Renewable Energy Online
Robin Knecht

Solar Resources and Systems

Lehrbrief

PUBLIKATION DER BILDUNGSALLIANZ MINT.ONLINE:
UNIVERSITÄT OLDENBURG, UNIVERSITÄT KASSEL, UNIVERSITÄT STUTTGART, FERNUNIVERSITÄT IN HAGEN, FRAUNHOFER-GESELLSCHAFT, DLR-INSTITUT FÜR VERNETZTE ENERGIESYSTEME (EHEMALS NEXT ENERGY)

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Das diesem Bericht zugrundeliegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung, und Forschung unter dem Förderkennzeichen 16OH12044 gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt beim Autor/bei der Autorin.

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Solar Resources and Systems

by

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This document has been typeset using the LaTeX2e bundle on TeX.

compilation date: 16th September 2017

Imprint:

Author:	Robin Knecht
Publisher:	Carl von Ossietzky University of Oldenburg
Edition:	First edition (2017)
Editor:	Robin Knecht
Layout:	Robin Knecht

Oldenburg, September 2017

Contents

Part I

Solar Energy Meteorology

2 — Solar Radiation Basics

Learning objectives

After processing this chapter you will

- be able to distinguish common measures for energy and power
- know about available energy resorces
- know about the future challenges concerning energy production
- understand the motivations behind photovoltaics

This chapter will introduce the basic terms of concepts required for the course. Hopefully most of this will be a repetition for you but not all of your colleagues might be on the same level. Furthermore we will look at mankinds energy situation at the moment and discuss the challenges waiting for us. After introducing the sun as a power source we will compare it with the resources in the form of fossil fuels. Finally we will introduce the very basic concept and characteristics of a solar cells and estimate how much photovoltaic is required to fulfill mankinds need for energy. The calculations in this lesson are rather rough estimates and should mainly give you an idea of the magnitudes involved in the challenge but they should teach you to read, extract and compare statistical data, and to handle the different units of power and energy.

2.1 Basic Terms

Definition 2.1

Energy is a measure for the amount of work E which can be accomplished or is required in a certain situation (unit: 1 Joule=1 J).

Energy is the general concept principal to all fields of physics. Depending on the specific field there exist multiple functional relationships to other physical quantities
(see Examples 2.1 - 2.3).

Definition 2.2

Power is a measure for the amount of work which is done in a certain amount of time (unit: 1 Watt=1 W). It is defined by the total energy E which is applied over a time period t.

$$P = E/t \tag{2.1}$$

In this course we will use the concept of energy and power in many situations. Depending on the context it is more useful or common to use other units. These will be introduced in the following examples.

Example 2.1 — Mechanics: Weightlifting.

In mechanics energy is defined by the product of a force F which is applied over a certain distance s.

$$E = Fs \tag{2.2}$$

In order to lift an object with a mass $m = 150\ kg$ a distance of $h = 2\ m$ into the air Arnold must overcome the gravitational acceleration $g = 10\ m/s^2$. Applying Eq. 2.2 using the force $F = mg = 1500\ N$ and $s = h$ results in $E = mgh = 1500\ N \cdot 2\ m = 3000\ Nm$.

The Newtonmeter (1 Nm=1 J) is the common unit for energy in mechanics.

The required energy is independent of the time it took to accomplish the work. This is considered when looking at the power.

It took Arnold $t = 3\ s$ to lift the object. Using Eq. 2.1 the power is $P = 3000\ J/3\ s =$

$1000\ W$.

Example 2.2 — Electronics: Light bulb.

An incandescent light bulb specified with a power consumption of 60 W is run for 2 h. According to Eq. 2.1 the energy can be expressed by $E = Pt = 120\ Wh$. The Watthour (1 Wh = 3600 Ws = 3600 J) is the typical energy unit for electronic devices.

Example 2.3 — Large and small magnitudes.

When talking about power and energy on a large scale it is common to designate the magnitude with a prefix. The power of a nuclear power plant is about 1 GW, world energy consumption is about 1 TW while the sun has a power of about $10^{26}\ W$. Some publications use historical energy units such as *tonne of oil equivalent (toe)*: 1 toe = 11.63 MWh to describe large amounts of energy.

On the other hand we will look at processes on the atomic scale. In semiconductors the relevant energies have a magnitude of about $10^{-19}\ J$. It is common in solid state physics to use the unit *electron volt* ($1\ eV = 1.602\ 10^{-19}\ J$) as energy unit on this scale.

While many reports talk about energy consumption they are actually often talking about energy per annum which by definition of Eq. 2.1 is actually a power. Energy is a useful measure when talking about the range of energy reserves but more critical to our day-to-day life is the availability of power at a specific moment.

One example is the peak-oil debate which concerns the moment when oil production decreases and not necessarily when oil as a fuel becomes rare. Another example is keeping electrical grids stable which is achieved by matching energy production with the consumption at any given time.

2.2 World energy demand

Figure 2.1 shows the world primary energy supply. Obviously the energy demand is ever increasing over the last decades which is contributed to two main factors: (i) increased population and (ii) improved life style.

The main contributors for renewable energies are hydro power and biofuels while other forms of renewable energies like photovoltaics, do not play any major role yet. However, while the amount of energy provided by renewable sources has also increased over the years the ratio of renewable versus total energy supply has remained nearly constant.

Is there an energy problem?

In order to estimate for how long energy is available it is useful to be familiar with the following terms

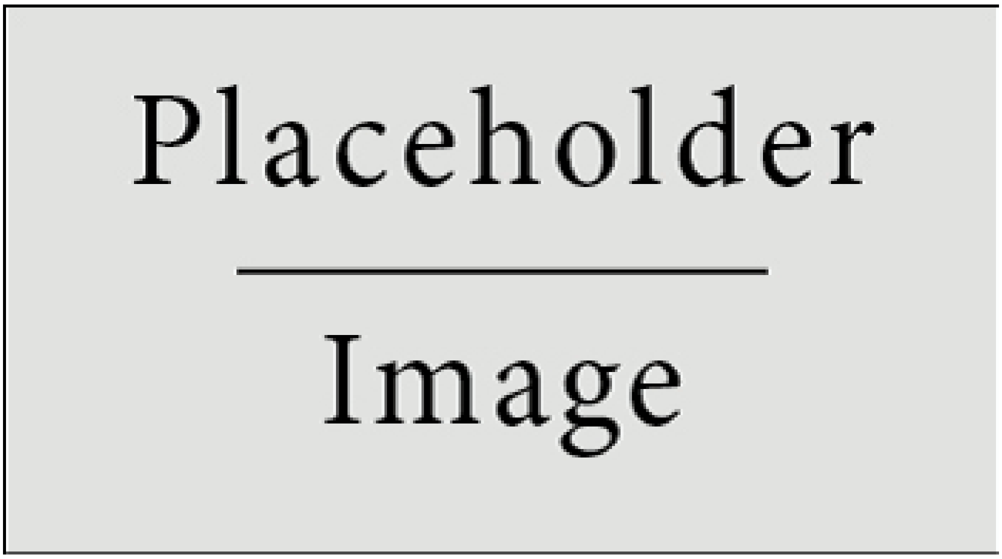

Figure 2.1: World total primary energy supply from 1971 to 2010 by fuel (Mtoe/a) (*Other includes geothermal, solar, wind, heat, etc.) (Source: [1])

Definition 2.3

Resource of a raw material is all the amounts which are speculated to exist. However, these deposits do not have to be evaluated yet.

Reserve is the fraction of the resource which can be obtained economically and has been evaluated.

Lifetime of a resource or reserve is the time span for which the raw material is going to last and is calculated by dividing the resource/reserve by the production per annum. It is distinguished between two types of lifetime. Static lifetime assumes a constant consumption (static) while dynamic lifetime considers the projected consumption in the calculation.

Table 2.1 summarizes the reserves and resources for several non-renewable fuels.

Fuel	Reserves	Resources
Natural Gas	7291	9142
Non-conventional Gas	191	103351
Crude Oil	6731	4152
Non-conventional Oil	2785	12993
Coal Total	2112	475747
Nuclear Fuels Total	1673	7794

Table 2.1: Reserves and resources of non-renewable fuels (in EJ) (Source: [2])

Exercise 2.1 — Fossil fuel lifetimes.

1. Adjust the numbers from Fig. 2.1 and Table 2.1 to the unit TWh.

2. Calculate the lifetimes of either reserves or resources of each raw material (for oil and gas combine conventional and non-conventional quantities)

2.3 Light

Light is electromagnetic radiation with quite particular properties. Depending on the situation it is convenient to describe it either as a wave (reflection, refraction, interference) or as a particle. While this duality was first discovered for light it is however not unique to light as even macroscopic particles can be described as waves (although with diminishing wavelengths) or other type of waves like mechanical oscillations can be described by particles.

The distribution in space x and time t of a monochromatic plane wave in one dimension can be described by equation

$$A(x,t) = A_0 \cos(kx - \omega t + \phi), \tag{2.3}$$

where A_0: amplitude
k: wave number
ω: angular frequency
ϕ: phase shift

The amplitude A_0 relates to the light intensity. The wavenumber relates to the wavelength λ via:

$$\lambda = \frac{2\pi}{k} \tag{2.4}$$

Note that when describing a three dimensional wave k becomes the wavevector $\vec{k}$. This becomes important in the description of solids later. The angular frequency relates to the period T by $\omega = 2\pi/T$. The reciprocal value of the period T is called the frequency ν.

Take care not to confuse frequency and angular frequency!

The wave velocity c can be expressed by

$$c = \lambda\nu \tag{2.5}$$

The velocity for a light wave in vacuum is a universal constant and the ultimate speed for any object in the universe. Therefore it is usually called c_0. Yet, for photovoltaics most of the time the wave character of light plays mainly a role when considering the optics e.g. for anti-reflective coatings, window layers or concentrator optics.

