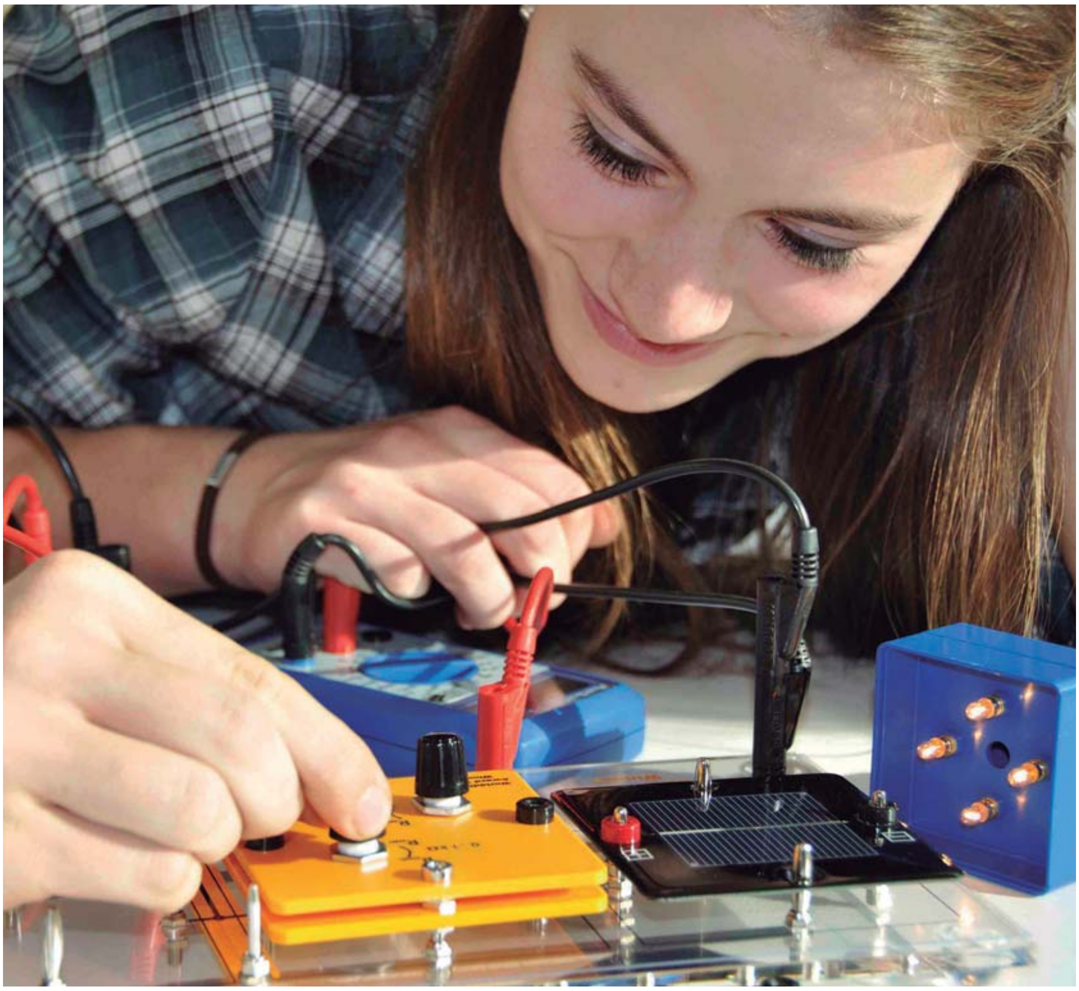
leXsolar-PV Large



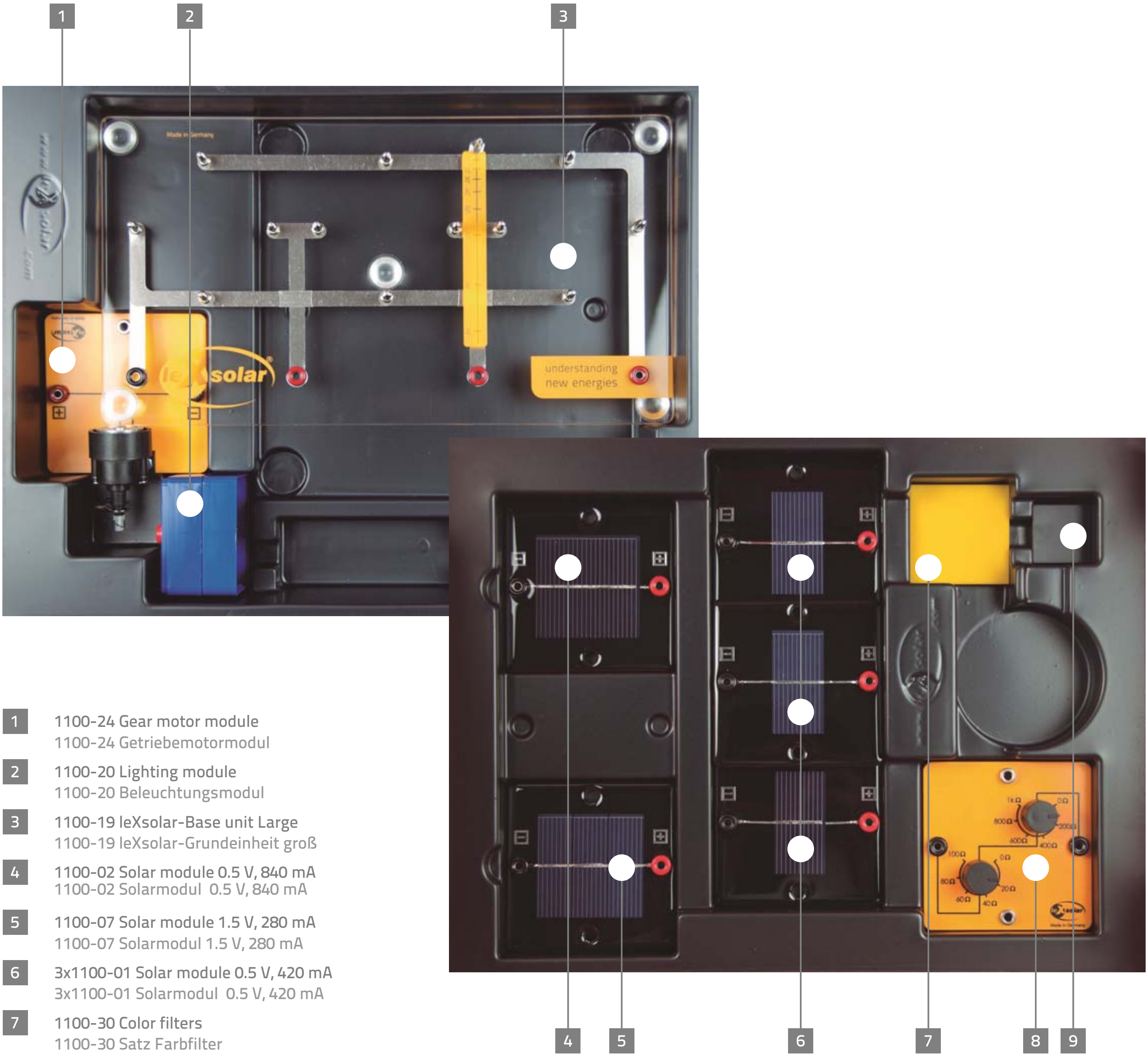
Teacher's Manual

Layout diagram leXsolar-PV Large

Item-No.1103

Bestückungsplan leXsolar-PV Large

Art.-Nr.1103



1	1100-24 Gear motor module 1100-24 Getriebemotormodul
2	1100-20 Lighting module 1100-20 Beleuchtungsmodul
3	1100-19 leXsolar-Base unit Large 1100-19 leXsolar-Grundeinheit groß
4	1100-02 Solar module 0.5 V, 840 mA 1100-02 Solarmodul 0.5 V, 840 mA
5	1100-07 Solar module 1.5 V, 280 mA 1100-07 Solarmodul 1.5 V, 280 mA
6	3x1100-01 Solar module 0.5 V, 420 mA 3x1100-01 Solarmodul 0.5 V, 420 mA
7	1100-30 Color filters 1100-30 Satz Farbfilter
8	1100-23 Potentiometer module 1100-23 Potentiometermodul
9	1100-29 Solar cell cover set (4 pieces) 1100-29 Satz Abdeckungen f. Solarzelle

Version number
Versionsnummer

III-01.24_L3-03-129_19.05.2016

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Layout diagram leXsolar-PV Large

