	0,018
7	0,034
8	0,030
9	0,019
10	0,017
…	….

F(h) indicates the fraction of daily energy consumed during the hour h.
(For a constant load profile write F(h)=1/24)



2-9 Genset

The generator set (genset) is characterized by its nominal power PGENnom, in kW. In hybrid systems with DC bus, it is assumed that the inverter is sized to supply the peak load AC demand and the genset is only connected for charging the battery, operating at its nominal power, when the state of charge SOC decreases below a certain minimum level ($SOCstart$). And it remains in operation until the battery recovers until a given SOC level $SOCstop$, which is higher than $SOCstart$. Both $SOCstart$ and $SOCstop$ are also indicated by the user in this tab (see Table 10).

Table 10. Characteristics of the generator set.

Generator set

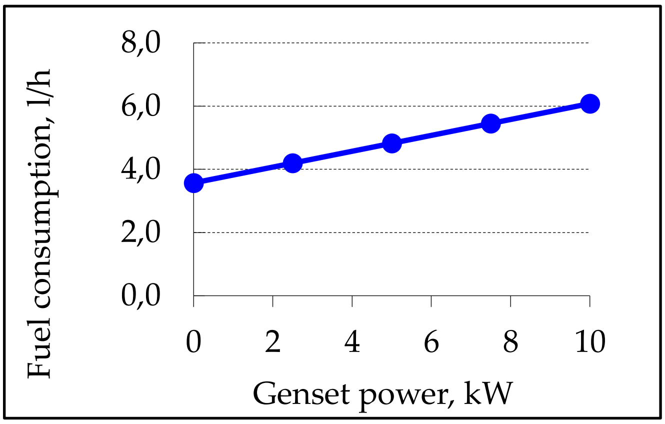
Parameter	Value	Units	Description
PGENnom	10	*kW*	Nominal power of the genset
SOCstart	0,2	-	State of charge for connecting the genset
SOCstop	0,3	-	State of charge for disconnecting the genset

The fuel consumption, expressed in L/h, is modelled by a linear equation [1] with the default fitting parameters (b0i, b1i, b0s and b1s) indicated in Table 11, which can be modified by the user. For example, a more simple and popular model is obtained using only the coefficients b1i and b0s (and setting b0i=b1s=0).

Table 11. Default parameters for the fuel consumption model.

Fuel consumption	Value	Units	Description
b0i	3,36719	*(l/h)*	Intercept coefficient 0
b1i	0,02031	*(l/h)/kWnom*	Intercept coefficient 1
b0s	0,25098	*(l/h)/kW*	Slope coefficient 0
b1s	-1,18E-05	*(l/h)/(kWnom·kW)*	Slope coefficient 1

Fuel consumption curve	
PGEN, [kW]	**F [l/h]**
0	3,57
2,5	4,20
5	4,82
7,5	5,45
10	6,08



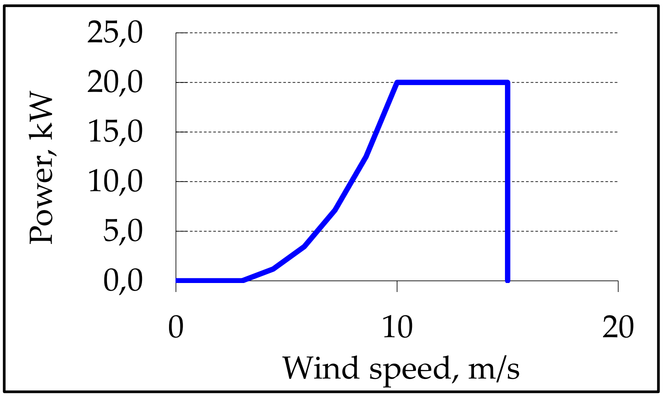
2-10 Wind

This tab contains the characteristics of the wind turbine indicated in Table 12, which is modelled using the power curve described in [1]

Table 12. Characteristics of the wind turbine.

Wind turbine			
Parameter	**Value**	**Units**	**Description**
PWnom	20	*kW*	Rated electrical power
Vnom	10	*m/s*	Rated wind speed
Vci	3	*m/s*	Cut-in wind speed
Vco	15	*m/s*	Cut-out wind speed
Cpeq	0,0206	*kW/(m/s)³*	Equivalent power coefficient

Power curve	
Wind speed, m/s	**Power, kW**
0	0,00
3	0,00
4,4	1,20
5,8	3,46
….	….



2-11 Pumping

This tab contains the parameters that describe the characteristics of the water source (well, borehole, etc.), the water tank and the motorpump. Figure 1 displays the characteristics of the water source, where it is assumed that a submerged motor pump elevates the water from the well to a water storage tank. The required parameters for simulation are indicated in Table 13, whose definitions and corresponding models are detailed in [1] The water tank capacity in m^3 is specified by the parameter WTC. However, in this version it is assumed that all the water flow is consumed instantaneously by the users. Hence, the tank never becomes full and its capacity, from the point of view of the system, can be considered as infinite.