Most of the time in this course we will consider light as a particle. Light particles are called photons and are described as massless objects moving with c_0. Although it has no mass it is attributed a discrete energy

$$E_\gamma = h\nu = \hbar\omega, \tag{2.6}$$

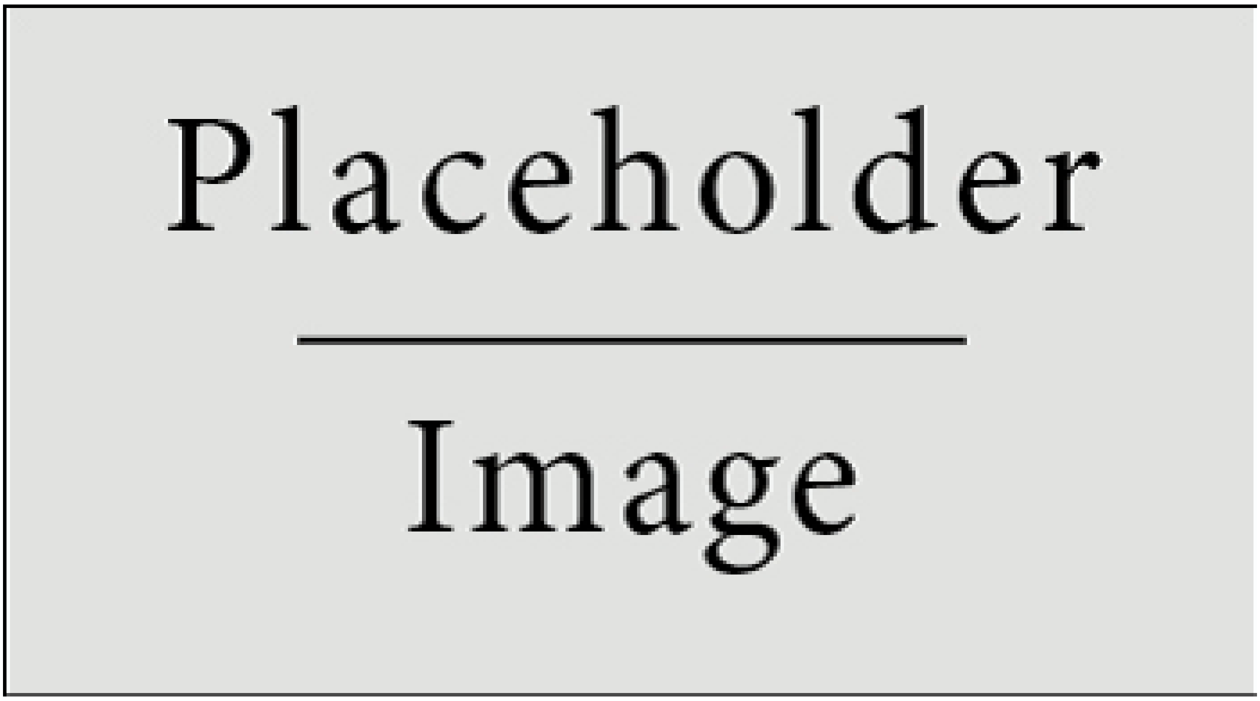

Figure 2.2: The electromagnetic spectrum. In the lowest row the color temperature of black bodies with an wavelength of maximum emission is shown (Source: [4])

where h: Planck's constant
$\hbar = h/2\pi$: Planck's reduced constant

Therefore a single photon relates to a specific frequency (or wavelength according to Eq. 2.5).

In the same way the light particle is attributed a momentum

$$p = h/\lambda = \hbar k \tag{2.7}$$

Figure 2.2 shows the electromagnetic spectrum, i.e. light with different frequencies which can take values from a wide range. The shorter the wavelength the larger the energy of the photons. The electromagnetic spectrum includes the visible colors but extends far beyond the range visible to humans in both directions. Light with frequencies above the visible spectrum (already starting with the ultraviolet) possesses enough energy to cause harm to the human body. For a more detailed view on the part of the visible spectrum see: Ref. [3].

Light can originate from many sources, two of which will be discussed in detail:

2.4 Relaxation in atoms/molecules

The electrons surround the nucleus of atoms in specific orbitals with very discrete energies. When the electron (usually in the obitals of lower energy) is excited by any means to an orbital with higher energy the energy difference between those energy levels is well defined. Upon relaxation back into the ground state the electron releases its surplus energy by emission of a photon with an energy of exactly the difference between those energy levels. Different elements/molecules possess very characteristic energy levels and thus a characteristic emission spectrum. This is widely used in determining the composition of many materials. A similar concept is used in light emitting diodes (LEDs) which can be manufactured to emit light with a very specific frequency.

2.5 Black body radiation

Definition 2.4 A **black body** is an object that absorbs all radiation that falls on it. In thermal equilibrium it absorbs as much radiation as it emits, however the emission spectrum depends on its temperature. This is described by Planck's law.

$$M_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{2.8}$$

where	M	spectral radiance
	T:	absolute temperature
	k_B:	Boltzmann constant

There exist many variations of Planck's law (see reference [5]) and depending on whether it is expressed in terms of E, λ or ν changes the formula significantly.

Figure 2.3 shows the emission spectra of black bodies at different temperatures. Note that the curves of the emission spectra never cross. As a first order estimate the sun (or more specifically its photosphere) is considered a black body. According to the suns emission spectrum it can be considered a black body with a temperature about 5780 K. From Planck's law Wien's displacement law can be derived which states that the product of the wavelength of the emission maximum and the temperature is constant.

$$\lambda_{max} T = const. \tag{2.9}$$

Obviously the term black body is misleading as the sun is yellow, the black refers only to the absorption characteristics of the object.

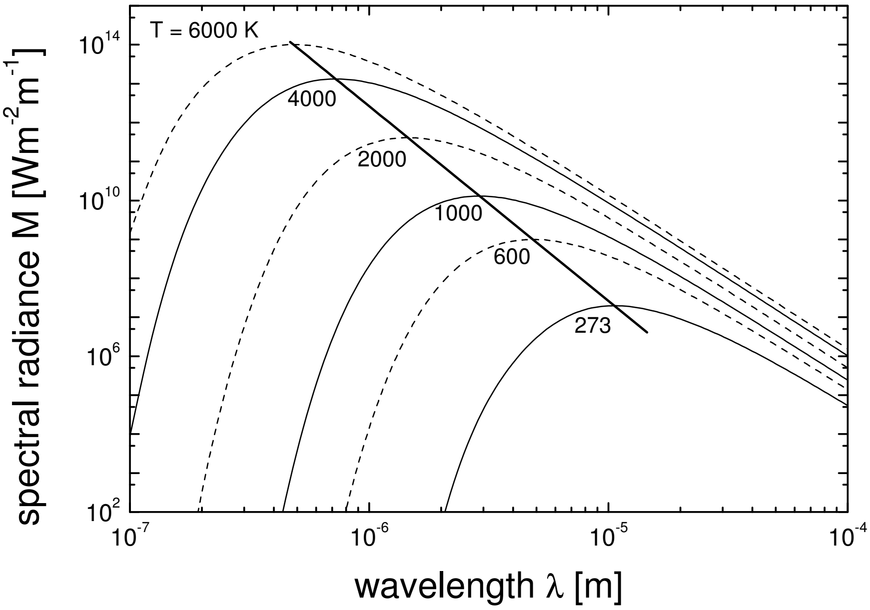

Figure 2.3: Black body spectra

Exercise 2.2 — Black body radiation.

1. Using Fig. 2.3 determine the value of the constant in Wien's law.
2. It could also be assumed very roughly that Earth is a black body with $\lambda_{max} \approx 10\ \mu m$. What is the temperature of Earth?
3. What is the wavelength of maximum emission for the sun? What color of the visible spectrum does this correspond to?
4. Please try to explain why the sun appears yellow instead.

Instead of the power P it is also common to use the power density Pd, i.e. power per area A:

$$Pd = \frac{P}{A} \tag{2.10}$$

From Planck's law we can further deduce the law of Stefan and Boltzmann:

$$Pd = \sigma \cdot T^4 \tag{2.11}$$

The power density the black body is emitting is the integral (i.e. the area under the curve) of Planck's law. The Stefan-Boltzmann constant $\sigma = 5.670 \times 10^{-8}\ Wm^{-2}K^{-4}$ can be expressed in terms of basic physical constants

Exercise 2.3 — Power from the Sun.

1. According to Eq. 2.11 how much power does the sun emit per squaremeter.
2. The radius of the sun $r_{sun} = 7 \times 10^8\ m$. Remember that it is actually the suns surface layer which is the black body. How much power does the sun emit in total?
3. When this power radiates into space it is distributed over a larger area. How much larger is the area at the sun-earth distance $r_{se} = 1.5 \times 10^{11}\ m$?
4. This is the factor the power density is decreased when it reaches Earth. The power density at the sun-earth distance is called the solar constant. How large is it?

This power density is distributed over a surface of a sphere with the radius of the Sun-Earth distance. The cross section of this sphere surface with the Earth is just a two dimensional circle with the same radius as Earth r_e = 6370 km. Furthermore, as Earth rotates this power is distributed across the whole Earth surface. Therefore the average power density as seen from Earth is just a fraction of the solar constant

$$\frac{A_{circle}}{A_{sphere}} = \frac{\pi r_e^2}{4\pi r_e^2} = \frac{1}{4} \tag{2.12}$$

This results in an average power density of about $340\ W/m^2$ on the Earth's surface. This power density corresponds to the 100% incoming solar energy in Fig. 2.4. This illustration shows that not all of the incoming power actually reaches the ground. About 30% are reflected back into space by the atmosphere, clouds or reflecting surfaces like glaciers. The reflection coefficient of 0.3 is called *albedo* and needs to be considered in the thermodynamic balance.

As mentioned before in thermal equilibrium a black body emits as much power as it absorbs (albeit at different wavelengths). This means that because Earth absorbs only about 70% of the incoming power its temperature and thus its black body emission only consider these 70% of the incoming power.

Exercise 2.4 — Sun's power density on the ground.

1. How large is the power density reaching the ground of Earth?
2. Using equation 2.11 how large should be the temperature on Earth?
3. How much total power actually reaches the ground of the Earth?