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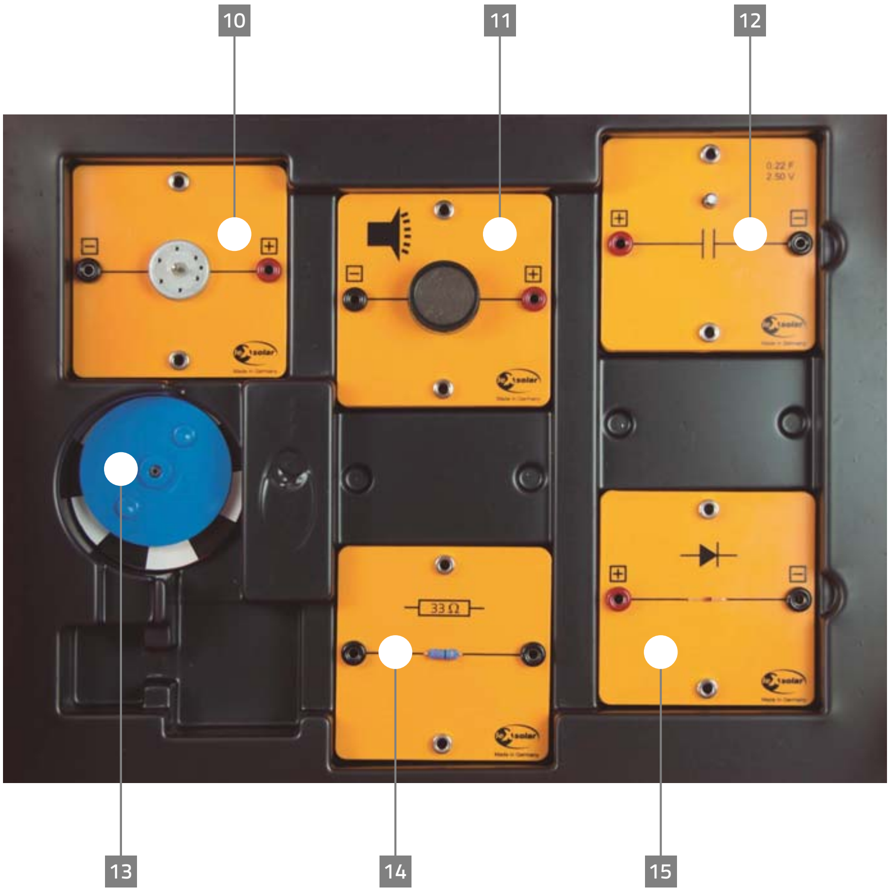

10	1100-27 Motor module without gear 1100-27 Motormodul ohne Getriebe
11	1100-25 Buzzer module 1100-25 Hupenmodul
12	1400-07 Capacitor module 220 mF, 2.5V 1400-07 Kondensatormodul 220 mF, 2.5V
13	1100-28 Color discs - Set 1 1100-28 Farbscheiben-Set I
14	1100-22 Resistor module 1100-22 Widerstandsmodul
15	1100-21 Diode module 1100-21 Diodenmodul

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leXsolar - PV Large

Teacher's manual

Chapter 1: Theoretical foundations about photovoltaics

1.1 Introduction

1.1.1 What is photovoltaics?

Photovoltaics (PV) is the direct conversion of light into electrical energy using solar cells (also called photovoltaic cells). By using sunlight it is a renewable energy source, by definition.

The emphasis is on direct, here, because all other renewable energies need at least one detour to generate electric power. This detour is a turbine with a generator in the case of heat energy as energy source (solar thermal, geothermic and biomass energy). In the case of kinetic energy as energy source (wind, hydro and tidal energy) at least a generator is necessary. Photovoltaics however does not need any of these appliances with moving parts. Hence it is low-maintenance and long-living. Due to this exceptional position there are high expectations of the future role of photovoltaics.

1.1.2 Photovoltaics in the spectrum of renewables

In principle only three of earth's energy sources can be considered as unlimited on the human time-scale. Those three establish a basis for all renewable energies. Though the denotation as renewable or regenerative energies is in fact wrong from the physical point of view, it is used widely.

Figure 1.1 shows the three energy sources (solar power, geothermic energy and rotational energy of the earth) and the forms of renewable energies which are supplied by them, respectively. The relation between the different forms of absorption, reflexion and utilization of solar energy is depicted in Figure 2.2. It is quite obvious that the energy conversion used by humanity is negligible compared to the total solar irradiation reaching earth. Hence, photovoltaics offers a nearly inexhaustible potential for human power supplies.

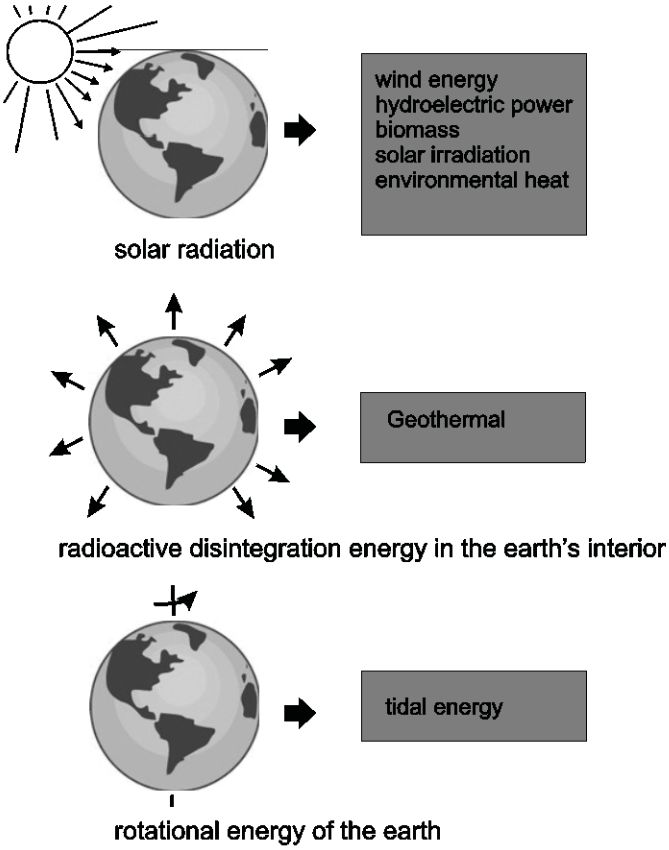


Figure 1.1: The sources of renewable energies.

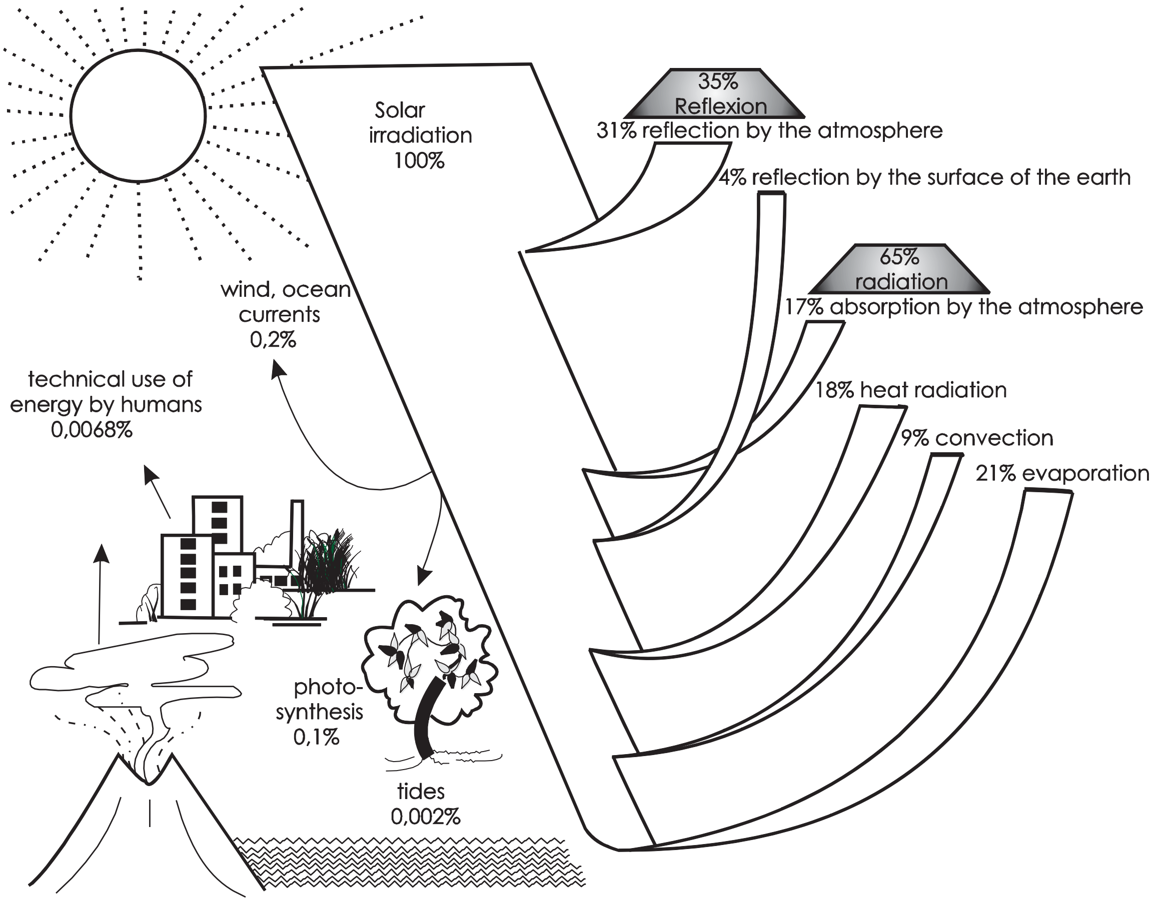


Figure 2.2: Energy balance of earth.

