Proposal for a Photovoltaic Curriculum

For Colleges in the Caribbean

Final Draft

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Background

The main reason for preparing a PV (photovoltaic) curriculum for the Community College SALC is that each island (St. Lucia, St. Vincent and Grenada and Barbados) has a college or even a technical college, with technical classes, in which renewable energies and energy efficiency subjects will be taught. In some cases they are already taught. So far, only some general subjects, for example solar water heater is partly integrated in teaching.

There is a demand to train the future technicians and students especially in PV installations and in solar thermal systems. In the long run the aspects of greener building should be taught as an integrated concept, which combines all aspects.

There are several initiatives like “Greening the College” in St. Lucia, or the introduction of a Renewable Energy module in Grenada, or the installation of PV systems in Grenada and St. Vincent. But so far these singular items are not fully integrated into the curricula.

The changes in energy policy, like the possibility for Net-Metering in Grenada, St. Vincent, soon in Barbados and maybe in St. Lucia, will create a demand for technicians in PV technology. Due to rising fuel costs technicians in solar thermal systems installations will be needed. In the long run it is expected, that the increased awareness of renewable energies and their possibilities will lead to an increased demand in energy efficient buildings.

The main objective is to support colleges in “greening their Campus”.

A grid-tied Photovoltaic system with around 5kWp will be installed at the SALCC. The permanent PV generator will be mounted on the roof of the technical complex of the college.

The second objective is the support for students to have basic knowledge in photovoltaic. Students will construct a non-permanent small demonstration house with a Photovoltaic system on the roof, which will be for educational purposes. Non-permanent means that it will only be there for a limited period and will be dismantled for the next generation of students in the next year.

Furthermore a separate demonstration device will be built for experimental purposes. It will consist of a roof structure built on the ground showing a complex roof design in order to simulate real installations and for students to learn more about the impact on the energy generated due to shading.

Preface

This curriculum course is divided into two main parts, -theory and experimental training.
The theory part will mostly be concerned with the understanding of the basic principles of various components of PV systems, installations, safety measures and regulations.
The experimental part is an integral part of the theoretical component of the course and as such it is considered to be a vital element of the curriculum. An experimental case such as **Solar Power Case** (around 1300 Euro) or **Solar Power Laboratory** (around 3500 Euro) from Christiani GmbH will be needed. With this case, students will have the possibility to do experiments in the laboratory before doing any work or project on a real Photovoltaic system. The experiments enable students to learn by application and experience.
The **Solar Power Case** performs a sophisticated teaching aid either to present the technology in theory and practice or to work on photovoltaic basic knowledge independently and in student groups.
By the Solar Power Case, own school projects can be planned, modelled and presented for decision process, for example a solar lighting of a showcase or an independent illumination of rooms etc. Besides this direct application, students are able to inform their parents, visitors and fellow students on photovoltaic during school celebrations and project days.
The **Solar Power Laboratory** provides students with practical understanding of both **off-grid** and **on-grid** technology.
The objectives of a Solar Power Case or Solar Power Laboratory are:

- The electric circuit: Understand the system with a source of energy, cables and consumer modules
- The energy accumulator: The link between the charging circuit and the consumer circuit
- The solar power system: Understand the individual functions and the work the components shall perform
- Measurements with the solar power circuit: Open-circuit voltage and short-circuit current at various light intensities, angles of incidence and temperatures
- Identifying the IV characteristic and the MPP
- The battery is the energy accumulator in the PV off-grid technology: Discharge protection and charging regulator; current distribution during charging and draining; internal-resistance measurements of module and battery, exhaustive discharge protection
- Electric circuits possible with the PV off-grid technology: Individual overvoltage protection functions; fuses, splitters and consumers
- Separate inverters: Voltage and current measurements; efficiency and AC voltage waveforms

The components of a Solar Power Laboratory case are:

- Photovoltaic module 12 V
- Halogen spotlight, dimmable, 230 V, 500 W
- Generator connector with voltmeter 15/150 V DC
- Overvoltage protection, 12 V
- Discharge protection diode
- Charging regulator 12 V, 4 A
- Exhaustive discharge protection 12 V, 15 A
- Lead gel battery 12 V
- Safety light (maintained operation) 12 V, 5 W
- Safety light (non-maintained operation) 12 V, 15 W
- General light 23 V, 15 W
- Relay 12 V, 30 A
- Resistor 10 Ohm, variable

- Load resistor, 2 kΩ, variable
- Supply connection unit
- Consumer, 12 V, E27; low-voltage socket
- Circuit breaker
- Relay 2 x 230 V
- Network monitoring relay 230/400 V
- Residual current protective device
- Digital multimeters (2 units)
- Safety divider 1, 3, 5 A
- Luxmeter (measurement device), 0 to 100,000 Lux
- Plug-in charging device for lead-gel battery
- Connecting lines with safety plugs (multi-contact), in various lengths and colours
- Energy-saving lamp 12 V, 11 W, E27
- Filament lamp 230 V, 15 W, E27
- Set of small electrical spare parts (storage box, automotive blade-type fuses, blade-type fuse withdrawing device, miniature fuses, festoon lamp)

Some technical colleges that have an electrical section have many of the experimental case components. The rest could be bought separately.
At the end of this curriculum a copy of the experimental sheet for off-grid PV system and On-grid PV system from Christiani GmbH is attached in an extra PDF file.

Chapter 1 Introduction

1.1 Renewable energy

Due to the increasing of extreme weather events such as floods, storms, dries the natural environment on which millions of people depend on is severely damaged. Those environmental disasters are the result of the burning of fossil fuel, particularly oil. The move to clean energy such as solar energy, wind energy, hydroelectric, bio-energy (energy from plants) energy is desirable and necessary in order to preserve the eco-spheres on which human life is dependant. The UN's Intergovernmental Panel on Climate Change (IPCC) predicted a temperature increase of between 1.4°C to 5.8°C over the next 100 years, depending on if industrialized societies and newly industrializing societies shift to a low carbon economy.[1] The temperature increase is the main cause of these extreme weather events. The use of renewable energy will reduce carbon dioxide and other gas emissions and help to avoid environmental catastrophes. For example a 1.5MW (megawatt) wind turbine, with 70 meters rotor diameter can generate 76 GWh (gigawatt-hours) of electricity in 20 years. At the same time a modern brown coal would need to burn 84000 tonnes of fuel to produce the same electricity.[2] It is easy to estimate how many tonnes of carbon dioxide CO_2 emission would be generated. It is assumed that coal-powered systems give off 1 kg of CO_2 for each kWh of electricity generated.[3]

Renewable energy presents business opportunities. Around one third of the world's population has no access to electricity most of them in rural areas. So think about what opportunities lie in renewable energy!

1.2 Sun as source of energy

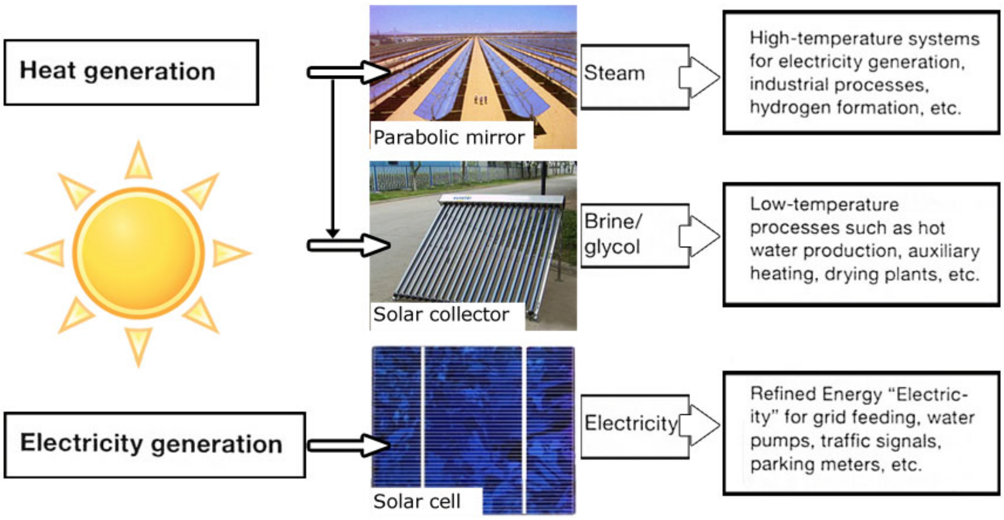

Figure 1.1: Systems for direct use of solar energy, source: solar power laboratory by Christiani

Solar energy is the most wide spread renewable energy. The amount of sunlight falling on the earth contains far more energy than we could ever use. In full sun periods we can reach about

[1] Photovoltaic for professionals from Karl-Heinz-Remmers
[2] Photovoltaic for professionals from Karl-Heinz-Remmers
[3] Solar power laboratory by Christiani

a maximum of 1000 watts of energy per square meter.[4] Solar energy is easier accessible than other energy resources. The initial cost is the main disadvantage of installing a solar energy system, largely because of the high cost of the semi-conducting materials used in building one. But after the initial investment has been recovered, the energy from the sun is practically free. Once installed, there are just very low recurring costs. The oil industry uses price per barrel as its unit of price measurement. The solar energy industry uses price per Watt Peak (Wp) as its primary unit of measurement. Solar energy is predictable and the yearly yield is fairly constant. At any given time during the day the sun is usually shining somewhere and solar electricity can be distributed from a region where the sun is shining to one where it is shining less. The use of solar energy is not associated with any environmental risks. Solar energy can be use in many forms. **(Figure 1.1)**
Sun supplies energy in the form of radiation.

1.3 Solar radiation

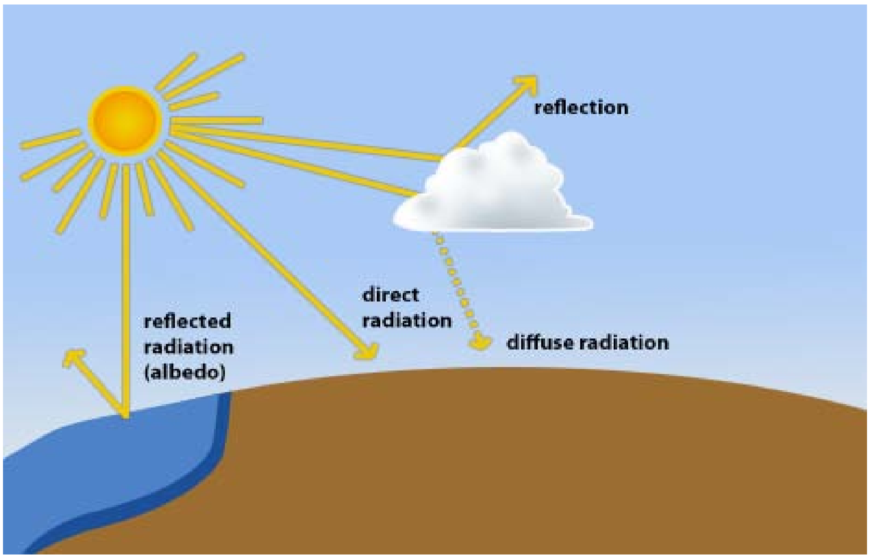

Figure 1.2: sunlight on his way through the atmosphere [5]

Million tonnes of hydrogen nuclei are fused per second within the sun to become helium nuclei. This nuclear fusion releases energy. Solar radiation is the energy emitted from the sun that travels through the space to the surface of the earth. A radiation can be diffuse or direct **(Figure 1.2)**. When a radiation is scattered, reflected, or absorbed by atmospheric constituents such as clouds, water vapour and dust we talk about **diffuse radiation.** On the other hand it is **direct radiation** on clear days where the sun prevails.

Solar irradiance is the power of solar radiation per unit area. It is commonly expressed in units of watts per square meter (W/m^2) or kilowatts per square meter (kW/m^2).[6]

The solar energy that constantly arrive the atmosphere is around **1,370 W/m²** and is called solar **constant**. The absorption of radiation by air, clouds and water vapour reduces the

[4] Photovoltaic for professionals from Karl-Heinz-Remmers
[5] Planning and installing photovoltaic systems, DGS, Germany
[6] Photovoltaic systems instructors resource Guide by American technical publishers.

radiation energy on earth. The **standard value** for the maximum radiation on earth is **1,000 W/m²**.[7]

In the city of Castries in St. Lucia we have an annual global radiation on horizontal area approximating 2015 $\mathrm{kWh/m^2}$ for an average temperature of 26°C. The monthly average is shown in Table 1.1.

Monthly Radiation onto 0° tilted surface and 0° south orientation in Castries, SAINT LUCIA		
Month	Global radiation ($\mathrm{kWh/m^2}$)	Temperature (°C)
Jan	153.26	24.7
Feb	151.87	24.6
Mar	182.28	25.0
Apr	181.44	25.8
May	185.26	26.5
Jun	172.80	26.9
Jul	177.82	26.9
Aug	186.74	27.0
Sep	167.76	26.7
Oct	162.94	26.4
Nov	146.88	25.1
Dec	145.82	25.1

Table 1.1: Monthly average solar radiation on horizontal surface, source: Meteonorm Valentin energy software.

When the surface is no more horizontal, the module has an inclination, the radiation changed. Table 1.2 is an example on 15° inclination angle.

Monthly Radiation onto 15° tilted surface and 0° south orientation in Castries, SAINT LUCIA	
Annual Value:	2.062 ($\mathrm{kWh/m^2}$)
Jan	175,22
Feb	165,68
Mar	188,74
Apr	178,11
May	174,78
June	159,85
July	166,23
Aug	179,24
Sep	168,78
Oct	172,92
Nov	164,57
Dec	168,09

Table 1.2: Monthly average solar radiation on a roof with 15°C inclination 0° south orientation in Castries St. Lucia, source: Valentin energy software

The two tables show the variation of solar radiation on inclined surface. By 15° inclination and 0° south orientation, the maximum energy yield will be obtained. For manual calculation of energy yield, table 1.2 is important. It is considered as the basic reference.

[7] Solar power laboratory by Christiani GmbH

1.3.1 Angle definition

To be able to calculate solar radiation data and the energy yield of photovoltaic generators the exact knowledge of the sun location is important. Its elevation and its azimuth describe the location of the sun at any given place (Figure 1.3). The **solar azimuth angle** is the horizontal angle between a reference direction and the sun. This angle varies between -180° and +180°. The module or **Panel azimuth** is also call **module orientation**. The **solar altitude angle** is the vertical angle between the sun and the horizon. During day times, this angle varies between 0° and 90°. It's also known as **solar elevation.** When it has 90° we talk about **zenith**. It's corresponding to the suns position on the equator at midday.

The altitude *h* and the zenith angle *z* are thus related by[8]:

$$h = 90° - z$$

The solar elevation and azimuth angle can be calculated with help from many online softwares such as http://squ1.org/wiki/Solar_Position_Calculator or http://www.satellite-calculations.com/Satellite/suncalc.htm.
In Saint Lucia "Castries" the **latitude** is 14.02° and the **longitude** is 60.98°. This also helps to determine the tilt angle.
The **tilt angle** and the **orientation** (generally points to south in the northern hemisphere and north in the southern hemisphere) of the photovoltaic (PV) array are the key to an optimum energy yield. The optimal angle of tilt for PV modules is equal to **the latitude** of your site. **For example** in the city of Castries the PV module should be oriented south and with a tilt angle of 14°.
Solar panels or PV arrays are most efficient, when they are perpendicular to the sun's rays at noon. That means the array Tilt is **90°- sun altitude at noon**

Month	Sun Altitude at noon	Array Tilt angle at noon	Array Points to:
JAN	56	34	South
FEB	65	25	South
MAR	76	14	South
APR	88	2	South
MAY	84	6	North
JUN	81	9	North
JUL	84	6	North
AUG	88	2	South
SEP	76	14	South
OCT	64	26	South
NOV	56	34	South
DEC	53	37	South

Table 1.3: Tilt and altitude angle, 14° latitude north, source: www.alternateenergy.net/angle_calc05.html

The **hour angle** is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^o per hour in the morning being negative and afternoon

[8] http://en.wikipedia.org/wiki/Solar_azimuth_angle

being positive. For example, at 10:30 am, the hour angle is -22.5° (15° per hour times 1.5 hours before noon).[9]

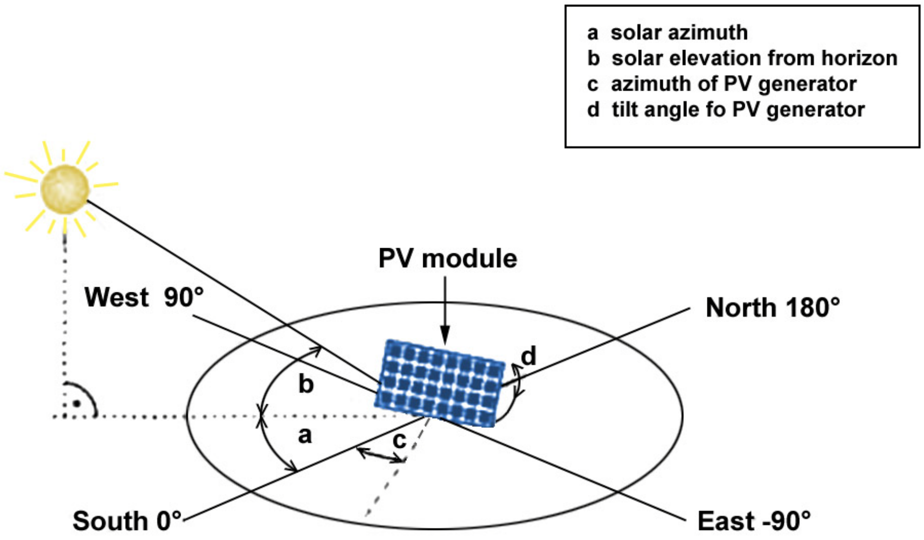

Figure 1.3: Depiction of angle in solar techniques.[10]

1.4 Photovoltaic

A photovoltaic system is a system that turns sunlight into electricity. This is also called **PV** system or photovoltaic energy**.** Photovoltaic energy has many locations such as South, east or west-facing roofs, building facades, open spaces, noise barrier walls, etc… The more sun shines the more electricity will be produced. No electricity is produced at night even if the moon seems very bright. To make it more understandable PV systems will be compared to water systems because there are similar ideas. Let us take the example of a rainwater collection system. The amount of water collected changes with the weather. "To collect solar energy, a solar module (picture 1.1) is used. It is equivalent to the roof in a rainwater system."[11]

Figure 1.1: Solar module, source: www.schottsolar.com/global/products/photovoltaics/schott-poly-225

[9] http://en.wikipedia.org/wiki/Hour_angle
[10] Planning and installing photovoltaic systems, DGS, Germany
[11] Photovoltaic systems technical training manual, UNESCO

1.4.1 Storage

“To store solar electricity, a battery (figure 1.2) is used. It is equivalent to a tank in a rainwater system.” [12]
Like water is needed when it is not raining, electricity is needed when the sun is not shining. If it rains a lot and no one uses much water the tank fills up. The same happens if the sun shines a lot and there is little use of electricity then the battery becomes full of electricity. At the same time if you use water from the tank faster than rain falling, the tank will run dry. If you use much electricity when there is not enough sunshine the battery will gradually falls and get empty.

The electricity produced can also be directly used without storage. *More on chapter 4*

Figure 1.2: Battery, source: www.homesolarpvpanels.com/deep-cycle-solar-batteries.php

1.4.2 Flow control, appliances and transport

Water tanks have valves on their outlet pipes to control the use of water. PV systems have a controller between the battery and appliances to control the use of electricity.
In PV system you can connect many appliances such as televisions, radios, refrigerators and lights but the system has to be designed for that. Just like the water system, there is often just a tap on it, but other appliances can be attached to the system such as showers and toilet flushes.
Electricity like water has to move from place to place. Pipes are used for water, wires or cables for electricity. As you might know, if pipes are not joined together correctly, they lick and not all the water does reach the appliance. The same happens if wires are not joined correctly, we will register higher losses of electricity.

1.4.3 Summary

Rainwater **PV system**

Rain	< Source >	Sunlight
Roof	< Collection >	Panels
Valves	< Control >	Controller
Tank	< Storage >	Battery
Pipes	< Transport >	Wires
Appliances	< Use >	Appliances

[12] Photovoltaic systems technical training manual, UNESCO

CHAPTER 2: Photovoltaic cells, modules or Panels and arrays

2.1 Solar cells

Solar cells convert light directly into electrical energy. They are in photovoltaic one of the most important components. No cells no Electrical energy. There are many type of cells; thin film cells, amorphous silicon, monocrystalline and polycrystalline silicon. Currently the crystalline silicon solar cells are the most used. Crystalline silicon is not a chemical element. It can be found in minerals like quartz.

Amorphous solar cells are cells without shape or form. The abbreviation is "a-Si". The efficiency level is between 5 and 7%. The form is freely selectable and the thickness between 1 an 3mm.

Monocrystalline solar cells have cell efficiency between 16 and 18%. They are also known as "Czochralski" solar cell and have the abbreviation "CZ-Si". The form is usually rounded, semi-square or even square. And the thickness 0.3mm

With the abbreviation"poly-Si", **polycrystalline solar cells** are less expensive than monocrystalline but have less efficiency level (between 12 and 14%). The form is usually rectangular or square and the thickness 0.3mm.