The results from Exercise 2.4 might be surprisingly low. Actually the specifics of Earth's atmosphere result in a surface temperature which is actually a lot higher.

In Fig. 2.5 several components of the atmosphere are shown to absorb parts of the spectrum. Note the effect of the atmospheric molecules in the visible and in the infrared regions. Below 3 μm especially the absorption bands of water vapor cause characteristic dips in the solar spectrum which become important in the characterization of photovoltaic materials. However the amount of absorption from the solar spectrum is moderate compared to the absorption in the infrared region above 3 μm. In this domain the effect of carbon dioxide as a second major component is quite significant. This is the wavelength region where Earth emits back into space, however

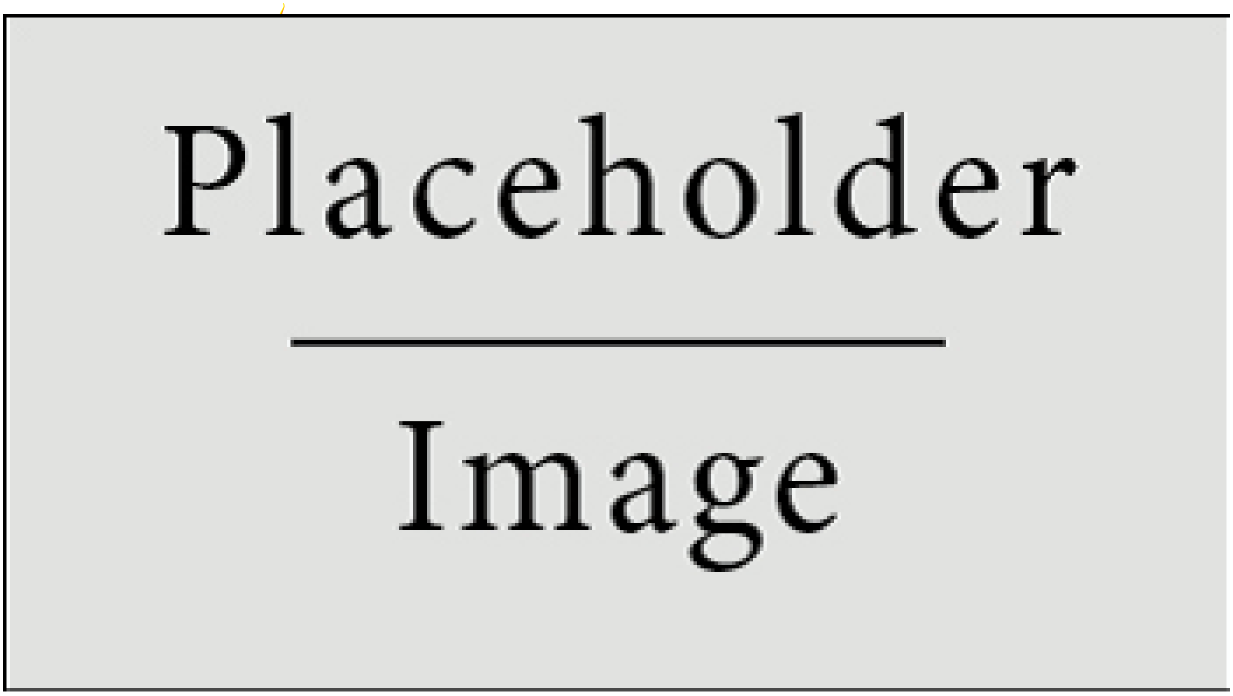

Figure 2.4: Earth's energy budget (Source: [6])

the atmosphere absorbs major parts of the Earths black body radiation. Because the atmosphere emits in all directions half of the power is reemitted onto the ground in addition to the sun's radiation and only the other half is emitted into space.

This selective behavior of the atmosphere in transmitting the greater part of the incoming solar radiation but blocking large parts of the terrestrial black body radiation is the natural greenhouse effect which causes the surface temperature of the Earth to increase about 33 K.

We see that the greenhouse effect is vital for life to thrive on Earth. But, we can also see that increasing the concentration of one of the absorbing components amplifies the greenhouse effect and might increase the Earth's temperature to potentially dangerous levels. The carbon dioxide concentration before the industrial revolution was about 280 ppm but has been steadily increasing since. Manmade emissions of about 30 Gt (which roughly equates to CO_2 per year) increase the carbon dioxide concentration about 1.5 ppm per year. Parallel to this increase in concentration an increase of global surface temperature was observed causing the melting of glaciers which results not only in the increase of the global sea level but also a decrease of the Earth's albedo which in turn causes an increase of the surface temperature.

It has been argued that in order to keep our biosphere stable an increase of not more than 2 K since preindustrial times is necessary. In Ref. [8] it has been reported that since the beginning of industrialisation 1 K has already been reached and carbon dioxide concentration has been increased by 100 ppm.

Exercise 2.5 — Global warming.

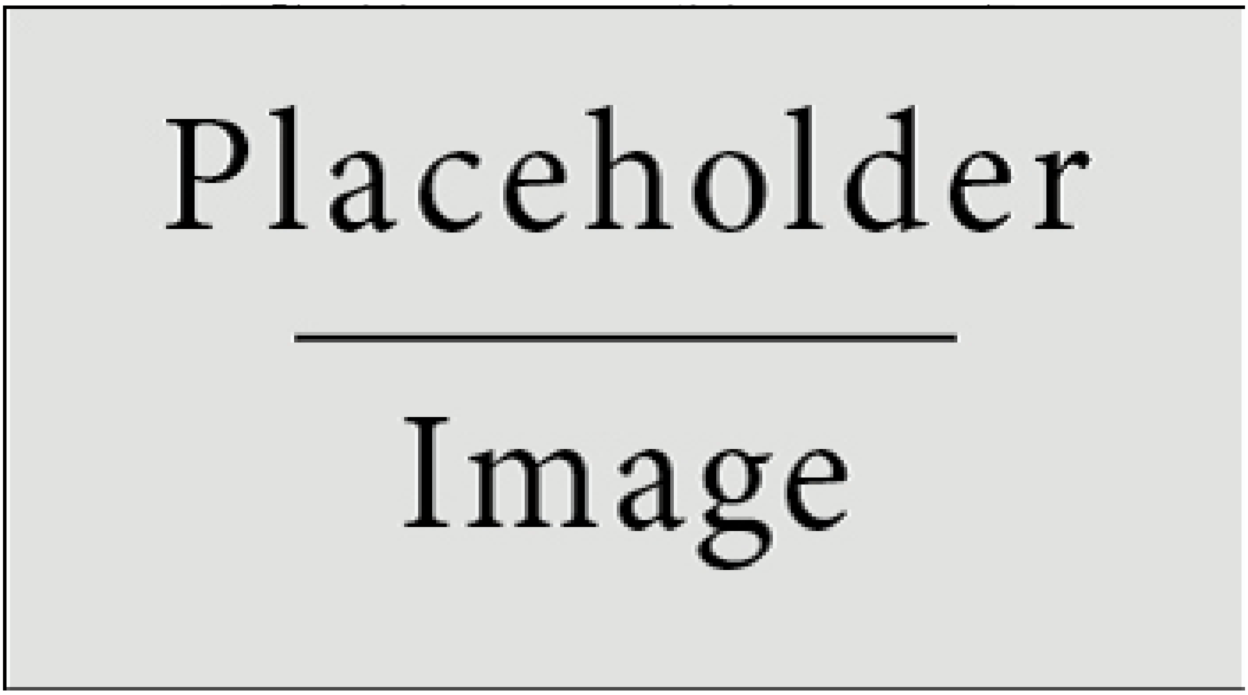

Figure 2.5: Radiation Transmitted by the atmosphere (Source: [7])

The following exercises are just very rough estimates but should give an idea about the magnitudes

1. In order to reach the 2 degree goal what is the maximum amount of carbon dioxide which may be emitted into the atmosphere?
2. Assuming coal to be the fossil fuel of the future (because of its lifetime) how much energy may be produced if the production of 1 kWh using bituminous coal emits 0.8 grams of carbon dioxide?

Comparing the results from Exercise 2.5 with the availablity of resources it is obvious that it is not the energy or even the power problem which requires the immediate change to renewable energy sources but the need to avoid climate change in order to keep the biosphere stable. It has also been argued (Ref. [9]) that compared to conventional fossil fuels the sun provides mankind with as much energy as required.

Not all of the solar energy can be used directly via photovoltaics or solarthermal applications, solar power also generates significant particle fluxes in the form of wind cycles, water cycles and drives chemical reactions which produce biomass via photosynthesis. By extension solar energy is stored in fossil fuels and only nuclear, geothermal and tidal energy sources are independent of the sun. However, it is to be noted that renewable power fluxes have a much lower density than fossil energy fluxes and they are considerably fluctuating by nature. This necessitates to store renewable energy, however storage capacity is problematic as no technological solution has yet resulted in energy densities comparable with fossil fuels.

Even before collecting the solar power on a photovoltaic panel further losses have to be accounted for. The seasonal and daily movement of the sun relative to a specific location creates different apparent thicknesses of atmosphere the sun light has to penetrate and results in different degrees of losses due to atmospheric absorption and scattering. This is described by the air mass factor (Ref. [**nelson**]):

$$n_{\text{AirMass}} = \frac{\text{optical path length to Sun}}{\text{optical path length if Sun directly overhead}} = \operatorname{cosec} \gamma_s \tag{2.13}$$

where γ_s angle of sun elevation

For Europe an average air mass of 1.5 at noon is considered reasonable.

Photovoltaics i.e. the generation of electricity from light becomes increasingly important in providing power to mankind. Its basic component is the solar cell as shown in Fig. 2.6 and it is composed of several key elements:

- A material which is able to absorb photons and generate charge carriers with a lifetime long enough to collect them.
- A back and a front contact which collect the charge carriers whereas the front contact needs to be transparent to the solar radiation.

