Training Letter Photovoltaics - Planning and Sizing PV Off-grid Systems

Dr. Barbara Tomaszewska	(PAS MEERI Krakow - Poland)
Aleksandra Kasztelewicz	(PAS MEERI Krakow - Poland)
Prof. Dr. Michael Hartmann	(SRH Hochschule Berlin – Germany)
Ing. Ec. Jürgen Weinreich	(SRH Hochschule Berlin – Germany)

Training Letter Photovoltaics – Planning and Sizing PV Off-grid Systems

PV off-grid systems consist of

- **Photovoltaic modules** which directly convert the solar energy into electrical power given in **Watt (W)**. The modules operate at a given **voltage U (in Volt)** and provide an **electric current I (in Ampere)**. The relation between these quantities is **P = U I.**

- The **batteries** to store the energy produced by the photovoltaic modules. The capacity of the battery is given in **Ah (Amperehours).**

- The **charge controller** to protect the battery from overcharging by the photovoltaic modules when strong sun light and from deep discharging by the loads (lead acid solar batteries should not be discharged more than 50% since otherwise the lifetime decreases significantly). The power of the charge controller is given by its **Amperage in Ampere (A).**

- The **inverter** to convert the 12VDC (or higher like 24 VDC or 48 VDC) from the batteries to 230 VAC. The power of the inverter is determined by its **Wattage in Watt (W).**

The following steps show how to determine the size, i.e. the relevant parameters described above, of the single components.

Sizing Off-grid PV Systems

A) Analyse the energy consumption of all loads like lamps, TV, etc.

Example

Loads	**Voltage U (Volt)**	**DC Power P_{DC} (Watt)**	**AC Power P_{AC} (Watt)**	**Daily operation time (h)**	**Daily energy consumption E (Wh/d)**
2 LED a 12 W in living area	12 or 24	2*12 = 24		3	72
1 LED a 12 W in workshop	230		1*12 = 12	3	36
Refrigerator	230		50		300
TV Set	230		50	2	100

Water pump	230		60	3	180
Laptop	230		50	5	250
Total		**24**	**222**		**938**

To execute this system and to supply all loads with power a total system power of 24 W + 222 W = 246 W and energy supply of 938 Wh will be needed.

These both quantities determine the necessary size of the components of the off-grid PV system as follows.

B) System voltage and size of the charge controller

Standard charge controllers operate at 12 V or 24 V and have to be selected according to the maximum Amperage given by

$$I = \frac{P}{U} = \frac{246\,W}{12V} = 20.5\,A$$

if we operate at 12 V. To have a reserve (recommended 25%) we would choose a charge controller of 30A at 12 V.
If we decide to operate at 24 V we get instead

$$I = \frac{P}{U} = \frac{246\,W}{24V} = 10.25\,A$$

and we can choose a charge controller of 15 A at 24 V.
Note: Here, the initial sizing of the charge controller was only done by considering the load side. At the end this value has to be checked also with the PV side. Both values must be smaller than the rated amperage of the charge controller chosen.

C) Size of the battery

We assume a depth of discharging of average 50% (DoD = 0.5) since otherwise the lifetime of the battery would decrease. Furthermore, cloudy days have to be buffered (typical 3days, factor D = 3). The battery capacity in Amperehours (Ah) is then estimated according to

$$C = \frac{D \times E}{U \times DoD}$$

DoD – Depth of Discharging (average 0.5)
D – number of cloudy reserve days (in d), also called autonomy days

E – energy demand (in Wh/d)
U – voltage (typical 12 V, 24 V, 48 V)

Example:

$$C = \frac{3\,d \times 938\,Wh/d}{12V \times 0.5} = 469\,Ah$$

if we operate at 12 V. One could take e.g. 4 batteries of 120 Ah all connected parallel. (recommendation: One should not connect more than 4 batteries parallel).

If we decide to operate at 24 V we obtain

$$C = \frac{3\,d \times 938\,Wh/d}{24V \times 0.5} = 234.5\,Ah$$

In this case one could install two parallel connected strings of batteries which are in series in each string.

D) Dimensioning of the inverter:

All loads operating at 230 V have to be supplied by an inverter, in total 222 Watt. A typical inverter size is 300 Watt. There are inverters for 12 V_{DC} as well as 24 V_{DC} input voltage.