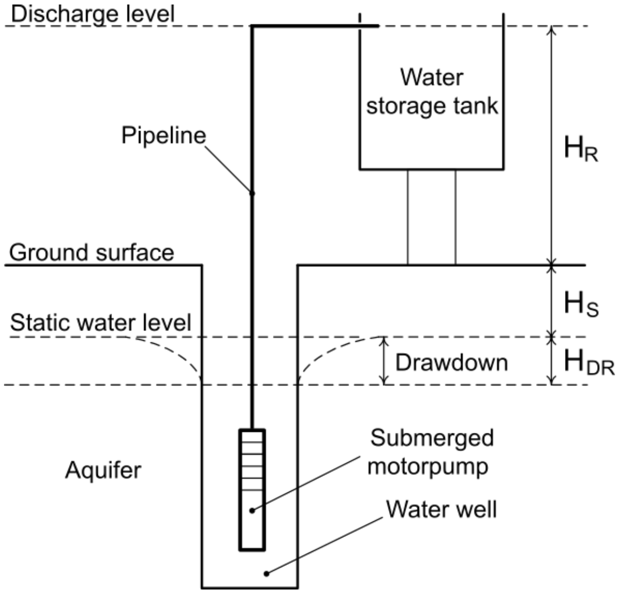


Figure 1. Characteristics of the water source.

Table 13. Input parameters for the water source and water tank.

Well/borehole	Value	Units	Description
Hs	12	m	Static head
Qtest	5	m^3/h	Constant test flow
Hdr	2	m	Drawdown at constant test flow
kw1	0,4	$m/(m^3/h)$	Aquifer loss.
kw2	0	$m/(m^3/h)^2$	Well loss.
Water tank	**Value**	**Units**	**Description**
WTC	1000	m^3	Water tank capacity
Hr	5	m	Discharge level

The system curve $H_T(Q)$ describes the variation of the total manometric head as a function of the flow rate Q, in m³/h, and it is expressed as a third-order polynomial using the fitting coefficients k_{S0}, $k_{S1}$and k_{S2}.

$$H_{\mathrm{T}} = k_{S0} + k_{S1}Q + k_{S2}Q^2 \tag{7}$$

Which are calculated as:

$$k_{S0} = H_S + H_R$$
$$k_{S1} = k_{\mathrm{w1}}$$
$$k_{S2} = k_{\mathrm{w2}} + \frac{H_{F,rated}}{Q^2_{rated}} \tag{8}$$

Table 14 shows the system curve parameters. Among these, the user must only indicate the value for $HF,rated$, which are the nominal friction losses at the rated, or nominal, flow of the pump. The remaining parameters k_{S0}, $k_{S1}$and k_{S2} are calculated by the excel sheet using the previous equations and the parameters given in Table 13.

Table 14. Nominal friction losses (indicated by the user) and calculated model coefficients of the system curve.

System curve	Value	Units	Description
HF,rated	2	*m*	Friction losses at rated flow
ks0	17	*m*	Total static head (Hs+Hr)
ks1	0,4	*m/(m³/h)*	Specific drawdown (aquifer loss)
ks2	0,08	*m/(m³/h)²*	Friction plus well losses

The characteristics of the motorpump are, on the one hand, the rated, or nominal, operating point $(Q_{\mathrm{rated}}, H_{\mathrm{rated}})$ and the water density, whose default value is 998.2 kg/m³ at 20 ºC.

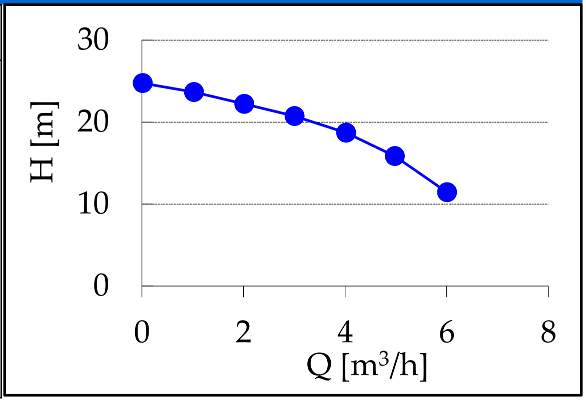
On the other hand, the user must introduce several points of the motorpump performance curves, which can be obtained from manufacturer datasheet:

- The head-flow curve $H(Q)$, at nominal speed.
- Power curves $P_1(Q)$ and $P_2(Q)$, at nominal speed.
- Motor efficiency $\eta_M(P_2)$.

For example, Figure 2 and Figure 3 display examples of these curves, which are included by default in the input template.