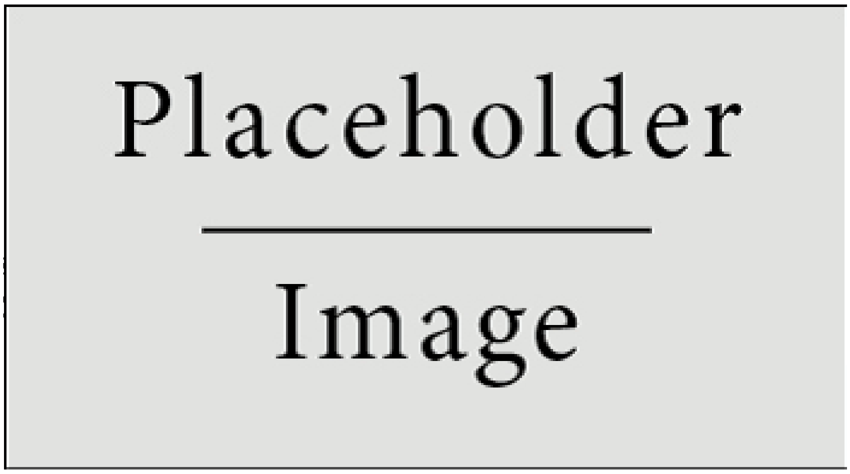

Figure 2.6: Basic structure of a solar cell (Source: [10])

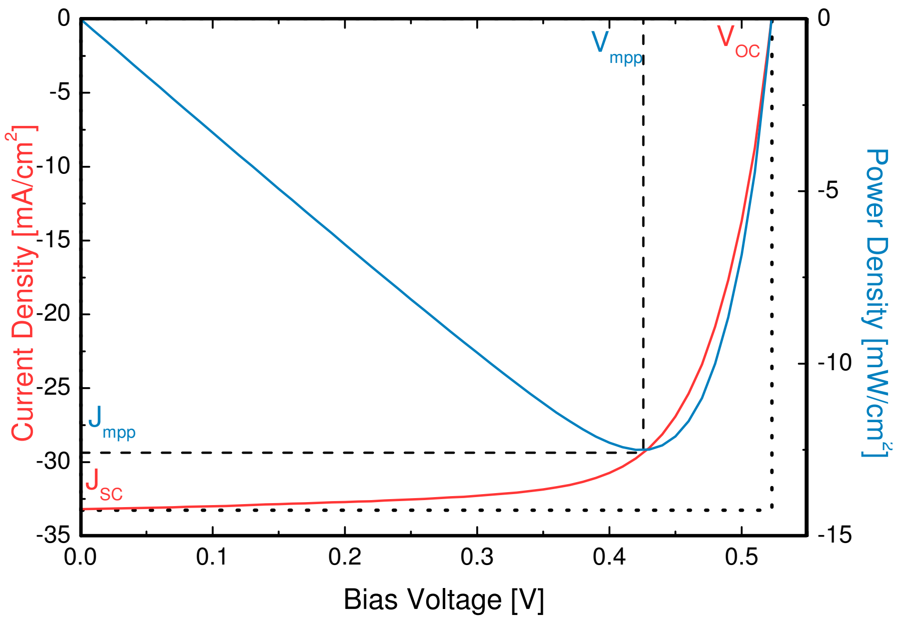

Figure 2.7: Current voltage characteristics of a typical photovoltaic device

Depending on the connected load the electric output parameters and the functionality of the photovoltaic device changes. For solar cells the three most important operation modes under illumination are[1]:

- The terminals are not connected (open circuit, infinite load): No current can flow and the device generates the largest photovoltage V_{OC}.
- The terminals are short circuited (no load): No photovoltage develops but the current density is maximized J_{SC}.
- The terminals are connected to a finite load: A current density $J < J_{SC}$ and a voltage $V < V_{OC}$ are generated.

Self-reflection 2.1
Consider the power density $Pd = VJ$. What is the generated power density in each of those three cases.

The actual power delivered by the photovoltaic device depends on the intensity of the incident light Pd_L, the cell temperature T, the cell area A_{cell} and as just shown the resistance of the connected load.

Figure 2.7 shows the current density - voltage (JV) characteristics of a typical photovoltaic device.

Exercise 2.6
Mark the three operation modes from before in Fig. 2.7.

[1]Instead of the current I it is common to use the current density $J = I/A_{cell}$ which is normalized for the cell area A_{cell} in order to allow for easy comparison of different devices.

At a specific load the output power maximizes, this is called the maximum power point (mpp). The ratio of the power determined at the maximum power point with the incident power on the device is the efficiency η.

$$\eta = \frac{Pd_{mpp}}{Pd_L} = \frac{J_{SC}V_{OC}FF}{Pd_L} \tag{2.14}$$

This defines the fill factor FF which is a measure for the squareness of the JV characteristics and is especially useful in comparing different devices of the same type.

In order to guarantee reproducability and comparability the nominal device characteristics are determined under standard test conditions (STC):

- Device temperature 25 °C
- Solar spectrum AM 1.5g
- Intensity $P_L = 1000\ W/m^2$

Exercise 2.7 — Photovolatic power generation.

1. Localize the datasheet of a commercial photovoltaic module and identify the nominal cell parameters. The power determined under STC is often called the peak power.
2. How many of these modules and how large of an area would be required if the total world power requirements would need to be fulfilled with this type of module considering the average illumination on earth. What nominal peak power would the whole power plant have?

So is there an energy problem? No! We have enough resources in the form of sun energy and fossil fuels. The problem is rather to make these ressources available in time. Therefore it should actually be considered a power problem which becomes apparent when looking at the required transformation and challenges connected with the electricity grid.

However the need to really transform the way mankind harvests its energy rather lies in the danger of climate change. Photovoltaics is but one of several renewable energies available but hit as a great potential due to the large amount of sun power incident on Earth.

2.8 Literature

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Header graphic: Sunrise From Space. Superb Wallpapers. Apr. 2013 . URL: http://wholles.com/wp-content/uploads/2013/04/Sunrise-From-Space.jpg.

♪♫ *Power of the Sun*. Bruce Dickinson . URL: https://www.youtube.com/watch?v=UOltLpCV5lo.

Part II

Photovoltaic Systems

8 — Photovoltaic Modules

Learning objectives

After processing this chapter you will

- know different types of modules
- know how PV systems are setup
- know some of the challenges related to grid-connected PV systems
- know some of the challenges of stand alone systems

In this chapter we take a practical look at photovoltaics. We will learn how solar cells are connected to modules and how modules are connected to systems. Finally we will discuss the two most relevant types of systems: the grid-connected PV system as it is commonly established in industrialized areas and the stand-alone system as it is used in rural areas where no close grid connection is possible.

8.1 Cells vs. Modules

8.1.1 Modularity of photovoltaics

One of the most important advantages of photovoltaics as a power source is its modularity. That means photovoltaic systems can easily be scaled up for any need or application. This is in contrast with most other power generators which are designed for a specific power be it in the kilowatt, megawatt or gigawatt range. Photovoltaics can be employed in very low power applications like the solar cells in calculators where they replace or support a battery or they might be employed in very large PV farms covering many soccer fields and providing power for hundreds of households.

All this can be done very easily and therefore PV systems can also be retroactively adjusted by adding or removing modules for proper dimensioning of the system to the required application which is a lot more complicated with other technologies. While this flexibility is very interesting on a technical level it is even more interesting to the customer. Avoiding oversizing of the system saves costs and undersized systems can easily be optimized. Also customers may only be able to afford a small system at first but depending on their financial situation they can expand their system and thus their quality of life relatively easily. While the physics behind the power generation is always the same different additional aspects have to be taken care of depending on the aplication, though.

8.1.2 Series connection

Photovoltaic modules are the most visible part of PV systems. They come in many shapes and sizes and correspondingly with different electrical parameters. While in the near future photovoltaic modules will be produced on non-planar maybe even flexible or textile surface the most common module is rectangular with a size in the range of squaremeters. No module consists of only one cell but is usually composed of many smaller solar cells. In order to achieve practical voltages solar cells are connected in series. Depending on the used technology though the series connection can be implemented very differently.

$$U_{\text{module}} = \sum^{N} U_i = NU_{\text{cell}} \tag{8.1}$$

Exercise 8.1
Pick a solar cell technology of your choice. How much voltage does one cell generate at normal operating conditions. How many of these cells need to be connected in series to achieve a voltage of 12 V as required by many practical direct current applications.

Notice, that while the voltages add up the current stays the same and is constant throughout the series connection. This has the consequence that the current is also limited by the cell producing the smallest current. In other words if only one cell of the whole module is defective or shaded the power generated by the module will be determined by this cell. This is a major challenge for PV system design.

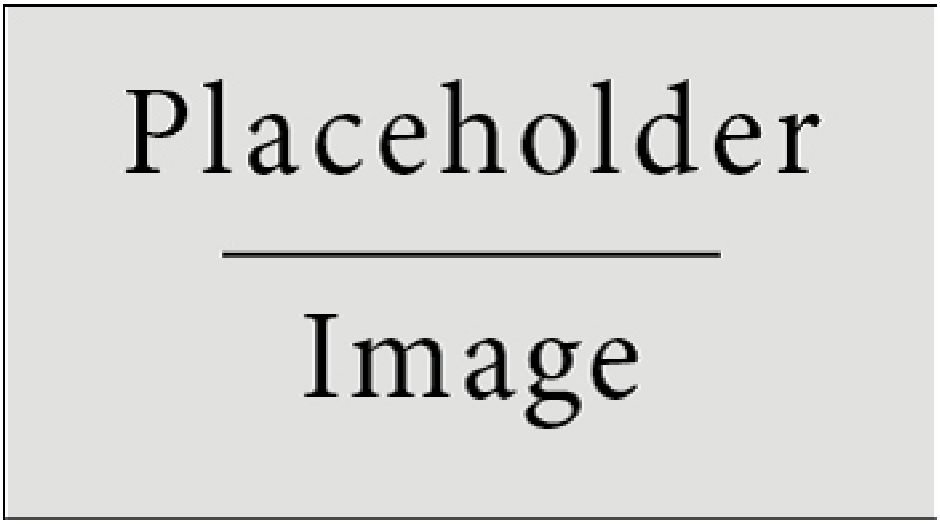

Figure 8.1: Series connection and current flow in modules made of solar cells made from a) wafers (Source: [1]) and b) monolithic series connection (Source: [2])

Conventional series connection

Figure 8.1a illustrates the most widely used type of series connection in PV modules. Silicon solar cells are manufactured from wafers with areas in the range of 10×10 to $20 \times 20\, cm^2$. As a front contact an alloy grid is employed to collect the charge carriers from the whole cell area. Then metal strips are connected to the front contact and reach over the edge in order to contact the next cell. The same is done to the back contact so it can be connected to the previous cell (see Fig. 8.2a). The series connection is now established by soldering the back contact from one cell to the front contact of another cell. This soldering spot though might introduce a series resistance to the circuit and might degrade over time. Therefore the whole module has to be encapsulated to protect the device from water and oxygen and thus corrosion. In the worst case the soldered connection breaks and thus renders the whole module defective.