Temperature has a big effect on solar cell output. A 30°C increase in temperature will reduce crystalline silicon cell output up to 15%. This means up to 0.5% for each 1°C increase in temperature. For amorphous silicon cell it is approximately 0.2% per degree Celsius increase.[13]

2.2 Structure and functional principle of a solar cell

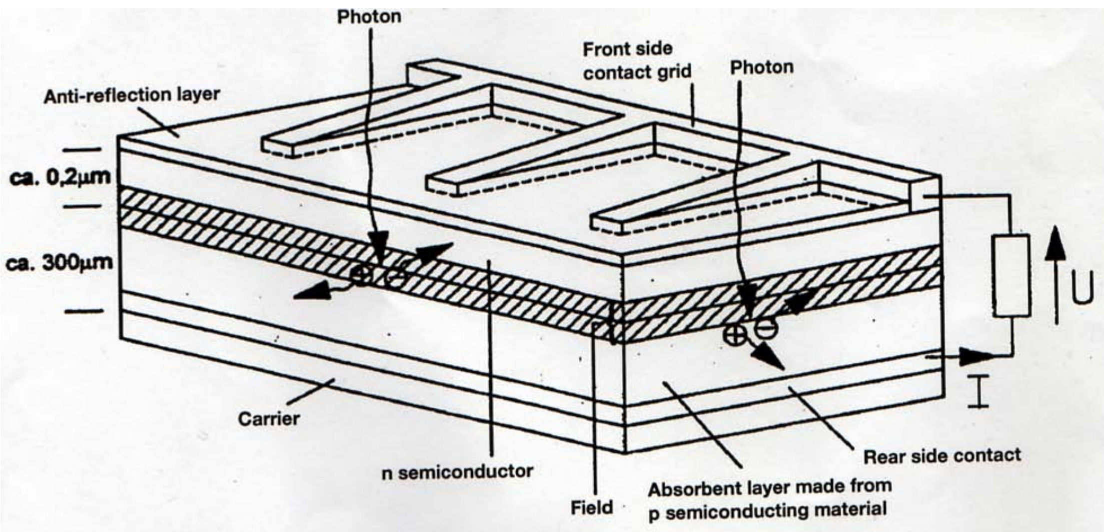

Figure 2.1: Structure of a solar cell, source: solar power laboratory, Christiani GmbH

A solar cell consists of a *p* semiconductor and *n* semiconductor sandwiched together and called "p-n transition". This p-n transition induces an electric field across the transition. The anti-reflection layer reduces the light reflection. It makes sure as much light as possible enters the cell. Metal contacts are attached on the front and rear sides in order to integrate the cells into an electric circuit. (Figure 2.1)

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[13] photovoltaic for professionals, Karl-Heinz Remmers

If light meets the electrons in the p-n transition, these particles are freed from their connections to their atom cores. Electrons and holes are formed. The electrons move to the n-zone and holes to the p-zone. Typical solar cells are 10 x 10 cm. Under full radiation they yield electricity of up to 3A per dm^2 with a voltage of 0,6V when no consumers are connected. The trend in the manufacture is rising to 20x20 cm.[14]

2.3 Modules, characteristics, and parameters

2.3.1 Modules

To convert sunlight to electricity in a Photovoltaic system, we need modules or panels. We talk about **modules**, when many solar cells are connected together. An **array** is a linked collection of photovoltaic modules, which are in turn made of multiple interconnected solar cells.[15] See Figure (2.2)

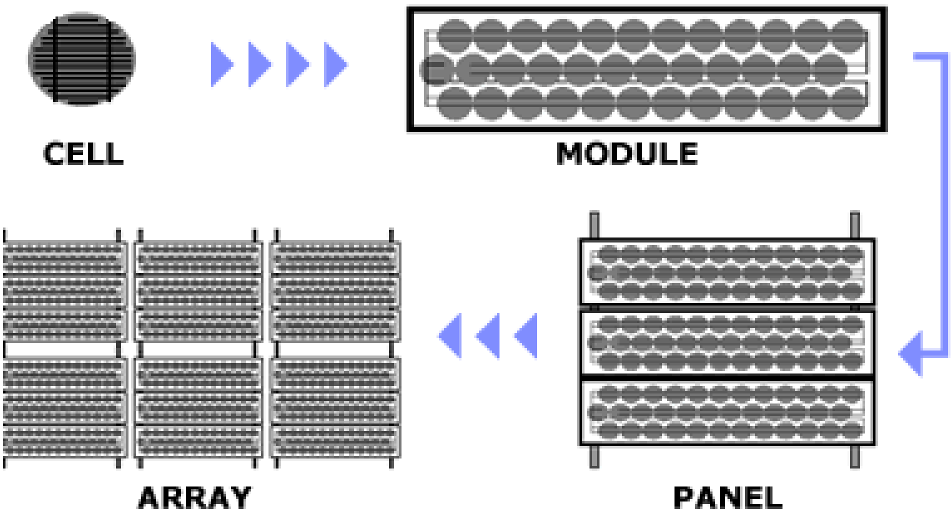


Figure 2.2: from cell to array, source: www.solardirect.com

Solar modules consist of multiple layers. The structure of solar modules also has to allow for stability and corrosion protection. Solar modules are mostly enclosed in an **aluminum frame**. This gives stability to the different layers and facilitates the assembly. (Figure 2.3)

[14] Solar power laboratory from Christiani
[15] http://en.wikipedia.org/wiki/Photovoltaic_array

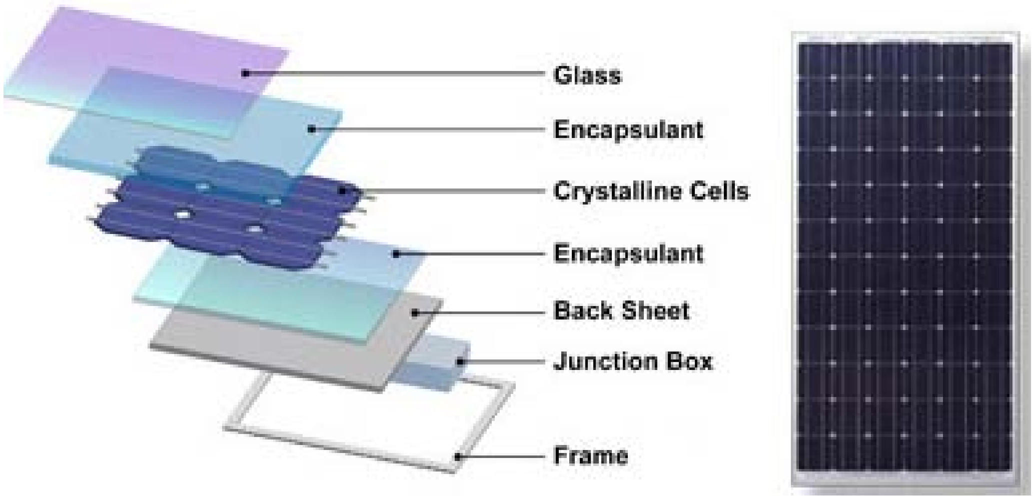


Figure 2.3: Solar module assembly, source: http://www.renewable-energy-concepts.com

To choose a module you have to pay attention to following points:

- The quality
- The standards(**IEC** "International Electrotechnical Commission" **61215** for crystalline silicon and **IEC 61646** for thin film, **IEC 61730** for PV module safety and **EN** 50380 for datasheets and nameplate information)
- The application (Grid-tied or stand-alone)
- 20 to 25 years warranty
- And the manufacturer (their experience, their services, endorsements from previous customers, ease of contact, if possible local representative, how long replacement modules will be available and the possible extent of insurance covering warranties and guarantees)

The connections to the panels have to be properly made to avoid high losses on the system. When cells are connected in series, the total voltage of the individual cells is added together. The amount of current is the same as on one panel. But if one cell breaks down, the circuit will be interrupted. The opposite occurs when connected in parallel.
For example if you have 4 panels (12V; 5A), in series connected the total voltage is 4 x 12V= 48V and the current is 5A. Connected in parallel the total voltage is the same 12V and the total current is 5A x 4 = 20A. Modules and cells are connected in series by connecting conductors between the negative terminals of one to the positive terminal of another.
In the following figures we see how arrays compose of 4 modules are connected. Notice that the nominal power (the product of the nominal current and the nominal voltage in Wp) is the same in both connections.

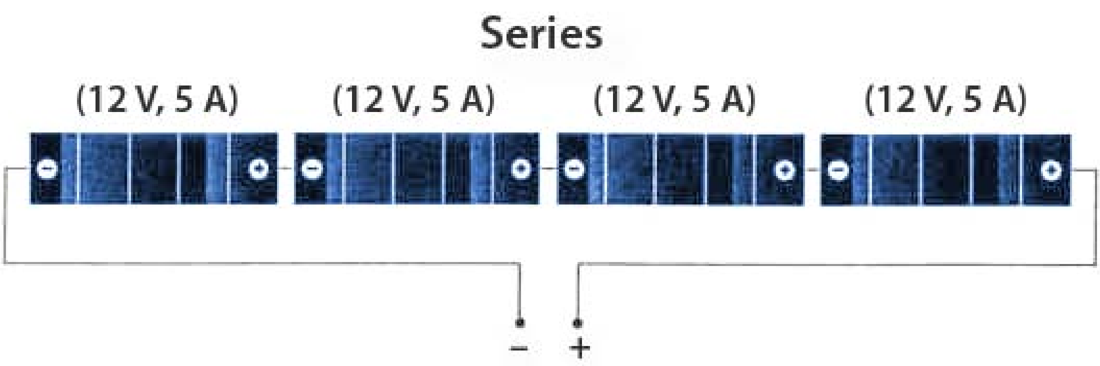


Figure 2.4: Modules connected in series

The total voltage is	12V+12V+12V+12V =48 V
The total current is	5 A
The total Power of the Array is	5A x48 =240 Wp

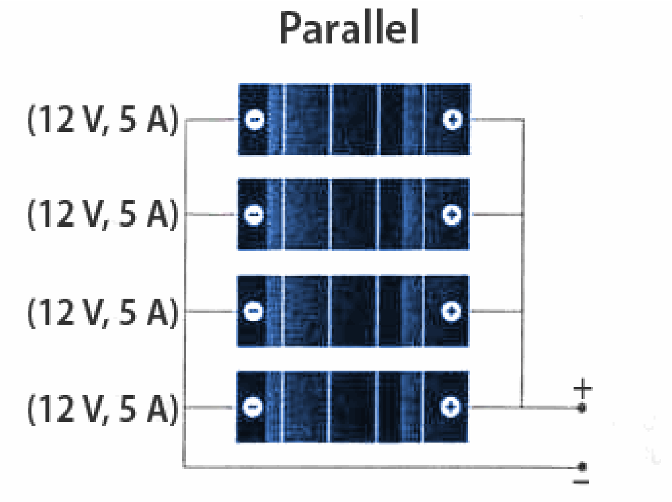


Figure 2.5: Module connected in parallel

The total voltage is 12 V
The total current is 5A x 4 = 20 A
The Power is 20A x 12V =240 Wp

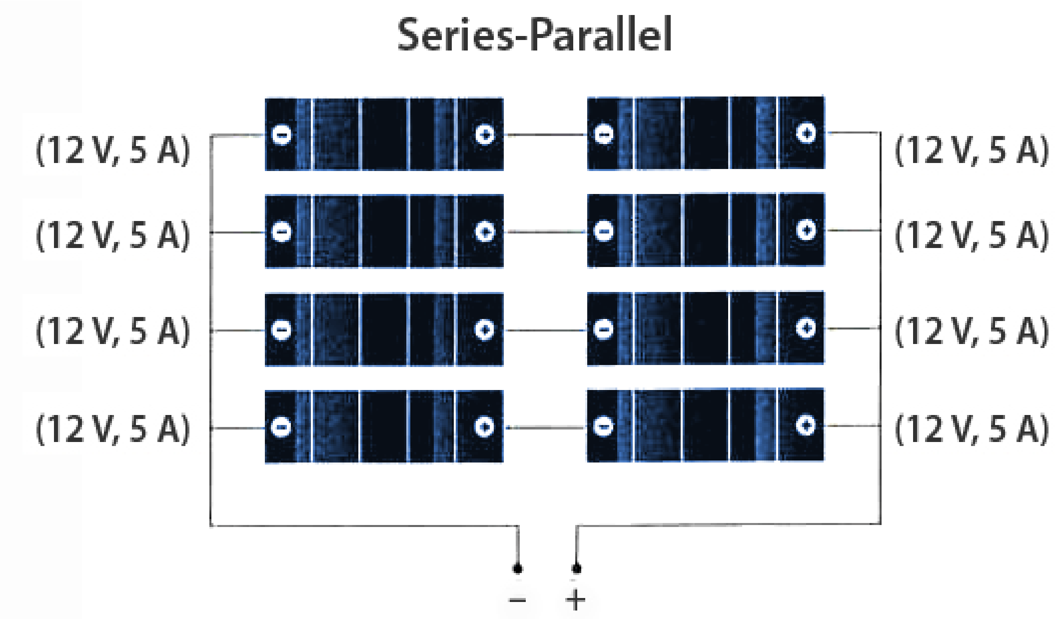


Figure 2.6: series-parallels connections.

The total voltage is	12V+12V+12V+12V =48 V
The total current is	5A x 2 = 10 A
The Power is	10A x 48V = 2 x 240Wp =480 Wp

The same calculation if u have 3, 4, 5 etc…series-parallels.

2.3.2 Characteristics and parameters

The characteristics for solar cells are shown using current-voltage characteristics. The characteristics of the modules mostly result from the serial connections of the individual curves.[16] As voltage increases from zero, the current begins at its maximum and decreases gradually until the knee of the curve is reached. With a surface of $1\,\mathrm{dm}^2$, at the radiation level of $\mathbf{1{,}000\ W/m^2}$, a current of 3A is usually present (Figure 2.7).[17]

In serial connection the current is constant and the voltage the sum of that produced by the individual cells. In parallel connections the voltage is constant and the current the sum of that produced by individual cells.

When solar cells can be short-circuiting without causing any damage we talk about **Cells short-circuit current** (I_{sc}). The short-circuit current depends on the solar radiation output and the cell surface area.

When there is no power flow the voltage that is measured is called **open-circuit voltage** (V_{oc})**.** For silicon solar cells the maximum output is 0.5 V. But generally the open circuit voltage is around 0.6V.

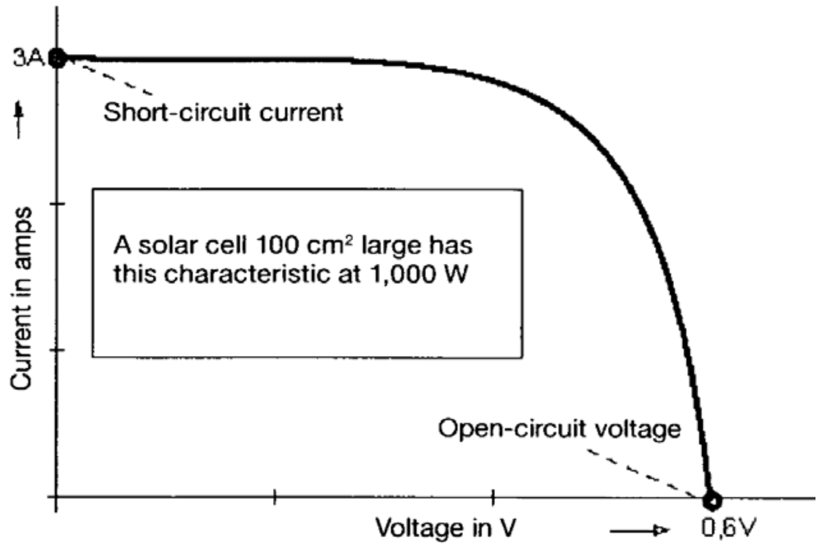


Figure 2.7: Cell characteristic, source: Solar Power Laboratory Christiani GmbH

The increase in temperature rises the **short-circuit current** like around **0.05%/°C** and drop the **open-circuit voltage** like **0.4%/°C.** (Figure 2.8)
"Due to the product formation at the output, the module output reduces by around 0.45%/°C when it warm up"[18] . The rate for amorphous silicon solar cells is 0.15 - 0.25%/°C, depending on how the cell is made.

[16] Solar Power Laboratory, Christiani GmbH
[17] Solar Power Laboratory, Christiani GmbH
[18] solar power laboratory, Christiani GmbH

Many manufacturer gives the **temperature coefficient of the short-circuit current** (%/°C) and **the temperature coefficient of the open-circuit voltage** (%/°C) on the electrical parameter (data sheet) of the module.

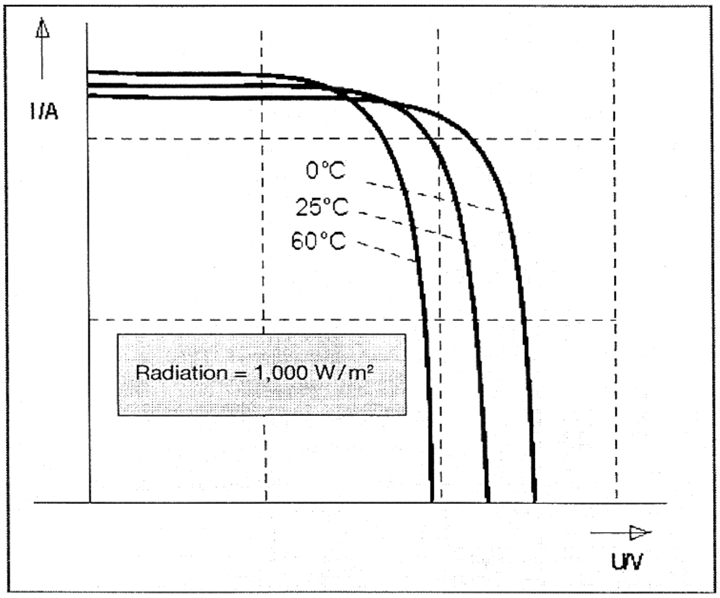


Figure 2.8: Current-voltage characteristics for various temperatures, source: Solar Power Laboratory Christiani GmbH

In practice manufacturers give the characteristics for their modules under different levels of radiation.

Example:

Siemens SM 20 module: At 1,000 W/m^2 and a temperature of 25° C, this module yields an output of 20W at the voltage of 15V.[19]

Every module has a **STC** (Standard-Test-Condition). These following values are usually standard:

- Radiation force: E= 1,000 W/m^2
- Cell temperature: $T_c = 25°C$
- Air mass: AM=1.5

The module parameters are determined by the manufactures (Table 2.1).

V_{MPP} is the nominal voltage also known as **V_N** (in Volt). It is the voltage at the maximum power point.
I_{MPP} is the nominal current also known as **I_N** (in Ampere). It is the current at the maximum power point (MPP).
P_{MPP} the nominal power output also known as **P_N** is in Watt peak. At this point the power output is at its maximum.

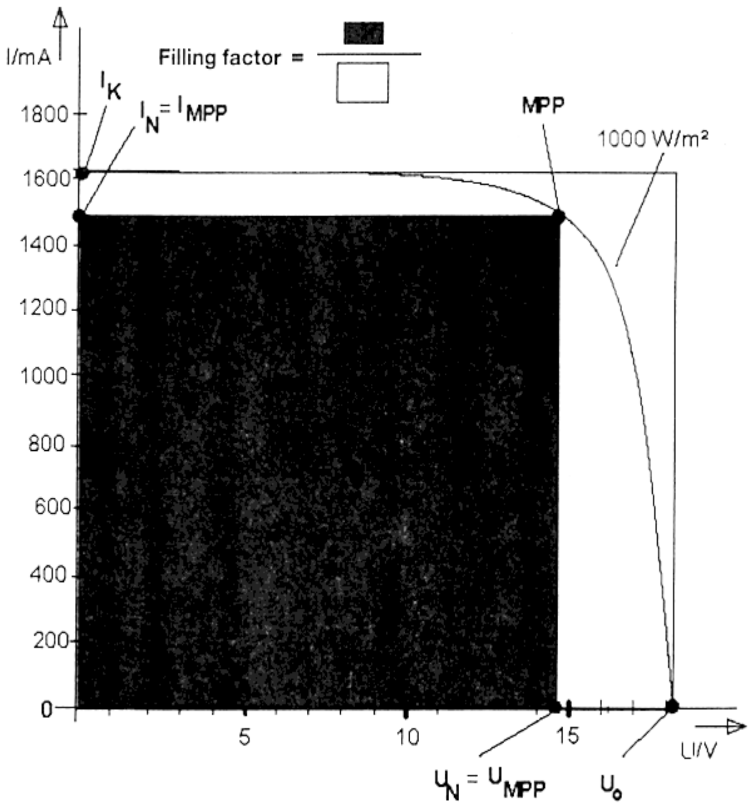
$$P_N = V_N \bullet I_N$$

[19] Solar Power Laboratory, Christiani GmbH

Electrical parameters	Symbols	Units
Nominal power	P_N	W_p
Minimum power	P_{min}	W_p
Nominal current	I_{MPP}	A
Nominal voltage	V_{MPP}	V
Short-circuit current	I_{sc}	A
Open-circuit voltage	V_{oc}	V
Maximum system voltage	V_{max}	V
Module efficiency	η	%
Thermal parameters		**Units**
NOCT		°C
Temperature coefficient of the short-circuit current		%/°C
Temperature coefficient of the open-circuit voltage		%/°C
Maximum permitted module temperature		°C
Maximum permitted module temperature		°C
Module under solar irradiance		°C
Module shaded (storage temperature)		°C

Table 2.1: Data sheet for a PV module, source: Planning and installing photovoltaic systems, DGS, Germany

2.4 Filling factor



$$F = \frac{V_N \bullet I_N}{V_{oc} \bullet I_{sc}}$$

Figure 2.5: Filling factor diagram, source: Solar Power Laboratory Christiani GmbH

The filling factor **F** informs us of the extent to which a module deviates from the ideal shape (figure 2.5). It is the ratio of the **maximum power point** (P_N) to the product of **open circuit**

voltage (V_{oc}) and the **short circuit current** (I_{sc}). This is a key parameter in evaluating the performance of solar cells. The filling factor for a good module is around 0.75.[20] Under 0.70 are the cell grade low and the module grade also.

2.5 Module output adjustment[21]

The highest output of the module is measured at the points of maximum output (MPP). Let's take an example for better understanding.