Pump curve

Q [m³/h]	H [m]
0,012	24,75
1,025	23,67
2,013	22,21
3,003	20,73
4,019	18,69
4,976	15,85
6,005	11,44



Power curves

P1, nominal curve of the power at the motor input, kW

Q [m³/h]	P1 [kW]
0,012	0,253
1,025	0,336
2,013	0,414
3,003	0,481
4,019	0,53
4,976	0,553
6,005	0,549

P2, nominal curve of shaft power, kW

Q [m³/h]	P2 [kW]
0,012	0,098
1,025	0,176
2,013	0,248
3,003	0,309
4,019	0,352
4,976	0,371
6,005	0,368

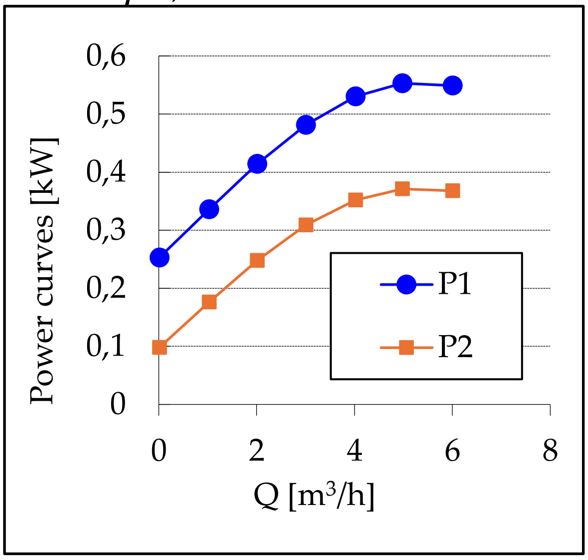


Figure 2. Example of pump curve H-Q and powers of a motorpump.

Motor power efficiency	
P2 [kW]	**Efficiency [%]**
0	0
0,098	38,6
0,176	52,4
0,371	67,2
0,5	71
0,7	73
0,9	72

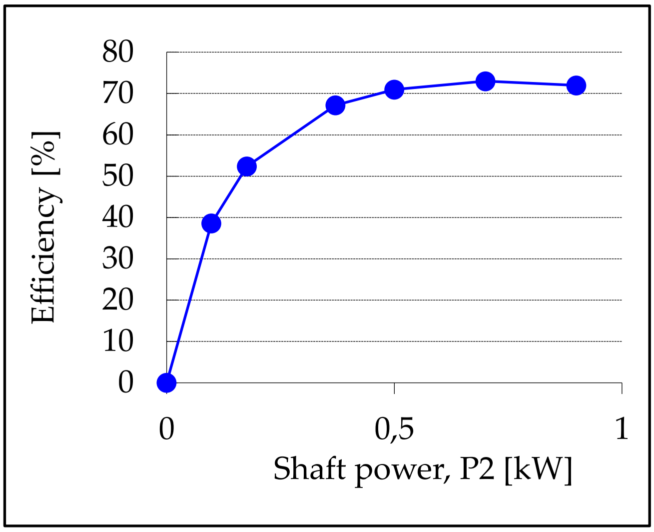


Figure 3. Example of the power efficiency curve of the motor.

Finally, the user must specify the parameters indicated in Table 15. The nominal power of the motor P2rated, the nominal speed RPMnom, the minimum speed for water cooling RPMcool, and the maximum speed RPMmax. If the operating speed is lower than RPMcool, the system stops. And, if the speed is higher than RPMmax, the power is limited to avoid surpass this maximum speed.

Table 15. Other motor parameters.

Motor	Value	Units	Description
P2rated	0,75	*kW*	Rated shaft power
RPMnom	2900	*rpm*	Rated speed
RPMcool	70	%	Minimum speed, relative to the rated speed, for water cooling.
RPMmax	120	%	Maximum speed, relative to the rated speed.

2-12 Options

This tab allows the selection of several options and models for simulation, which are displayed in Table 16. The equations of the available models are described in [1]

Table 16. Simulation options

Simulation options			
Parameter	**Value**	**Units**	**Description**
Application	1	-	PV application. Options: 1. Grid-connected 2. Stand-alone PV system 3. Hybrid DC bus 4. Hybrid AC bus (Work in progress) 5. Water pumping
Soiling and incidence losses	1	-	Degree of soiling on the PV generator under normal incidence. Options: 1. Clean (0%) 2. Low (2%) 3. Medium (3%) 4. High (8%)
Diffuse model	2	-	Diffuse sky model Options: 1. Isotropic 2. Anisotropic (Hay) 3. Anisotropic (Perez)
Diffuse fraction	1	-	Monthly diffuse fraction: Options: 1. Page 2. Collares-Pereira 3. Erbs 4. Macagnan
Ground reflectance	0,2	-	Ground reflectance (0 to 1)
Simulation step	600	s	Simulation step (60 to 3600 seconds)

3 Simulation results

3-1 Introduction

This document describes the list of output variables available in the Matlab workspace after performing a simulation. Besides these variables, at the end of each simulation, the program displays as result a Sankey diagram using a function called drawSankey [2]

3-2 Output variables

PVlite generates as main result the time series of different simulated variables, which are matrices of $Nsteps$ rows and $Ndays$ columns, where $Nsteps$ is the number of simulation steps per day and $Ndays = 365$. Each column represents the daily variation of the simulated variable, being the first column January 1 and the last one December 31. Besides, PVlite integrates the previous matrices to obtain daily parameters (1x365 arrays), which are themselves integrated to provide monthly parameters (1x12 arrays) and, finally, yearly parameters (1x1 or single variables).