The advantage of this approach is that the variation of the quality in the production output can be levelized. Each cell is tested before being built into a module and sorted to cells with similar characteristics. In this way the best cells can be connected to create premium modules which are not limited by worse cells and have a large efficiency while the other cells are used to manufacture cheaper less efficient modules. Defective cells can be sorted out and thus the quality of the production output can be improved considerably.

Monolithic series connection

Thin film production allows for an alternative connection method which is more cost-efficient than the manual connection described for wafers as it can be integrated nicely into the production process. In order to realize the so-called monolithic serial connection mechanical and laser scribing steps are introduced during manufacturing (see Figure 8.2b). Characteristic of this type of modules is the pinstripe design where the individual cells are very narrow but extend across the whole width of the module (Fig. 8.1b).

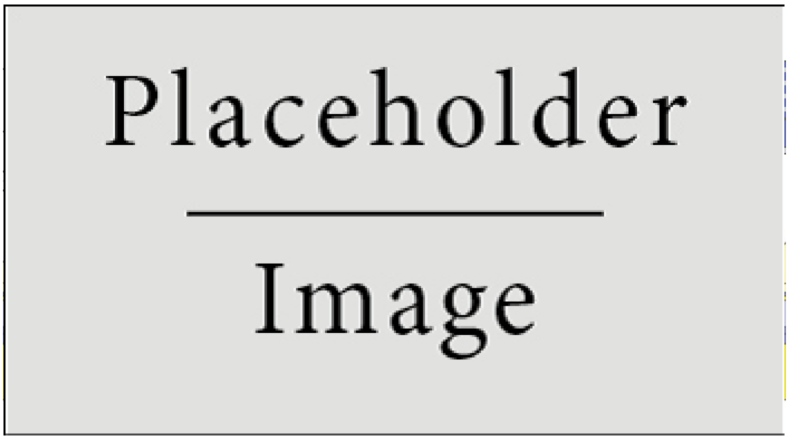

Figure 8.2: Illustration of the a) soldering type and the b) monolithic series connection (Source b: modified from [3])

Three patterning steps P1-P3 are required to realize a monolithic interconnection of cell stripes: P1 separate the back electrodes and P3 seperates the front electrodes of the adjacent cells, while P2 establishes the series connection between neighboring cells by the direct connection of the two electrodes.

This has the main advantage that no additional collection grids are necessary which reduces shadow casting. However, this is offset by the disadvantage that the region between P1 to P3 cannot be used for power generation leaving parts of the aperture area unused. The main disadvantage though is that defective cells can not be sorted out as in the conventional process and the whole module is defective. Therefore depending on the production quality and stability this connection type might be more expensive if too many modules cannot be sold due to singular defective cells. Because of this some manufacturers of thin-film solar cells use the non-integrated approach to ensure a good quality and reasonable production output.

Exercise 8.2
Discuss the effect of different shading conditions on modules manufactured with the two connection types discussed above. Is one effectively more productive under varying shading conditions or does it not matter at all? Use Figure 8.1 to support your claims.

Because modules are just a series connection of cells their electrical characteristics look very similar to those of the individual cells (just with larger voltages) plus the influence of any series resistance which might be introduced. Therefore solar modules are characterized just like solar cells and modelled using the Schockley equation. However, a few details are important to note:

When a module is exposed to standard test conditions instead of the cell temperature the module temperature is considered. Due to differences in the thermal connection to the environment this might make a difference. Additionally due to the large size of a module a temperature measurement at one spot might not be sufficient and multiple temperature sensors are required to measure at homogeneous conditions.

In order to avoid the thermal effects during the measurement modules are usually characterized using flashers. The modules are kept in the dark at $25\,^{\circ}\mathrm{C}$ and are exposed to the radiation only for a very short amount of time when the $J(U)$ characteristic is measured with very fast electronics. Because of this short excitation the module is not expected to heat up and thus assumed to be at the standard temperature.

Furthermore when characterizing a module the total aperture area is considered (basically the frame) when the efficiency is calculated instead of the active or cell area which are actually sensitive to photons. Because of the non-avoidable inactive space between the cells the efficiency of modules is naturally lower than those of laboratory cells.

Notice, that we have been using the current density J throughout the course. On PV module datasheets however usually the $I(U)$ characteristic is given. On the datasheet you can also find the device area A, therefore the current density $J = I/A$ can be easily calculated. As we are taking a more macroscopic viewpoint in this chapter we will use both physical quantities. Notice as well, that in PV datasheets the $I(U)$ characteristics is usually mirrored around the voltage axis (see Figure 8.3b). The reason is the convention of the current direction. While engineers consider the electrical current to flow from positive to negative, physicists acknowledge that the real charge carriers in most situations are usually the negatively charged electrons. As we have learned with the hole and electron picture it does not really matter, we just have to make sure that we are aware of the sign convention used in a given situation.

8.2 Characteristics

8.2.1 Operation point

Until now we have always only considered the photovoltaic generator and its $I(U)$ characteristics exclusively. Also we have silently assumed that we operate the solar cell at the maximum power point. In fact many researchers call the maximum power point the operation point, however, that is very misleading. Actually the operation point is determined by the operation voltage U_{op} with the respective operation current $I_{op} = I(U_{op})$. In other words the operation point is given by the $I(U)$ characteristics and that is exactly its purpose. The maximum power point is just the best operation point under certain conditions if power generation is your goal.

But a PV generator on its own provides no service. The reason why we are in need of power is because we want to operate an appliance (load). An electrical system is the connection of a generator with a load. The most basic circuit connecting a generator with a load is given in Figure 8.3a. The load actually has a $I(U)$ characteristic as well.

Example 8.1 — Ohmic load.
An ohmic load like a heating coil is characterized by its resistance R. The $I(U)$ characteristic of these types of loads is given by Ohm's law:

$$I = \frac{1}{R}U \tag{8.2}$$

The $I(U)$ characteristics of an ohmic load is shown in Fig. 8.3b.

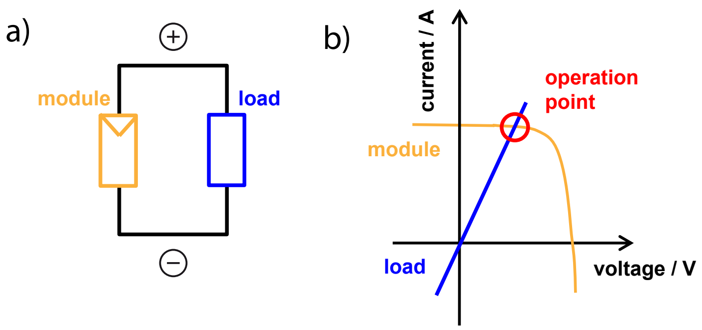

Figure 8.3: a) Most basic circuit of a photovoltaic device and a load b) Current and voltage matching between the generator and the load determine the operation point. The grey roman numerals designate the quadrants of the coordinate system (see text).

Consider the circuit shown in Figure 8.3a. Obviously we have no intersections therefore the current passing through the PV device I_{PV} and the load I_{load} must be the same. Furthermore the load is connected such that the voltage generated by the PV module U_{PV} fully drops across the load U_{load}. Therefore these conditions must be met:

$$U_{\text{PV}} = U_{\text{load}} \tag{8.3}$$

$$I_{\text{PV}}(U_{\text{PV}}) = I_{\text{load}}(U_{\text{load}}) \tag{8.4}$$

These conditions are met exactly where in Figure 8.3b the $I(U)$ characteristic of the load intersects with the $I(U)$ of the PV generator and that point is considered the operation point. Notice, that just like the $I(U)$ characteristics of the PV generator changes with the environmental parameters (i.e. temperature, irradiation) the same might be true for the load characteristics. Therefore the operation point changes during operation.

It depends on the position of the operation point if the PV device generates power or actually consumes power. In quadrant I. in Fig. 8.3b both the current and the voltage are positive and by extension the power $P = IU$ is positive as well. That is where we want to operate our PV device. However, if the operation point is in quadrant II. or IV. either the current or the voltage and by extension the power becomes negative. Operating the device in these regions actually consumes power.

We can measure the $I(U)$ characteristics of a photovoltaic device in quadrant I. by connecting various loads to it. As each load crosses the $I_{\text{PV}}(U)$ in a different operation point we can determine one point of the $I(U)$ characteristics by measuring the voltage as well as the current for this specific load. By connecting the operation points obtained for different loads we can track the $I(U)$ characteristics. In this case the load resistances are considered a sink for the power generated in the PV generator.

Using this method we can only track the $I(U)$ characteristics in the power generation mode (i.e. positive I and U, I. quadrant). If we want to measure the $I(U)$ characteristics in quadrant II. (negative bias) or quadrant IV. (current reversion) we actually have to provide power using a power source (like a power pack) as the photovoltaic device is actually now consuming power. The combined measurement of the $I(U)$ characteristics for positive and negative bias is possible with so-called source-measure-units (SMU) which can automatically act as both a power source and a power sink making the measurement of the solar cell characteristics much more comfortable.

8.2.2 Cell series connection

Let us consider the series connection of two equal solar cells where one cell is fully illuminated but the other one is partially shaded in connection to a load. Figure 8.4 shows the $I(U)$ characteristics of both solar cells and the hypothetical operation points if both were connected to the load on their own. In that case both cells would operate at different operation voltages and currents. However, the Kirchhoff laws state that in this particular circuit the same current I_{op} flows through all devices. But which current to choose?