E) Sizing of the PV module:

The size of the PV module is estimated according to

$$P_{Peak} = \frac{E}{(1 - V_{temp})\,(1 - V_{sys})\,E_{d,0}} = \frac{E}{E_d}$$

with

E – Energy demand in kWh
$E_{d,0}$ – Average daily solar irradiation in kWh for a 1 kWp reference module obtained from a data base
V_{temp} – Average losses of the module due to temperature effects (the higher the temperature the lower the efficiency of the module).
V_{sys} – Overall system losses (typical 14% = 0.14) comprising Ohmic losses of the connecting wires, losses of the charge controller, inverter and batteries and potentially losses of the PV modules if they don’t operate at the MPP.

In E_d in the second formula above all losses（V_{temp} and V_{Sys}） are already taken into account，i.e.

$$E_d = (1 - V_{temp})(1 - V_{Sys})E_{d,0}$$

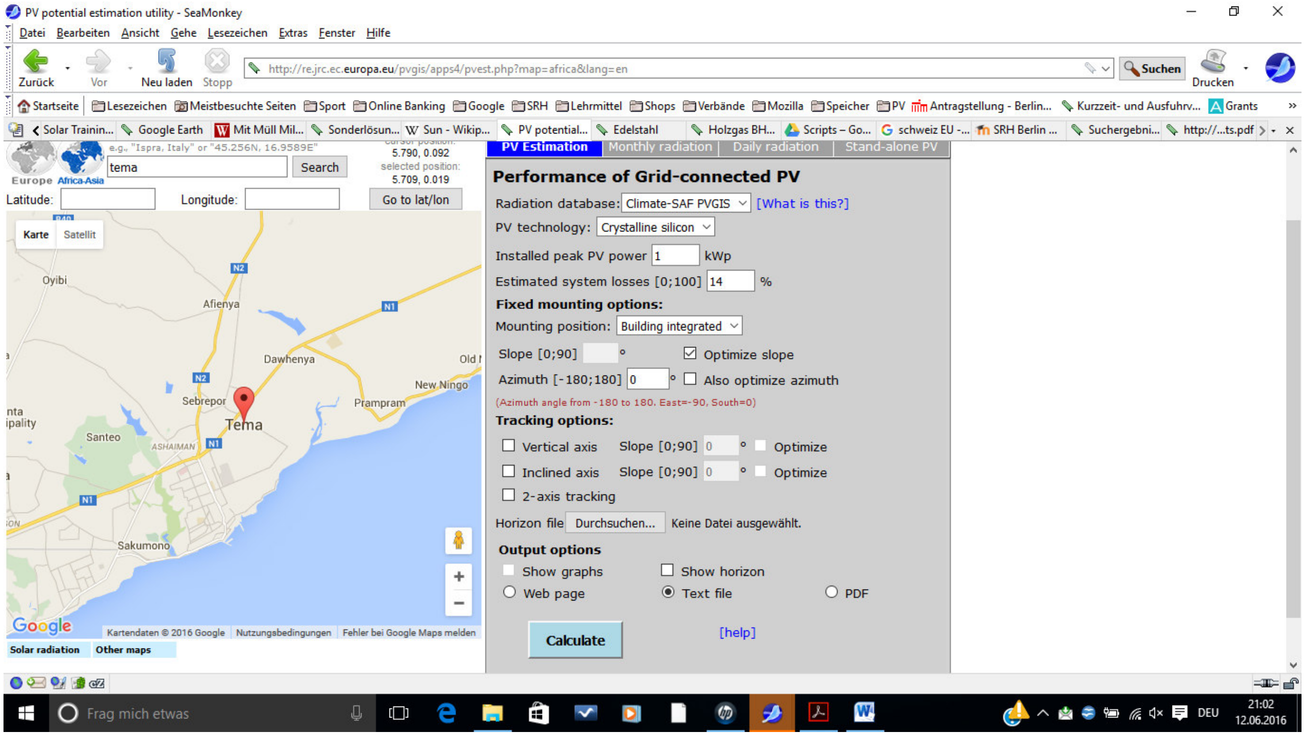
If using PVGIS as a data base http://re.jrc.ec.europa.eu/pvgis/，the losses can be specified in the input matrix（see example below） and E_d is immediately obtained in the output．

Example:

Using PVGIS we can choose regions in Europe or Africa-Asia to obtain the irradiation data． For Tema （Ghana），the following input data are specified in the "PV Estimation" on the right hand side of the input mask（see screen view below）：

- Radiation Data Base as given
- PV technology：Crystalline Silicon
- Installed PV Peak Power：1 kWp
- Estimated System Losses：14% （this is V_{Sys} in the formula above）
- Mounting Position：Building integrated
- Slope：Optimize slope
- Tracking option are not considered （leave it free）
- Output option：Web or Text or Pdf

Note that the temperature loss（V_{temp}） is automatically included in PVGIS．



http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en

tema

cursor position: 5.790, 0.092

selected position: 5.709, 0.019

Performance of Grid-connected PV

Radiation database: Climate-SAF PVGIS [What is this?]