3-2-1 Astronomical variables

Table 17. Astronomical variables.

Variable	Unit	Definition	Size
Eo	-	Eccentricity correction factor of the earth's orbit	1x365
delta	rad	Solar declination	1x365
ET	rad	Equation of time	1x365
ws	rad	Sunrise angle	1x365
Hours	h	Clock time	Nstepsx365
w	rad	Solar hour (true solar time)	Nstepsx365
tetazs	rad	Solar zenith angle	Nstepsx365
gammas	rad	Solar altitude	Nstepsx365
fis	rad	Solar azimuth angle	Nstepsx365
BOd0	$Wh \cdot m^{-2}$	Daily extraterrestial horizontal irradiation	1x365

3-2-2 Meteorological variables

3-2-2-1 Radiation on the horizontal surface

Table 18. Horizontal irradiances (Nstepsx365 matrices).

Variable	Unit	Definition
G0	$W \cdot m^{-2}$	Global
B0	"	Beam
D0	"	Diffuse

Table 19. Daily parameters (1x365 arrays).

Variable	Unit	Definition
KTd	-	Daily clearness index
KDd	-	Daily diffuse fraction
G0d	$Wh \cdot m^{-2}$	Daily global horizontal irradiation
B0d	$Wh \cdot m^{-2}$	Daily beam horizontal irradiation
D0d	$Wh \cdot m^{-2}$	Daily diffuse horizontal irradiation

Table 20. Monthly parameters (1x12 arrays).

Variable	Unit	Definition
Gdm0	$Wh \cdot m^{-2}$	Monthly average of daily global horizontal irradiation (input data)
G0m	$Wh \cdot m^{-2}$	Global horizontal irradiation
B0m	"	Beam horizontal irradiation
D0m	"	Diffuse horizontal irradiation

Table 21. Yearly parameters (1x1).

Variable	Unit	Definition
G0a	$Wh \cdot m^{-2}$	Global horizontal irradiation
B0a	"	Beam horizontal irradiation
D0a	"	Diffuse horizontal irradiation

3-2-2-2 Radiation on the inclined surface

Table 22. In-plane irradiances (Nstepsx365 matrices).

Variable	Unit	Definition
G	$W \cdot m^{-2}$	Global (G=B+D+R)
B	"	Beam
Bn	"	Normal beam component
D	"	Diffuse (Diso+Dcir+Dhor)
Diso	"	Isotropic diffuse component
Dcir	"	Circumsolar diffuse component
Dhor	"	Horizon diffuse component (Perez model)
R	"	Reflected
Gef	"	Global effective (including dust and incidence effects, Gef=Bef+Def+Ref)
Bef	"	Beam effective
Def	"	Diffuse effective
Ref	"	Reflected effective

Table 23. Monthly parameters (1x12).

Variable	Unit	Definition
Gm	$Wh \cdot m^{-2}$	Global irradiation
Gefm	"	Global effective irradiation
Bm	"	Beam irradiation
Dm	"	Diffuse irradiation

Table 24. Yearly parameters (1x1).

Variable	Unit	Definition
Ga	$Wh \cdot m^{-2}$	Global irradiation
Gefa	"	Global effective irradiation
Ba	"	Beam irradiation
Da	"	Diffuse irradiation

3-2-2-3 Temperatures

Table 25. Ambient and cell temperatures (Nstepsx365 matrices).

Variable	Unit	Definition
Ta	ºC	Ambient temperature
Tc	ºC	Cell temperature

3-2-3 PV system

3-2-3-1 Powers

Table 26. Powers, in kW (Nstepsx365 matrices).

Variable	Definition	PV application
PPV0	Ideal effective PV power (including angle of incidence and dust losses).	All
PPV1	PPV0 less temperature losses	All
PPV2	PPV1 less DC wiring losses	All
PPV3	PPV2 less power losses caused by inverter clipping, battery disconnection, etc.	All
PPV	Final available PV power (PPV=PPV3).	All
PDC	Power at the inverter input	All
PAC0	Power at the inverter output	All
PAC1	PAC0 less AC wiring losses	All
PAC	Final AC power	All
PLOAD	Load power consumption	All excepting pumping systems
PGRID	Grid power (positive, if it is injected or exported to the grid and negative, if it is consumed from the grid).	Grid-connection
PGRIDI	Power injected in the grid	Grid-connection
PGRIDC	Power consumed from the grid	Grid-connection
PSELF	Self-consumed power	Grid-connection
PBAT	Battery power (positive for battery charging and negative if the battery is discharging)	Stand-alone and hybrid systems
PGEN	Genset power	Hybrid systems
PWIND	Wind power	Hybrid systems

P1	Input electrical power to the motor	Pumping systems
P2	Mechanical output power of the motor (shaft power)	Pumping systems
PH	Hydraulic power (PH=PH0+PH1+PH2)	Pumping systems
PH0	Hydraulic power required to overcome the static head.	Pumping systems
PH1	Additional hydraulic power required by aquifer losses (linear losses)	Pumping systems
PH2	Additional hydraulic power required by friction and well losses (quadratic losses)	Pumping systems

3-2-3-2 Energies

Daily, monthly and yearly energies are obtained by the integration of the all powers indicated in the previous section and expressed in kWh.