1.1.3 Costs

Nowadays the biggest problem of photovoltaics is the relatively high costs. A kilowatt hour (kWh) electricity generated by a photovoltaic power plant today (2008) costs 0.20 … 0.50€ depending on the plant's location. Believable studies anticipate a price of about 0.10€ in 2030. The main reason for this cost reduction is the so called economy of scales. The higher the quantity of produced goods the cheaper it becomes because of the development of production processes.

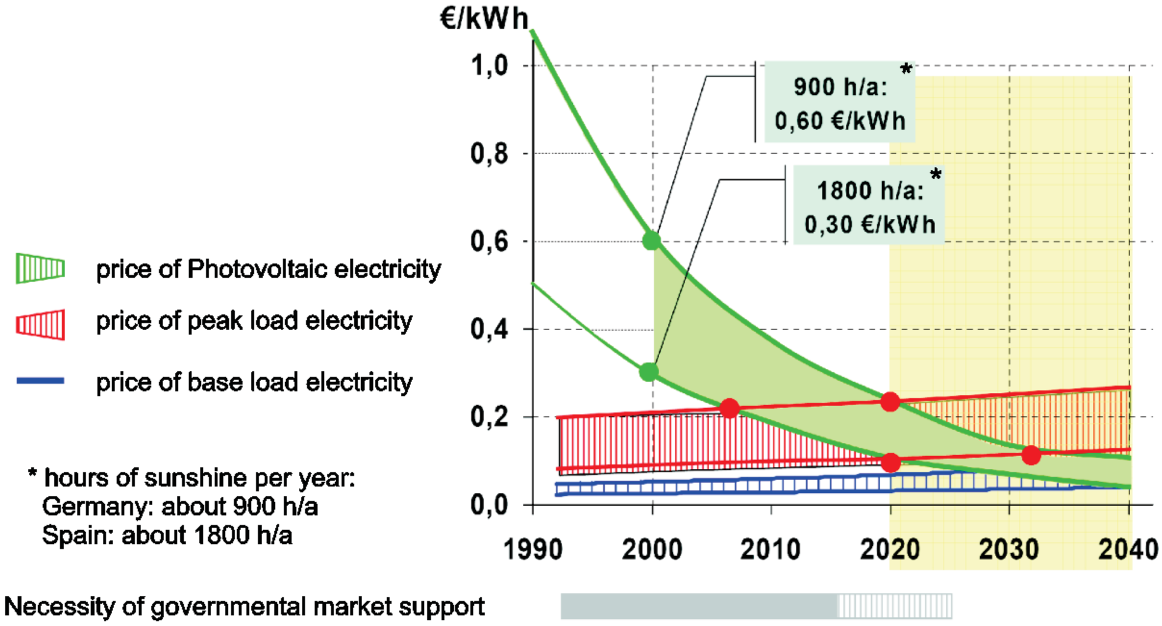


Figure 1.3: Estimated cost trend of electricity generated from photovoltaics compared to electricity from non-renewable energy sources. Source: SCHOTT-Solar

Figure 1.3 shows the costs for electricity generated from photovoltaics at two locations with different solar illumination. In order to compare different locations one defines the so-called peak-load-hours. This value corresponds to the time by which the sun would have to illuminate a defined area with maximum power (1000W/cm^2) in order to transmit the same total energy as reaches the surface of the location during a whole year.

In Germany this value is between 900h and 1200h. However, for Spain it is 1800h and for the so-called sunbelt, the deserts of the northern hemisphere, it reaches 2000h. Consequently in sunny regions it is possible to generate more than twice the power per year than Germany using the same photovoltaic power plant. The expenses for power generated by photovoltaics are therefore only half as much as in Germany. This fact is reflected by Figure 1.3, as well. The costs of electricity from PV power plants in Spain will, according to the forecast of Figure 1.3, reach the costs of conventional base load electricity before 2030. In Germany this is expected not before 2040. However, the price of conventional peak load electricity will be reached much earlier which would make governmental market support unnecessary.

1.1.4 Efficiency

Often also the power conversion efficiency (PCE) of solar cells is called a problem. At the moment it is typically 14 … 17%. As described below (Chapters 2 and 3) the efficiency of solar cells is limited by physical reasons. Hence there will be no solar cell on the market with efficiencies of more than 25% in 2030.

But the quantity of solar irradiation theoretically allows the complete coverage of mankind's power requirement by photovoltaic technology also with nowadays efficiencies. Solar irradiation exceeds the requirement by a factor of at least 10.000. Because economic efficiency is a result of costs *and* power conversion efficiency, PCE is not a big problem of photovoltaic technology at all.

1.1.5 Applications

Photovoltaics can either be used for feed-in public network or supplying isolated applications or buildings far away from public network. When using photovoltaics for feed-in an inverter is necessary besides the solar module to change from direct current (DC) to alternating current (AC) used by the network. Currently photovoltaics' contribution to the overall electric power requirement is very low. In Germany it is 1.6% (2006). This percentage is generated by large-scale photovoltaic power plants with wattages of some Megawatt (MW) one the one hand and by small solar plants on top of private roofs with wattages of 1 … 10 kW on the other hand. At the moment photovoltaics is only competitive due to government aid in terms of the Renewable Energy Sources Acts. These laws were enacted in many European countries in the last years starting in Germany in 2000.

Nevertheless photovoltaics is competitive for supplying isolated applications already today. For isolated applications or buildings whose connection to public network would be too expensive, photovoltaics in combination with suitable storage solutions like accumulators and other energy sources like wind power can assure power supply.

Well-known and widely-used isolated solutions with solar cells are calculators or wristwatches.

1.2 Materials used for photovoltaics

A solar cell converts radiation energy, i.e. the energy of photons, directly into electrical energy. This happens due to the so called photovoltaic or photoelectric effect for which three requirements have to be met:

1. The radiation has to be absorbed.
2. The absorption of light has to result in the generation of mobile negative and positive charges.
3. The charge carries have to be separated, i.e. their Coulomb attraction has to be overcome.

Those requirements can be fulfilled using certain polymeric compounds, organic dyes, electrolyte-semiconductor-contacts or inorganic semiconductors. Solar cells made of the first three material combinations are still in the research stage and reach laboratory efficiencies of 5% (Polymers and organic dyes) and 10% (electrolyte/semiconductor). In contrast, conventional silicon solar cells show efficiencies of > 15%. The new concepts still suffer of problems with stability and low power conversion efficiencies. Currently those issues are under investigation and it remains to be seen if one of the concepts can establish on the market in future.

The best-understood solar cell is the semiconductor solar cell with a conventional p/n-junction. It is the only one manufactured in mass production and used on a large scale for electrical power generation. Therefore this booklet will deal exclusively with semiconductor solar cells

Semiconductors fulfill the above mentioned requirements of the photovoltaic effect. The absorption of light leads to the excitation of mobile charge carriers, the electrons and holes, which can be separated in the electric field of a p/n-junction.

1.3 Phenomenological explanation of the p/n-junction

1.3.1 The semiconductor crystal

Silicon is the commonly used semiconducting material for the fabrication of solar cells. In the table of elements it appears in the fourth main group which means that a silicon atom has four valence electrons. Those valence electrons are responsible for the formation of stable bonds between neighboring silicon atoms in the semiconductor crystal. Figure 0.4 a) schematically depicts the structure of such a crystal: In the ideal case the atomic cores of silicon form a stable crystal lattice. Since all electrons take part in the covalent bonds, there are no free charge carriers in the crystal. However, it is possible that some electrons are released by adding energy (e.g. in the form of heat) to the system and are then available as free charge carries. At room temperature already a small part of the electrons is *thermally activated* in this manner (see Figure 0.4 b)). In the place of the formerly bound electron a “hole” is being left. Formally one assigns a positive charge to it.

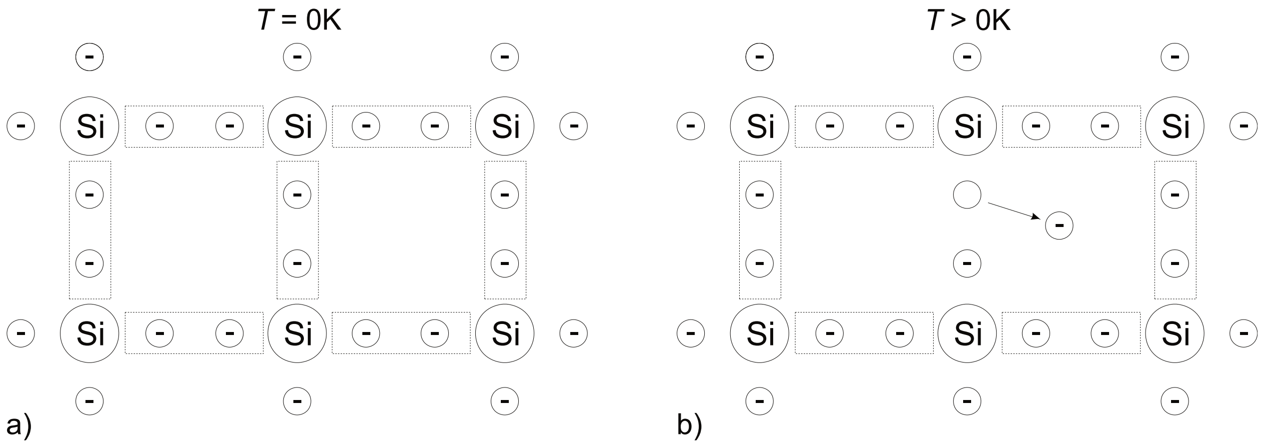


Figure 0.4: a) Schematic illustration of double bonds between the valence electrons of silicon atoms in a crystal lattice. At a temperature of 0K there are no free charge carries in the crystal. b) Electrons can be released from the bonds by thermal activation and consequently contribute to the current as free charge carriers. Formally a positive charge is assigned to the resulting vacancy which is called p-hole.