It would be nice if we had something like a combined $I(U)$ characteristic for both solar cells. Using Eq. 8.1 we know that we can construct this for a series connection by adding the voltages. In order to obtain an expression for the voltages for each device we form the inverse of the $I(U)$ characteristic: $U(I)$. This can be achieved graphically by rotating the $I(U)$ graph by 90 degrees).

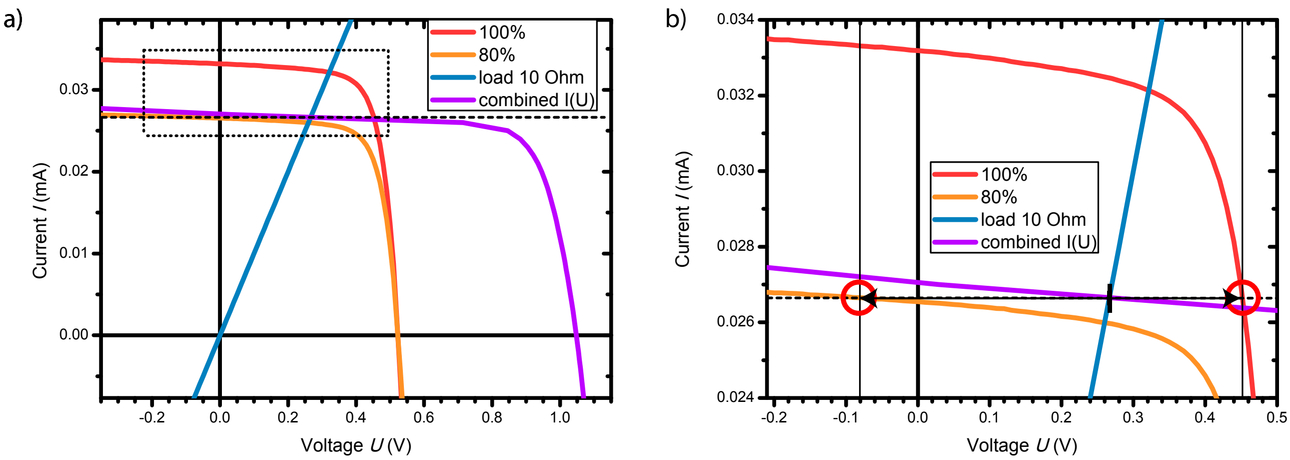

Figure 8.4: a) Finding the operation point of two unequally illuminated solar cells connected in series b) Zoomed-in view (dotted rectangle in a)) to emphasize the load behaviour of the shaded cell

Adding the voltages results in $U_{tot}(I) = U_{full}(I) + U_{partial}(I)$. The inverse of $U_{tot}(I)$ would then be the $I(U)$ characteristic of the combined solar cells. This combined characteristic is illustrated in Figure 8.4 as well and we see that neither operation point of the original cells is the correct one but a new operation point arises. We can further see that the combined $I(U)$ characteristic is indeed limited by the shaded cell regarding the current but not the voltage.

However, notice that the current of the combined $I(U)$ characteristic is in fact slightly larger than the current of the shaded cell. This has a very important consequence when operating the combined PV generator at small loads. After the the operation current flowing in the system I_{op} has been determined using the combined characteristics we can find at which operation points the individual cells are operating.

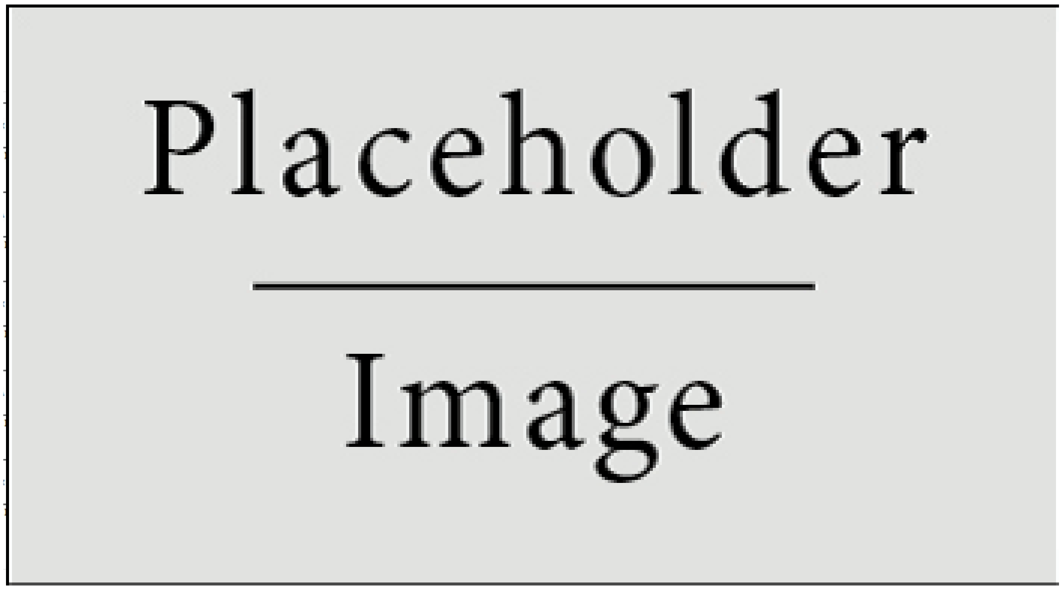

Figure 8.5: a) A shaded/defective cell in a module consumes a significant amount of the power generated in the rest of the module which is lost in the form of heat (Source: [4]) b) The warmer cell can be detected using infrared photography. (Source: [5])

In case the load is large enough such that the operating current I_{op} is smaller than the short circuit current density of the shaded cell I_{sc}^{shaded} everything is as expected: Both cells are producing power albeit not at their respective optimal points. Yet, if the load is so small that $I_{op} > I_{sc}^{\text{shaded}}$ the operation point of the shaded cell is infact in quadrant II. of the $I(U)$ characteristics (emphasized in Fig. 8.4b). In other words the shaded cell is no longer operating in the power generation mode but actually consuming power and acting as an additional load. Therefore the cell does not generate a voltage but a voltage drop across the device (=negative bias voltage).

This effect is pronounced and occurs earlier the more the cell is shaded or if more fully illuminated cells are in the series connection and can lead to a situation where a substantial fraction of the power generated in the illuminated part of the module is consumed in the shaded cell(s) (see Figure 8.5a). This power is generally transformed into heat, so that the shaded cell will become very hot which might actually damage the cell and thereby the whole module. This effect can be visualized using infrared thermocameras and is shown in Figure 8.5b.

8.2.3 Bypass diodes

The farther the operation point of the shaded cell is to the negative of the $I(U)$ characteristics the more power is lost. At large negative bias in real solar cell the current is usually not constant. At the so-called breakthrough voltage avalanche ionization occurs which effectively breaks the device. In order to counteract these effects some manufacturers use bypass diodes in their devices. A bypass diode is a semiconductor diode with a turn-on voltage similar to the U_{oc} of the solar cell which is reversely connected in parallel to the solar cell (Inset in Fig. 8.6a).

Figure 8.6a shows both the $I(U)$ characteristics of the solar cell as well as the $I(U)$ characteristics of the reverse diode. According to the Kirchhoff circuit rules both devices share the same voltage drop and the currents need to be added: $I_{tot}(U) = I_{cell}(U) + I_{bypass}(U)$. The combined $I_{tot}(U)$ of this structure is also indicated in Figure 8.6a. Instead of staying at a relatively constant level for large negative voltages as the regular solar cell would the bypass diode becomes active at small negative bias and bypasses the current flow avoiding any damage to the cell. The result is that the current might become quite large already at small negative voltage.

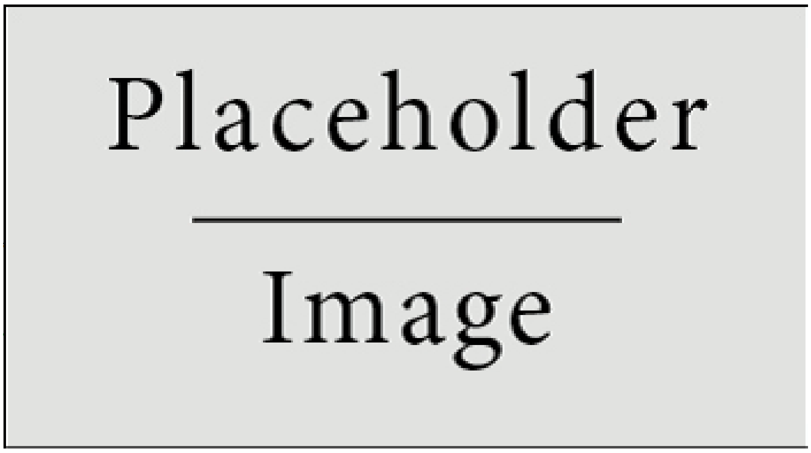

Figure 8.6: a) The modified $I(U)$ characteristic of a solar cell with an antiparallel bypass diode (see inlet for circuit) b) The improved $I(U)$ characteristics of two unequally illuminated solar cells due to the bypass diode (compare with Fig. 8.4a) c) Improved $I(U)$ characteristic in a module where multiple solar cells are connected to a bypass diode. (Source c: [6])

In other words, should the cell be shaded and $I_{op} > I_{sc}^{\text{shaded}}$ then the operation point for a bypassed cell will be at smaller voltages and thus avoid power loss, overheating and potential cell failure. You can also picture this as follows: When adding up the inverse characteristics the premature voltage drop in the combined characteristic caused by the lower current of the shaded cell will actually be prevented due to the bypass diode (see Fig. 8.6b).

Unfortunately bypass diodes are expensive, complicate the electronic setup of the module and actually cause efficiency losses. Therefore it is common not to equip each cell with a single bypass diode but to use one bypass diode for multiple cells. While this increases potential losses it is an economic trade-off. See Fig. 8.6c for the performance of a module where multiple cells are using one bypass diode. Notice, that in modules with monolithic integrated series connection no bypass diodes can be implemented at all. In most cases bypass diodes are implemented into the module connection box.