Lets take a radiation of $200\,W/m^2$ If a comparison is made of the areas of **maximum output at 13.5 V x 300 mA = 4 Watts** the operating point is at **3 V x 350 mA = 1 Watt** it can be seen that only a fraction (= 1/4) of the available output is used. That means **the adjustment is incorrect.**
A maximum uptake of output is only possible with a so-called **MPP regulator** or **MPP tracker**, which regulates the load from the consumer in such a way, that the operating point is always in the MPP.
If a battery is connected (e.g. 12 V) the voltage will remain largely stable in a broad load area. This means that the solar module is always operated in the range of the MPP (maximum power point). An automatic load distribution is performed between the module and the battery so that the battery is charged in the open-circuit phase of the module and as the load rises, the battery takes on a greater proportion of this load.

2.6 Module and cell efficiency [22]

The efficiency level is basically the use/cost ratio.
A differentiation is made between:

- Cell efficiency level 14 - 17% for standard commercially available monocrystalline cells
- Module efficiency level is around 12% for standard commercially available monocrystalline modules.
- System efficiency level = overall efficiency of modules and system technology:
  For off-grid systems it is between 5 - 6%.
  For on-grid systems it is around 10%.
  In order to specify the difference in the standard energy yield according to **STC** with the actual energy creation from the system, the PR value ("**Performance Ratio**") was introduced. It is the ratio of the energy generated to the energy under STC conditions.

This produces the following formula:

$$\mathbf{PR = E_{Real}/E_{STC}}$$

We can't talk about efficiency without talking about the loses. Following losses are mostly registered.

- Reflection losses (4%): A part of the sunlight that falls on the cell is reflected by the cell surface.

- Non-absorbed radiation (loss of approx. 23%): A part of the sunlight is not sufficiently rich in energy to cause a charge separation (it cannot lift a valence electron into the conduction band. Electrons in the conduction band are free electrons that are no longer bound to atoms).

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[20] Solar power laboratory, Christiani GmbH
[21] Solar power laboratory, christiani GmbH
[22] Solar power laboratory, Christiani GmbH

- Overly strong radiation (loss of approx. 30%): If the radiation has more energy than is necessary for separating charges (to lift valence electrons into the conduction band), this excess energy is deflagrated. It heats the cells unnecessarily.

- Other losses: Temperature, shadow on the conductor, early charge carrier recombination before reaching the PN transition and electrical resistance losses.

2.7 Exercises on chapter 1 and 2 (source: Solar Power Lab., Christiani)

1. How much energy is radiated by the sun on the entire surface area of Saint Lucia (619.15 km²) it annual radiation was at a level of $2015\,\mathrm{kWh}/\mathrm{m}^2$

2. How many tonnes of CO2 output could be prevented with the photovoltaic output of 4 GW, when coal-powered plants emit 1 kg of CO2 into the atmosphere for every kWh of power produced? Use a basis of 1,000 hours of sunlight per year for your calculations.

3. Give reasons for the use of photovoltaic technology.

4. Name the three principle possible locations for photovoltaic energy production equipment.

5. What is meant by open-circuit voltage?

6. What are the results of a serial connection of solar cells and solar modules?

7. What are the results of a parallel connection of solar modules?

8. What are the differences between a solar module and a solar collector?

9. Give a simplified description of the function of a solar cell when light falls on it and the power circuit is complete.

10. Which extreme value characterises the current-voltage curve of a solar cell?

11. What is meant by MPP?

12. The point where a solar cells output is at its maximum is referred to as MPP. Approximately how great are the voltage and current at the MPP, if the cell temperature is 25 °C and a radiation of 1,000 W/m^2 is present?

13. Calculate the filling factor and nominal output of the solar module with this data sheet

Voltage at nom. power	17,00 Volt
Open Circuit Voltage	21,00 Volt
Current at nom. power	1,74 Ampere
Short Circuit current	1,93 Ampere

14. How do the current, voltage and output of a solar module change when it warms up in summer?

15. Why is the cell efficiency level of a module always greater than the module efficiency level?

16. What types of solar cells you know? Specify the approximate efficiency level.

17. A solar module consists of 36 polycrystalline silicon solar cells, each 10 x 10 cm. The data sheet specifies an open-circuit voltage of 21.6 V. How are the solar cells of this module connected?

18. What is meant by the standard test conditions (STC)?

CHAPTER 3 Stand-alone Photovoltaic Systems

Figure 3.1: Stand-alone PV systems, source: www.luckypowertech.com

3.1 Introduction

Stand-alone photovoltaic systems also known as off-grid systems or island systems are designed to operate independent of the electrical grid. Mostly used in rural areas or developing countries, where the electricity grid is largely confined to the main urban areas, and where a substantial proportion of the rural population does not have access to most basic energy services.

PV modules can be used for:

- Mobile systems in cars, caravans and boats.
- Pumping systems: to supply water to villages, for land irrigation or livestock watering.
- Electrification of alpine huts, weekend and holidays chalets.
- Refrigeration systems: particularly to preserve vaccines, blood and other consumables vital to healthcare programs.
- Lighting: for homes and community buildings such as schools and health centers to enable education and activities to continue after dark.
- Battery charging stations: to recharge batteries, which are used to power appliances ranging from torches and radios to televisions and lights
- Solar home systems: to provide power for domestic lighting and other appliances such as TVs, radios, sewing machines, etc.

3.2 Basic description

In a typical stand-alone PV system the DC electricity produced by the module is used to charge batteries via a solar charge controller. If DC appliances are to be powered by the system, they are usually connected to the battery via appropriate-sized fusing. DC lights are usually connected to the charge controller. If AC mains voltage appliances are to be powered, this is done via an inverter connected directly to the batteries. The inverters used in stand-alone systems and the inverters used in grid-tied systems, though they both convert DC electricity to AC electricity are very different devices and are rarely interchangeable. In stand-alone PV systems it is crucial that the energy produced is sufficient to cover the energy requirements of the loads.
A **year-round operation design** is a system design with the month with the lower irradiance. This is mostly used in stand-alone PV system.

3.3 Stand-alone components

PV systems for stand-alone applications mostly used the following basic components: Modules, charge controllers, batteries, inverters, cables, fuses and plug connections.

3.3.1 Modules

In a stand-alone PV system the module should be able to produce enough electrical energy to power all the electrical appliances. The module here usually does not have a maximum power point (MPP) tracking (MPPT), just in larger systems. PV modules in a stand-alone system operate at the battery voltage. It varies with battery state of charge, and with the loads on the system (any appliances and lights that may be on). For a 12V system, it varies from about 11 to 14.5V.
In order to charge a 12V battery, the PV module must apply a voltage that is higher than that of the battery (14.5V). PV modules for smaller system are made with a MPP of around 17V when measured at a cell temperature of 25°C. This can drop to 15V due to system losses. This means a MPPT is not needed when connected to a 12V battery.
For larger system MPPT varies the ratio between the voltage and current delivered to the battery, in order to deliver maximum power. As the MPP of the PV array varies with temperature and other conditions, MPPT tracks this variance and adjusts the ratio accordingly.
Modules chosen for charging batteries in stand-alone system need to have enough cells in series to deliver the required voltage. Generally 6 cells are connected in series for every 2V battery cell.[23]
The module converts sunlight instantly into DC (direct current) electric power. And need to be configured to match the system DC determined by the battery.

3.3.2 Charge controllers

In a PV system, a charge controller has the main function to protect the battery from overcharging and deep discharging. It runs the solar generator at the optimum operating point and offers the battery a longer life. A charge controller works like a valve on a rainwater collection system that prevents the water tank from overflowing.[24] This is usually connected between the module and the battery.

[23] Photovoltaic for professionals, Karl-Heinz Remmers
[24] photovoltaic systems technical training manual, UNESCO

This solar charge controller can be used to control system sizes of up to 8400 Wp.

- Three voltage levels (12 V, 24 V, 48 V).
- Current between 55 and 110A

More info at:
www.stecasolar.com/index.php?Solar_charge_controllers

Figure 3.2: Charge controller, source: www.stecasolar.com

Charge controllers have following main functions[25]:

- Protect the battery from discharge. It is usually a **low voltage disconnect** (LVD)
- Protect the battery from overcharging by limiting the charging voltage. It is usually called **high voltage disconnect** (HVD)
- Prevent current flowing into PV array at night. Usually called **reserve current.**
- Disconnect a load current circuit from the battery when the battery is discharged.
- Charge the battery quickly, harmlessly and fully at various temperatures.

Most charge controller data sheets give information on its function. Carefully read it. And notice that incorrect installation may damage both controller and battery.
Controllers can be connected in series or parallel with the modules. When the battery is full, a **series controller** (controller connected in series with the module) shuts off the module power using a switch or relay and special switching transistors.
Parallel controllers (connected in parallel with the module across their output wires) usually reduce the module power when the battery is full. But since the module continues producing power, the waste power is used as short-circuit current in the modules without any problems.
Some controllers have a MPPT but they cost more.

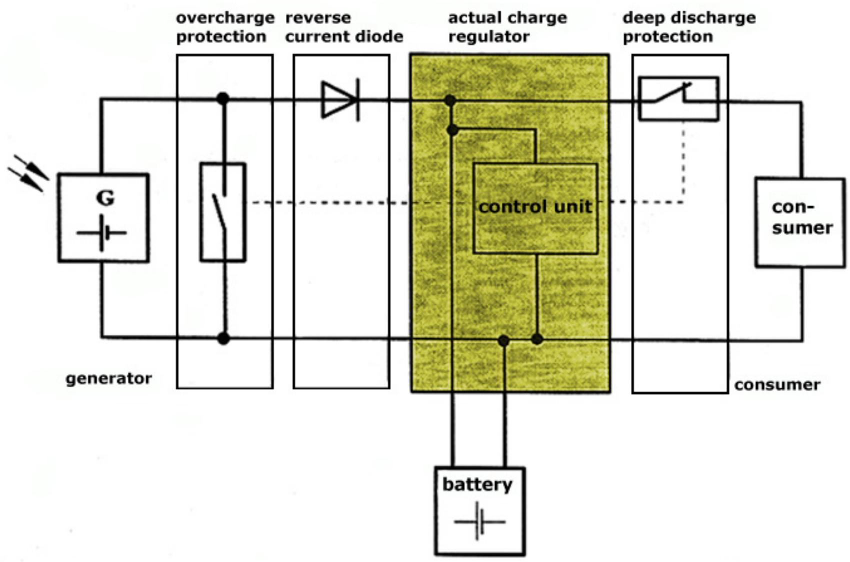

Figure 3.3: Basic circuit of a controller, source: solar power laboratory, Christiani GmbH

[25] Photovoltaic for professionals, Karl-Heinz Remmers and Planning and installing photovoltaic systems, DGS, Germany

3.3.3 Batteries

Battery is used to store electricity produced by a solar panel for later use. In stand-alone PV system, battery is one of the most expensive components and has the shortest life and damaged quickly by poor maintenance and incorrect use.

Lead-acid battery (figure 3.3) is the most used in stand-alone PV system. The main materials in the battery are lead and sulphuric acid. This acid is very dangerous and need to be handled carefully. Always read the precaution notice before use. Lead-acid batteries are made of cell. A cell has a nominal voltage of 2VDC. Six of this connected in series gives us a 12V battery. 12 give us 24V etc.

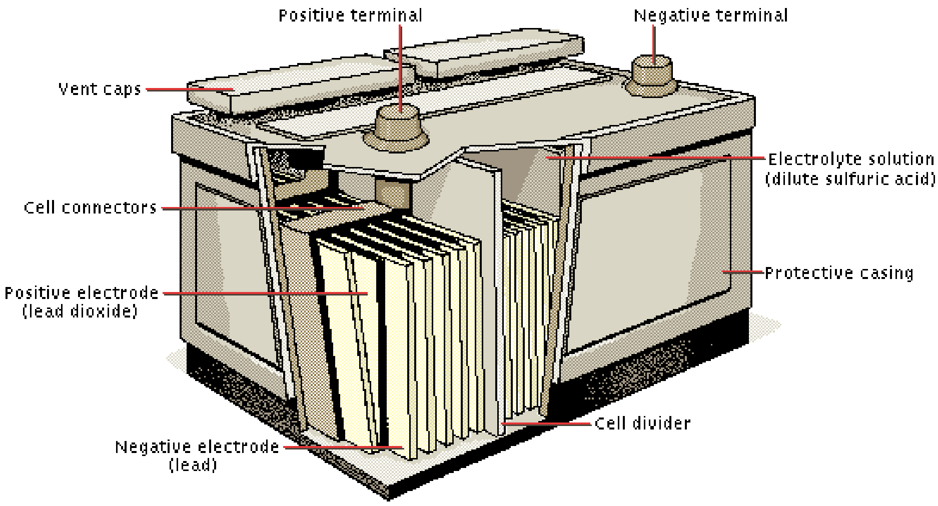

Figure 3.3: Lead-acid battery, www.stoneyroads.com

The state of charge (SOC) is the percentage of energy remaining in the battery compared to the fully charged capacity.[26] That means a battery that has half of its capacity removed is 50% SOC

Self–discharge is the gradual reduction in the state of charge of a battery while at steady-state condition.[27]

Depth of discharge (DOD) is the maximum allowed for a battery to discharge. Battery should never be fully discharge in order to have a longer life.

The electrical storage capacity of a battery is measured in **Amp-hours** (Ah). This describes for how many hours a current can be delivered for a fully charged battery before it is discharged. If a battery delivers 1A in 100h the capacity is 100Ah. The capacity of a battery is affected by current in which it is discharged and its temperature. As a rule of thumb capacity is reduce by 1% with each °C drop in temperature.[28] That means for example if a manufacturer says a battery has a capacity of 100Ah in a temperature of 25°C, the battery will have just 75% by 0°C.
The battery operating temperature should be keep between 10 and 35°C. Never exceed 50°C, which will cause permanent damage. The optimum operating temperature for lead-acid battery is 25°C. Notice that high temperature reduces the life time of the battery.

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[26] Photovoltaic systems instructors resource Guide by American technical publishers
[27] Photovoltaic systems instructors resource Guide by American technical publishers
[28] Photovoltaic for professionals, Karl-Heinz Remmers

Battery Ah-efficiency is the ratio of the number of Ah that can be taken out and the number of Ah put into the battery. Mostly in PV systems a return of 75% of the energy put into it is good.[29]

$$\eta_{Ah} = \frac{\text{discharge current} \bullet \text{discharge time}}{\text{charge current} \bullet \text{charge time}}$$ [30]

Energy requirement Wh-efficiency is calculated as follows:

$$\eta_{Wh} = \frac{\text{discharge voltage} \bullet \text{discharge current} \bullet \text{discharge time}}{\text{charge voltage} \bullet \text{charge current} \bullet \text{charge time}}$$ [31]

The advanced version of the lead-acid battery is **Lead-gel battery**. The advantages of a lead-gel battery are:

- Longer lifetime.
- Hermetically sealed.
- No gassing.
- Installation in any position and location.
- Maintenance free

The life of a battery depends mostly on the DOD, the average temperature of the battery over its lifetime, its exposure to prolonged periods of low discharge. The life is given in "**cycles".** It is the number of complete charge and discharge a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. A battery is considered to be exhausted when it can only supply 80% of its capacity. Many battery manufacturers informed the costumers of the battery discharge time, and the battery cycle. They are usually on the data sheet of the battery in the form of diagrams.
On a battery data sheet "C_{20}"simply means that the capacity given is attained with an approximately 20 hours discharge current.

3.3.4 Inverters

SUNNY ISLAND 2012 / 2224
For system from 1 to 9 kW
Nominal power at 25°C: 2000 W / 2200 W
Nominal battery voltage: 12 V / 24 V
Output nominal voltage: 230 V
More info on www.sma.de/en/products/off-grid-inverters

Figure 3.4: Sinus inverter, source: www.sma.de/en/products/off-grid-inverters

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[29] Photovoltaic for professionals, Karl-Heinz Remmers
[30] Solar laboratory, Christiani GmbH
[31] Solar laboratory, Christiani GmbH

In a stand-alone PV system modules and batteries produce DC electricity. But most electrical appliances run on AC. So to be able to use conventional 230V AC appliances stand-alone inverters are used. Inverters in stand-alone systems are usually called **battery-based inverters**. These are usually connected to batteries. The inverter size depends simply on the total power required for the AC appliances. Before using an inverter in a stand-alone system we have to be sure the systems has AC appliances. If a system also has DC appliances it is clever and normal to separate the system. In this case appliances are connected directly to the DC appliances over low voltage disconnect.

Inverters in stand-alone systems should be **sinus inverters**,[32] because they supply an output voltage, which is comparable to the voltage in the public grid. They should have the following characteristics[33][34]:

- Sine wave output
- Stable AC voltage and frequency output
- High efficiency (more than 90%) at full and part load
- High level of reliability
- Low electromagnetic interference
- Low power consumption in stand-by-mode
- Overvoltage and overcurrent protection
- Should allow remote monitoring
- Should protect against overvoltage and incorrect polarity

Inverters do shut down if battery voltage gets too low, but this is to protect the inverter not the battery.
If inverters are not correctly connected to batteries they can be destroyed.
Square-wave inverters and Trapezoidal inverters are other types of inverters
Square-wave inverters don't have voltage regulation. The voltage can fall dramatically with many loads connected. This is mostly used for operating entertainment electronics and some type of motors.
Trapezoidal inverter is similar to square-wave. The effective output voltage is constant and independent on the input battery voltage.

3.3.5 Electrical appliances, lights and loads

Energy efficient and low energy appliances are recommended in PV stand-alone systems. The power of watt of appliances is important. With the number of hours they run a day, you can determine the **Watt-hour** (Wh) they consume. It is good to know the energy required each day in order to determine the number of PV modules and batteries needed.

Compact fluorescents are lighting devices available in DC and AC versions. They have a high efficacy and a very low energy consumption (table 3.1). Halogen lamps are better than standard incandescent lamps, but are generally not recommended because of their low efficacies. This means incandescent lamps should be completely avoided.

Flat screens and laptops are better than desktop computers with high on energy consumption. High efficiency refrigerators and TV videos are also available with 12V/24V DC.

Note that a system with only DC has limitations, because the DC-appliances are rare. A system works correctly when it is good sized.

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[32] Planning and installing photovoltaic systems, DGS, Germany
[33] Photovoltaic for professionals, Karl-Heinz Remmers
[34]Planning and installing photovoltaic systems, DGS, Germany

Fluorescent lamps (W)	Incandescent lamps (W)	Hour of used per day (h)	Daily/yearly energy requirement Incandescent lamps (kWh)	Daily/yearly energy requirement Fluorescent lamps (kWh)
28 Watt T5	150 Watt	4	0.6 / 219	0.11 / 40.9
32 Watt T8	150 Watt	4	0.6 / 219	0.13 / 46.7
34 Watt T12	150 Watt	4	0.6 / 219	0.136 / 49.64
18 Watt CFL	75 Watt	4	0.3 / 109.5	0.07 / 26.28

Table 3.1: Fluorecent lamps compared to Incandescent.
source: en.wikipedia.org/wiki/Compact_fluorescent_lamp

3.4 Stand-alone PV system sizing

To size a stand-alone PV system it is important to estimate the daily electricity consumption (Wh). It is the product of the nominal power P_N (W) of the appliances and the number of hours (h) they run. When this is clarified, the correct size of the PV module needs to be determined.

3.4.1 Modules sizing

Usually the month with the lowest average daily solar radiation on horizontal surface during the period the system will be operational is used for sizing. For example in St. Lucia this will be November and December if the system has to be used through the year. Every module has a nominal power in Watt-peak.
Modules are usually connected in series, parallel or series parallel. This depends on the input voltage of the battery or inverters. The module output voltage has to be below the input voltage of the inverter.

The following formula can be used to size a PV-system.

$$W_{pv} = E \div G \div \eta_{sys}$$ [35]

E = the daily energy requirement in watt-hour (Wh)
W_{pv} = Peak wattage of the module (Wp)
G = average daily number of "peak sun hours" in the design month for the inclination and orientation of the PV module. Not the same with the hours of sunlight. This corresponds to the ratio of the daily solar radiation in the design month for the inclination and orientation and the standard irradiance $1\,\text{kWh}/\text{m}^2$

η_{sys} = Total system efficiency expressed as a factor (1 is 100%) but generally can be taken as 60%. This is the product of all losses that the system provided. The system provides following losses:

- 20% for a PV module not operating in MPP
- between 2% and 3% losses due to voltage drop in cables from PV array to battery to loads
- 2% losses in a good quality charge controller

[35] Photovoltaic for professionals, Karl-Heinz Remmers

- 10% losses in good quality inverter
- 10% battery losses, battery Ah efficiency
- 2% losses in distribution cables from PV battery to loads

To estimate the **value of G** many sizing software are recommended such as PV-SOL from Valentin Energy software (www.valentin.de), (http://re.jrc.ec.europa.eu/pvgis/) or (www.pvsyst.com). This software safe time and propose several options. It can also be done manually with a solar yield diagram (Figure 3.5). This is available from some module manufacturers.

For example in Castries (St. Lucia) in January the monthly average radiation on horizontal surface is 153 kWh per square meter (see 1.3 solar radiation). This corresponds to a daily average radiation of 4.9 $\mathrm{kWh}/\mathrm{m}^2$ on horizontal surface. The standard irradiance is $1\,\mathrm{kWh}/\mathrm{m}^2$. The number of peak sun hour on horizontal area is $4.9\,\mathrm{kWh}/\mathrm{m}^2$ over $1\,\mathrm{kWh}/\mathrm{m}^2$ equal to 4.9 peak sun hour.

On 15 ° incline plan 0° south orientation at the same month (table 1.2) the daily average is $175\,\mathrm{kWh}/\mathrm{m}^2$ /31 = 5.6 $\mathrm{kWh}/\mathrm{m}^2$ this corresponds to 5.6 peak sun hour.

Looking at the yield diagram (Figure 3.5), 15° tilt angle and 0° south correspond to 100% efficiency.

Example: A system in January in Castries needs 500W to operate. It uses 4 hours a day. With the previous climate conditions, what Wp of module will be needed for the system?

E = 500W x 4h = 2000Wh
G = 5.6
η_{sys} = 0.6

$W_{pv} = E \div G \div \eta_{sys}$ = 595 Wp will be needed.