The conductivity of a semiconductor increases with increasing temperature. In reality however, it is not even under cleanroom conditions possible to fabricate completely pure silicon crystals. There will always be a considerable impurity concentration due to atoms of different kind which affect the intrinsic (material specific) conductivity. Therefore there will always be a finite amount of free charge carries even close to zero temperature. The intrinsic carrier density for silicon at 20°C is for example $n_i = 10^{10}\text{cm}^{-3}$, i.e. there are 10^{10} free electrons and 10^{10} free holes per cubic centimeter. The density of impurities in the crystal is typically approximately 10^{16}cm^{-3} and is hence by orders of magnitude bigger than the number intrinsically free charge carriers. This means the properties of the crystal are dominated by the impurities.

It is also possible to systematically implement such impurities into the crystal in order to manipulate its properties. This process is called *doping* and is indispensable for the fabrication of efficient semiconductor devices.

1.3.2 Doping of semiconductors

The density of electrons n and holes p is equal for a perfect crystal in thermodynamic equilibrium (T = *const*., no illumination). By implementing impurity atoms (doping) it is possible to systematically manipulate n and p. For example the introduction of a phosphorus atom at a silicon lattice site leads to an increase of the concentration of electrons in the conduction band. This is due to the phosphorus atom possessing five valence electrons (since it is in the fifth main group of the periodic table) of which only four are needed for the formation of covalent bonds to the neighboring Si-atoms (see Figure 0.5). The remaining electron is easily separated from the core. Therefore one finds an enhanced number of free electrons in phosphorus-doped silicon. Nevertheless the crystal stays neutral as whole since the corresponding number of stationary, positively charged phosphorus atom cores is left behind. If denoting them with N_D one can express the neutrality condition in an n-doped semiconductor as follows:

$$n = p + N_{D.}$$

On the other hand the implementation of atoms from the third main group of the periodic system (e.g. boron) leads to the increase of the concentration of holes since only three electrons are available for the bonds to the neighboring Si-atoms. (see Figure 0.6).

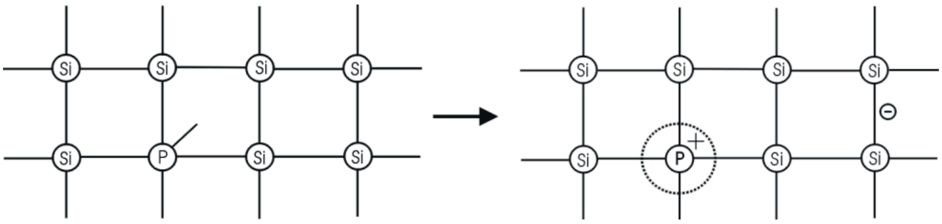


Figure 0.5: n-doping of a Si-crystal with phosphorus. The fifth valence electron of phosphorus does not find a partner to form a chemical bond and is therefore easily released from the core atom. This results in the formation of a free electron and a positively charged phosphorus atom.

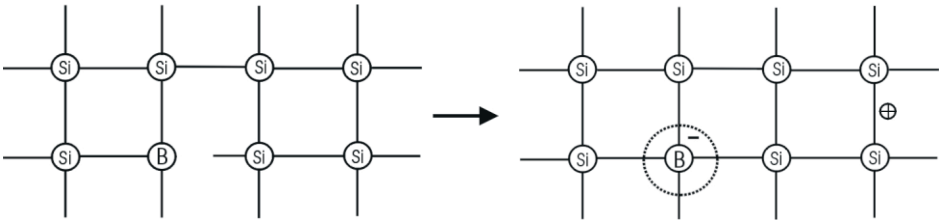


Figure 0.6: p-doping of a Si-crystal with boron. The missing fourth valence electron of boron is compensated by an electron of the silicon valence band. Since this electron is now missing in the valence band, it leads to the formation of a free hole while the boron atom remains negatively charged.

Independently of doping the following relation between the concentrations of electrons n and holes p holds true:

$$n_i^2 = np$$

In an undoped (intrinsic) semiconductor we find $n = p$ and n_i is equal to the intrinsic carrier density which is characteristic for a certain semiconducting material. From the above stated relation it can be deduced that rising the concentration of one sort of charge carriers results in the drop of concentration for the other sort. The predominant sort of charge carriers is called *majority carriers* while the others are called *minority carriers*. E.g. in n-doped silicon the electrons are the majority carriers. The majority carriers are responsible for the formation of a space charge region with internal electrical field while the properties of the minority carriers are important for the photocurrent at the p/n-junction under illumination.

1.3.3 The p/n-junction

The formation of the space charge region and the built-in voltage by diffusion of minority carriers

Technically a p/n-junction is built by letting phosphorus diffuse into a p-doped (boron-doped) crystal at high temperatures. At room temperature the dopants cannot diffuse anymore and a fixed doping profile is created. We now want to consider an ideal p/n-junction in which a homogeneously p-doped region abuts directly on a homogeneously n-doped region. Figure 0.7 illustrates this schematically. A charge exchange will take place at the interface between the two layers – a part of the free electrons from the n-layer (majority carriers) diffuses to the p-layer (a diffusion always takes place from a region with high concentration to a region with low concentration) and there recombines with free holes. In return, holes from the p-doped region diffuse to the n-region and likewise recombine with electrons there. That is why the concentrations of free electrons and holes is strongly reduced in the region around the interface which is now depleted of free charge carriers and therefore also called *depletion region*. However, the density of stationary positively and negatively charged atom cores of the dopant atoms (here: boron and phosphorus) stays unchanged and leads to the formation of a space charge region. The part of the space charge region which is located on the n-side is positively charged (phosphorus atom cores) while the part on the p-side features a stationary negative charge (boron atom cores).

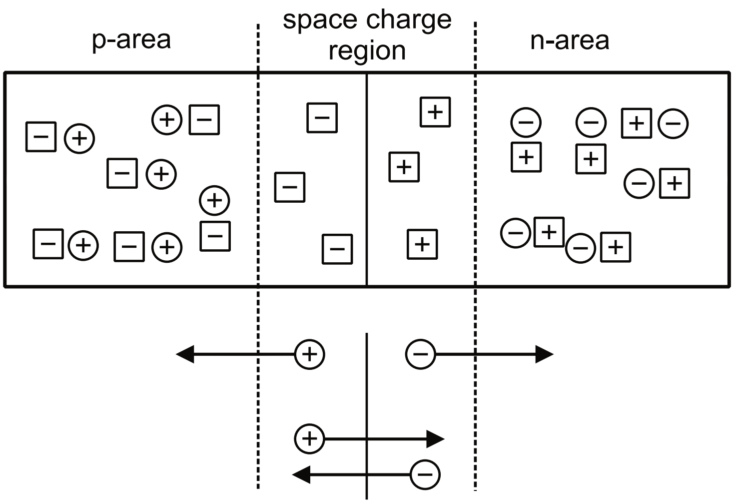


Figure 0.7: Schematic illustration of the arrangement of charged dopants and free charge carriers at the p/n-junction under dark conditions. The spherical, hollow symbols denote free electrons and holes, while the squares are the stationary, charged dopants. The latter are responsible for the formation of the space charge region. The regions far away from the space charge region are electrically neutral.

Due to the diffusion of charge carriers in the interfacial layer a voltage drop is generated at the junction: A positive charge located at the interface between p- and n-region would feel a force accelerating it towards the p-region since it would be attracted by the positive space charge there (see. Figure 0.7). This force apparently acts opposite to the direction of diffusion, so that an equilibrium between both processes will establish. A force F interacting with a charge Q is a hint for the existence of an electric field E ($F = EQ$) which is being caused by a voltage. This voltage emerging form the p/n-junction corresponds to the work which is necessary to transport a positive charge across the space charge region from the p- to the n-region. It is called *built-in voltage*.

The p/n-junction under illumination: Separation of charge carriers and diffusion of minority

When illuminating a p/n-junction the energy of the incident light leads to the generation of free electrons and holes. Charge carriers excited within the space charge region are immediately separated by the field forces: Holes are extracted towards the p-region and electrons to the n-region (compare Figure 0.7). However, the following estimate will show that using only the contribution of photons which are absorbed in the space charge region does not suffice. The absorption coefficient of silicon at a wavelength of λ = 820nm, which corresponds to a light energy of hf = 1,7eV, is α = 600cm^{-1}. At this wavelength silicon absorbs the maximum amount of light. The penetration depth of light into the semiconducting crystal results as $d = 1/\alpha = 16$µm. (A description of the underlying physical principles of this calculation can be found in Chapter 0). The extension of the space charge region in silicon is typically in the order of w = 1µm. Hence, the bigger part of the light is absorbed outside the space charge region. There has to be a mechanism allowing the light absorbed there to contribute to the photocurrent. This mechanism is the diffusion of minority carriers: When a photon is absorbed outside the space charge region (e.g. in the p-region) the emerging charge carriers move randomly. If this electron reaches the edge of the space charge region it is extracted by the electrical field of this region. The space charge region is a sink for the electrons form the p-region. Despite the random, undirected movement of electrons a well-directed current emerges which contributes to the current of the solar cell. If the electrons would have an infinite lifetime, all of them could reach the space charge region sometime and could be of use for the photocurrent. Since they also do, however, recombine with holes (e.g. at defect states, grain boundaries, surfaces, etc.) they have a finite lifetime. During this time they cover an average distance by their random walk which is called *diffusion length* L_D. It is essentially important that the diffusion length of the minority carriers is bigger than the penetration depth of the light. In this case the excited charge carriers from the whole area in which the absorption takes place reach with the space charge region with a high probability. Once a minority carrier has reached the space charge region it is roped through it by the electrical field. Afterwards it can pass the rest of the solar cell without problems as majority carrier and thereby contributes to the current which can be extracted from the solar cell externally. If interfering the extraction of charge carriers to the external circuit by a load resistance the photocurrent is reduced slightly. This leads in turn to an accumulation of photogenerated charges resulting in the photovoltage.