8.2.4 PV power plants

The power provided by one solar module might not be sufficient for the required application. Because modules are designed to already provide usable voltages the currents are often too low. The current can be increased by connecting multiple modules (which provide the same voltage) in parallel:

$$I_{sys,par} = \sum^{N} I_{module} \tag{8.5}$$

$$U_{sys,par} = U_{module} \tag{8.6}$$

Notice, that just as discussed with the bypass diodes before in parallel circuits the combined $I(U)$ characteristics is found by simply adding the individual $I(U)$ characteristics of the connected modules. This is a results of the basic Kirchhoff rules for electrical circuits. When the operation point of the combined $I(U)$ characteristic is found it is again useful to look at which operating points the individual modules are operating.

If the operation voltage U_{op} is lower than the open circuit voltage U_{oc}^{shaded} of the shaded module then both modules are in the power generation regime. If however, $U_{op} > U_{oc}^{\text{shaded}}$ then the current in the shaded module reverses or in other words current is flowing into the module and power is consumed (IV. quadrant). In order to avoid this directly after a module output a protective resistance is placed to prevent this.

Yet, in general the voltage in a shaded module does not change as significantly as the current therefore the shading effect is much less dramatic than in the series connection. Approximately the main effect is that the shaded module adds less current to the total. The other modules are affected by this only slightly (a very small drop in the voltage).

For any application which requires a larger voltage than provided by the module (for example an inverter) we can easily connect multiple modules in series just as we did with the cells in the module. A series connection of multiple modules is called a string and by connecting multiple strings in parallel we can realize any current or voltage our application might require. The series connection of modules in a PV system has the same downsides as the series connection of cells in a module. Obviously, bypass diodes can also be incorporated in strings in order to avoid those effects discussed previously. Due to the same reasons it is recommended that all modules in a string are always in the same environmental conditions.

Example 8.2 — Unfavorable roof alignment.
Should you want to setup a PV system on the top of a roof with the slopes oriented to the east and the west it is better to connect the cells such that all the modules facing east are connected in a string and all the modules facing to the west to connect in a separate sting in parallel to optimize system performance.

Very large PV power plants covering the size of soccer fields can actually be considered as many small independent PV systems as the strings will be connected to many different loads (e.g. inverters) such that large fractions of the plant do not affect each other.

Exercise 8.3 — Energy lab.
The PV power plant at the Energylab of the university of Oldenburg [7] is (probably) one of the oldest still running PV systems in the world. The monocrystalline modules which constitute the generator are almost 40 years old [8]. One of the four inverters at the Energylab of the university of Oldenburg is a SMA sunny boy 1100 (Datasheet: [9]).

If you had an arbitrary number of modules and area available design a PV system with these components which is not too small and not too large and fits the requirements of the inverter.

After reading about parallel and series circuits you might come to the conclusion that parallel circuits are better as the effect of shading is not so detrimental. However, in that case large currents are generated which have to be transported using cables. As the cable resistance and as such the losses in the cable increase linearly with the current thick cables would be required in order to reduce those losses. This however, increases the cost of the system which is why PV systems are often designed for high voltages.

8.3 Connection Types

8.3.1 Stand alone systems

Solar home systems (SHS) are closed PV power systems which are not connected to any grid. They can be further characterized by a spatial closeness of the generator and the load and are often operated by the same person. They are mainly used in remote areas with no access to the utility grid and applications range from powering satellites or space stations, mountain huts, rural areas in developing countries and so on. Solar home systems become economic in these locations because alternatives for access to power are even more expensive.

In principle the most primitive SHS is shown in Fig. 8.3a and consists just of the generator and a load. Obviously the load can only be operated when the sun is shining strong enough which limits the amount of time the load can be operated. Furthermore any power that could be generated when the load is not used is lost. The operator has the main interest in running the load when it is needed and therefore this emphasizes the necessity for power and load management which in the case of SHS are both within the responsibility of the operator.

One method (of many) of measuring the performance of a solar home system is the so-called loss of load probability (LOLP). If during a time Δt the system is not able to provide enough power to operate the load P_L we take note of this amount of energy $P_L \Delta t$. The loss of load during a time $T = \sum \Delta t$ is then the cumulative amount of energy which we could not provide over the cumulative amount of energy required to satisfy our load profile $P_L(t)$:

$$LOLP = \frac{P_L \sum_{LOLP} \Delta t}{P_L \sum \Delta t} \tag{8.7}$$

A loss of load probability equal to 1 means that the generator is never able to provide sufficient power to the load or in other words the generator is undersized. A loss of load probability equal to 0 means that the generator is always able to provide sufficient power to the load which is the desired case, however, it is possible that the generator is oversized and a large fraction of power is actually lost. It is reasonable to define similarly a loss of power probability (LOPP) which measures how much of the generated power P_{PV} cannot be used:

$$LOPP = \frac{P_{PV} \sum_{LOPP} \Delta t}{P_{PV} \sum \Delta t} \tag{8.8}$$

Optimizing these measures is the task of system sizing.

In many cases the times when the sun shines and provides us with usable energy do not match the times when we want to operate a load (e.g. a lamp during the night). This will result in a large LOLP and a large LOPP. By introducing a storage device into the system both measures can be greatly improved and the asynchronity of power generation and power consumption be leveraged. Therefore in most solar home systems a battery is included and connected to the rest of the setup as illustrated in Fig. 8.7:

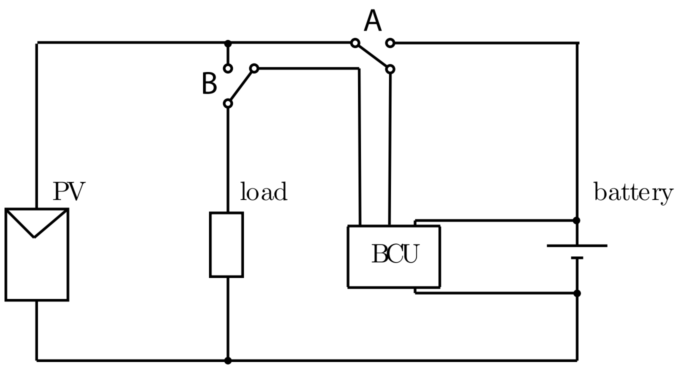

Figure 8.7: Circuit of a solar home system consisting of PV generator, load, battery and BCU. The switches at A and B are controlled by the BCU.

The most common type of battery used is the lead-acid battery (nominal voltage: 2 V per cell). As this is not a course about energy storage batteries have to be discussed only very briefly. Depending on the operation point of the system lead-acid batteries can act as power generator or load (just like PV devices). Just like all devices discussed until now batteries are characterized by a $I(U)$ characteristic (see Fig. 8.8a). Most importantly notice, that the voltage provided by a battery is not constant. In fact according to the $I(U)$ characteristics it changes depending on the current flowing into or out of the battery.

However, just like the $I(U)$ characteristics of loads and PV systems is not constant the $I(U)$ characteristics of batteries depends on other factors such as the state of charge (SOC) for example. In other words a fully charged battery has a different electrical behavior as a depleted battery (see Fig. 8.8a). The higher the state of charge the larger the open circuit voltage U_{oc} of the battery therefore U_{oc} can serve as a very rough estimate for the SOC. However, if for lead-acid the batteries the terminal voltage exceeds 2.4 V extreme electrolysis of the water molecules within the battery plates causes mechanical stress which can cause damage within the battery plates. Beside the non desired loss of water this bears the danger of explosions if kept in a closed container. On the other hand if the battery voltage drops below 1.85 V the electrodes

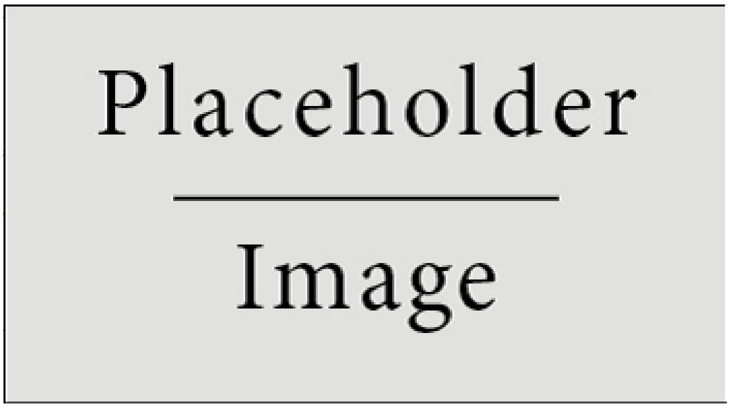

Figure 8.8: a) $I(U)$ characteristics of a charged and a depleted 6 V battery i.e. 3 lead-acid cells in series. (Source: modified from [10]) b) Principle of pulse width modulation (Source: [11])

start to decompose effectively destroying the battery. Therefore the battery is considered empty (SOC=0%) at approximately 1.85 V and fully charged (SOC=100%) at about 2.4 V.

As indicated in Fig. 8.7 the battery is connected in parallel to the PV generator and the load. The operation point of this system is found just like in the case of parallel modules. As it is unclear if the battery will act as power source or power sink the graphical method to determine the operation point has to be modified slightly. For any point in the circuit the Kirchhoff law $I_{in} = I_{out}$ can be written as $I_{in} - I_{out} = 0$. From Fig. 8.8a we see that the current reverses when switching from charging into discharging mode so when including the battery current into the equation it automatically takes account of the sign. In this modified method the load current has to be subtracted and we obtain the difference current $\Delta I(U)$. The operation voltage which establishes can be found as the voltage axis intersect (sometimes called root) of the difference current.