With the help of a yield diagram for Europe (figure 3.5): If a roof has a tilt angle of 50° and oriented 60° southwest the daily radiation will be expected to 85% of 5.6 $\mathrm{kWh}/\mathrm{m}^2$ equal to $4.7\,\mathrm{kWh}/\mathrm{m}^2$ and **G=4.7 peak sun hours** by a standard irradiance of $1\,\mathrm{kWh}/\mathrm{m}^2$. Yield diagrams are good for small systems. For big systems solar simulation software is strongly recommended to estimate the yield correctly.

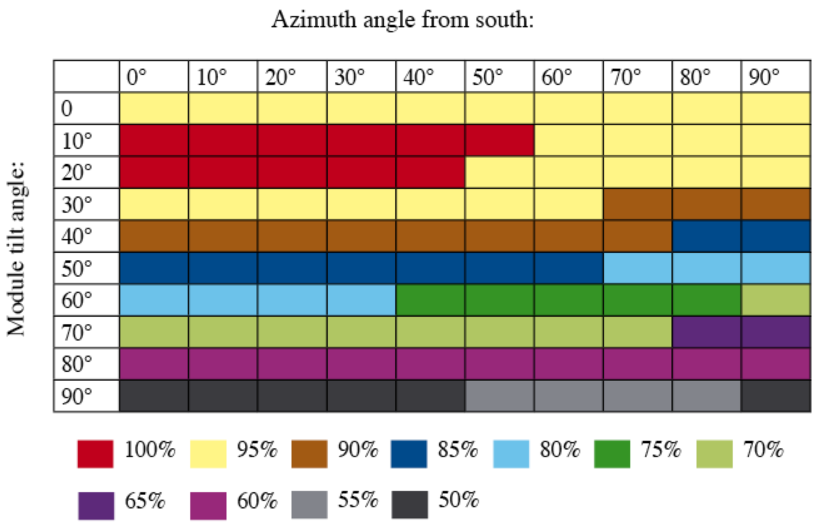

Figure 3.5: Solar yield diagram for Europe, source: PV-SOL (Valentin energy software)

3.4.2 Controller sizing

The charge controller has to have enough ampere capacity to pass the maximum current a PV module can provide. It is the current at the nominal power I_{MPP}. This could be found on the data sheet of the Module. Pay attention on the modules interconnection (series, parallel, or series-parallel).

Example: A 12V module has 120Wp. Estimate the minimum size of the controller?
The fastest and easier way will be to divide the 120Wp with 12V that will be 10A.
So a minimum size of the controller will be 10A.
The most controllers are hybrid. That means they are at the same time charge and discharge controller.

3.4.3 Battery sizing

In a stand-alone PV system the battery needs to be chosen to store energy for many days used without going over the DOD.

Following formula can be used.

$$Q = (E \times D) \div (V \times T \times \eta_{inv} \times \eta_{cable})$$ [36]

Q = minimum battery capacity required in amp-hours (Ah)

E = the daily energy requirement in (Wh)

A = the number of days of storage required

V = the system DC voltage (V)

T = the maximum allowed DOD of the battery usually on battery data sheet

η_{inv} = inverter efficiency. This is 1 if there's no inverter

η_{cable} = the efficiency of the cables delivering the power from battery to loads

3.4.4 Cable selection and sizing

There are many types of cable. It is always important to use the correct one when installing a PV system. Cables used for homes are always made of copper. Aluminium cables are also available but never use it because this will not work properly unless correctly installed with special connectors, which are difficult to obtain. Aluminium wiring is very unforgiving of improper installation.
Aluminium cable oxidises, or corrodes when in contact with certain types of metal, so the resistance of the connection goes up. This causes it to heat up and corrode or oxidize still more. The wire will start getting very hot, melt the insulation it's attached to, and possibly cause a fire.
In some countries, home hazard insurance will not cover homes with aluminum wiring, and some insurance companies that claim to cover it charge a higher premium than for homes with copper wiring.
Following requirements should be fulfilled for a module wiring:

[36] Photovoltaic for professionals, Karl-Heinz Remmers

- Temperature resistance
- UV resistance
- Double insolated (insulation is mainly intended to prevent)
- Resistance to moisture and wet
- Flexible and easy to work with
- Size for low voltage drop

Every cable has a voltage drop on it. This is a problem in stand-alone systems because the batteries may not be properly charged. The reason is the resistance Ω (ohms). The more the cable resistance has the more voltage drop. This is calculated with following formula:

$\Delta V = I \bullet R_c$ [37]

ΔV is the drop of voltage ; I is the current in the cable (A) and R_c is the resistance of the cable (Ω), which depends on the cable length and the cross-section.

Basic formula for calculating cross-section:

$$A_M = \frac{2 \bullet P \bullet L}{\kappa \bullet \Delta V \bullet V}$$ [38]

$$A_M = \frac{2 \bullet P \bullet L}{\kappa \bullet \Delta V \bullet V} = \frac{2 \bullet V \bullet I \bullet L}{\kappa \bullet I \bullet R_C \bullet V} = \frac{2 \bullet L}{\kappa \bullet R_C}$$

$$R_C = \frac{2 \bullet L}{\kappa \bullet A_M}$$

ΔV is the voltage drop; "κ" is the electrical conductivity (Cu = $56 m/mm^2 \Omega$ for copper)

"A_M" is the cross-section; "P" is consumer power; "L" is the cable length (2 loaded wires)

Example: A home has a 200 W consumer with 12V rated voltage and is 10 m away. The drop of voltage is 10%.

ΔV is 10% of 12V = 1.2 V

$$A_M = \frac{2 \bullet P \bullet L}{\kappa \bullet \Delta V \bullet V} = \frac{2 \bullet 200 \bullet 10}{56 \bullet 1.2 \bullet 12} = 4.96\ mm^2$$

This result will be rounded to the next standard value 6 mm^2

The standard cross-section sizes are $2.5 mm^2$; $4 mm^2$; $6 mm^2$; $8 mm^2$; $10 mm^2$; $12 mm^2$; $14 mm^2$; $16 mm^2$; $18 mm^2$; $20 mm^2$; $22 mm^2$; $24 mm^2$; $26 mm^2$; $28 mm^2$; $30 mm^2$; $32 mm^2$.

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[37] Photovoltaic for professionals, Karl-Heinz Remmers
[38] Solar power laboratory, Christiani

3.4.5 Sizing example

Sizing a 24VDC system voltage home in Castries (St. Lucia)

1. *The loads and appliances and the daily energy requirement*

Loads and Appliances	Power rating of appliances (W)	Quantity	Total power required (W)	Hours of use per day (h)	Daily energy requirement (Wh)
Fluorescent lamp kitchen, rooms	20W	5	100W	3	300Wh
TV	60W	1	60W	2.5	150Wh
Microwave	700W	1	700W	0.5	350Wh
Refrigerator	80W	1	80W	3	240Wh
Lighting outside	100W	2	200W	0.3	60Wh
Totals			1140W		1000Wh

Table 3.1: Appliances and daily energy requirements.

The home roof has an inclination of 50°C and is orientated 60° southwest. The system is design for January and will have 3 days storage.

2- Module sizing (like in 3.4.1)

G = 4.7 peak sun hour

η_{sys} = 0.6

E =1000Wh daily energy requirement.

$$W_{pv} = E \div G \div \eta_{sys} = 1000Wh \div 4.7 \div 0.6 = 355Wp$$

This means the minimum size of the module will be 355 Wp.

3- Sizing battery (like in 3.4.2)

V = 24VDC the system voltage.

D = 3 days

E = 1000 Wh

T = 0.5 from data sheet

η_{inv} = 0.9

η_{cable} = 3% = 0.97

$Q = (E \times D) \div (V \times T \times \eta_{inv} \times \eta_{cable})$ = (1000Wh x 3)/ (24V x 0.5 x 0.9 x 0.97) = 286.369 Ah

Because we have a 24VDC home system 2 batteries with 24V/150Ah connected in parallel will be chosen for a total of 24V/300Ah. Or 4 batteries of 12V/150Ah connected in series-parallels.

4- Inverter

The system needs an inverter because we have just AC appliances. The total power required for AC appliances is 1140W that means a 1500W sinus inverter with 24VDC input will be recommended.

Summary:

We selected a 90Wp mono-crystalline PV module with 12V nominal rating voltage, with 21VDC open-circuit voltage, with a nominal current of 5.3A and with 17V nominal power voltage (Data sheet). If we divide 355 by 90 we will have 3.95 so 4 modules will be selected and connected in series-parallel. This means we have 2 strings, each string has 2 modules connected in series, and the 2 strings are connected in parallel. The total voltage is 2 x 12 V = 24VDC and the current is 5.3A x 2 =10.6A.

The current produced by the Module determines the charge controller. In this case it is 10.6A. The charge controller has a minimum of 10.6A. We can choose 15A in case of any expansion.

The inverter: a 1500W sinus inverter with 24VDC input.

The battery: 2 batteries with 24V connected in parallel (because we have a 24VDC system voltage) and with a capacity of 150Ah each.

3.5 Exercises for chapter 3 (source: Solar Power Laboratory, Christiani)

1. Lead-gel batteries are nowadays used increasingly in solar power systems. What advantages do these batteries have?
2. Why is a battery Wh-efficiency always smaller than its Ah-efficiency?
3. What does the capacity specification with the condition C_{20} indicate on a battery?
4. What is the biggest disadvantage of cheap, serial regulators?
5. Why can batteries be fully charged more quickly using charge regulators with “pulse width regulation"?
6. When using square-wave inverters in Off-grid systems, what problems can occur?
7. Can a 100 watts refrigerator be run using a 150 watts inverter without any problems?
8. An off-grid PV installation for a traffic system near Castries must provide 500 Wh at 12 V DC daily. There are several solar modules available with V_N = 17 volts and PMP=80 watts. The modules are south-west-facing and mounted at an angle of 30°. The batteries to be installed are lead-gel for 12 volts and 90 Ah. Calculate the number of modules and batteries for January with a discharge factor of 50% and 4 reserve days. How is the battery connected?
9. What is year-round operation design?
10. What disadvantage arises from designing for year-round operation?
11. When running the solar cables for an off-grid PV system, particular stresses and dangers must be taken into consideration. Please name them.

12. A 24 volt back-up power system is supplied via a single, 4 mm^2 solar cable, 15 m long, from a 200 watt module. Is the cross-section sufficient?

CHAPTER 4 Grid-tied Photovoltaic Systems

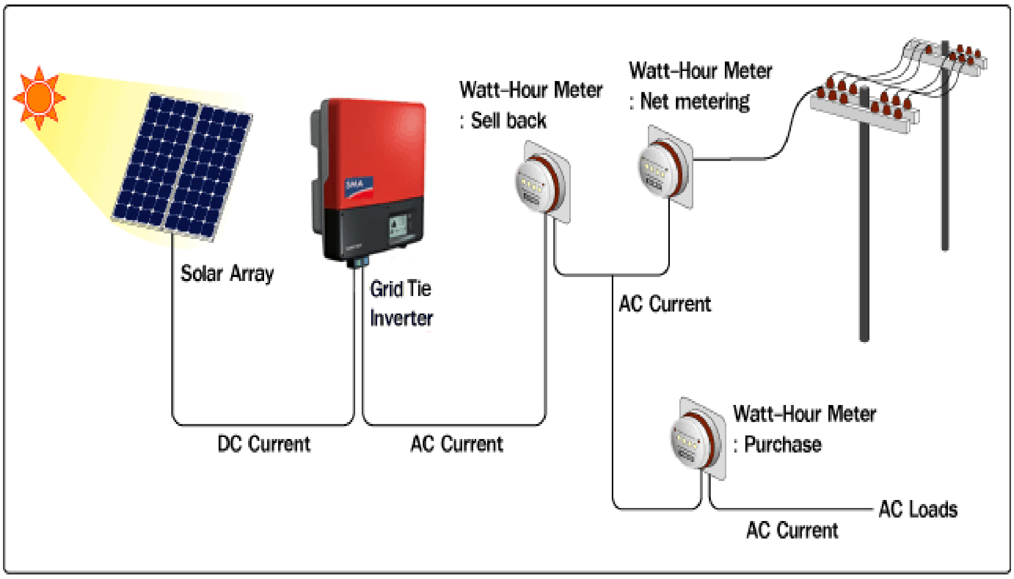

Figure 4.1: Grid-tied PV Systems, source: www.vsolar.ca

Grid-tied PV systems (figure 4.1) also called **On-grid** because they are connected to the electricity grid. Different from stand-alone PV systems, grid-tied PV systems generate electricity and send the surplus of energy back to the public grid. The public grid will act like a storage battery. It is a given and taken system. This means if the PV array is not supplying enough electricity in the system appliances (for example at night). The public Grid supplies it and your utility meter will run forward. If your solar power array produced enough electricity more than what your appliances need, your utility meter would begin to run backward.

But in some areas where the electricity grid always has failure, a **back-up battery** is added to the system (Figure 4.2). The system will be called **PV grid-tied system with Back-up battery**. In this case the energy surplus will be send to the grid just after the battery is fully charged. A charge controller will be added, a special inverter may be needed. The system will provided more losses due to additional components. Batteries protect the system from short-time blackouts but add more cost and maintenance to the PV system.

On-grid can also be used as business opportunity. That means the energy produced is totally sold to the public grid companies.

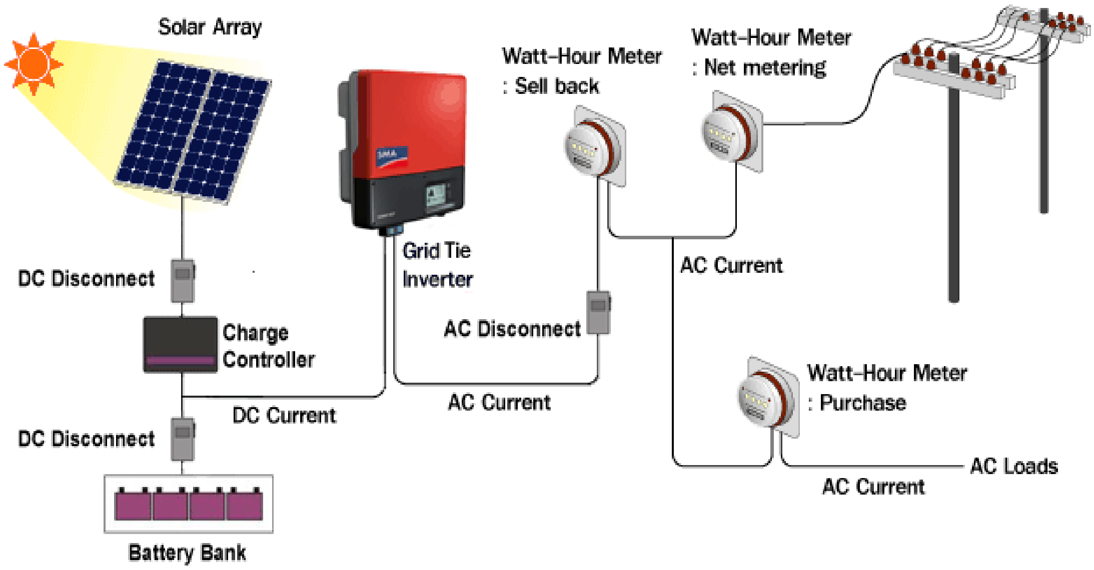

Figure 4.2: Grid-tied PV system with battery back-up

4.1 Principal components

- Modules or Array
- Junction box
- Charge controller
- DC isolation switch
- AC isolation switch
- Back-up battery for grid tied system with back-up battery
- Grid-tied Inverter
- Export and import meter
- Fuse box
- Loads

Description:

In a grid-tied photovoltaic system, the DC electricity produced by the PV array is connected to the junction box. A cable from this junction box feeds the DC electricity to the grid-tied inverter. The inverter converts this DC electricity into AC, which is either consumed by the building loads and appliances or fed on to the grid. The inverter is either connected to the main AC fuse box or directly to the incoming cables from the grid. An export meter meters the amount of electricity that the PV system puts onto the grid. An import meter meters the amount of electricity imported from the grid[39].
Usually it is one single meter called an **import-export meter** or, in the USA, **net-metering.**[40]
A grid-tied photovoltaic system with battery back-up is comparable to a PV stand-alone system connected to the utility.

4.2 Grid-tied inverters concepts

Inverters for use in grid-tied systems are not the same as those used in stand-alone systems. These inverters have a MPPT. They have to convert the DC electricity into the AC and feed it

[39] Photovoltaic for professionals, Karl-Heinz Remmers
[40] Photovoltaic for professionals, Karl-Heinz Remmers

onto the grid at the required voltage, frequency and phase. They can import power from the grid and export power onto the grid.
Grid-tied inverter has to fulfil some technical requirements (EN 50081, EN 60555, EN 50178)

- Sine wave output
- High efficiency (AC) minimum 90%
- Protection against overcurrent and overvoltage
- Must allow remote monitoring
- International standard incl. EMC
- Visual display of array output, fault indicators etc.

Some security measures (EN 61000, EN 60950) should be taken in account such as[41]:

- Phase correction (in case of differently charged line phases)
- Protection against phase oscillation
- Control of insulation of PV generator
- Reaction power control
- Environment (IEC)

In grid-tied photovoltaic systems many inverters concepts such as central inverter concept, string inverter concept, and module inverter concept are available. But we will focus on two concepts.

4.2.1 Master/slave central inverter concept

The master-slave concept is mostly used by larger PV systems. Like you see on figure 4.3 mostly 2 or 3 inverters are used. For sizing, the total power is divided by the number of inverters.[42] In this concept when the power limit of the master device is reached, the second or third will be connected. In order to load the inverters equally, the master and slave rotated in a specific cycle.[43]

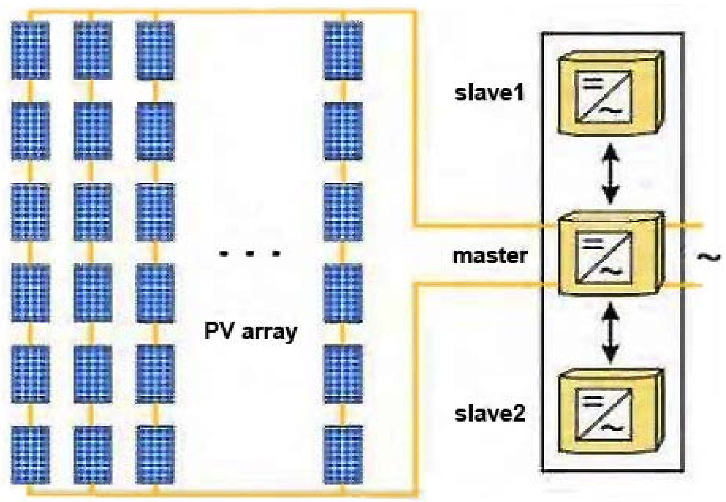

Figure 4.3: master-slave concept with central inverter unit source: solarpraxis

This concept has an advantage that in lower irradiance just the master inverter operates. This gives a better efficiency than just 1 central inverter at the same time the cost is higher.

[41] Sven Homscheid, Technical advisor CREDP-GTZ
[42] Planning and installing photovoltaic systems, DGS Germany
[43] Planning and installing photovoltaic systems, DGS Germany

4.2.2 String inverter concept

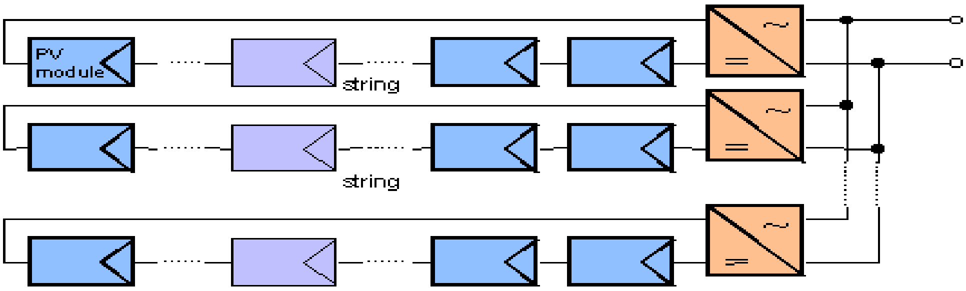

Figure 4.4 String inverter concept, source: www.volker-quaschning.de

This concept is appropriated for PV systems with differently oriented arrays or systems with shading. The string inverter concept has also many advantages[44]:

- In large systems, if one inverter fails, only part of the output will be lost.
- Partial shadowing of string do not affected the system
- The module cabling is reduced
- The DC main cable is unneeded
- The junction box is also unneeded
- String inverter facilitates the installation of the PV system because they are often mounted near the PV module and connected string to string. This can reduce the installation cost
- Performance of each individual string is optimized by separate MPPT of each individual string, leading to a higher output

4.3 Junction box

Junction box is most of the time supplied with the module. It is usually used to connect all the cables that are to feed into the inverter, when the PV array is composed of many strings.[45]
These are the main functions:

- Connecting together cables coming from the module strings
- Facilitating testing of the modules strings
- Housing over voltage protection
- Housing string fuses

However "*national electrical codes need to be referred to when deciding whether to use a PV combiner box or not, and regarding the requirements for string fuses and surge/overvoltage protection.*"[46]

4.4 Sizing

4.4.1 Sizing the inverter and efficiency

By buying an inverter you should take into consideration the nominal AC power $P_{n\ AC}$ (the AC power that the inverter can output), the nominal DC power $P_{n\ DC}$ (PV power for which the inverter is designed), the voltage range which the inverter will tract the MPP of the Array $V_{MPP\ min(inverter)}$ and $V_{MPP\ max(inverter)}$, Maximum DC input voltage $V_{DC\ max(inverter)}$ (maximum

[44] Solar laboratory, Christiani Gmbh ; Planning and installing photovoltaic systems, DGS Germany
[45] photovoltaic for professionals, Karl-Heinz-Remmers
[46] photovoltaic for professionals, Karl-Heinz-Remmers

voltage that may be present at the inverter), the maximum DC current $I_{DC\ max}$ and the maximum AC current $I_{AC\ max.}$ This also helps for the module-inverter compatibility. These are mostly given from the manufacturer on the data sheet.
For the compatibility following aspects have to be taken into consideration:

- The size of the inverter (W) should never be less than 90% of the peak wattage (W_p) of the Array. If we have 5kWp PV array the inverter should be between 4.5KW and 5KW
- the voltage range which the inverter will tract the MPP of the Array must match the operating voltages of the array
- The inverter must be able to bear the maximum array voltage and current.