1.4 Photovoltaics – advanced explanation

This chapter will introduce the properties of a semiconductor crystal from the perspective of solid state physics. The processes contributing to the generation of the photovoltage will be treated in the framework of the band model.

1.4.1 Band model and energy Gap

According to quantum theory the electrons of single, isolated atoms of a semiconducting material (e.g. silicon) are arranged in so called orbitals. An orbital corresponds to the special region in which there is a finite probability to find an electron. A definite energy is attributed to each orbital. Now quantum theory predicts (as did the Bohr-Sommerfeld model before) that the electrons of an atom can fill only orbitals having a certain, discrete energy while all other energy eigenvalues are forbidden states. When building up a crystal lattice from such atoms (as it is the case for most semiconducting materials) the orbitals of neighboring atoms overlap. On the one hand this leads to the delocalization of single electrons which do not belong to a certain atom anymore, but are rather blurred over a larger region of the crystal, thereby forming wavelike states. On the other hand the discrete energy levels of the atoms are broadened in order to form energy bands, i.e. regions in the energy spectrum in which the electrons can be found (see Figure 0.8). The energy gap E_G, a characteristic parameter of a semiconductor which strongly influences the performance of the solar cell, is defined between the last fully occupied band, the *valence band*, and the next higher band which does not contain any charge carriers at the absolute zero point of the temperature ($T = 0$K), the *conduction band*. When electrons are excited from the valence band to the conduction band (e.g. thermally or optically) they can contribute to the current. Such an excitation requires the minimum energy value of E_G. So in order to generate a free electron in a solar cell, the incident light particle (photon) must have a minimum energy of $hf = E_G$. Here f is the frequency of the incoming light and h is the plancks constant. (Note that the energy of a photon does not depend on the intensity of the light but only on its frequency or wavelength.)

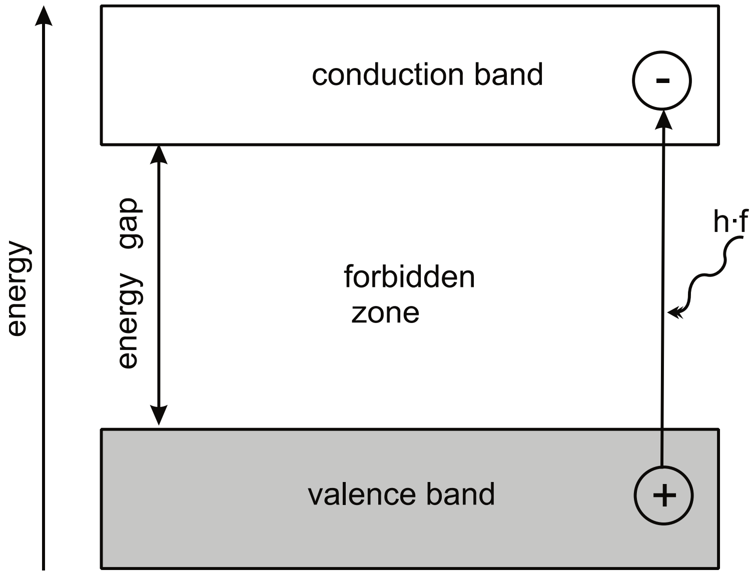


Figure 0.8: Schematic illustration of the band structure of a semiconductor and the generation of an electron-hole-pair by the absorption of a photon having the energy $E = hf > E_G$.

1.4.2 Absorption and absorption spectrum

The absorption is described by the absorption constant α which is defined by the absorption law (Lambert-Beer-law):

$$\Phi = \Phi_0 e^{-\alpha d}$$

Thereby $\Phi 0$ refers to the intensity of incident light and Φ to the light intensity after covering a distance of length d in the material. If d is the total thickness of the material, then

$$\Phi/\Phi_0$$

is the portion of light that has not been absorbed. The absorption spectrum, i.e. the dependency of the absorption constant on the wavelength of light or on the energy of the photons $\alpha(\lambda)$ depends on the band structure of the semiconducting material. The spectra of different semi-conductors are shown in Figure 0.9.

When the light has covered the distance $d = 1/\alpha$ in the semiconductor the light intensity is reduced by the factor e. Therefore the value $L_G = 1/\alpha$ is denoted as depth of penetration. Figure 0.9 shows how the individual semiconductors absorb photons of a certain frequency. Thus, as described above, photons with energy less than the band gap will not be absorbed. The graph also shows that the absorption of silicon is considerably worse than of other semiconductors. For example, if using silicon rather than gallium arsenid (GaAs) a considerably thicker layer is necessary to absorb the same luminous flux. However, the Si-band gap of 1.12eV is beneficial considering the solar spectrum, and the advanced technology of Si-solar cells as well as widespread deposits of silicon on earth argue for the usage of silicon in solar cells.

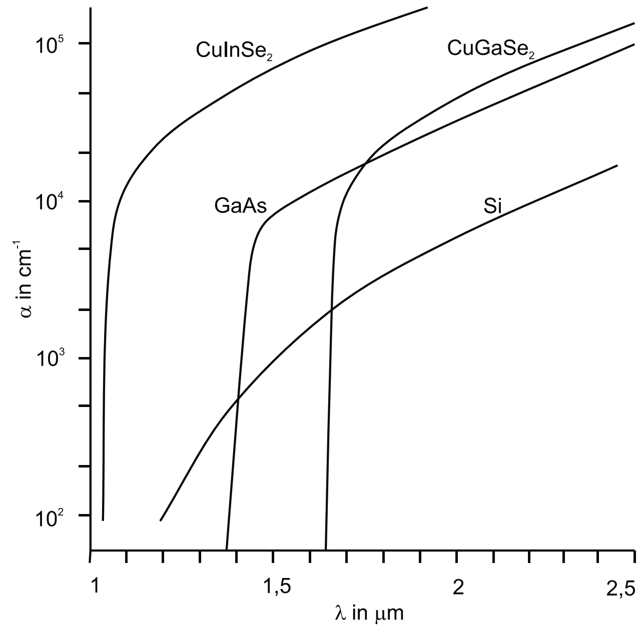


Figure 0.9: Absorption spectra of some important semiconductors.

Though, it is not possible to draw direct conclusions from the different absorption spectra of the respective materials about the dependency of the cell power on the energy of the incident photons. This so-called spectral response of solar cells is widely influenced by other effects (doping, surfaces et cetera).

1.4.3 Why is there an ideal bandgap for solar cells?

According to the facts mentioned above it could be assumed that a material is more suitable for solar cells the smaller its bandgap, because in that case the proportion of photons not being absorbed due to their low photon energy is the smallest. There is, however, also an opposing effect: As a matter of principle the maximum voltage (expressed in volt) a solar cell can de-liver is always slightly smaller than the bandgap (expressed in eV) divided by the elementary charge e (see Figure 0.11). Thus solar cells with a higher bandgap tend to deliver higher voltages. Regarding both effects quantitatively and considering the spectral distribution of the sunlight it turns out that there is an ideal bandgap. Gallium Arsenide is very close to the ideal bandgap. However, between approx. 1eV and 1.8eV the curve of the maximum possible efficiency versus the bandgap is very flat, so that apart from germanium and cadmium sulphide all materials shown in Figure 0.10 can be used to manufacture cells with similarly high efficiencies.