PV technology: Crystalline silicon

Installed peak PV power 1 kWp

Estimated system losses [0;100] 14 %

Fixed mounting options:

Mounting position: Building integrated

Slope [0;90] ° ☑ Optimize slope

Azimuth [-180;180] 0 ° ☐ Also optimize azimuth

(Azimuth angle from -180 to 180. East=-90, South=0)

Tracking options:

☐ Vertical axis Slope [0;90] 0 ° ☐ Optimize

☐ Inclined axis Slope [0;90] 0 ° ☐ Optimize

☐ 2-axis tracking

Horizon file Durchsuchen... Keine Datei ausgewählt.

Output options

☐ Show graphs ☐ Show horizon

○ Web page ● Text file ○ PDF

[help]

The following output is obtained:

Latitude: 5°42'32" North,

Longitude: 0°1'7" East

Nominal power of the PV system: 1kWp

Inclination of modules: 7deg.

Orientation (azimuth) of modules: 0deg.

Fixed angle

Month	Ed	Em	Hd	Hm
1	4.43	137	6.45	200
2	4.34	122	6.37	178
3	4.64	144	6.83	212
4	4.24	127	6.28	188
5	3.87	120	5.58	173
6	3.49	105	4.99	150
7	3.60	112	5.18	161
8	3.82	118	5.51	171
9	4.10	123	5.92	178
10	4.41	137	6.43	199
11	4.34	130	6.31	189
12	4.31	134	6.25	194
Year	4.13	126	6.01	183

Ed: Average daily electricity production from the given system (kWh)

Em: Average monthly electricity production from the given system (kWh)

Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

PVGIS (c) European Communities, 2001-2012

Thus we have an annual average of the solar irradiation of about E_d = 4.13 kWh/(kW_p*d) (see yellow number in the output) which gives for the size of the module

$$P_{Peak} = \frac{0.938\ kWh/d}{4.13\ \frac{kWh}{kW_p * d}} = 0.23\ kW_p$$

We can choose e.g. two 130 W_p modules 12 VDC connected parallel. The current is then I=260 W_p / 12 V = 22 A which matches to the specified charge controller above (see the note in B)).

Alternatively we could use one 250 W_p module for 24 V which also matches the specified charge controller of 15 A.

F) Sizing of the cables

Sizing of the cables means to determine an appropriate cross section or length so that the cable losses are minimized.

Every wire has a certain resistance, symbolized by R, which impedes the free flow of electric charges. This leads to a voltage drop along the wire. The unit of the electrical resistance R is Ohm, symbolized by Ω, and defines the voltage drop (in Volt) at a defined current of 1 Ampere:

$$1\Omega = \frac{1V}{1A}$$

The resistance is specific for each material and depends on the length L and the cross section A of the wire according to

$$R = \frac{L\,\varrho}{A}$$

where ρ is the so called specific resistance of the material the wire is made of and for a length of 1m and a cross section of 1 mm^2. Typical values can be found in tables. For copper or aluminum its e.g.

Copper: $\varrho_{Cu} = 0.0179\ \frac{\Omega\, mm^2}{m}$

Aluminum: $\varrho_{Al} = 0.0294 \frac{\Omega\, mm^2}{m}$

Thus copper is better suited for wiring than aluminum since it has a smaller specific resistance leading to a higher conductance. (The conductance κ is the reciprocal of the specific resistance, thus it is $\kappa_{Cu} = 56 \frac{m}{\Omega\, mm^2}$ and $\kappa_{Al} = 34 \frac{m}{\Omega\, mm^2}$). The following example shows the efficiency loss due to the resistance for different cable cross sections.