"Under no circumstances should the maximum voltage and current of the PV array exceed the input voltage and current ratings of the inverter. This can damage the inverter. Overloaded electrical components will also age more quickly and the working life of the inverter will be reduced"[47]
For a good functioning inverter the temperature should not be above 70°C. Precautions should be taken for that. If is not possible to avoid a hot location, an inverter with ventilating fan should be chosen. At ambient temperatures between 20 and 30°, a temperature between 40°C and 80°C may occur in the inverter. To avoid such high temperatures, it is recommended to provide the inverter with an additional cooling. Installing an inverter under the roof in a space which gets too hot is not advisable. Somewhere that remains cool throughout the year is ideal. The inverter temperature range should be taken into account when selecting the location.
Inverters efficiency is usually given on the data sheet. Some manufacturers give the efficiency according to your location.

4.4.2 Sizing the DC cable and DC main Cable

Compared to stand-alone PV system grid-tied PV system also has to be rated for higher temperature ranges (-40°C to 120°C) and rated higher voltage bigger than 2KV. Cables should be well sized to avoid system failure or even fire.

Sizing DC cable

Electrical parameters	Symbol	Unit
Simple length of module and string cable	L_M	m
Line losses of module and string cable at STC	P_M	W
Cross-section of module and/or string cable	A_M	mm²
Electrical conductivity (Copper κ_{Cu} = 56; Aluminum κ_{Al} = 34)	κ	m/(Ω x mm$^{2)}$
String power at STC	P_{St}	W
String voltage	V_{MPP}	V
String current	I_{St}	A
Number of PV generator strings	n	-

Table 4.1: Electrical parameters for sizing the DC cable source: DGS Germany

$$A_M = \frac{2 \bullet L_M \bullet I_{st}}{1\% V_{MPP} \bullet \kappa}$$ [48]

[47] photovoltaic for professionals, Karl-Heinz-Remmers
[48] Planning and installing photovoltaic systems, DGS Germany

Or

$$A_M = \frac{2 \bullet L_M \bullet I_{st}^2}{1\% P_{st} \bullet \kappa}$$ [49]

Or

$$A_M = \frac{2 \bullet L_M \bullet P_{st}}{1\% V_{MPP}^2 \bullet \kappa}$$ [50]

The value of A_M is rounded to the next value of standard cable cross-sections (2.5 mm^2, 4 mm^2, 6 mm^2…).

The total cable loss on modules is calculated as following.

$$P_M = \frac{2 \bullet n \bullet L_M \bullet I_{st}^2}{\kappa \bullet A_M}$$ [51]

Sizing the DC main cable

The DC main cable must be able to carry the maximum occurring current produced by the PV array. The cross-section is calculated as following

Electrical parameters	Symbol	Unit
Simple length of DC main cable	$L_{DC\ CABLE}$	m
Line losses of DC main cable	$P_{DC\ CABLE}$	W
Cross-section of DC main cable	$A_{DC\ CABLE}$	mm²
Electrical conductivity (Copper κ_{Cu} = 56; Aluminum κ_{Al} = 34)	κ	m/(Ω x mm$^{2)}$
Nominal power of PV generator	P_{PV}	W_p
Nominal voltage of PV generator	V_{MPP}	V
Nominal current of PV generator	I_n	A

Table 4.2 Electrical parameters for sizing the DC main cable

$$A_M = \frac{2 \bullet L_{DC\ cable} \bullet I_n^2}{((1\% \text{ or } 2\%) \bullet P_{pv} - P_M) \bullet \kappa}$$ [52]

2% is in the low voltage concept.

[49] Planning and installing photovoltaic systems, DGS Germany
[50] Planning and installing photovoltaic systems, DGS Germany
[51] Planning and installing photovoltaic systems, DGS Germany
[52] Planning and installing photovoltaic systems, DGS Germany

4.4.3 Sizing the AC supply cable

Electrical parameters	Symbol	Unit
Simple length of AC supply cable	$L_{AC\ CABLE}$	m
Line losses of AC supply cable	$P_{AC\ CABLE}$	W
Cross-section of AC supply cable	$A_{AC\ CABLE}$	mm²
Electrical conductivity (Copper κ_{Cu} = 56; Aluminum κ_{Al} = 34)	κ	m/(Ω x mm²)
AC nominal current of inverter	$I_{n\ AC}$	A
Nominal grid voltage (single-phase: 230 V, three-phase 400 V)	V_n	V
Power factor (between 0.8 and 1)	cos φ	-

Table 4.2 Electrical parameters for sizing the AC supply cable

Mostly the AC cable connecting the inverter to the consumer unit is oversized in other to reduce the voltage drop.

With single-phase (230V nominal grid voltage) is the cross-section:

$$A_{AC\ CABLE} = \frac{2 \bullet L_{AC\ cable} \bullet I_{nAC} \bullet \cos\phi}{3\% V_n \bullet \kappa}$$ [53]

With three-phase (400V nominal grid voltage) is the cross-section:

$$A_{AC\ CABLE} = \frac{\sqrt{3} \bullet L_{AC\ cable} \bullet I_{nAC} \bullet \cos\phi}{3\% V_n \bullet \kappa}$$ [54]

5kWp PV system produced a cable cross section up to 6 mm^2.

The cable loss of the selected cable cross-section is calculated as following:

For single-phase

$$P_{AC\ CABLE} = \frac{2 \bullet L_{AC\ cable} \bullet I_{nAC}^{2} \bullet \cos\phi}{A_{AC\ CABLE} \bullet \kappa}$$ [55]

For three-phase

$$P_{AC\ CABLE} = \frac{\sqrt{3} \bullet L_{AC\ cable} \bullet I_{nAC}^{2} \bullet \cos\phi}{A_{AC\ CABLE} \bullet \kappa}$$ [56]

[53] Planning and installing photovoltaic systems, DGS Germany
[54] Planning and installing photovoltaic systems, DGS Germany
[55] Planning and installing photovoltaic systems, DGS Germany
[56] Planning and installing photovoltaic systems, DGS Germany

4.4.4 Sizing the Module (Number of modules in a string)

On the data sheet of a module a **current temperature coefficient** (A/°C), the **voltage temperature coefficient** (V/°C) and **the power temperature coefficient** (%/°C) is given.

The Maximum number of Modules in a string is calculated as following:

$$n_{max} = \frac{V_{DC\ max(inverter)}}{V_{oc(module\ 15°C)}}$$ [57]

This calculation is for tropical climate. For regions with summer and winter $V_{oc\ (module\ -10°C)}$ should be used.
In data sheet the V_{oc} is always given at the STC (Standard conditions) temperature of 25°C to have $V_{oc\ (module\ 15°C)}$ following calculation is done:
At 15°C the different of temperature to the STC is 25°C - (15°C) = 10°C.
$V_{oc\ (module\ 15°C)} = V_{oc}$ + 10 x Voltage temperature coefficient (V/°C)

The minimum number of modules in a string is calculated as following:

$$n_{min} = \frac{V_{MPP\ min(inverter)}}{V_{MPP(module\ 70°C)}}$$ [58]

From 25°C to 70°C we have an increase of temperature of 45°C
$V_{MPP\ (module\ 70°C)} = V_{MPP\ (25°C)}$ – 45 x Voltage temperature coefficient (V/°C)
(For more details See 5.6 Example).
IN grid-tied PV system with back-up battery the battery is size like in PV stand-alone.

4.5 DC disconnect and AC disconnect

DC disconnect and AC disconnect can also be circuit breakers. "A **circuit breaker** is an automatically-operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. Its basic function is to detect a fault condition and, by interrupting continuity, to immediately discontinue electrical flow. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation."[59]
DC disconnect is also called DC isolation switch. When PV array is exposed to light (produce a voltage). DC disconnect is needed in order that the array can be disconnected from the inverter during installation, repair or maintenance in voltage free conditions. Fire workers can also used it to disconnect the array from the system in case of fire on the roof. "*According to the IEC 60364-7-712 standard, electrical installations of buildings, requirements for special installation or locations, solar photovoltaic (PV) power supplies systems, an accessible load switch is required between the PV generator and the inverter"*[60]
The DC disconnect enable disconnection of the PV array from the grid must be capable of disconnecting the array from the inverter under full current. It is recommended to install it directly before the inverter. It should be double-pole. Sometimes it is integrated into the PV

[57] Planning and installing photovoltaic systems, DGS Germany
[58] Planning and installing photovoltaic systems, DGS Germany
[59] http://en.wikipedia.org/wiki/Circuit_breaker
[60] Planing and installing photovoltaic systems, DGS germany

combiner box, if this is easily accessible. In certain circumstances the PV combiner box may not be necessary, but the DC disconnect always is.[61]

Like the DC disconnect**, AC disconnect** also called AC isolation switch have to be bipolar (double-pole). Automatic circuit breakers are usually used as AC isolators.[62] For low voltage system, they are usually called **Miniature Circuit Breakers** (MCB, rated current up to 100A) or **Molded Case Circuit Breaker** (MCCB, rated current up to 1000 A). They are protective devices that can be switched back on after they are triggered and they automatically isolate the PV system from electricity grid if an overload or short circuit occurs[63]. AC disconnect is connected between inverter and electrical loads or between inverter and meter. And the meter is installed between grid and inverter.

4.6 Metering

Metering requirements and options vary from country to country and from utility companies to utility companies. The utility companies must be consulted. In systems where most of the electricity generated is to be used in the building itself the situation known as offset, there may be no metering also known as net-metering requirement. In this case it is recommended that a meter be installed to at least record the output of the PV array. Metering electricity sold on to the grid and purchased from it through a single meter is known as net-metering. Meters will usually be installed by the utility company and remain their property. Several configurations are possible.

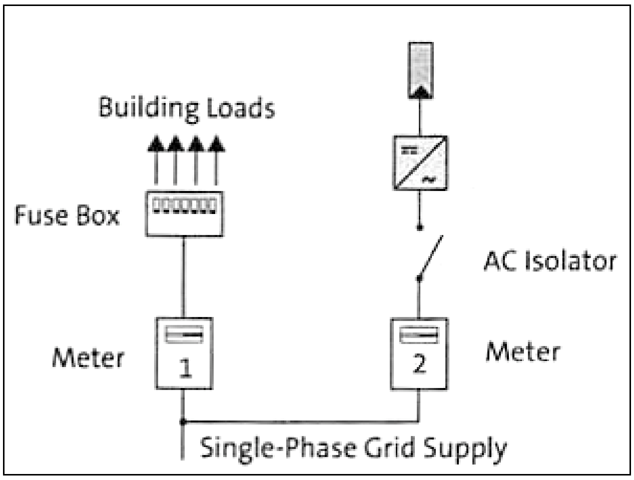

Figure 4.5**:** 2 meters single-phase configuration, source: photovoltaic for professionals, Karl-Heinz Remmers

A single-phase configuration (figure 4.5) means the connection to the grid is made with the grid incoming cable. Meter 1 count the incoming electricity from the grid and meter 2 count the units of electricity put onto the grid. There is an AC isolator between the Meter and the inverter.

In **Figure 4.6**, the connection to the grid is via a fuse in the fuse main box. The single meter is an **export-import meter.** The consumption will be “offset” by the electricity produced by the PV array so it does not have to import as much as it normally has to. A AC disconnect may be connected between the inverter and the fuse box depending on the national security code.

[61] Photovoltaic vor professionals, Karl-Heinz Remmers
[62] Planing and installing photovoltaic systems, DGS germany
[63] Planing and installing photovoltaic systems, DGS germany

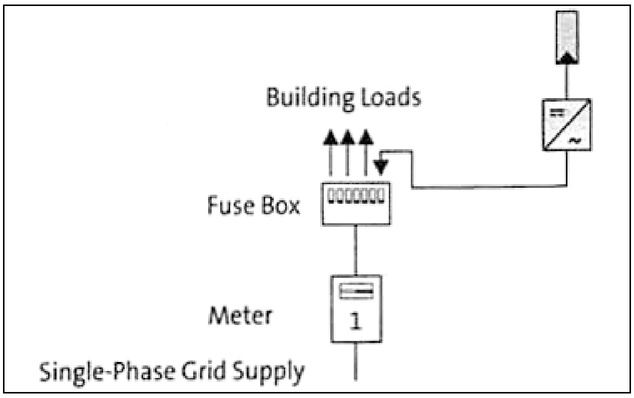

Figure 4.6**:** Export-import meter**,** source: photovoltaic for professionals, Karl-Heinz Remmers

In **figure 4.7** the connection to the grid is via a fuse in the building fuse main box. Meter 2 counts the number units electricity produce by the array. And meter 1 is an export-import meter. Monitoring this system will be easy.

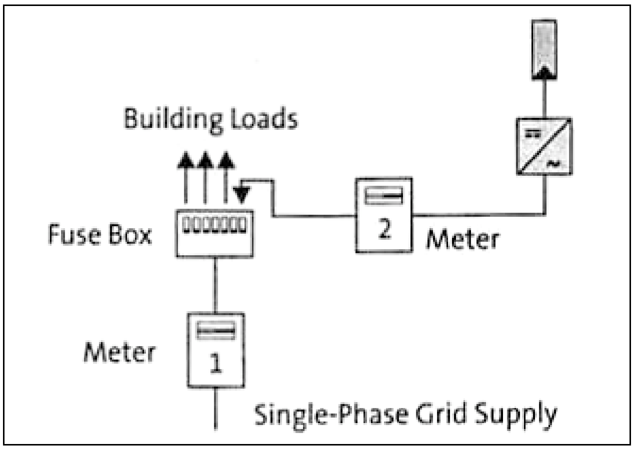

Figure 4.7**:** source: photovoltaic for professionals, Karl-Heinz Remmers

We can also have two or three-phase grid supply it all depends on the number of single-phase arrays that are connected together.

4.7 Monitoring

The monitoring devices mostly have the following functions:

- Continual data recording and automatic data transfer
- Related software
- Solar radiation and temperature sensors

High-quality inverters incorporate remote data communication and data logging features, which allow the system owner to monitor performance via a laptop or PC, or a website. Real-time performance, daily output, yearly output, system faults could be monitored.[64]

Other possibility of local monitoring includes monitoring by a local PC remote display located in the living room for example. The connection between inverter and display is

[64] photovoltaic for professionals, Karl-Heinz Remmers

usually wireless. Wireless transmission of this data is particularly useful. A modem can enable it to be viewed at other locations[65].

Other monitoring systems use powerline carrier communication, which transmits the data to a display over the normal house wiring (via grid). However, the PV monitoring manufacturers mostly informed you how the monitoring system is installed[66].

65 http://www.pvresources.com/en/monitoring.php
66 photovoltaic for professionals, Karl-Heinz Remmers

CHAPTER 5 Installation, commissioning and maintenance in Stand-alone and grid-tied PV system.

5.1 Shading in PV systems

A shadow on a PV module has a great effect on the solar yield. The shading is a big problem and should be avoided where ever possible. Unfortunately for some geographical locations and houses is shadow inevitable. In such cases a good planning and sizing should be made. With help of an simulation software with 3-D animation such as PV-SOL Expert 4.0 (Valentin energy software) the shadow could be simulated and the losses due to shadow will be determined.
When a solar cell is in the shade, it can't produce current anymore. Solar cells are usually connected in series therefore cell-shaded acts like a blocking diode. It is subject to the total voltage of the other cells and the diode break down. And this will heat up the cell and cause permanent damage to the module. This effect is the **"hot spot effect".**[67] Even little shadows caused by wires, treetops can also cause drops in output. Shading is a chain reaction. That means when one cell is shaded the output of the module is reduced the output of the array will be reduced too.

5.1.1 Types of shading in PV system

Occasional shading
Snow, leaves, bird droppings, dust, and other dirt are the cause of occasional shading. PV modules with a tilt (inclination) angle of a minimum of 13° can be cleaned from rain. In dry periods the modules have to be carefully cleaned by hand. The manufacturer instruction on cleaning modules has to be read.

Permanent shading
Trees, neighbouring buildings, hills, distance tall buildings, dormer windows, satellites dishes are the cause of permanent shading. In this cases when there is nothing possible to do, the problem has to be taken into consideration by sizing the modules.

5.1.2 Shading analysis

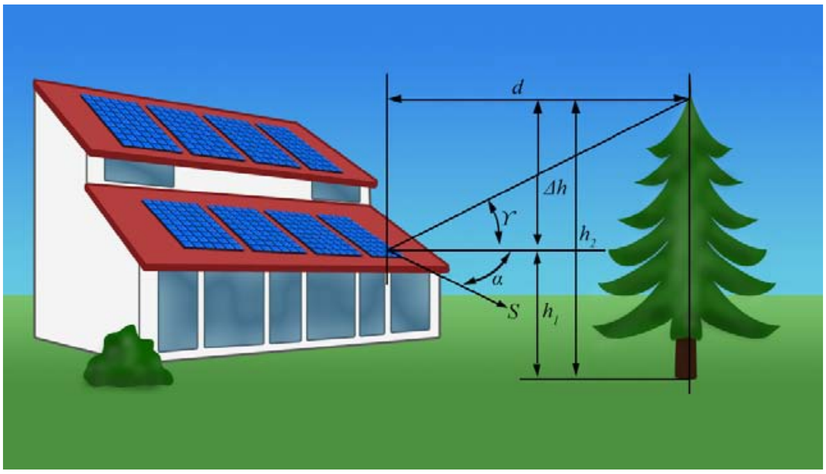

Figure 5.1: Angles, source: Planning and installing photovoltaic systems, DGS Germany

[67] Photovoltaic for professionals, Karl-Heinz Remmers

The shadow outline for the surrounding area can be found using[68]:

- Shading analyzer (photographic or using a digital camera and software)
- Sun path diagram on transparency
- Site plan and sun path diagram.

Shade can also be determined by calculating the elevation angle γ and the azimuth angle α on figure 3.6.

$$\tan\gamma = \frac{h_2 - h_1}{d} \rightarrow \gamma = \arctan\left(\frac{h_2 - h_1}{d}\right) = \arctan\left(\frac{\Delta h}{d}\right)$$ [69]

5.1.3 Shading solutions

Solution 1:

If the shadow is just occasionally **bypass diode** is installed in the module connection box to prevent and avoid hot-spot damages.[70] With this diode, current that suppose to bypass the affected cell is allowed.

"A solar cell loses most output if 10 - 20% of it is in shadow. If 20 standard cells are connected in series and there is critical partial shadowing (10 -20%), the loss in output with the shaded cells is approx. 20 W that these cells can usually cope without any problems. Larger losses in output lead to discolouration or the formation of bubbles in the cell encapsulation. The cell material can be thermally destroyed. During inspection, it is difficult to distinguish between small hot spots and soiling. They cause the efficiency of the system to deteriorate.

With standard modules with 36 -40 cells in series, each group of 18 - 20 cells is fitted with a bypass diode in the module connection box to prevent such damage.

In 2007, the company, Spelsberg, developed a bypass circuit without diodes which enables losses to be decreased still further with better overvoltage tolerance when there is shading." [71]

The bypass diode is connected in parallel to string of cells (Figure 5.2). The reduced output and possibility of damage to cells and modules caused by shade can be mitigated by the use bypass diode. The diode short circuits the affected area and allows the current to bypass it.

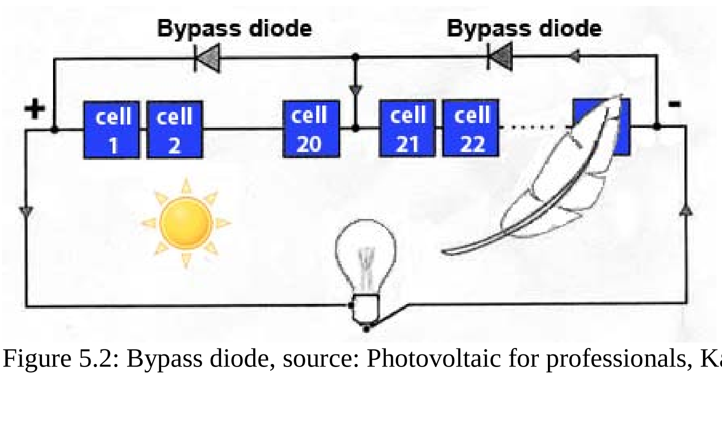

Figure 5.2: Bypass diode, source: Photovoltaic for professionals, Karl-Heinz Remmers

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[68] Planning and installing photovoltaic systems, DGS Germany
[69] Planning and installing photovoltaic systems, DGS Germany
[70] Photovoltaic for professionals, Karl-Heinz Remmers
[71] Solar power laboratory, Christiani

“A bypass diode is already connected in parallel to each cell during the production stage in **shade-tolerant modules**. However, this is expensive and only worthwhile for systems with larger levels of partial shading. “[72]

Solution 2: Modules connected in parallel

“The worst case of reverse current, when all the strings feed a parallel shaded string, occurs when the system is in open-circuit operation and the consumer is switched off.

Even when there is a very large number of strings, the current produced is only at the level of the nominal short-circuit current. A module can cope with this without any problems in reverse direction also.

However, if one wishes to prevent losses of current in general, individual strings can be decoupled using so-called string diodes.