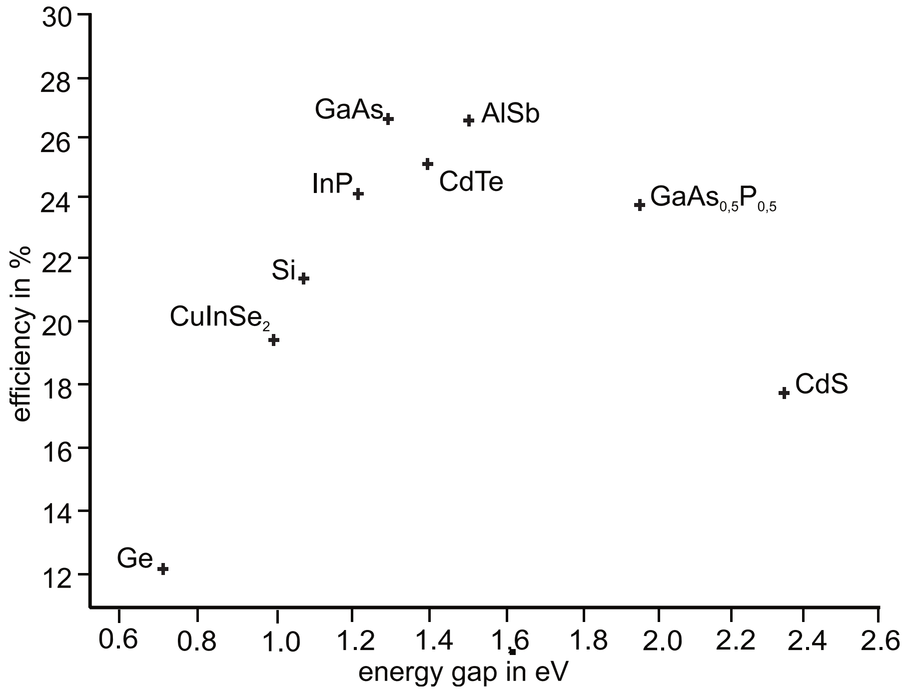


Figure 0.10: Theoretically attainable efficiency at 20°C as a function of the size of the bandgap E_G.

1.4.4 Properties and behavior of the charge carriers in the crystal: Generation of electron-hole pairs under illumination

The previous sections covered the formation of energy bands and energy gaps in the semiconductor, the absorption of photons and the associated generation of charge carriers. This section covers the behavior of these charge carriers in the crystal.

If an electron is transferred by light excitation from the formerly full valence band into the initially vacant conduction band, it is obvious that the electron can now move in the conduction band as a negatively charged carrier. But what does this missing electron mean to the valence band? The easiest way to visualize this is picturing a tube almost completely filled with water, closed at both ends and containing some isolated air bubbles. If an air bubble is moving to the right this process can in principle be described as a very complicated movement of the water to the left; but the picture of the single air bubble moving to the right is much easier and demonstrative. Similarly the missing electron in an almost filled band (like the valence band) is considered to be the air bubble in the electron lake and is called p-hole or defect electron, respectively. Because with a completely filled valence band the whole crystal, composed of electrons and positively charged nuclei, is electrically neutral, a positive charge can be assigned to a missing electron. A collective movement of the electrons (e.g. to the right) can now be described as a movement of a hole (e.g. to the left). The hole behaves like a positively charged free carrier.

In summary one can say that by the absorption of a photon an electron is added to the conduction band while a hole is formed in the valence band (generation of electron-hole pairs). Photoexcitation leads to the formation of electrons and holes in the same quantity.

Considering this picture it is possible to explain the principle of the p/n-junction within the framework of the band model. The processes involved in photocurrent generation in solar cells are outlined in Figure 0.11.

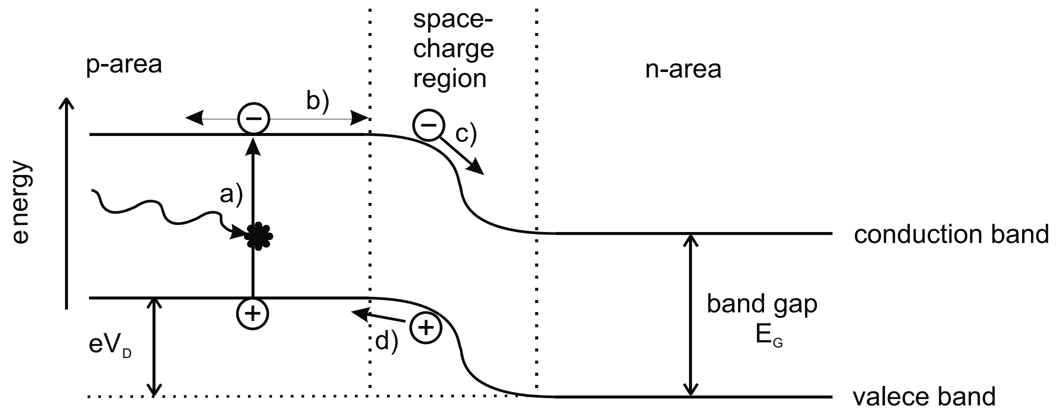


Figure 0.11: Recombination of excited charge carriers.

Electrons and holes can recombine, i.e., an electron from the conduction band is falling into a hole in the valence band and is accordingly no longer available for charge conduction. The energy of the electron-hole pair is emitted in the form of light or leads to the heating of crystal. For this reason the recombination is decreasing the energy efficiency of the solar cell. The recombination process occurs with a certain probability so that it results in an average lifetime τ_n and τ_p for electrons and holes, respectively. Their values depend on the nature of the dominating recombination process. Possible important processes are direct transitions between the bands and recombination via defects or impurity atoms. Using silicon the first recombination path is unlikely so that in case of a suitably low defect concentration the lifetime of the charge carrier can be very high. This advantage partly balances the disadvantage of the low absorption of silicon but requires very high-grade material (chemical purity and structural perfection).

Additional origins of recombination are the surface of the semiconductor material as well as semiconductor metal contacts (i.e. the electrodes of the solar cell), because here the semiconductor lattice has defects. Recombination losses at the surfaces and electrodes can be minimized by selecting suitable doping profiles which lead to the repulsion of the excited minority carriers from the surfaces.

Charge carrier mobility, conductivity, schubweg and diffusion length

Another important property of the charge carriers is the so-called carrier mobility μ in the electric field E resulting from the drift velocity v_d:

$$\mu = v_d / E.$$

The mobility of the charge carriers determines the conductivity σ of the crystal which is an important parameter of the material:

$$\sigma = e(n\mu n + p\mu_0).$$

Here n and p refer to the density of electrons and holes, respectively, and $\mu_{n/p}$ to their mobility. The mobility has an impact on the so-called schubweg, which denotes the distance a charge carrier can drift during its lifetime τ in the electric field. The Schubweg is an important quantity for the photoconduction of a semiconducting material (application: photoconductive cell). The more important value for solar cells is the diffusion length L_D of excited charge carriers, which refers to the distance a charge carrier moves within the field-free material before it recombines (compare section 4.2.3). This quantity also depends on the mobility since the diffusion constant D of the charge carriers is directly proportional to their mobility.

1.4.5 Design of the solar cell

The structure of the solar cell is similar to the structure of a semiconductor diode. It consists of a negatively and positively charged doped layer of a semiconducting material (silicon) whereas the upper layer facing the light is the negatively doped layer of every solar cell.

In silicon solar cells the n-layer of the solar cell has an approximate thickness of only 1µm, in contrast the p-layer which comprises 0.5mm. To improve the incoupling of the light there is an antireflection coating on the surface of the solar cell. In high-performance cells the light incoupling is furthermore increased by microstructures at the surface which scatter the light into the cell. That way the light travels a longer way in the material resulting in higher absorption. On the front of the cell there is the

grid electrode which is, in most cases, made of silver. Depending on the quality of the cell the back contact is made of a grid or a metal coating made of aluminum or silver.
There are different types of silicon solar cells. The two most common types are single-crystalline or monocrystalline cell on one hand which consists of a single silicon crystal. It provides a very high efficiency which is due to the lack of grain boundaries in a monocrystalline material which could act as recombination centers.
On the other hand there are polycrystalline cells. They consist of several crystals and have lower efficiencies than monocrystalline cells due to the recombination losses at the grain boundaries. Furthermore they are easier to produce and therefore cheaper.

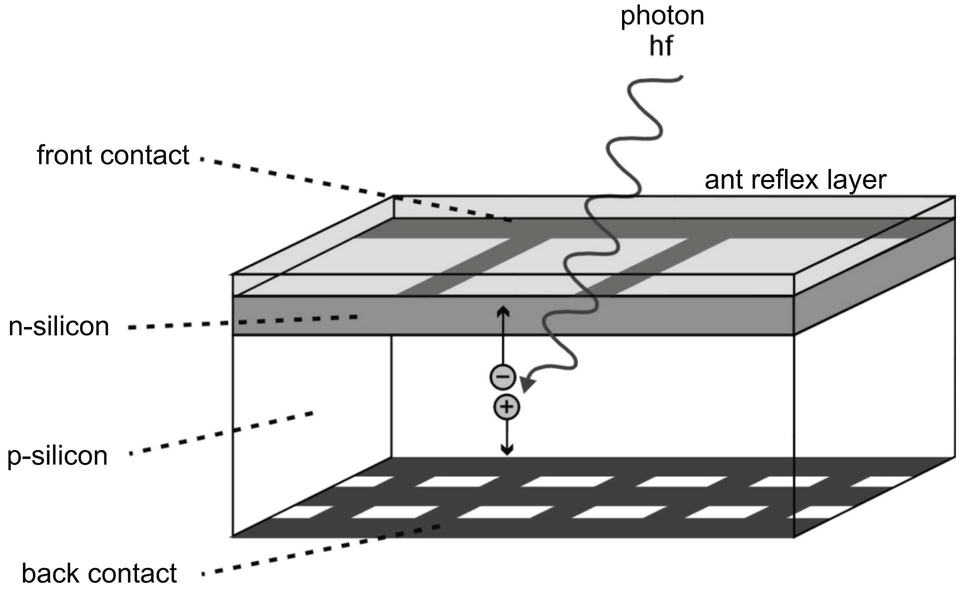
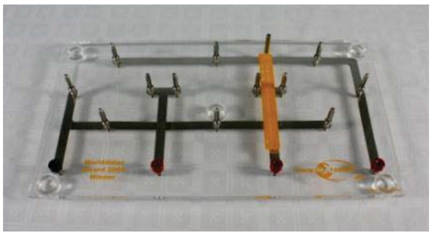


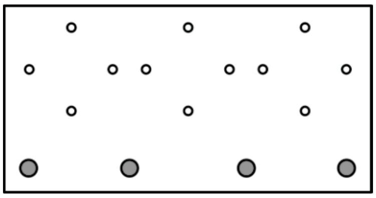
Figure 0.12: Schematic structure of a solar cell.