The battery is probably the most critical part of the SHS. It is very expensive and has an average lifetime of about 5 years (compare with the 20years+ of the PV modules). However, the lifetime of the battery is determined significantly about how it is treated. A battery which is almost always depleted might die within one year while careful control might extend the lifetime to over 10 years. Teaching the operators the proper treatment of the SHS is crucial for the sucess of solar home systems. In order to make the management of the system a little bit more comfortable so-called battery charge units (BCU) are incorporated into the system which in their most primitive form control if the system operates in the allowed range for the battery and disconnect the load if the voltage drops too low. More sophisticated versions of these BCU's use complicated microelectronic logics to estimate the SOC better, feature maximum power point trackers (see Fig. 8.10a) and use pulse width modulation (see Fig. 8.8b) to charge the battery. The different types of BCU's are a lesson on its own and are left for another lecture.

Exercise 8.4 — SHS Circuit.
Look at Fig. 8.7. What do you think the purpose of switches A and B is. Do they make sense the way they are implemented into the circuit?

Photovoltaic Pump Systems

Not always electricity is the desired form of energy therefore using batteries as storage medium is not always efficient. One example are photovoltaic pump systems (PVP) as employed for irrigation of fields in rural areas. Here the electricity delivered by the photovoltaic system is just a means to power a pump. The pump lifts water from a low altitude to a high altitude thus increasing the potential energy of the water which is the actual purpose of the whole system. Water at high altitude can be stored much better than the chemical energy in batteries it is therefore the preferred form of energy storage. This type of energy storage where the product (here: the high potential energy water) is stored directly is called product storage.

8.3.2 Grid connected systems

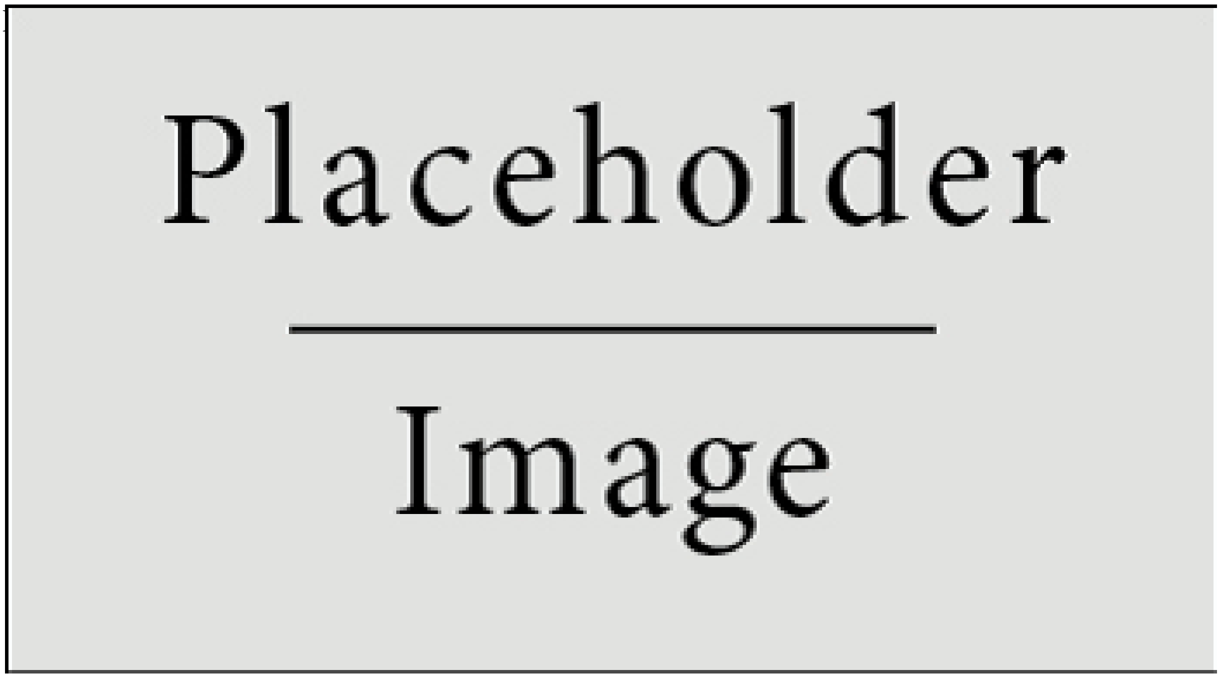

Figure 8.9: Typical grid connected PV system configuration (Source: [12])

In grid connected PV systems the grid is the main load of the system. The AC power consumption grid is connected to the local DC power generation circuit by means of an inverter. The inverter receives the DC power generated by the PV modules and transforms it into an AC signal which is synchronous in frequency and phase with the utility grid. A common method of this transformation is pulse width modulation and the efficiencies are in the range above 90% [13]. Modern inverters have commonly intelligent electronics incorporated which are able to adjust the load and as such the operation point. So-called maximum power point trackers periodically scan the temporary $I(U)$ characteristic of the system to find the point of maximum power output in order to optimize the energy yield (see Fig. 8.10a).

In order to feed the power into the low voltage distribution grid (in Germany about 230/400 V) the inverter actually has to form a signal with a voltage larger than the utiliy grid voltage. Traditionally in the distribution grid the voltage decreases from the High Voltage/Low Voltage transformation station with distance to the household (see Fig. 8.10b). The energy supplier is responsible

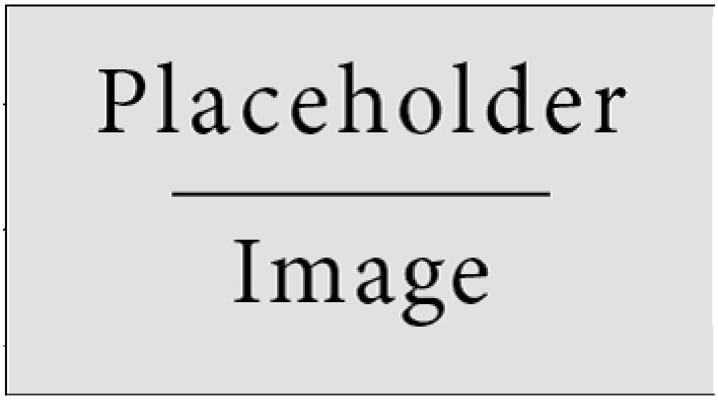

Figure 8.10: a) Working principle of the 'Mountain-climb' MPP-tracking algorithm (Source: [11]) b) Voltage grading between transformer station and households in the distribution grid (Source: [14])

to keep the deviations smaller than 10%. However, now grid connected PV power plants lift the voltage up when they are generating power thus reversing the slope from the household to the transformer station. Unfortunately these deviations are now weather dependent which make it harder for the grid managers to control the grid state. Interestingly the maximum short term voltage is achieved on cloudy days. As the modules are not constantly illuminated they are colder and have such a much larger maximum power. If the sun breaks through a hole in the clouds the full sun power is incident on a colder more efficient module creating the short term voltage maxima.

In grid connected photovoltaic power plants in general the produced power is not consumed on site. Therefore the interests of the producer are separated from the interests of the consumer. In order to ignite investments into the PV technology some nations passed legal acts that provide the producers with the luxury that the generated renewable power will be bought in any case [15] (purchase obligation). One could say that in this situation the utility grid is an infinite sink that accepts all power that is generated.

However, as discussed in chapter 2 this is far from the truth. The energy used at any moment (i.e. the consumed power) must be generated at exactly that moment. This challenge is the main task of power and grid providers and not too much of a problem if the amount of PV power is negligible. However, when the power generated by PV (or other renewable for that matter) becomes significant ways must be found to use the generated energy. Turning down traditional power generator plants is an option when there is a large amount of renewable power generation. However, the times when energy production from renewable energies exceeds the power consumption is increasing. In this case no further power plants can be turned off and the renewable power actually need to be disposed of (due to the purchase obligation). This manifests as negative prices for power at the energy exchange stock markets.

This situation destabilizes the utility grid. Therefore load management becomes an issue again, though the difference to the SHS is that the responsibilities have shifted. Actually the frequency of the utility grid indicates if production and consumption of power are balanced. Therefore in utility grids with a large fraction of renewable energy the feed-in must be managed as well. When there is too much power fed into the grid some inverters need to stop or decrease the amount of power fed into the grid using the smart grid approach or grid frequency detection electronics.

Naturally this causes a conflict of interest of the participating players and is the current subject of political debate.

However, producers of PV power have to realize that it can not be taken for granted that all of the produced power can actually be fed into the grid. As this compromises the economic viability of the investment in PV the producers of PV power are asked to consume as much power as possible on-site themselves as domestic electricity. In order to increase the amount of power used as domestic electricity electronic 'smart' loads are being developed and batteries incorporated into households although the latter are only now becoming profitable [16]. Interestingly the measures LOLP and LOPP become relevant again for grid connected PV power plants as well and instead of putting up as much PV modules as possible the correct sizing of systems should be considered. This is especially true in the future when purchase obligations are no longer given and PV power has to be traded on the market.

8.3.3 Designing PV systems

The same PV system performs very differently depending on its location. Obviously the incoming power depends on the solar irradiation of the location where the system is set up. However, beside that local weather patterns greatly determine the number of sunshine hours and amount of diffuse versus direct sunlight but also ambient temperature and wind speed. In order to correctly size a PV system (providing satisfactory LOL and LOP) these factors have to be considered. Simulation tools such as RETScreen [17], HOMER [18] or INSEL [19] provide different models of varying accuracy to accomplish this task.

A very important parameter affecting the performance of the system is the tilt angle of the module and how well it faces the sun. In the most sophisicated version the modules are placed on solar trackers which follow the movement of the sun across the sky. The choice of the tilt angle actually depends on the application. If as in most grid connected system the goal is to generate as much power as possible to feed into the grid a smaller tilt angle is preferable as in the summer time when the most power is incident on the modules the sun stands very high in the sky. If the goal is rather to increase the time of self-sufficiency (as in SHS) a larger tilt angle is actually preferable as the operation of the load also needs to be guaranteed in the winter time when the sun is weaker and lower in the sky. Therefore any optimization needs to consider the application of the load.

Other factors to consider are the available area, shading obstacles and the cost of the overall system (including construction, racks, cables, inverters and maintenance).

Actually in order for renewable energies in general to become a success even the generator and load operators themselves should be considered as part of the system as human factors.

8.4 Literature

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