Example:

Assume that the copper cable from the PV module to the charge controller is 5m. Since we have "+" and "−" wires, the total length is $L = 10m$. In the following examples we consider the resistance and voltage loss for two different cable cross sections:

a) A = 1.5 mm^2

$$R = \frac{L\,\varrho}{A} = \frac{10m \times 0.0179\,\Omega\, mm^2/m}{1.5mm^2} = 0.12\Omega$$

We assume that the PV module has a voltage of $U = 12V$ and a power of $P = 250W$. This gives a current of $I = \frac{P}{U} = \frac{250W}{12\,V} = 20.8A$

The voltage loss U_{loss} due to the resistance is then $U_{loss} = R \times I = 0.12\Omega \times 20.8\,A = 2.5\,V$

This causes also a power loss of $P_{loss} = U_{loss} \times I = 2.5\,V \times 20.8\,A = 52\,W$ which is about 21% power loss compared to the rated power (250W).

b) Now we consider a larger cross section $A = 6mm^2$

$$R = \frac{L\,\varrho}{A} = \frac{10m \times 0.0179\,\Omega\, mm^2/m}{6\,mm^2} = 0.03\,\Omega$$

This causes a voltage loss of $U_{loss} = R \times I = 0.03V \times 20.8A = 0.624\,V$ which gives a power loss of only $P_{loss} = U_{loss} \times I = 0.624\,V \times 20.8A = 13\,W$, i.e. only 5.2%.

Conclusion: The bigger the cross section of the cable the lower is the voltage and power loss. In practice, the power loss should be restricted to 1-3%.

Therefore we obtain from the above formulas for the appropriate cross section

$$A = \frac{L\,P_{PV}\,\rho}{0.03\,U^2} = \frac{L\,P_{PV}}{0.03\,\kappa\,U^2} = \frac{L\,I^2}{0.03\,\kappa\,P_{PV}}$$

P_{PV} – rated power of the module
U – rated voltage of the module
I – rated amperage of the module

Example: L = 10 m, P = 250 W, U = 12 V

$$A = \frac{L\,P_{PV}}{0.03\,\kappa\,U^2}$$

$$= \frac{10m \cdot 250W}{0.03 \cdot 56m/\Omega mm^2 \cdot 12^2V^2} = 10\,mm^2$$

In order to restrict the cable losses to 3% a cross section of 10 mm^2 is required if we operate at a system voltage of 12 V.

Operating at 24 V we obtain

$$A = \frac{L\,P_{PV}}{0.03\,\kappa\,U^2}$$

$$= \frac{10m \cdot 250W}{0.03 \cdot 56m/\Omega mm^2 \cdot 24^2V^2} = 2.6\,mm^2$$

Standard sizes for cables in photovoltaics are:
0.75 mm^2
1.5 mm^2
2.5 mm^2
4.0 mm^2
6.0 mm^2
10.0 mm^2
16.0 mm^2
35.0 mm^2

In practice, the following diagrams can be used for a 12V or a 24V photovoltaic system respectively, in order to determine the cable cross section.

Typically, PV modules are delivered with cable cross sections of 4 mm^2 or 6 mm^2. Using these fixed cable cross sections the length between PV modules and charge controller should be as short as possible. It can also be estimated from the above formula according to

$$L = \frac{0.03\, A\, \kappa\, U^2}{P_{PV}}$$

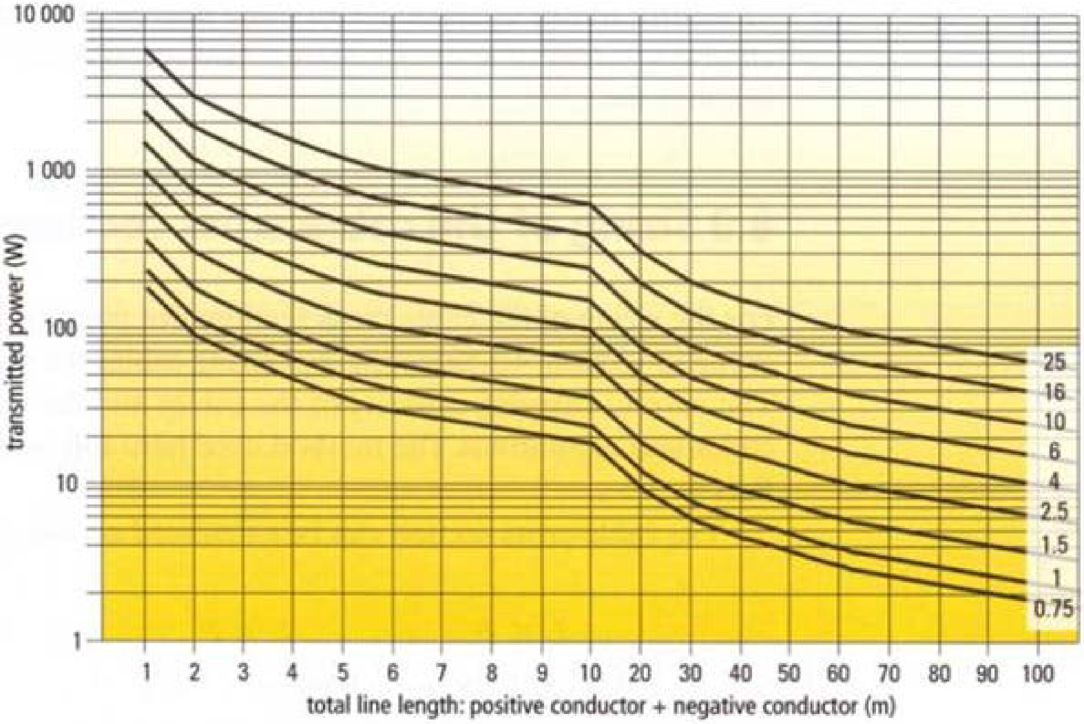
Example: For a 4 mm^2 cable cross section this gives e.g.