Chapter 2: Description of the experimental components of leXsolar - PV Large

In the following schedule every component of the leXsolar-PV Large is listed. For every component there is the name with article number, a picture, the pictogram for the circuit diagram and operating instructions. With the aid of the article number it is possible to reorder a specific component.

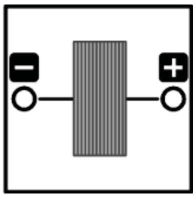
Base unit 1100-19





The base unit is a breadboard where up to 3 components can be plugged in a series and parallel connection. The current flows along the wires on the bottom side. To connect the components on the base unit with other components, there are 4 terminals at the lower end.
The printed circuit diagrams show the connections in a series and parallel connection. To change between series and parallel connection, the modules have to be turned by 90°.
To the right of the center, there is the shadow bar with angle scale. This shadow bar can be used to align pluged-in solar modules in a certain angle to a light source. The light should be small and be at a big distance to the base unit in order to create a well-defined shadow.

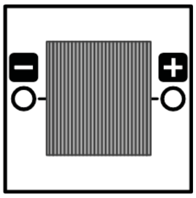
Solar module 1100-01 0,5V 420 mA



Specifications:

Material: polycristalline silicon
Open circuit voltage: 0,5V
Short circuit current: 420mA
Maximum power: 0,2Wp

Solar module 1100-02 0,5V 840 mA

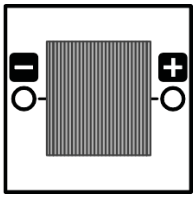


The specifications about open circuit voltage and short circuit current can be found on the back surface.

Specifications:

Material: polycristalline silicon
Open circuit voltage: 0,5V
Short circuit current: 840mA
Maximum power: 0,4Wp

Solar module 1100-07 1,5V 280 mA



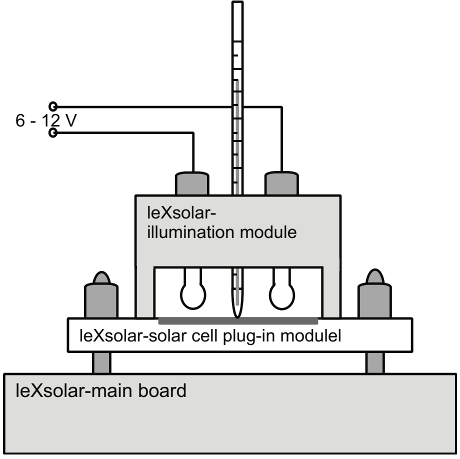
This solar module is a serial connection of three solar cells.

Specifications:

Material: polycristalline silicon
Open circuit voltage: 1,5V
Short circuit current: 280mA
Maximum power: 0,13Wp

Lighting module (1100-20) with PowerModule (2105-00)

The lighting module is operated with the PowerModule or any other variable polwer supply (0…12V). There are 4 light bulbs inside the lighting module. They can or cannot contribute to the lighting by screw or unscrew. It is not recommandable to change the illuminance by changing the voltage since the spectrum of the light will change, which leads to measuring errors. The lighting module has to be setted on the solar cell (see figure). Tale care that the lighting should lie as long as necessarry on the solar cell because of the heat built-up of the solar cell due to heat radiation. Between both connections there is a hole for the laboratory thermometer to measure the temperatur of the solar cell. The PowerModule is a compact and intuitively usable voltage source. First, the attached power adapter has to be connected to a power outlet and to the top right input jack. The voltage can be chosen with the „+“- and „-“ -buttons and will be displayed by LEDs. When the desired voltage is chosen, the voltage will be applied by using the yellow on/off- button. In case of a short circuit or currents greater than 2 A the PowerModule will switch off immediately.

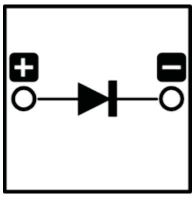


<u>Specifications:</u>

Lighting modules
Operating voltage: 0-12V
Maximum power: 4W
Maximum illuminance: 200W/m^2
Aperture of the light source: 6x6cm

PowerModule
Output voltage: 0-12 V
Output power: max. 24 W
Adjustable in 0.5 V steps
Overcurrent detection >2 A and automatic shutoff
Input voltage: 110-230 V, 50-60 Hz (with enclosed power adapter)

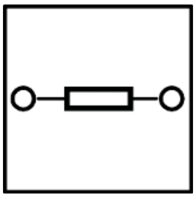
Diode module 1100-21



Specifications:

Schottky diode
$U_{forward}$ = 0.33 V
Maximum current: 200 mA (500 mA Peak <1 s)

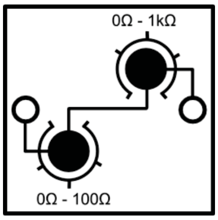
Resistor module 1100-22



Specifications:

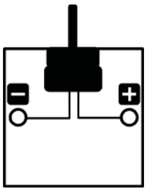
Maximum power: 2W

Potentiometer module 1100-23



The potentiometer module holds a 0-100-Ω-potentiometer and a 0-1-kΩ-potentiometer. Both are serially conneted, so that the potentiometer can attain resistances between 0 Ω bis 1100 Ω. The measuring error amounts to 5 Ω for the small resistor and 20 Ω at other one. The maximum current amounts to 190 mA.

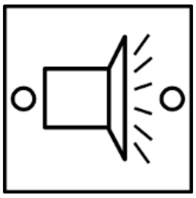
Gear motor module (1100-24) with mit hook weight 20g (L2-05-024)



Specifications:

Starting current: ≅ 20mA
Starting voltage: ≅ 0,35V
Minimum operating current: 10mA
Maximum voltage: 4V

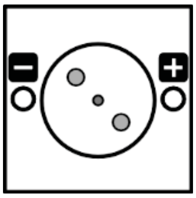
Horn module 1100-25



Specifications:

Starting voltage: 0.7V
Starting current: 0.3mA

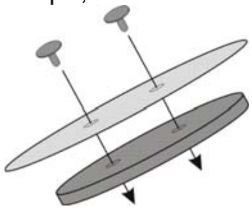
Motor module without gear (1100-27) with color disks– Set 1 (1100-28)



Specifications:

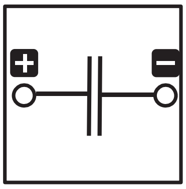
Starting current: 20mA
Starting voltage: 0.35V

The color disks are: red-green-blue, red-blue, red-green, green-blue und 3 black-white color disks. The color disks are fix at the motor module by use of the plastic disk. The plastic disk holds 2 clips, which fix the disk at the plastic disk (see figure).



In the center of the plastic disk is a hole, which will be placed on the pin of the motor.

Capacitor module 1400-07



The capacitor module has a capacity of 220 mF and is able to apply a maximum voltage of 2.5 V. Do not apply a higher voltage than 2.5 V during charging. If you want to discharge the capacitor quickly, it can be short-circuit since there are fuses inside the module which avoid high currents. To charge the capacitor quickly, it is possible to connect it directly with the PowerModule. Power on the PowerModule at a voltage of 0.5 V and increase the voltage by 0.5 V every 10 s. Charge the capacitor at the end voltage for 30 s.

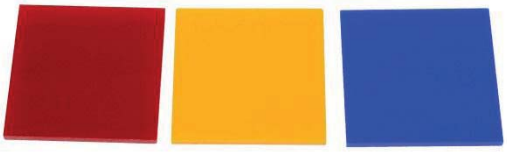
Specifications:
Capacity: 220 mF
Voltage: 2,5 V

Solar cell cover set 1100-29

Specifications:

Size: 3x3cm

Color filters 1100-30



1. Understanding the leXsolar base unit

Task

Examine the different circuits to learn more about the base unit.