The names of these energies are created using the following convention. First, the initial P (of power) is replaced by E (of energy). Second, one of the suffixes "d", "m" or "a" is added after the name to indicate, respectively, a daily, monthly or annual energy. For example:

EPVd Daily PV energy (1x365 array).

EPVm Monthly PV energy (1x12 array).

EPVa Annual PV energy (single variable).

3-2-3-3 Figures of merit, energy efficiencies and energy losses

Table 27. Figures of merit (daily values). For monthly and yearly values, change the final d by m or a, respectively.

Variable	Unit	Definition	PV application
LLHd	-	Loss of load hours (Fraction of time without electricity service to the loads)	Stand-alone and hybrid systems
PRd	-	Performance ratio PRd=EACd/(PVnom*Gd/1000)	All
PRHd	-	Hydraulic performance ratio PRHd=EHd/(Pvnom*Gd/1000)	Pumping systems
SCd	%	Daily self-consumption (SCd=100*ESELFd/EACd)	Grid-connection
SSd	%	Self-sufficiency (SSd=100*ESELFd/ELOADd)	Grid-connection

Table 28. Figures of merit (only yearly values).

Variable	Unit	Definition	PV application
LLPa	-	Loss of load probability (Fraction of energy not supplied to the load. If the load power consumption is constant, LLPa=LLHa).	Stand-alone and hybrid systems
Yr	Hours	Reference yield (Yr=Ga/1000)	All
Ya	Hours	Array yield (Ya=EPVa/PVnom)	All
Yf	Hours	Final yield (Yf=EACa/PVnom)	All
LCa	%	Capture losses (LCa=100*(Yr-Ya)/Yr)	All
LSa	%	System losses (LSa=100*(Ya-Yf)/Yr)	All

Table 29. Daily energy losses. For monthly and yearly values, change the final d by m or a, respectively.

Variable	Unit	Definition Energy losses caused by:	PV application
LOSS_INCd	%	Angle of incidence and dust	All
LOSS_TEMd	%	Temperature	All
LOSS_WDCd	%	DC wiring	All
LOSS_SATd	%	Limitation of PV power by inverter clipping, a fully charged battery, etc.	All
LOSS_INVd	%	Inverter	All
LOSS_WACd	%	AC wiring	All
LOSS_MOTd	%	Motor	Pumping
LOSS_PUMPd	%	Pump	Pumping
LOSS_MPd	%	Motor pump	Pumping

Table 30. Daily energy efficiencies. For monthly and yearly values, change the final d by m or a, respectively.

Variable	Unit	Definition	PV application
ETAId	%	Inverter efficiency	All
ETAMd	%	Motor efficiency	Pumping
ETAPd	%	Pump efficiency	Pumping
ETAMPd	%	Motor-pump efficiency	Pumping

3-2-3-4 Other parameters

Table 31. Other parameters.

Variable	Unit	Definition	PV application
FUEL	L/Sstep(*)	Fuel consumption (Nstepsx365 matrix)	Hybrid systems
FUELd	L	Daily fuel consumption	Hybrid systems
FUELm	L	Monthly fuel consumption	Hybrid systems
FUELa	L	Yearly fuel consumption	Hybrid systems
GENONa	Hours	Yearly tunning hours of the genset	Hybrid systems
Q	m^3/step	Water flow (Nstepsx365 matrix)	Pumping
Qd	m^3	Daily water pumping	Pumping
Qm	m^3	Monthly water pumping	Pumping
Qa	m^3	Yearly water pumping	Pumping
SOC	-	State of charge	Stand-alone and hybrid systems
SOCdmin	-	Daily minimum SOC	Stand-alone and hybrid systems
SOCdmax	-	Daily maximum SOC	Stand-alone and hybrid systems
SOCdavg	-	Daily average SOC	Stand-alone and hybrid systems
SOCda	-	Yearly average of daily average SOC	Stand-alone and hybrid systems

(*) Sstep is the simulation step.

3-3 Sankey diagrams

Next figures show several examples of Sankey diagrams, which are displayed by PVlite after performing a yearly simulation using as input one of the excel templates available in the program folder.

Figure 4 shows a Sankey diagram of a grid-connected PV system. The input of the diagram is the reference yield, in kWh/kWp or hours, and the output is the final yield, also expressed in kWh/kWp. Besides the final yield, the diagram also displays several annual figures of merit, such as the performance ratio or the capture losses. Energy losses, indicated with vertical arrows, are relative to the reference yield and the displayed values are lower than the calculated energy losses indicated in Table 29.