12 V system voltage: L_{max} = 3.8 m

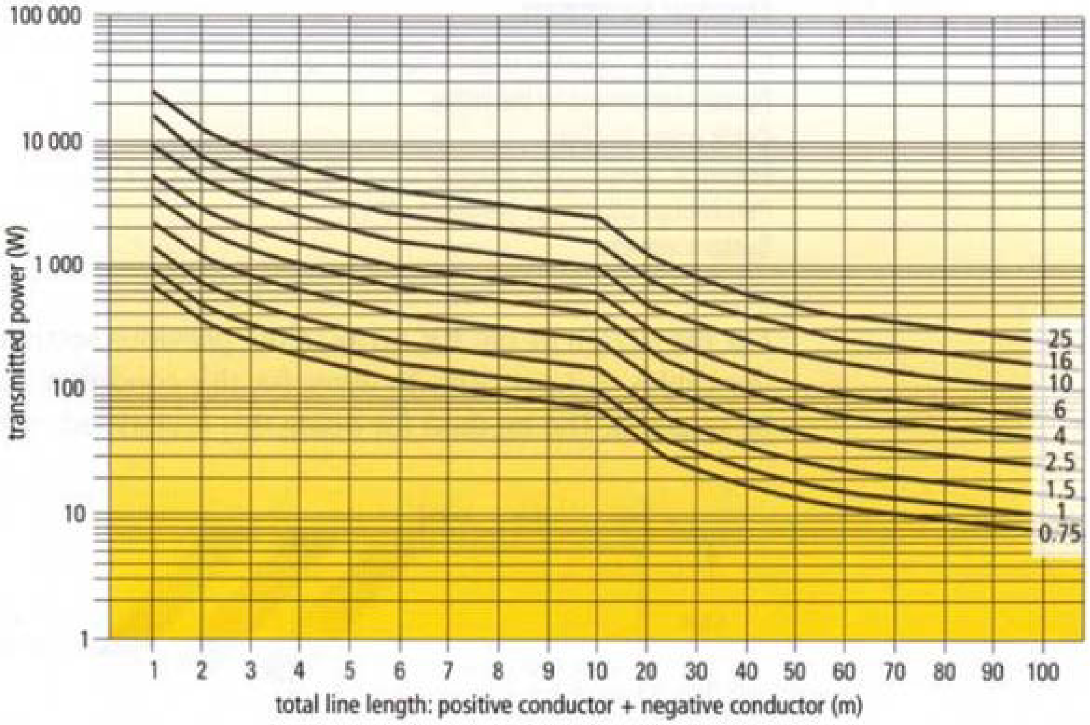
24 V system voltage: L_{max} = 15 m

Thus, if a long wire between PV modules and charge controller is required one should use a system voltage of 24 V.