In normal operation, string diodes are operated in the forward direction. This also results in unavoidable forward losses of 0.5 to 1.0 V. lf Low-loss Schottky diodes are fitted, the losses are reduced to 0.3 V”[73]

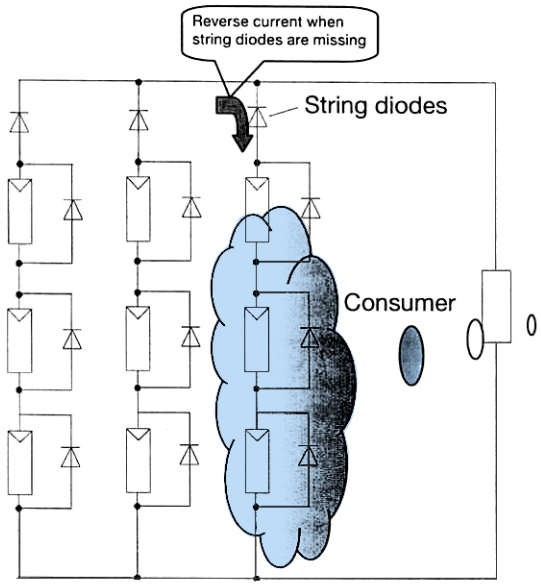

Figure 5.3: Module array with string diode source: Solar power laboratory, Christiani

Practical tip:

“When there are less than 6 parallel strings, string diodes are usually no longer necessary. Faulty string diodes are very often a problem. The loss of voltage with string diodes and hence loss due to heat is also not inconsiderable. There are not expected to be any safety problems for modules due to reverse current. ”[74]

Solution 3: Tilted PV Arrays

In PV system the highest yield is attained when there is an optimum inclination (tilt). On flat roofs and open spaces, the system is mounted horizontally (figure 3.7). In this case we just have to be sure that:

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[72] Solar power laboratory, Christiani
[73] Solar power laboratory, Christiani
[74] Solar power laboratory, Christiani

- There is enough space between the modules to avoid them shading each other
- The ground-mounted structures have to be high enough to avoid shade from growing plants and mud and dirt due to heavy rains have to be avoided.

"If there is limited space on a flat roof or area of the ground, it may be possible to reduce the module inclination in order to have more modules. While the output of the individual modules will be reduced slightly, the overall array output will be increased because there are more modules. However, caution is called for, depending on latitude."[75]

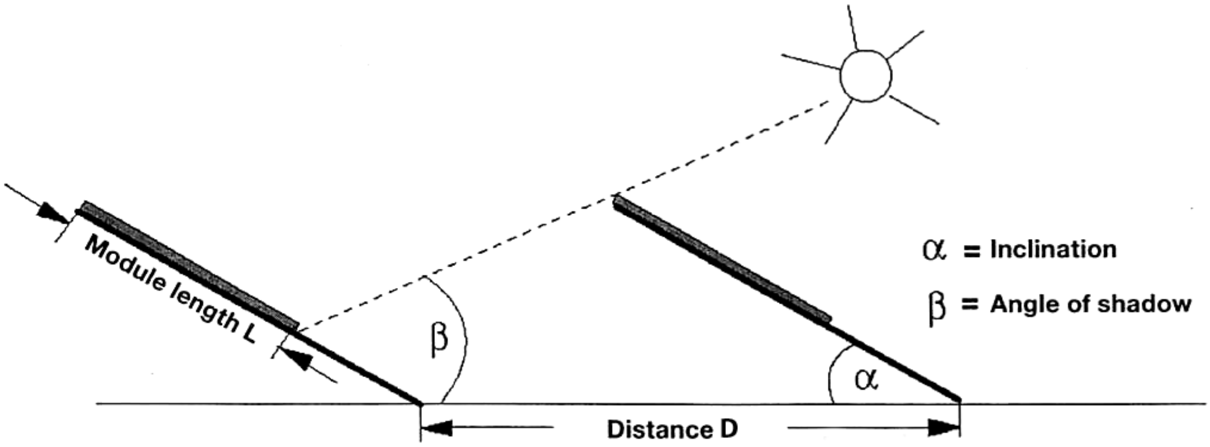

Figure 5.4: Tilt module, source: Solar power laboratory, Christiani

$$D = \left[\frac{\sin\alpha}{\tan\beta} + \cos\alpha \right] \bullet L$$

Solution 3: Module string arrangement

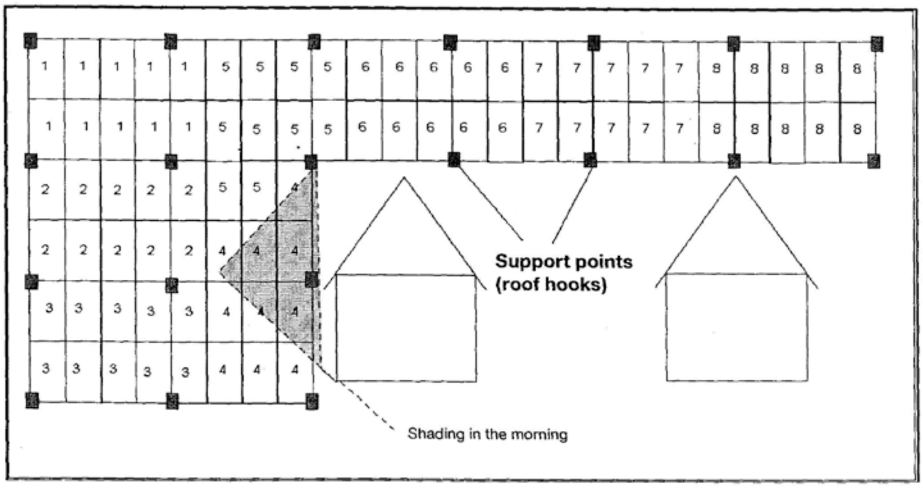

Figure 5.5: Module arrangement plan with roof hooks. Source: solar power laboratory, Christiani

In the module arrangement plan the modules are divided into different strings and are numerated. Modules in shade area can be combined to form one string. As showed in figure 5.5 the array has a string of 10 modules (count the total of 1, 0r 2…) the number 4 are combined together so that just the string number 4 is shade.

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[75] Photovoltaic for professionals, Karl-Heinz Remmers

5.2 Module mounting

Before working on roofs, national health and safety legislation and guidelines should be strictly complied with.

Modules have different mounting structures; they can be installed on roofs, on freestanding structures, or on ground-mounted structures on façades etc. Roof-mounted is the most common. In most cases many manufacturers offer some advices when modules are ordered. We will just talk about the 3 most used structures.

Mounting structure materials

Stainless steel and aluminum steel are the most common and galvanized steel is acceptable. Screws, nuts and bolts should be stainless steel. If not they can begin to corrode shortly after the structure has been installed. To have an appropriate module mounting racks, a rack manufacturer (e.g. www.unirac.com, www.zomeworks.com) or the module manufacturer should be consulted. The environmental conditions of the area, such as pollution, and the type of roof need to be taken into consideration.

Roof mounting structures

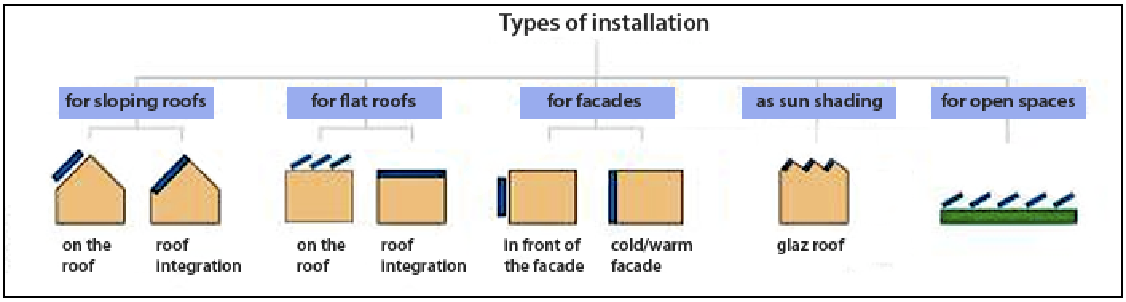

Figure 5.5: roof structure, source: DGS Germany

Modules can be mounted in different ways on different types of roofs. For example:
On a sloped roof, in a sloped roof, on a flat roof, in a flat roof, and glazed roof. The roof structures are also different. We can find hipped roof, broach roof, gable roof, etc…
These following points are important for a roof-mounted system:

- All the relevant details of the roof on which it is to be fixed should be sent to the supplier of the mounting devices, e.g. these are the orientation of the roof, the surface area of the roof, the structure and type of roof, the height of the roof, the angle inclination of the roof and also the age of the roof.
- For further works on the roof such as fixing, dismantle, space may be needed between the modules
- For all services a roofer may be required. Depending of the roof situation (age, height etc…)

Roof integrated mounting structures are too complicated and need much time and effort to install

Flat roofs and free standing mounting structures

- Not all roofs are suitable for freestanding mounting structures. The effect of the wind on the structure is one consideration. The modules act like sails and the structures themselves are usually weighed down with aggregate or cement.
- They need to be high enough off the roof (or ground) to avoid being plashed with dirty water.

- Sufficient space needs to be left between the rows of modules so that the rows do not shade each other
- Protection against theft is an issue. This means unauthorized removal should be very difficult.
- On high roofs exposed to high winds, wind load may have dangerous effects on the structure. The integrity of a structure might need to be enhanced by fixing the rows of modules to several points on the roof. The wind speed should be taken in consideration. This should stop any movement or toppling over of the rows of modules.
- The services of a roofer should be engaged - holes may need to be made in the roof and sealed.

Example 1: Flat roof installation

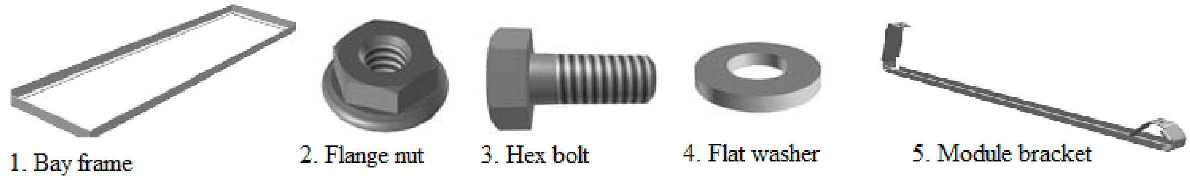

Figure 5.6: Mounting components, source: www.unirac.com

1. The bay frames should be laid on the roof where array will be mounted. Connect bay frames together using bolts, washers and flange nuts
2. 2 module brackets should be attached to each module using hex bolts, washers and flange nuts. The module brackets should be set at the optimum tilt angle (15° in Castries).
3. Attach the module brackets with module to the bay frame.
4. Concrete blocks should be placed in the bay frames (figure 5.7). The weight of the blocks depends on the wind speed/load, the module sizes.

This mounting system is easy to assemble.

Figure 5.7 Flat roof mounting, source: www.unirac.com

Example 2: Sloping roof

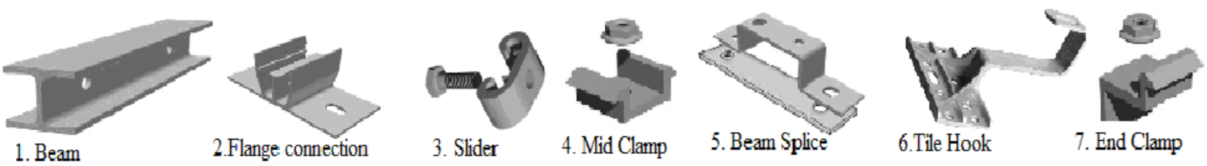

Figure 5.8: Components, source: www.clicksys-beam.com

1. The **beam** should be attached to the **flange connection**. The flange connection is also used to join the beams. **Beam splice** is also an option.
2. The flange connection should be attached to the rafters

3. **3.** Appropriate number of **sliders** should be installed. This depends on the number of modules to be installed
4. **4.** Module should be attached to the beam using the **mid clamp**. And **end clamp** should be used at the end of the attachment.

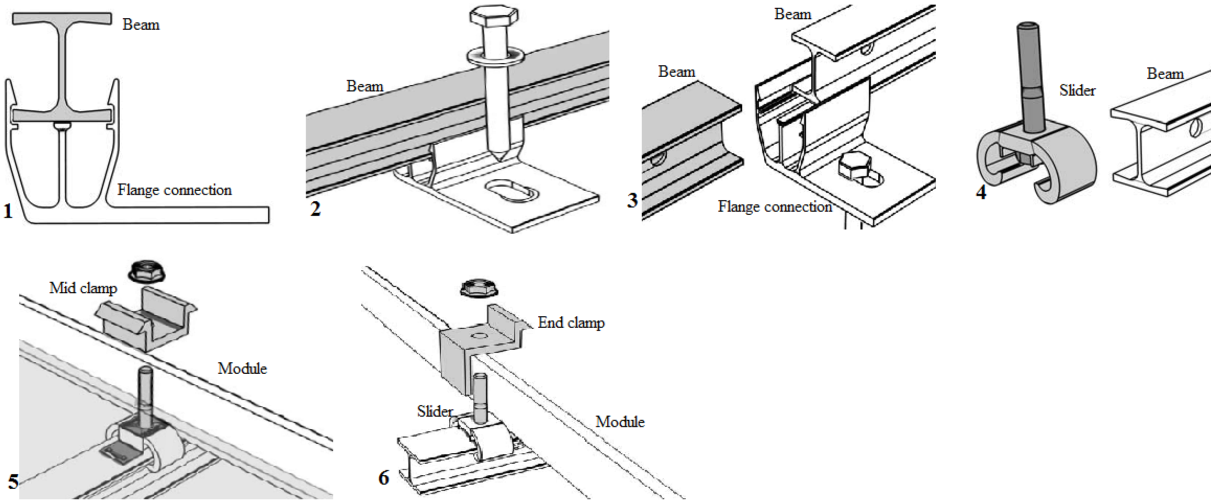

Figure 5.9: Mounting steps, source: www.clicksys-beam.com

If the roof is made of tiles, tile hooks should be mounted. (Picture 5.10)
After mounting the tile hooks, the appropriate number of beam sliders should be installed. The beams can be joined using beam splice.
The beams should be attached to the tile hooks.
The modules should be attached to the beam using mid clamp and end clamp (figure 5.11).

Figure 5.10: Tile hooks mounting, source: Schletter GmbH

Figure 5.11: Beam-tile hooks attachment, module mounting, Source: www.solarzentrum-allgaeu.de

The advantages of mounting on flat roofs or on the ground

- The modules can be installed at optimum orientation and inclination.
- Good airflow at the back of the modules.
- The installation is very straightforward, speedy and economical.
- Modules can easily be removed for repairs and maintenance (though theft of modules might be made easier).
- Mounting modules on the ground is even more straightforward, speedy and economical, and the load bearing capacities of a roof does not need to be taken into consideration. However, it may be difficult to avoid shading in built-up areas.

5.3 General information about working on PV systems and safety guideline

Different laws and electrical codes in different countries regulate the installation and commissioning of grid-tied PV systems. The country utility companies have to be consulted. Before starting any installation **the instructions and manuals should be read carefully.**
The following procedures mostly look like this:

1. Obtaining all necessary permits (familiar with relevant codes, legislation and utility companies, necessary building permits)
2. Installation of the system (qualifications required for personnel carrying out work)
3. Inspection and testing of the system.
4. Permission to connect. (Permits required from utility companies for grid-connection; net-metering requirements)
5. Connection to the grid and system commissioning.

In some countries in stand-alone systems some permits are needed too. In this case familiar with relevant codes, legislation and necessary building permits.
Working with electricity is very dangerous and there are additional dangers associated with working with PV modules. Never work on any PV arrays if there is any thunder or lightning in the area.

These can be summed up as follows:

- All the usual safety precautions that are taken when working on electrical circuits should be adhered to, taking into consideration the additional dangers associated with working with PV modules
- PV modules always produce a voltage when exposed to light
- PV modules will continue to produce a voltage even when there is a fault or short circuit
- PV modules are a limited current source (the fuses may not blow or the circuit breakers may not open if there is a fault). That means fuses and circuit breakers do not operate in the way they do in normal AC mains power circuits
- Damaged cables should be temporarily taped with insulating tape, eventually repairing or replacing them
- Fuses should not be removed when a circuit is under load-to do so can cause arcing
- PV arrays are often configured to produce relatively high and dangerous DC voltages
- Danger of falls from roofs due to electric shock
- The PV array should be disconnected from the inverter by having the DC disconnect/isolator in the open/off position when any working on the DC side of the installation

"When installing **stand-alone PV systems**, all the usual precaution's taken when working on electrical system need to be observed. The batteries in these systems present additional dangers and many electricians will not be used to working with DC electricity and the particular electrical characteristics on PV arrays."[76]

Some general guidelines[77]:

- All measures regarding battery safety should be strictly observed
- Children, unauthorized persons and animals should be kept away from potential hazards

[76] Photovoltaic for professionals, Karl-Heinz Remmers
[77] Photovoltaic for professionals, Karl-Heinz Remmers; planning and installing photovoltaic, DGS Germany; Photovoltaic systems, UNESCO

- Before carrying out any task, the relevant section of the manufacturer's manual should be read
- Components should be checked to make sure they are not damaged
- Components should connected/disconnected in the correct sequence
- Work should only be done in dry conditions
- No work should be done on PV arrays if there is any lightning in the area
- Systems should be inspected and tested before commissioning
- National codes and safe working practices should always be complied with

PV arrays in stand-alone systems operate at much lower voltages -typically 12 VDC or 24 VDC, which reduces the shock hazard (but modules can be connected up incorrectly and give higher voltages). Never disconnect the batteries from the charge controller while the PV modules are still connected to the charge controller. The high open circuit voltage of the modules can damage the charge controller. Always disconnect the modules from the charge controller before disconnecting the batteries. During system installation, always connect the batteries to the charge controller before connecting the modules to it.

Inverters are rarely reverse polarity protected. If an inverter is connected up incorrectly to a battery, it can be seriously damaged. Connecting the positive terminal of the inverter to the negative of the battery and vice versa can destroy the inverter. This will not be covered by the inverter warranty.

"Fuses and breakers installed on the DC side need to be rated for DC and the appropriate voltage. Also, the PV array is a current limited generator and its short circuit current will only be about 20% greater than its operating current, which means that fuses and circuit breakers will not give anywhere near the same level of protection that they give in more conventional circuits. National codes should be referred"[78]

5.3.1 Lightning protection

In reality, many small stand-alone PV systems do not have lightning protection. Modules on roofs or on poles attached to buildings should not be higher than the highest point of the building. The metal module frame above an isolated household can act as a lightning conductor. Charge controllers very often-incorporate minimal surge protection such as a voltage suppressor to protect against induced over-voltages. In regions of frequent storms, a double pole disconnect/isolator should be installed (even on small systems), so that the PV array can be isolated from the rest of the system when there is a risk of lightning strike.

No work should be carried out on any PV arrays if there is any thunder or lightning in the area.

If there is a lightning protection system already on the building, the PV installation will generally need to be connected to it. However, the existing lightning protection system might be old and not compliant with the current code and needs to be upgraded if changes and additions are made to it. It might also be damaged

"In general, the installation of a PV array on a building does not increase the risk of a lightning strike if the height of the building has not been increased or only marginally. However, on flat roofs, the modules will increase the height of the roof ground mounted arrays also need protection. The more expensive an installation is, the greater the need to protect it. But even the best lightning protection system is not a replacement for adequate

[78] Photovoltaic for professionals, Karl-Heinz Remmers

insurance. And some insurance companies may insist on lightning protection. The long shadow cast by a lightning conductor can cause significantly reduced array output. This can particularly be a problem with arrays on flat roofs and with ground mounted arrays. So if one is being installed, its position relative to the array needs to be taken into consideration and lightning protection system designers and installers need to be aware of this. The problem may be overcome by placing the lightning conductor behind the array (relative to the sun) or possibly the use of all shorter lightning conductors."[79]

In area with high lightning strikes it is dangerous to have electrical systems without lightning protection. PV systems can be damaged by direct lightning strikes and by nearby lightning strikes. If there is no lightning protection system, the lightning will flow over the installation and more or less destroy it completely, structural damage and fire can also result. It is recommended and necessary to install a lightning protection system.

The installation of lightning protection requires a specialist. Incorrectly installed lightning protection systems can actually increase the risk of danger to persons and cause damage to equipment. Lightning protection is also linked to grounding/earthing and codes and regulations regarding grounds differ considerably from one country to another. Utilities may also need to be consulted

5.3.2 Grounding/earthing

It is not usual to ground stand-alone PV systems with one or two modules (< 100 Wp) and with system voltages under 24 VDC, but national codes need to be referred to. Usually the inverter ground terminal (if there is an inverter), the PV array and the negative battery terminal are connected to a single ground electrode. Ground fault circuit interrupters (also known as residual current devices or RCDs) may or may not be required. For inverter grounding requirements it is necessary to refer to inverter manuals. The sizes of ground conductors will usually be specified in national codes. Measures against lightning protection can complicate the requirements.

"The metal frames of modules and the metal mounting structure need to be grounded/earthed. As in most electrical installations, the purpose of grounding is to ensure that in fault conditions leading to metal enclosures or structures becoming hot/live, the voltage does not rise significantly above ground/earth potential and to ensure that fuses and circuit breakers disconnect the supply within time limits. Usually either the metal components of the PV array will be connected to each other and to the main grounding point, which may need to be installed. If there are no metal parts in the array (for example, in a roof integrated system using laminates rather than framed modules), no grounding may be required. Inverters will usually also need to ground. It is important to bear in mind, that there are not only electrical hazards originating in the PV array itself but that, under fault conditions the PV modules and array mounting structure can be made hot/live by the grid itself Some codes may specify the use of ground fault interrupters (GFIs in the USA) (residual current circuit breakers RCCBs or RCDs in the UK), and the type which is to be used. USA codes require GFIs built into the grid-tie inverter. "[80]

In all decisions regarding grounding/earthing requirements for PV modules frames, PV array mounting structures and grid-tied inverters, national electrical codes need to be consulted and implemented.