Figure 5 shows the Sankey diagram of a PV pumping system, which includes other energy losses, such as those of the motor and the pump. The output of the diagram is energy at the inverter output (AC energy), which coincides with final yield, and the hydraulic energy, also expressed in kWh/kWp, which is lower than the AC energy owing to the energy losses of the motorpump. As result, the hydraulic PR (PRH) is relatively low. The diagram finally shows the specific pumping, which indicates the yearly volume of pumped water expressed in m^3/kWp.

In the last example, Figure 6 shows the Sankey diagram of an hybrid PV system, where the inputs are the contributions of the PV source (90%) and the genset (10%), both expressed in kWh, which are necessary to supply a full energy service for an AC load that consumes 18250 kWh per year.

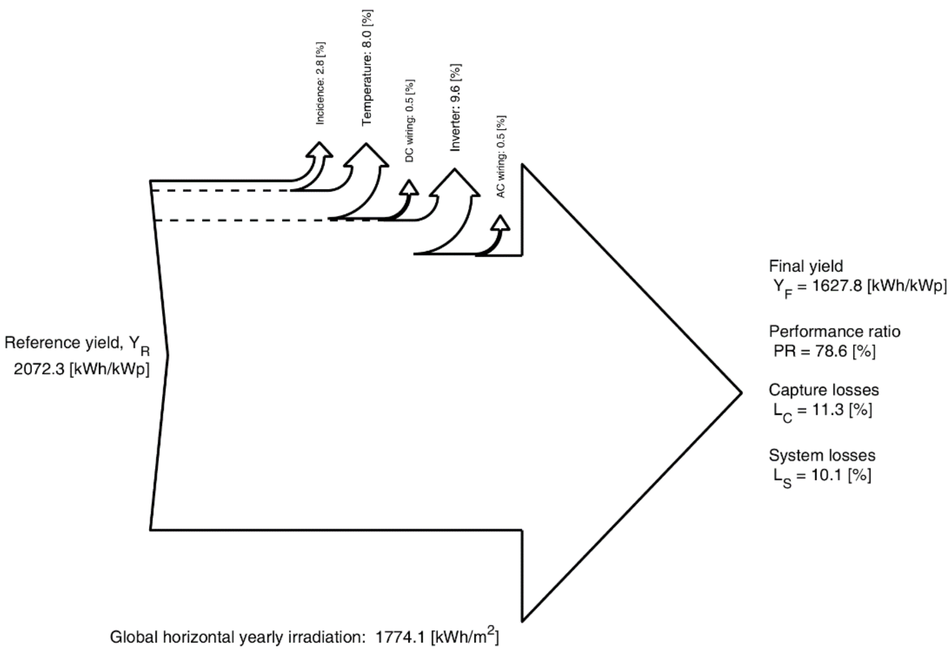


Figure 4. Sankey diagram for a grid-connected PV system.

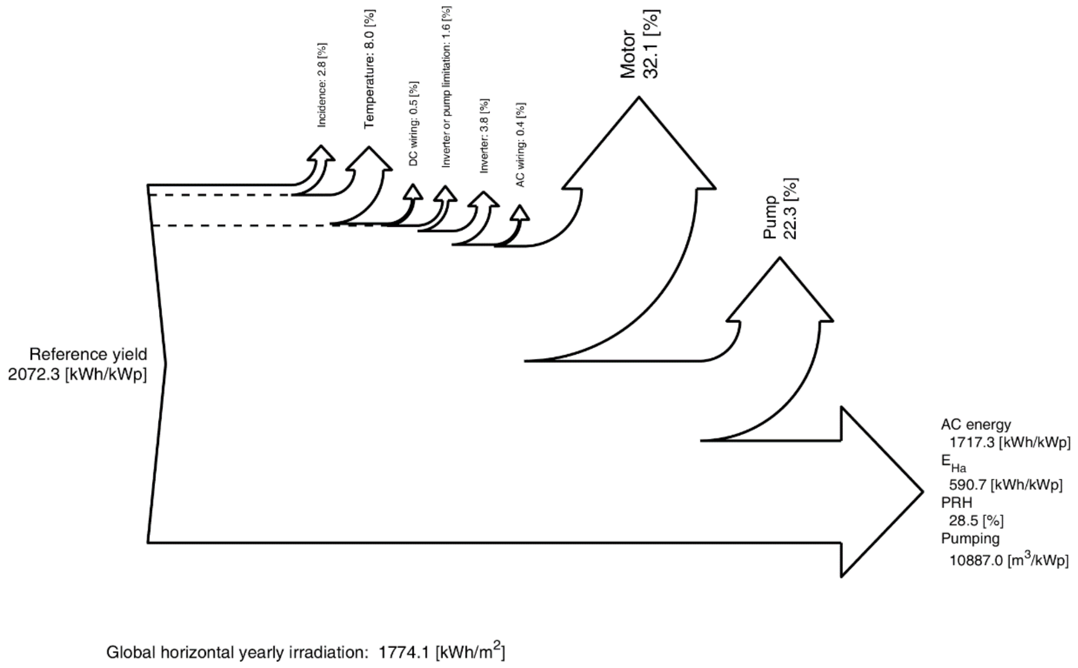


Figure 5. Sankey diagram for a PV pumping system.