Cable cross sections for a 12V system: cable losses 3%



Cable cross section for a 24V system: cable losses 3%



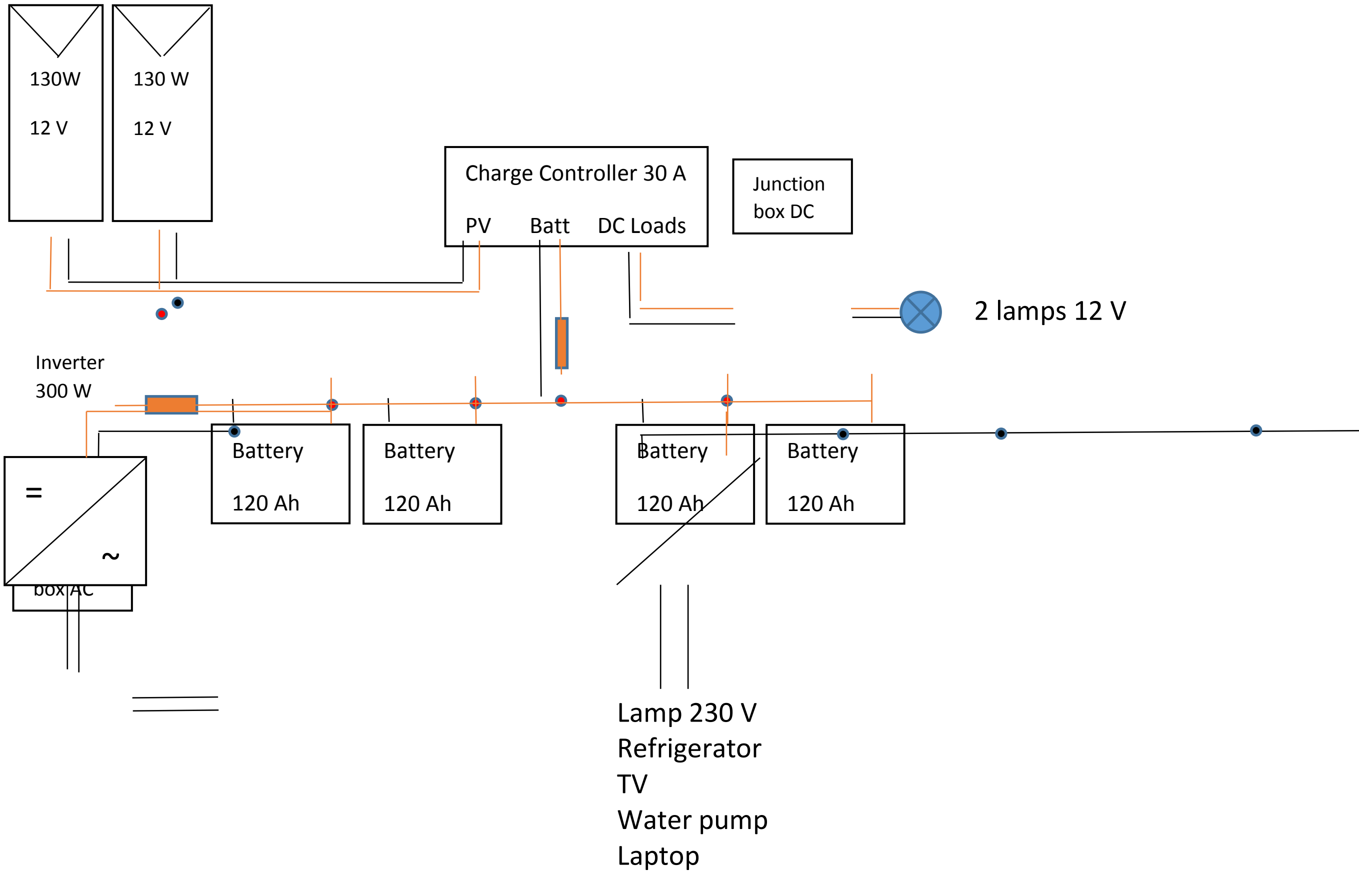
G) Fuses

Fuses are used in order to protect the system from overcurrent due to dysfunction. The amperage of the fuses is chosen to be the maximum allowed current, i.e. in our example 30A for 12 V system voltage and 15A for the 24 V system voltage.