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[79] Solar power laboratory, Christiani ; photovoltaic for professionals Karl-Heinz Remmers

[80] Photovoltaic for professionals, Karl-Heinz Remmers

5.3.3 Battery safety

Batteries are hazardous. Only suitable trained/qualified persons should work on large battery banks or in battery rooms. The main safety issues are:

Sulphuric acid is corrosive. In both liquid and vapour form it can cause blindness and damage to skin and mucous membranes (mouth, throat, lungs). Protective goggles and gloves should be worn and a supply of fresh water always at hand - one large bucket or dish for washing and one for rinsing.

- The hydrogen gas produced by vented batteries becomes explosive when mixed with the oxygen in the air. Naked flames, smoking or any sources of sparks can cause ignition. Battery rooms and enclosures should be well ventilated at their highest point.
- Attention should always be paid to correct polarity when connecting cells/batteries to each other or to inverters and other system components. Short circuits can be made by incorrect connections and reverse polarity can damage equipment, especially inverters.
- While working on batteries, all metal jewellery such as rings, watches, chains, should be removed. These can cause short circuits and melt, causing burns.
- Batteries should never be charged without a charge regulator.
- Tools should be insulated and placed on the floor when not in use. A non-insulated tool falling across the terminals of a battery can cause a short circuit.
- Battery temperatures should not be allowed to exceed 50 °C. They should not be exposed to direct sunlight.
- Used batteries are toxic waste and need to be disposed correctly. In many countries, battery suppliers are obliged to accept and recycle old batteries.

"*If the positive pole and the negative pole of a battery cell or battery are connected together with an object made from a conducting material such as screw driver, the battery will short circuit. This can lead to explosion and fire. The utmost care is called for when working on batteries"*[81]

5.3.4 Battery rooms

The batteries should be installed in a separate room, usually adjoining the main building. Battery rooms should be well-ventilated, dry, cool yet frost-proof and vibration free. Ventilation should be natural but in small rooms a ventilation fan may be needed. In fact, in extremely hot or cold climatic conditions, having the battery room below ground level (up to 2 m) can mitigate the excesses of temperature. The floor as well as walls should be protected against the effects of acid-resistant plaster or paint can be used. Doors need to open outwards.

Door thresholds should be at least 10 cm high. Warning notices should point out the dangers and forbid naked flames/smoking. Batteries should be laid out in such a way that they are easily accessible at least from one side to facilitate the taking of electrolyte readings and maintenance. Battery racks are available from battery manufacturers, which hold the batteries securely in place. No equipment such as inverters, controllers, switches or fuses should be installed in the same compartment as the batteries. This equipment may spark and batteries produce corrosive fumes that will destroy expensive hardware. These items should never be installed directly above batteries.

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[81] photovoltaic for professionals, Karl-Heinz Remmers

5.4 General maintenance

It does not take much time and money to regularly maintain a solar PV system but it may take a lot to repair the system if it fails. Regular maintenance makes the difference between a PV system that works without problems for years and one that is always breaking down. Following have to be done:

- Remove all sources of shade on the array and rinse the array to remove the accumulated dust, dirt, and other debris. Some debris, such as bird droppings, may need to soak a bit to fully remove it.
- Check the combiner box (es) and look for any dirty, loose, or broken connections, and correct as necessary
- Open all disconnect switches. Use the ohmmeter section of the voltmeter to check the grounding system connections. If the ohmmeter shows more than 25 Ohms, that means corrosion or a poor connection is present, which must be located and corrected.
- It is very important to keep complete records of maintenance. Many problems with solar PV systems happen slowly so, without proper records, problems may not be noticed until it’s too late to fix them easily.
- Check panels regularly for dirt, shade, tight connections and secure mounting.

- Pigs, mice, rats, dogs, birds and insects have all been known to cause damage to PV system wiring and components. Always visually check all wires and components for damage and insect nests.
- Controllers must be checked for loose wires and secure mounting. They should be opened and checked for cleanliness and insects.
- PV systems work better and longer if they are kept clean.
- Each maintenance visit has to be recorded.
- Hydrometer readings for each cell of a battery should be made at every visit. Each reading should be written down along with the date and time. If problems occur in the system, the record of these readings will be very valuable in finding and repairing the source of the trouble.

5.4.1 Troubleshooting and repair

When the system is installed, a record should be made of the installation and the operating characteristics of all components. This should include at least a complete wiring diagram, notes on hours of shade, the number of amperes required to operate each appliance, the set points of the controller, and the amperes and volts available from the panels at noon on clear day.

These problems may occur:

- A load does not operate properly or not at all
- The inverter does not operate properly or not at all
- The array has low or no voltage or current.
- The back-up battery does not operate properly

1. Array trouble repairs

If the array is not producing DC electricity the following checks have to be done:

- Check and record the inverter’s input voltage and current level from the array.

- Check all switches, fuses, and circuit breakers. Blown fuses have to be replaced and reset the breakers and switches.
- Check for broken wires and loose or dirty connections in the inverter. Replace all damaged wires and clean and tighten all connections.
- A fused combiner box can save a lot of time when checking each module or sub-array string. Remove the fuses and then check and record the open-circuit voltage and current reading for each circuit string.
- If the output voltage is low, it could indicate that some modules in the series string are defective or disconnected and need to be replaced.
- Low current output could also be caused by cloudy conditions, a defective blocking or bypass diode, a damaged module, one or more parallel connection between modules in the string is broken, loose, or dirty, or some parallel connections the module are broken, loose, or dirty. Replace defective diodes and clean and tighten all connections. Some of the array may be shaded, significantly reducing the array's current output. Remove the shade.

2. **Inverter trouble**
   Blown fused may be the reason of lack of power output from the inverter but also a broken wire, a ground fault, or any of the inverter's internal disconnects.
   The load on the inverter may have too high of a current demand. The loads should be replaced or the inverter with one with a larger output.
   Turn off the inverter, repair any faults, and start the inverter again.

3. **Loads**
   Check the fuses and circuit breakers. Are there blown fuses or tripped breakers? If so, locate the cause and fix or replace the faulty component
   Check for broken wires and any loose connections. Clean all dirty connections and replace all bad wiring. With the power off, check for and repair any ground faults. Replace the fuses and reset the switches. If they blow or trip again, there is a problem short, which must be located and repaired.
   If the load does not operate properly, check the system's voltage at the load's connection. Low voltage could mean that the wire feeding the circuit is too small and too long and needs to be upgraded to reduce the voltage drop.

4. **Battery**
   A battery failure usually happens slowly and is the result of a long series of small changes. Its changes may be caused from inside the battery due to age or adding impure water, or from outside the battery.
   Outside problems can result in damage due to over-discharging the battery, leaving it partially charged for a long time or strongly overcharging it.
   Whenever a battery has to be replaced, check every part of the PV system, including all wiring, to make sure that everything is working properly. Otherwise the new battery may have its life shortened because some other part is faulty.
   When you replace a battery, try to find the same type and size as the one installed in the PV system when it was new.

5.5 Cost estimation

Since January 2010 a good complete solar system with quality components and crystalline module is estimated to cost between 2500€ and 3000€ per kWp without installation fees in

Germany[82]. The cost depends on the total size of the PV system. Bigger is the PV system cheaper are the components cost per kWp. The installation fees depend on each country.
To analyze and compare the PV systems and public utility the **life-cycle cost** is used[83]. It is the cost of all expenses incurred over the life of an electricity generating system. This cost includes initial costs, maintenance costs, energy costs, repair and replacement costs.
The costs of utility connections are simple to calculate. It is just the initial connection cost and annual energy costs (the electricity bills).
For example, let's consider a 2000Wp PV system. The total system costs is 9000€, this includes installations costs and other fees. The total electricity bill is 900 euro each year. That means the system saves 900€ in costs each year if the PV system replaces completely the utility costs. If not utility cost should be reduced in calculation. After 10 years, the total saved costs is 900€ x 10 = 9000€.
This cost covered the total system cost. That means the payback period is 10 years.

5.6 Examples and Exercises

Example:

Sizing a 5kWp PV system in Castries (St. Lucia) on a slope Roof (length L=9 m, and Width 5 m)
Chosen module:
Photovoltaic-Module: CSI CS6P-230; EUR 435,93 From Canadian Solar INC company

- 60 high-efficiency polycrystalline solar cells
- Unique frame design to reinforce sealing and to prevent freezing and warping
- Strong aluminium frames to strengthen the load hold and to stand against high wind
- Special mounting holes on the frames for long and short side mounting
- High transparency low iron tempered glass with enhanced stiffness and impact resistance
- Advanced EVA encapsulation system with multilayer back sheets to better protect modules

Electrical Performance

Under Standard Test Conditions (STC) of irradiance of 1000W/m², spectrum AM 1.5 and cell temperature of 25°C

		CS6P-200	CS6P-210	CS6P-220	CS6P-230	CS6P-240
Maximum Power	Pmax	200W	210W	220W	230W	240W
Voltage at Maximum Power	Vmp	28.9V	28.9V	29.3V	29.8V	30.4V
Current at Maximum Power	Imp	6.93A	7.26A	7.52A	7.71A	7.91A
Open Circuit Voltage	Voc	36.2V	36.4V	36.6V	36.8V	37.0V
Short Circuit Current	Isc	7.68A	7.91A	8.09A	8.34A	8.61A
Maximum System Voltage		1,000V				
Temperature Coefficient	Voltage (Voc)	-0.35 %/°C				
	Current (Isc)	0.060 %/°C				

*NOCT (Normal Operating Cell Temperature): 45¡ **Module power tolerance: ±5W (approx. ±2.5%)

Table 5.1: Data sheet module, source: CSI

Length*Width*Depth = 1638 mm x 982 mm x 40 mm
Weight =18.5kg and 60 polycrystalline Cells.
1.638m $1.638\ \text{m} \bullet 0.982\ \text{m} = 1.608\ \text{m}^2$ for 230 Wp. This is equivalent to 7 m^2/kWp

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[82] http://www.photovoltaik-preisvergleich.de/
[83] Photovoltaic Systems Resource Guide

1. Roof size needed: $5 \bullet 7\ m^2 = 35\ m^2$
Total module need is 5000Wp/230Wp= 21.7 we will first consider 22 modules for a total power of 22 x 230 Wp = 5060Wp
Modules should be checked if laid out on portrait format or landscape format. This depends on the Length and the Width of the roof. If a roof has (length L=12 m, and Width 9 m)

2. How to check if the module fit the roof

- In portrait format

$$\frac{\text{Roof Length L}}{\text{Module Width}} = \frac{12\text{m}}{0.982\ \text{m}} = 12.2$$

$$\frac{\text{Roof width W}}{\text{Module length}} = \frac{9\ \text{m}}{1.638\ \text{m}} = 5.6$$

This makes a total of 12 x 5 = 60 This means the maximal number of modules laid in portrait format that could fit the roof is 60 (12 modules and 5 strings or 5modules and 12 strings). This is over the total of modules we needed (22).

- Same in landscape format we have

$$\frac{\text{Roof Length L}}{\text{Module length}} = \frac{12\text{m}}{1.638\ \text{m}} = 7.3$$

$$\frac{\text{Roof width W}}{\text{Module width}} = \frac{9\text{m}}{0.982\ \text{m}} = 9.1$$

9 x 7 is approximately 63 so maximum 63 (9 modules and 7 strings or opposite) modules can fit in landscape format.
The modules can be laid in both formats. Always chose the format in which more modules could be laid (the system could be extended). In this case landscape format.

3. Checking the module Voltage
From the data sheet:
Voltage temperature coefficient -0.35% x Voc/°C= -0.0035 x 36.8 = - 0.129V/°C
V_{MPP}(at 25°C) = Vmp = 29.8V
V_{MPP}(at 15°C) = 29,8 + 10x 0.129 = 31.09V
V_{MPP}(at +70°C) = 29.8 – 45 x 0.129 = 24V
V_{oc}(at 25°C) = Voc = 36.8V
V_{oc}(at 15°C) = 36.8 + 10 x 0.129 = 38 V

4. Inverter selection.
Inverter nominal power P_{MPP}(inverter) is between 90% and 100% of P_{MPP}(array) this is between 90% x 5020 = 4518 W and 5060 (this range is chosen because in case of good sunny days with radiation at the STC or over the STC, the inverter should not be undersized), so 4 inverters can be chosen for a string-inverter concept. Sunny boy 1200

Input (DC)	Sunny Boy 1100	Sunny Boy 1200*	Sunny Boy 1700	Sunny Boy 2500	Sunny Boy 3000
Max. DC power	1210 W	1320 W	1850 W	2700 W	3200 W
Max. DC voltage	400 V	400 V	400 V	600 V	600 V
PV-voltage range, MPPT	139 V – 320 V	100 V – 320 V	139 V – 320 V	224 V – 480 V	268 V – 480 V
Max. input current	10 A	12.6 A	12.6 A	12 A	12 A

Table 5.2: data sheet inverter, source: www.sma.de

5. Module configuration

Maximum number of modules on a string $= n_{max} = \frac{V_{DC\ max(inverter)}}{V_{oc(module 15°C)}} = \frac{400}{31.09} = 12.8$

Minimum number of module on a string $= n_{min} = \frac{V_{MPP\ min(inverter)}}{V_{MPP(module\ 70°C)}} = \frac{139}{24} = 5.8$

Therefore the maximum number of modules is 12 and minimum 6 on a string.

6. Array configuration and inverter compatibility

With 22 modules we can't have 4 Strings of 6 modules with 1 inverter on each string, so the PV system should be extended to 24 modules. To be sure the voltage compatibility has to be checked.

V_{MPP}(at 70°C) = 6 x 24V = 144V this is **above** the lower voltage of MPP-range (139V) acceptable

V_{MPP}(at 15°C) = 6 x 31.09V = 186 V this is **bellow** the upper limit of the MPP voltage range (320V) also acceptable

V_{oc}(at 15°C) = 6 x 38= 228V this is **bellow** the maximum inverter input voltage (400V) also acceptable

The current at the MPP of the module is 7,71A this is **bellow** the maximal input current of the inverter (12.6 A) so good!

PV system Summary

This is a **string-inverter concept**. The array has a total wattage of 5.520kWp consists of 24 modules with 230 Wp each. The array is configured in 4 strings of 6 modules.

For Grid-tied with battery back-up, the battery should be sized like in PV stand-alone system.

Exercises 4 and 5

1. Describe the counter arrangement in a customer system for each case when solar power is fed into the grid with and without cost-covering payment.
2. Using the yield diagram, define the percentage energy yield of a PV system in the east or west facade.
3. What nominal roof output would you give for a roof 11.5 m long (from top to bottom) and 11 m width (from east to west), if output of 130 watts per m2 can be installed with the system technology chosen?
4. A string concept with 6 inverters is planned for the PV system with 12 kWp What DC output should each inverter have?
5. What ways do you know for improving the efficiency of the whole system from the planning example?

6. What string cable cross-sections do you use for the wiring when the inverters in the cellar are connected over a conduction path 10 m long? With module current of 4.7A, the voltage of 216 V, 1% drops of voltage.
7. What must you consider when choosing a location for installing the inverter?
8. What options do you know for disconnecting a DC load?
9. What protective measures must be considered for transformer-less inverters?
10. When installing the PV modules on the roof, what must you consider if no lightning protection facility has been fitted on the roof yet?

Project:
Sizing and mounting a grid-tied PV system on a Roof of a temporary building in Castries. Capacity between 0.4 and 0.6kWp

5.7 Solution Sheets

Solution sheet Chapter 1 and 2

1. **How much energy is radiated on the entire surface area of Saint Lucia (619.15 km^2) by the sun if annual radiation is at a level of 2015KWh/m^2?**

   $E = 2015 kWh/m^2 \times 619.15 \times 10^6 m^2 = 1{,}247 \times 10^9 kWh$

2. **How many tonnes of CO2 output could be prevented with the photovoltaic output of 4 GW, installed around the world in 2007, when coal-powered plants emit 1kg of CO2 into the atmosphere for every kWh of power produced?**

   Use a basis of 1,000 hours of sunlight per year for your calculations.
   CO2 avoidance=4×10^6 kW x 1,000h x 1 kg/kWh=4×10^9 kg
   This quantity corresponds to a CO2 saving of 4 million tonnes.

3. **Give reasons for the use of photovoltaic technology.**
   - Energy production without noise, exhaust, poisonous substances.
   - Creates jobs in industry, commerce and trade
   - No major additional structures required - roof surfaces can be used
   - Durable and positive ecological and energy balance.
   - No hazardous waste produced at the end of its service life, only recyclable materials

4. **Name the three principle possible locations for photovoltaic energy production equipment**.
   South, east or west-facing roofs, building facades, open spaces, noise barrier walls, etc.

5. **What is meant by open-circuit voltage?**

   Open-circuit voltage is the voltage measured at a voltage source without any consumers connected. For a PV cell, the open-circuit voltage is around 0.6 V when illuminated.

6. **What are the results of a serial connection of solar cells and solar modules?**

   If solar cells are connected in series, the total voltage of the individual cells is added together: The current remains constant in all cells. If one cell breaks down, the entire circuit is interrupted.

7. **What are the results of a parallel connection of solar modules?**

If solar modules are connected in parallel, the total currents of the modules are added together. The voltage of the modules should be constant in all circumstances as otherwise compensation currents flow and the lowest voltage determines the overall voltage. If one module breaks down the remaining modules can continue to supply a current.

8. What are the differences between a solar module and a solar collector?

A solar module supplies electrical energy when the sun shines. A solar collector can heat up a liquid when the sun shines and thereby supply warm water.

9. Give a simplified description of the function of a solar cell when light falls on it and the power circuit is complete.

When light falls on the solar cell, electrons in the P-N threshold area are freed from the Si atoms and flow to the N layer. The holes of these electrons flow to the P layer as more electrons flow from the P layer towards the P-N threshold. The electrons in the N layer can only flow back to the P conductor via a closed, external circuit as the internal path is blocked by the electrical field between the N and P layers.

10. Which extreme value characterises the current-voltage curve of a solar cell?

The short-circuit current "I_{sc}" and the open-circuit voltage “V_{oc}". The point of maximum power (MPP) lies between them.

11. What is meant by MPP?

The MPP (Maximum Power Point) designates the value of a Voltage-current characteristic at which the product of voltage and current is greatest.

Solution Sheets for Off-Grid Photovoltaic Technology

12. The point where a solar cell’s output is at its maximum is referred to as MPP Approximately how great are the voltage and current at the MPP, if the cell temperature is 25 °C and a radiation of 1,000 W/m^2 is present?

A normal silicon solar cell with an edge length of 10 cm has a nominal voltage of 0.5 V and a nominal current of 3 A in standard test conditions (STC).

13. Calculate the filling factor and nominal power of the solar module.

$$F = \frac{V_N \bullet I_N}{V_{oc} \bullet I_{sc}} \quad =(17 \times 1.74) /(21 \times 1.93)=0.729$$

P_N=17 x 1.74= 29.58 Wp

14. How do the current, voltage and output of a solar module change when it warms up in summer?

The current rises and the voltage drops when the module heats up.
This means the output also drops as the voltage drops 10 times as much as the current rises. Output drops approx. 0.5% per °C.

15. Why is the cell efficiency level of a module always greater than the module efficiency level?

The cell efficiency level is calculated by comparing the cell surface with the radiation surface.
A solar module, which is made from many cells, has gaps in the surface without active solar material. This means that the efficiency level of the module will always be worse than the cell efficiency level.

16. What types of solar cell are there? Specify an approximate efficiency level for each of the cell types.

The basic difference is between monocrystalline cells with an efficiency level of 16% and multi or polycrystalline cells with an efficiency level of 12%. There are also amorphous cells with an efficiency level of approx. 6%. There are thin layer cells and semiconductors with an efficiency of 10%.

17. The cell connection

Each cell has an open circuit voltage of 0.6 V. we have 21,6V/ 0.6V = 36 cells or 36X0.6V = 21.6V that means the cells are connected in series.

18. What is meant by the standard test condition (STC)

STS is simply the standard value of radiation (1000W/m^2), temperature (25°C) and Air Mass (1.5), manufacturers use as reference.

Solution Sheet Chapter 3

1. Lead-gel batteries are nowadays used increasingly in solar power systems. What advantages do these batteries have?

The advantages are:
- Longer lifetime
- Hermetically sealed
- No gassing
- Installation in any position and location
- Maintenance free

2. Why is a battery Wh-efficiency always smaller than its Ah-efficiency?

Because the ratio of the discharge voltage to the charge voltage is calculated in here as an additional factor and this is always smaller than 1.

3. What does the capacity specification with the condition C_{20} indicate on a battery?

The capacity shown is attained with an approx. 20 hour discharge current.

4. What is the biggest disadvantage of cheap, serial regulators?

When a battery is deep-discharged, there is not enough supply voltage for the electronics of these types of regulators to switch the charge current on. As a consequence, the battery remains deep discharged for a long period of time and becomes permanently damaged.

5. **Why can batteries be fully charged more quickly using charge regulators with "puIse width regulation"?**

   With these regulators, a high current can be used for charging up to the final voltage. After a pause of approx. one second, the battery voltage has again fallen to the switch-on value and another pulse of charge current follows.

   A lead-gel battery can be 80% charged in 10 minutes. This is in contrast to standard charging, which requires 14 hours.

6. **When using square-wave inverters in off-grid systems, what problems can occur?**

   If square-wave inverters are used, the voltage shape can cause consumers to malfunction. The voltage can fall dramatically with larger loads because these inverters do not have voltage regulation.