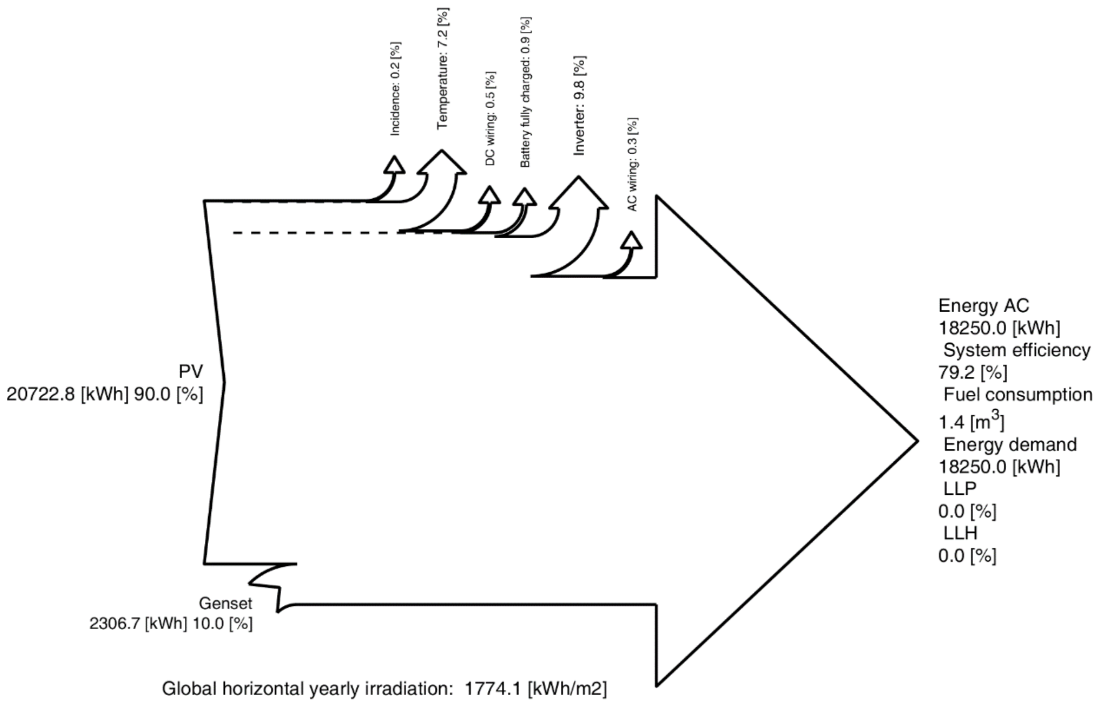


Figure 6. Sankey diagram for a hybrid PV system.

4 Simulation exercises

4-1 Introduction

This chapter describes several simulation exercises, which can be written by users with basic programming skills using PVlite scripts. These exercises illustrate the possibilities of PVlite for solving common problems found in the design and optimization of PV systems. The script of each exercise has the name ExerciseX.m and can be directly executed from the command line writing:

>> ExerciseX

4-2 Exercise 1

This script plots the yearly global irradiation on the tilted plane, assuming it is oriented towards the Equator, as a function of the inclination of the PV generator and also finds its optimum value. Figure 7 shows an example of the collected yearly irradiation in Madrid, whose maximum is 2072.3 kWh/m² at 35º tilt.

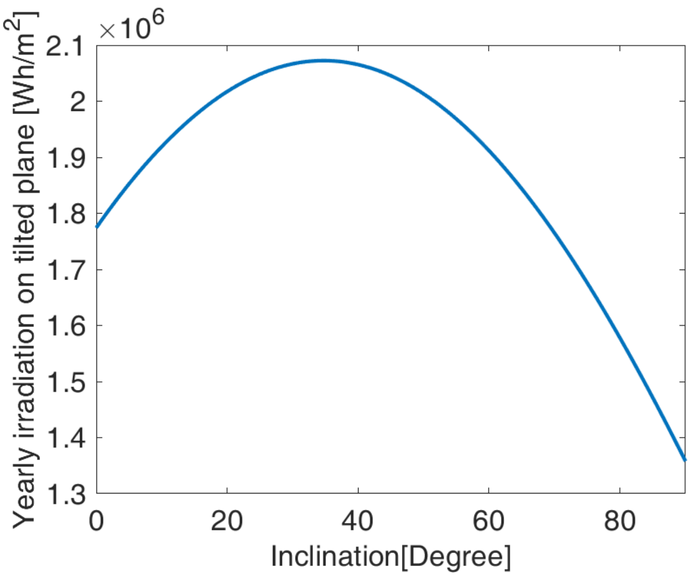


Figure 7. Yearly global irradiation on the tilted plane oriented towards the Equator, as a function of the inclination, in Madrid.