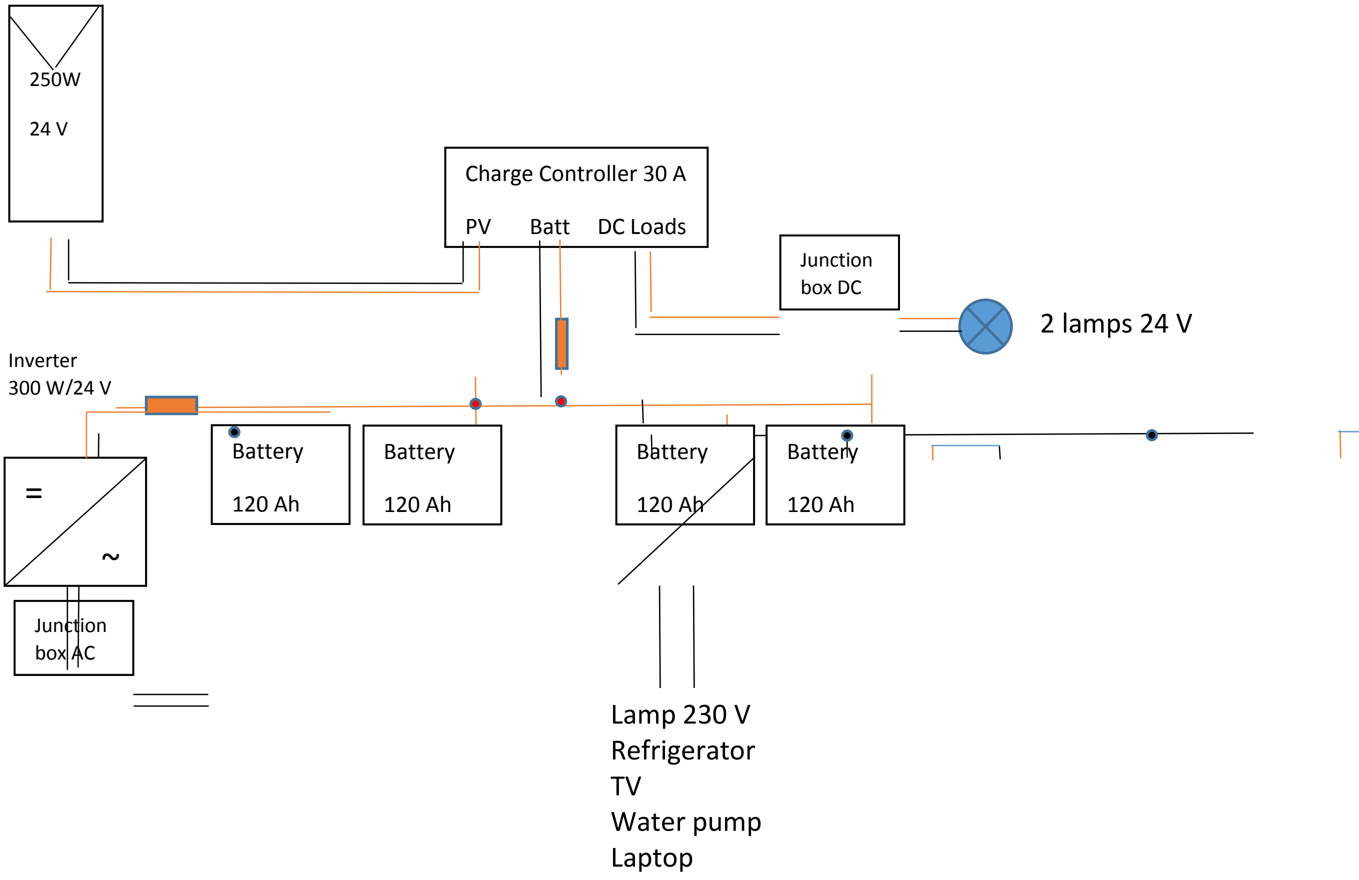
H) System Diagram

Example:

a） Complete off-grid PV system, 12V



b） Complete off−grid PV system，24V



Templates for Planning and Sizing

A） Electric Power Consumption Analysis

Loads	**Voltage U (Volt)**	**AC Power P_{AC} (Watt)**	**DC Power P_{DC} (Watt)**	**Daily operation time (h)**	**Daily energy consumption E (Wh/d)**
Total					

B） System voltage and size of the charge controller

$$I = \frac{P}{U}$$

C） Size of the battery

$$C = \frac{D \times E}{U \times DoD}$$

DoD – Depth of Discharging （average 0.5）
D – number of cloudy reserve days （in d）
E – energy demand （in Wh/d）
U – voltage （typically 12 V, 24 V, 48 V）

D） Dimensioning of the inverter:

E） Sizing of the PV module:

$$P_{Peak} = \frac{E}{E_d}$$

F） Sizing of Cables

G） Fuses

H） System Diagram