7. **Can a 100 watts refrigerator be run using a 150 watts inverter without any problems?**

   With refrigerators, the switch-on power is often 5 to 10 times higher than the nominal power. An inverter must therefore also have such power reserves.
   In this case, the power from the inverter is not sufficient to start the refrigerator:

8. **An off-grid PV installation for a traffic system in Castries must provided P = 500 Wh/day at 12 V DC all day long. There are several solar modules available with V_N = 17 volts and P_{MPP}, = 80 watts.The modules are south-west-facing and mounted at an angle of 15°. The batteries to be installed are lead-gel for 12 volts and 90 Ah . Calculate the number of modules and batteries for January with a discharge factor of 50% and 4 reserve days. How are the batteries connected?**

   - The solar radiation in Castries in January at the horizontal is 153.3 kWh/m^2 (Table1.1)
   - The solar radiation in Castries in January with 15° inclination is 175.kWh/m^2 (Table1.2). This correspond to a daily radiation of 175/31= 5.6 kWh/m^2
   - In STC **G**= 5.6 peak sun hour (see 3.4.1)
   - The daily capacity needed **Q** is 500Wh/ 12V = 41.67 Ah
   - The nominal current $\mathbf{I_N}$ delivered by the module is 80W/17V = 4,7A
   - In January the capacity from each module is $\mathbf{I_N}$ **x G** = 4.7A x 5.6 = 26.3 Ah
   - The number of modules correspond to 41.67Ah/ 26.3 Ah= 1.58 this will be rounded to **2 modules**.
   - DOD is 50%= 0.5. We have 4 reserve days.
   - The total battery capacity should be Q x 4/0.5 = 41.67 x 8 = 333.36Ah
   - We have 90 Ah batteries. That means 333.36 Ah / 90 Ah = 3.704. **4 batteries are needed** and connected in parallel. " Notice that the efficiencies and losses were ignored"

9. **What is a year-round operation design?**

   It is when the month with the lowers lower solar radiation is chosen to design and size a PV system. For Castries with 15° inclination this will be June

10. **What disadvantage arises from designing for year-round operation?**

    During all the other months, particularly in summer, the dimensions of the system are far too high.

11. **When running the solar cables for an off-grid PV system, particular stresses and dangers must be taken into consideration. Please name them.**

- Weathering (temperature, UV light, moisture, ice, storms)
- Rodents, hail and storm (mechanical protection, cable ties)
- Risk of arcing
- Lightning strike, overvoltage protection

12. **A 24 volt back-up power system is supplied via a single, 4 mm^2 solar cable, 15m long, from a 200 watt module. Is the cross-section sufficient?**

- The current flowing is 200W/24 V = 8.33A
- The drop of Voltage is $\Delta V = I \times R_c$ (cable resistance).

  $R_c = 2 \times 15\ m / (56\ m / mm^2 \times \Omega \times 4mm^2) = 0.134\,\Omega$ (see 3.4.4)

  $\Delta V = 8.33\ A \times 1.34\ \Omega = 1.11V$

- With a permitted voltage drop of 1% = 24 V x 1% = 0.24 V the standard cross section is insufficient. This most be increase still we have a voltage drop of 0.24V and this will be $A_M = 25\ mm^2$

Solution Sheet Grid-tied PV system

1. **Describe the counter arrangement in a customer system for each case when solar power is fed into the grid with and without cost-covering payment.**

- With cost-covering payment, in-feed and consumption counters are connected parallel to the house connection.
- Without cost-covering payment, both counters are fitted in series to the house connection. The two counters are equipped with a return stop.
- The house installation is parallel to the PV system so that only the unused solar power is fed into the public grid.

2. **Using the yield diagram, define the percentage energy yield of a PV system in the east or west facade.**

With an inclination of 90° and an east or west orientation, the energy yield is about 60% of the maximum.

3. **What nominal roof output would you give for a roof 11.5 m long (from top to bottom) and 11 m width (from east to west), if output of 130 watts per m2 can be installed with the system technology chosen?**

If the distances to the edge are to be 0.5 m, the usable area is 10.5 m x 10 m =105 m^2 0.5m x 2 =1 m have to be reduced from the long and the width.
With 130 W/ m^2, the output generated is 105 m^2 x 130 W/m^2 = 13.65 kW

4. **A string concept with 6 inverters is planned for the PV system with 12 kWp What DC output should each inverter have?**

Inverter is size to have from 90 to 95 % of 12 kWp this is between 10.8 and 11.40 kW. Divided by 6, that means each inverter most have an output between 1.8 and 1,9 kW.

5. **What ways do you know for improving the efficiency of the whole system from the planning example?**

   - Ensure that the modules have good rear ventilation to keep the temperature low
   - Keep the cables as short as possible
   - Select inverters that are efficient

6. **What string cable cross-sections do you use for the wiring when the inverters in the cellar are connected over a conduction path 10 m long? With module current of 4.7A, the voltage of 216 V, 1% drops of voltage.**

   After calculation just like in stand –alone exercises $R_c = 0.46\ \Omega$ and $A_M = 0.78\ mm^2$. The next standard cross section will be chosen. It is $2.5\ mm^2$

7. **What must you consider when choosing a location for installing the inverter?**

   The inverters should be installed in a cool location. The surrounding area should be free of damp, dust and corrosive vapours.

8. **What options do you know for disconnecting a DC load?**

   Many companies manufacturing inverters supply their own DC disconnection devices for the inverter or these devices are already incorporated in the inverter (e.g. SMA).

   The industry supplies DC disconnectors in the form of "type K" circuit breakers or as power switches with arc extinguishing.

9. **What protective measures must be considered for transformer-less inverters?**

   With transformer-less inverters, a type B RCD must either always be integrated or be fitted by the installation engineer when connection is made to the grid. The module support frames must be included in the protective equipotential bonding and the modules must conform to protection class II.

10. **When installing the PV modules on the roof, what must you consider if no lightning protection facility has been fitted on the roof yet?**

    If the PV system is installed in an area, which is not particularly at risk from lightning, lightning protection is not needed.
    The exception to this is when a transformer-less inverter is used, whereby the support frame must always have protective earthing or where the support frame is close to an earthed metal object (less than 0.5 m).

5.8 Experiment Sheet from Solar power laboratory Christiani GmbH

(PDF attachment)

CHAPTER 6 Appendices

6.1 Abbreviations

Poly-Si:	Polycrystalline silicon
CZ-Si:	Monocrystalline silicon
a-Si:	Amorphous silicon
AC:	Alternating current
AM:	Air mass
Approx.:	Approximate
DC :	Direct Current
E:	Energy Requirement
EN:	European Norm
IEC:	International Electrotechnical Commission
cm :	Centimeter
mm:	Millimeter
km :	Kilometer
kWh:	Kilowatt = 1000 Watts
MW:	Megawatt = 10^6 watts = 1000 W
W:	Watts
G:	Peak sun hour
A_M:	Cross-section
LED:	Light Emitting Diode
LVD:	Low voltage disconnect
HVD:	High voltage disconnect
DOD:	Depth of discharge
SOC:	State of charge
STC:	Standard Test Conditions
INV:	Inverter
mA :	Milliamp
h :	Hour
MPP:	Maximum Power Point
MPPT:	Maximum Power Point Tracking
PV:	Photovoltaic
PR:	Performance Ratio
Q:	Battery Capacity
Wh:	Watthour
Wp:	Peak Watt
W_{PV}:	Peak Wattage of Module
kΩ:	Kiloohm
η :	Efficiency
V_{oc}:	Open-circuit voltage
I_{sc}:	Short-circuit current
€:	Euro
$:	Dollars
mm^2:	Square millimeter
m^2:	Square meter
T_c:	Temperature
°C:	Degree Celsius

6.2 Physical Units

Property	Unit
Current I	A: Ampere
Voltage V	V: Volt
Resistance R	Ω: Ohm
Capacity Q	Ah: Ampere hour
Power P	W: Watt kW: Kilowatt = 1,000W MW: Megawatt = 1,000,000 W GW: Gigawatt = 1,000,000,000W
Energy **E**	Wh: Watthour kWh: Kilowatthour …
Solar power	W/m^2: Watts per square meter
Solar energy/ peak sun hour	kWh/m^2: Kilowatthours per square meter
Solar energy/annual	$kWh/m^2/year$: Kilowatthours per square meter per annum

6.3 Information sources

Books

- **German solar energy society (DGS): Planning and Installing Photovoltaic Systems: A guide for Installers, Architects and Engineers. Earthscan ,2008, 384pages**

  The course outline is made for training of technicians and other professionals who want to get trained in doing business in the PV sector, the level is suitable for vocational schools. This book is too complicated for basis knowledge in photovoltaic systems. It is too extensive, too much information and few exercises.

- **Paul Christiani: Solar Power Laboratory - Experiment manual - Off-grid an on-grid technology (Teacher documents), Christiani GmbH (2nd Edition)**
- **Paul Christiani: Solar Power Laboratory - Experiment manual - Off-grid an on-grid technology (Student handbook), Christiani GmbH (2nd Edition)**

  These manuals provide an introduction to off-grid and on-grid technologies. These text books are made for vocational school level in Germany. The theory part of the manual is too compact. Not enough details to facilitate comprehension. The experimental sheet is good
- **Karl-Heinz Remmers, Christian Dürschner, Falk Anthony: Photovoltaic for professionals. Earthscan ,2007, 215pages**

  Even if in general the level of this book is high, it answers the entire beginner's questions as well as serving as a textbook and work of reference. It gives a comprehensive overview step-by-step examples are described of how to go about installing systems right from the first customer contact. Many useful tips are given to help avoid mistakes. The book seams to be the best to suit the purpose of this training course. However the level is also high.

- **James P. Dunlop, NJATC: Photovoltaic Systems Resource 2E. American Technical Publishers, 2009, 469pages**

  The Resource Guide includes an Instructor's Guide, Instructional Outlines, an Illustrated Glossary, Solar Radiation Data Sets, Sun Path Charts, Forms and Worksheets, Pretest, Posttest, Answer Keys, PowerPoint Presentations, Electronic Slides, a Solar Time Calculator, Media Clips, Reference Material, and Test Development Software. The Instructor's Guide includes material for developing a comprehensive lesson plan. It is too academic. The level is too high. It is suitable for universities and technical universities. The media clips are good and make comprehension easy. Furthermore it offers a practical view.

- **Herbert A. Wade: Solar Photovoltaic Systems Technical Training Manual. UNESCO Toolkit. UNESCO Publishing, 2003, 124 pages**

  This book is easy to understand and very basic. It is just for stand-alone systems. This is suitable for trainees in developing countries, and people with no technical knowledges.

- **Godfrey Boyle: Renewable Energy (Reference book for teachers): Renewable Energy (Paperback) Oxford University Press, 2004, 464 pages**

  This is the general textbook for undergraduate students for the wider subject of Renewable energies, good as reference book for teacher/lectures

- **SEI (Solar Energy International): Photovoltaic: Design and Installing Manual. New Society Publishers, 2007, 320 pages**

  These two textbooks are used in the US for apprenticeship training and should be checked, if they are better applicable to the local conditions here, then the German market based ones.

Solar module manufacturers

Company Name	Country	Contact details
1 Soltech Inc	United States	**Tel:** 1 972-231-1158 **Fax:** 1 972-231-0873 **E Mail:** 1soltech@1soltech.com
Aleo Solar	Germany	**Tel:** 49 441 219 88-0 **Fax:** 49 441 219 88-15 **E Mail:** dettmann@aleo-solar.de
Alfasolar Vertriebsgesellschaft GmbH	Germany	**Tel:** 49 5 11 131 71 90 **Fax:** 49 5 11 131 71 92 **E Mail:** mail@alfasolar.de
Aplicaciones Tecnicas de las Energía **(ATERSA)**	Spain	**Tel:** 34 915 178 452 **Fax:** 34 914 747 467 **E Mail:** atersa@atersa.com
Beijing Hope Solar New Energy Co., Ltd	China	**Tel:** 86 10 69500086 **Fax:** 86 10 69509987 **E Mail:** hopeed@vip.163.com
Canadian Solar Inc.	Canada	**Tel:** 1 905 828 2437 **Fax:** 1 905 828 9062

Complete alphabetical list to be found on http://www.solarbuzz.com/solarindex/ModuleManufacturers.htm

Inverter manufacturers

Company Name	Business	Contact Details
Advanced Electronic Supply (AES)	Rectifiers (AC/DC) up to 10kW and DC/DC converters up to 500W	**Tel:** 386 68 321111 **Fax:** 386 68 322901 **E Mail:** aes@aes.si
SMA Technology AG	Grid tied Sunny Boy Inverters Stand alone Sunny Island http://www.sma.de/en/products/overview.html	**Tel: +495619522-0** **Fax: +495619522-100** **E Mail: info@SMA.de**
Analytic Systems	DC-DC Voltage Converters, DC-AC Power Inverters, AC-DC Power Supplies, DC & AC Source Battery Chargers, Configurable and Custom Power Solutions	**Tel:** 1 (604) 543-7378 **Fax:** 1 (604) 543-7354 **E Mail:** info@analytic systems.com

Complete alphabetical list to be found on:
http://www.solarbuzz.com/solarindex/InverterManufacturers.htm

Charge controllers manufacturers

Company Name	Business	Contact Details
Morningstar Corporation	ProStar, SunSaver, Sunlight, Sunguard Charge Controllers	**Tel:** +1 215 321 4457 **Fax:** +1 215 321 4458 **E Mail:** info@morningstar corp.com
Steca Solar	3Amps - 140 Amps charge controllers and other components	**Tel:** +49 83 31 85 58-0 **Fax:** +49 83 31 85 58-11 **E Mail:** solar@steca.de
Apollo Solar	TurboCharger T80 Charge Controller	**Tel:** 1 203 790 6400 **Fax:** 1 203 792 0300 **E Mail:** johnp@apollo-solar.net
SMA Technology AG	Sunny Island Char	**Tel: +495619522-0** **Fax: +495619522-100** **E Mail: info@SMA.de**

Complete alphabetical list to be found on:
http://www.solarbuzz.com/solarindex/RegulatorManufacturers.htm

Battery manufacturers

Company Name	Business	Contact Details
Concorde Battery Corporation	Marine, RV, PV System and Deep Cycle batteries	**Tel:** 1 626 813 1234 **Fax:** 1 626 813 1235
Exide Technologies	Lead Acid Batteries	**Tel:** 1 800 782 7848
Hoppecke Batterien	Standby batteries	**Tel:** 49 2963 61-0 **Fax:** 49 2963 61-449
MK Batteries	Sonnenschein dryfit Gel Cell batteries	**Tel:** 1 714 937 1033 **Fax:** 1 714 937 0818 **E Mail:** info@mkbattery.com
Moll Batterien		**Tel:** 49 95 739622-0 **Fax:** 49 95 739622-11 **E Mail:** info@moll-batterien.de

Complete alphabetical list to be found on
http://www.solarbuzz.com/solarindex/BatteryManufacturers.htm

PV mounting system manufacturers

Unirac, www.unirac.com
Direct Power and Water, www.directpower.com
Professional Solar Products, www.prosolar.com
IBC Solar, www.ibc-solar.de/EN/

Sizing and design software

PVSOL, PVexpress, Valentin Energy Software, www.valentin.de
Solar Dimension, Solaris Energie Consulting, Wolnzach, Germany, www.soldim.de
RETScreen, RETScreen International, www.retscreen.net
PV design Pro, Maui Solar Energy Software Corporation, www.mauisolarsoftware.com
PV Syst, www.pvsyst.com

Online Sources

http://squ1.org/wiki/Solar_Position_Calculator
http://www.satellite-calculations.com/Satellite/suncalc.htm
http://www.alternate-energy.net/angle_calc05.html
http://en.wikipedia.org/wiki/Hour_angle
http://www.solardirect.com
http://en.wikipedia.org/wiki/Photovoltaic_array
http://www.renewable-energy-concepts.com
http://www.stecasolar.com/index.php?Solar_charge_controllers
http://www.stoneyroads.com
http://www.south-facing.co.uk/ImageBank/Performance-Chart.gif
http://www.luckypowertech.com
http://www.vsolar.ca
http://www.sunscapesolar.net
http://www.volker-quaschning.de
http://www.sma.de
http://re.jrc.ec.europa.eu/pvgis
http://www.photovoltaik-shop.com
http://www.solarbuzz.com
http://www.licensedelectrician.com/Store/AT/Photovoltaic_Sys.htm

12 V wire sizing table – standard wire (metric)

Load		Distance between battery and load (m)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
W	A	Standard size wire needed (mm²)																			
6	0.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
10	0.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
12	1.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
13	1.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
15	1.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
18	1.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
20	1.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4
22	1.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4
24	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4
28	2.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4
30	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	4
32	2.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	6	6
34	2.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6
36	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6
38	3.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6	6
40	3.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6	6
45	3.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	6
48	4.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	8	8
50	4.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	8	8
55	4.6	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	6	6	8	8	8	8
60	5.0	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	6	8	8	8	8	8
65	5.4	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	8	8	8	8	8	10	10
70	5.8	2.5	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	8	10	10	10
72	6.0	2.5	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	10	10	10	10
75	6.3	2.5	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	10	10	10	10
80	6.7	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	10	10	10	12	12
84	7.0	2.5	2.5	2.5	2.5	4	4	4	6	6	6	8	8	8	8	10	10	10	12	12	12
85	7.1	2.5	2.5	2.5	2.5	4	4	4	6	6	6	8	8	8	8	10	10	10	12	12	12
90	7.5	2.5	2.5	2.5	2.5	4	4	6	6	6	6	8	8	8	10	10	10	12	12	12	12
96	8.0	2.5	2.5	2.5	4	4	4	6	6	6	8	8	8	10	10	10	12	12	12	14	14
100	8.3	2.5	2.5	2.5	4	4	4	6	6	6	8	8	8	10	10	10	12	12	12	14	14
108	9.0	2.5	2.5	2.5	4	4	6	6	6	8	8	8	10	10	12	12	12	14	14	14	16
110	9.2	2.5	2.5	2.5	4	4	6	6	6	8	8	10	10	10	12	12	12	14	14	14	16
120	10.0	2.5	2.5	2.5	4	4	6	6	8	8	8	10	10	12	12	12	14	14	16	16	16
130	10.8	2.5	2.5	4	4	6	6	8	8	8	10	10	12	12	14	14	14	16	16	18	18
140	11.7	2.5	2.5	4	4	6	6	8	8	10	10	12	12	14	14	14	16	16	18	18	20
150	12.5	2.5	2.5	4	4	6	6	8	8	10	10	12	12	14	14	16	16	18	18	20	20
160	13.3	2.5	2.5	4	6	6	8	8	10	10	12	12	14	14	16	16	18	20	20	22	22
170	14.2	2.5	2.5	4	6	6	8	8	10	12	12	14	14	16	16	18	20	20	22	22	24
180	15.0	2.5	2.5	4	6	6	8	10	10	12	12	14	16	16	18	18	20	22	22	24	24
190	15.8	2.5	4	4	6	8	8	10	12	12	14	14	16	18	18	20	22	22	24	26	26
200	16.7	2.5	4	4	6	8	8	10	12	12	14	16	16	18	20	20	22	24	24	26	28
220	18.3	2.5	4	6	6	8	10	12	12	14	16	18	18	20	22	22	24	26	28	28	30
240	20.0	2.5	4	6	8	8	10	12	14	16	16	18	20	22	24	24	26	28	30	32	32
260	21.7	2.5	4	6	8	10	12	14	14	16	18	20	22	24	26	26	28	30	32	32	32
280	23.3	2.5	4	6	8	10	12	14	16	18	20	22	24	26	28	28	30	32	32	32	32
300	25.0	2.5	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	32	32	32	32

24 V wire sizing table – standard wire (metric)

Load		Distance between battery and load (m)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
W	A	Standard size wire needed (mm²)																			
Under 100	Under 4.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.5	4.5	5.5	6.5	7.5
100	4.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4
110	4.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4
120	5.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	4
130	5.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	6	6
140	5.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	6	6	6
150	6.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6
160	6.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6	6
170	7.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	4	6	6	6	6	6	6
180	7.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	6
190	7.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	8	8
200	8.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	4	6	6	6	6	6	6	8	8
220	9.2	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	6	6	8	8	8	8
240	10.0	2.5	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	6	8	8	8	8	8
260	10.8	2.5	2.5	2.5	2.5	2.5	4	4	4	4	6	6	6	6	8	8	8	8	8	10	10
280	11.7	2.5	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	8	10	10	10
300	12.5	2.5	2.5	2.5	2.5	2.5	4	4	4	6	6	6	6	8	8	8	8	10	10	10	10
350	14.6	2.5	2.5	2.5	2.5	4	4	6	6	6	6	8	8	8	10	10	10	10	12	12	12
400	16.7	2.5	2.5	2.5	4	4	4	6	6	6	8	8	8	10	10	10	12	12	12	14	14
450	18.8	2.5	2.5	2.5	4	4	6	6	6	8	8	10	10	10	12	12	12	14	14	16	16
500	20.8	2.5	2.5	2.5	4	6	6	6	8	8	10	10	10	12	12	14	14	16	16	16	18
550	22.9	2.5	2.5	4	4	6	6	8	8	10	10	12	12	12	14	14	16	16	18	18	20
600	25.0	2.5	2.5	4	4	6	6	8	8	10	10	12	12	14	14	16	16	18	18	20	20
650	27.1	2.5	2.5	4	6	6	8	8	10	10	12	12	14	16	16	18	18	20	20	22	22
700	29.2	2.5	2.5	4	6	6	8	10	10	12	12	14	14	16	18	18	20	20	22	24	24
750	31.3	2.5	2.5	4	6	8	8	10	10	12	14	14	16	18	18	20	20	22	24	24	26
800	33.3	2.5	4	4	6	8	8	10	12	12	14	16	16	18	20	20	22	24	24	26	28
850	35.4	2.5	4	6	6	8	10	10	12	14	16	16	18	20	20	22	24	26	26	28	30
900	37.5	2.5	4	6	6	8	10	12	12	14	16	18	18	20	22	24	24	26	28	30	30
950	39.6	2.5	4	6	8	8	10	12	14	16	16	18	20	22	24	24	26	28	30	32	32
1000	41.7	2.5	4	6	8	10	10	12	14	16	18	20	20	22	24	26	28	30	30	32	32

Important: If the appliance to be connected had a motor (refrigerator, freezer, pump, etc,) so starts under load, user the row showing double the watts of the appliance. For example, if a refrigerator requires 60 W, use the 120 W row.

Ceiling fans and desk fans do not need larger wire because their motors do not start under load. *(Source: Solar Photovoltaic Systems Technical Training Manual, UNESCO Toolkit)*