4-3 Exercise 2

This script plots a contour 2D map with the variation of the reference yield as a function of the inclination and orientation. Figure 8 shows and example for Madrid. As usual, large variations of the inclination and orientation cause relatively low energy collection losses regarding the optimum value.

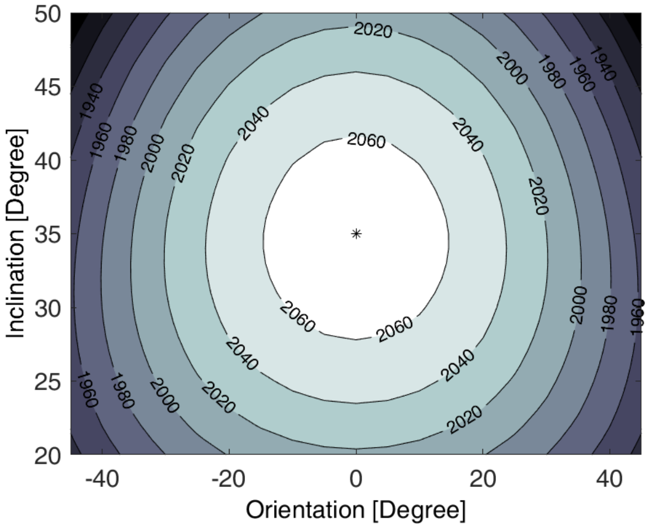


Figure 8. Reference yield of PV generator installed in Madrid as function of the orientation and inclination angles. The asterisk indicates the optimum (2072.3 kWh/kWp).

4-4 Exercise 3

This script calculates the monthly average of daily irradiations G_{dm} on tilted planes with different inclinations. Table 32 shows an example for Madrid.

Table 32. Monthly average of daily global irradiation G_{dm}(inclination, orientation), in Wh/m^2, in Madrid.

Month	$G_{dm}(0)$	$G_{dm}(20,0)$	$G_{dm}(30,0)$	$G_{dm}(40,0)$	$G_{dm}(50,0)$	$G_{dm}(60,0)$
January	2080	3077	3466	3766	3967	4064
February	3130	4271	4686	4979	5141	5168
March	4690	5746	6059	6214	6207	6038
April	5600	6103	6133	6015	5751	5350
May	6640	6717	6528	6190	5715	5118
June	7670	7482	7142	6645	6006	5246
July	8030	7951	7638	7149	6500	5709
August	7000	7414	7345	7095	6669	6082
September	5370	6269	6480	6524	6398	6107
October	3700	4825	5210	5459	5565	5526
November	2390	3440	3842	4144	4339	4418
December	1910	2940	3350	3673	3898	4020

4-5 Exercise 4

This script finds the optimum inclination for a stand-alone PV generator using the worst month approach knowing the monthly averages of daily load consumption.

4-6 Exercise 5

This script plots iso-reliability LLP curves for a stand-alone PV system as a function of the PV generator and battery capacities. Figure 9 shows an example for Madrid using as input TMY PVGIS data. These curves are displayed just for illustration purposes, since the correct estimation of the LLP would require performing long-term simulations, more than 10 years, using real time series of meteorological input data.

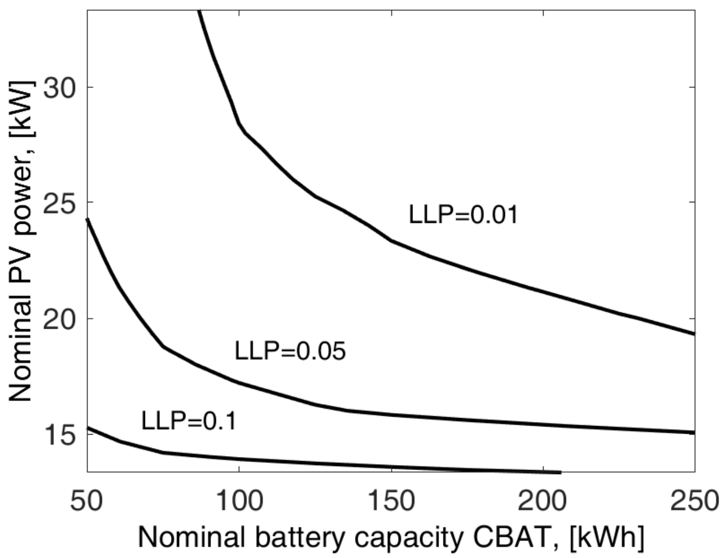


Figure 9. Iso-reliability LLP curves for Madrid using as input TMY data.

References

[1] J. Muñoz. Modeling of solar radiation, PV components and systems in PVlite, v2.3, 2024, https://blogs.upm.es/javiermunoz/

[2] James SPELLING, KTH-EGI-EKV, spelling@kth.se. Function drawSankey, Version: 02.11.2009.