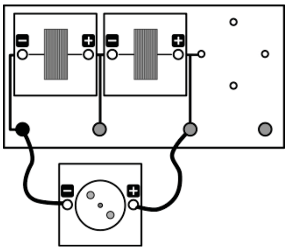
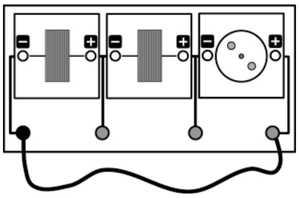
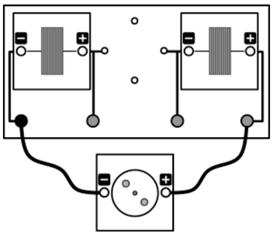
Required devices

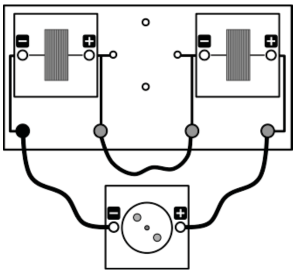
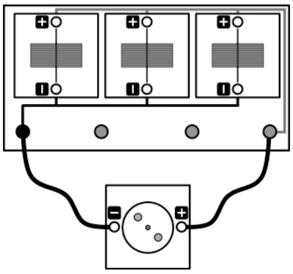
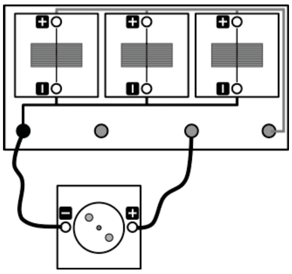
- leXsolar base unit
- 3 small solar cells
- leXsolar-motor
- 3 cables

Procedure:

1. Set up the circuits 1 – 6 and check each time, if the motor rotates.
2. Examine the base unit for each circuit and draw the circuit diagram. Decide, whether it is a series or parallel connection.
3. Describe the energy conversions and the physical processes during the experiment with circuit 1.

Evaluation

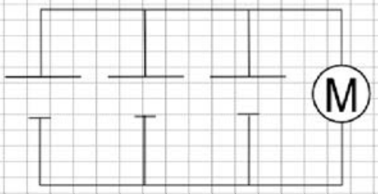
Circuit 1	Circuit 2	Circuit 3
		
Does the motor rotate? ☒ yes ☐ no	Does the motor rotate? ☒ yes ☐ no	Does the motor rotate? ☐ yes ☒ no
It is a: ☒ series connection ☐ parallel connection	It is a: ☒ series connection ☐ parallel connection	It is a: ☐ series connection ☐ parallel connection

Circuit 4	Circuit 5	Circuit 6
		
Does the motor rotate? ☒ yes ☐ no	Does the motor rotate? ☐ yes ☐ no	Does the motor rotate? ☐ yes ☐ no
It is a: ☒ series connection ☐ parallel connection	It is a: ☐ series connection ☒ parallel connection	It is a: ☐ series connection ☐ parallel connection

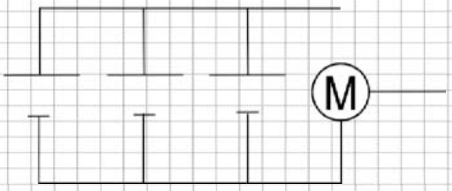
Circuit 1, 2, 4

Circuit 3

Circuit 5



Circuit 6



3.

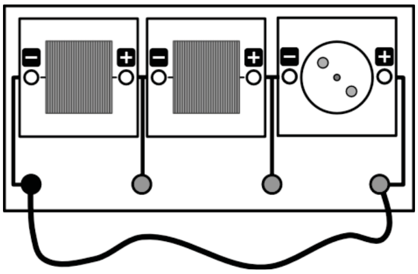
Light energy is converted in electric energy in circuit 1. The motor convert electric energy into rotational energy. To do this process, electrons use the light energy to leave the atomic bond and leave a hole. Due to the intrinsic electric field in the depletion region of the solar cell, the electrons and holes move, if the circuit is closed.

2.1 The basic setup for experiments with the color disks

Task

Examine the optical illusions of the color disks.

Setup

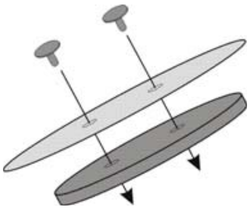


Required devices

- 1 leXsolar base unit
- 1 large solar cell
- 1 large solar module
- 1 motor module
- 1 cable

Procedure

Set up the experiment according to the circuit diagram.
Now clip the rotation disk onto the motor. The cardboard disk is secured by two colored plastic clips.



If necessary you can use a plug to take the clips off the rotation disk. Carefully press the plug against the clip from underneath.

2.2 Color qualities

Cardboard disk

Procedure:

Rotate the disk. Place your hand above it so that there is a shadow over one half! Your results will help you understand the color system better.

Color: Which color does the disk have? __rosa________________

Brightness: On the shaded side the color seems…

☐ brighter than on the illuminated side

☐ as bright as on the illuminated side

X darker than on the illuminated side

Hue: The color in the middle of the disk seems…

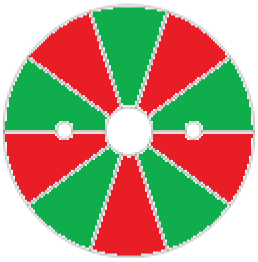
☐ paler than at the edge

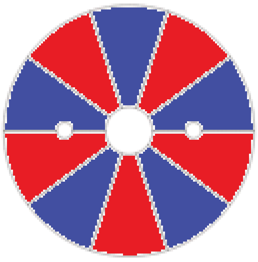
☐ the same as at the edge

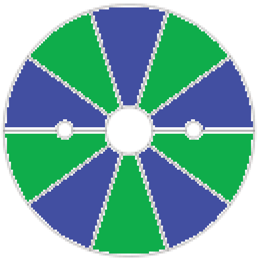
X stronger than at the edge

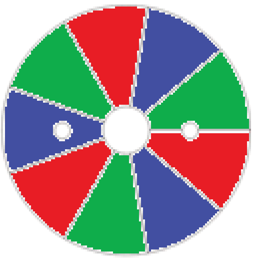
2.3 Additive color mixing

Cardboard disks


Green-red


red-blue

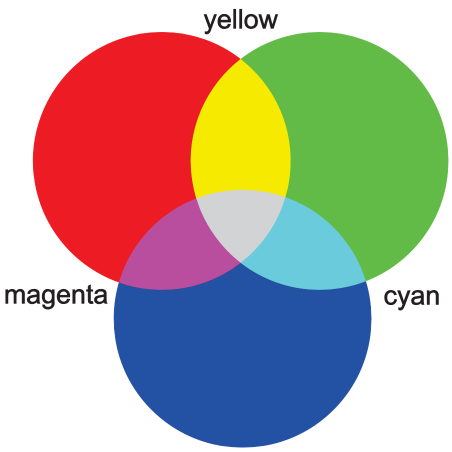

green-blue


green-red-blue

Procedure

The segments of the disks have different colors when the disk is not in motion. Let the disks rotate quickly to make the colors mix.

Now color the different segments in the picture below! Start with the pure colors red, green and blue. Then, with the help of your observations, color the four blending segments. Label the marked areas!



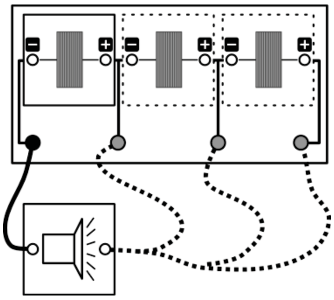
11. Behavior of voltage and current in series and parallel connections of solar cells

11.1 Behavior of voltage and current in series and parallel connections of solar cells (qualitative)

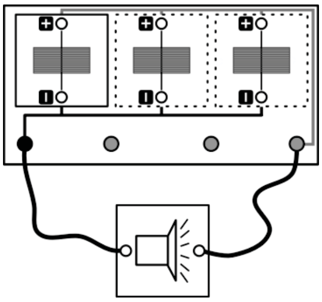
Task

Examine the behavior of a horn depending of different series and parallel connections and draw conclusions about voltage and current.

Setup



Circuit 1



Circuit 2

Required devices

- leXsolar-base unit
- 3 small solar cells
- horn module
- Cables
-

Procedure

1. Set up a series connected circuit (circuit 1). First use one, then two, then three solar cells. Do not forget to plug in the cable in right red jack. Color the respective squares in the table.
2. Now set up a parallel connected circuit (circuit 2). Take care, that the illuminance conditions are the same.

Evaluation

	Series connection					Parallel connection				
One solar cell	■	□	□	□	□	■	□	□	□	□
	No	<	faint sound	<	loud	no	<	faint sound	<	loud
Two solar cells	■	■	■	□	□	■	□	□	□	□
Three solar cells	■	■	■	■	■	■	□	□	□	□

Draw conclusions about the voltage and current.

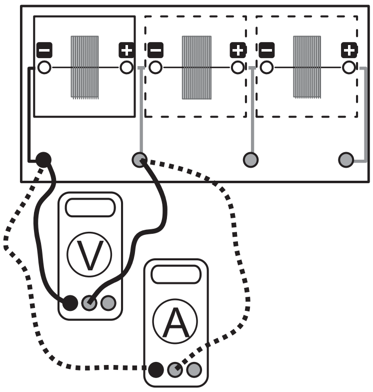
When the solar cells were connected serially, the horn becomes louder the higher the number of solar cells was. So the voltage and current has to be increased. When the solar cells were connected parallel, the horn does not make sounds. So the voltage and current were too low.

11.2 Behavior of voltage and current in series and parallel connections of solar cells (quantitative)

Task

Examine the behavior of total voltage and total current in series and parallel connections.

Setup



Required devices

- leXsolar-base unit
- 3 small solar cells
- 1 voltmeter
- 1 amperemeter
- Cable

Primary notes

In this experiment only short-circuit currents and open-circuit voltages are measured. These cannot be measured simultaneously.

Procedure

1. Set up the experiment according to the circuit diagram.
2. Measure the current and voltage of one solar cell (see circuit diagram)!
3. Modify the circuit so that two resp. three solar cells are connected in series. Again, measure the current and voltage.
4. Carry out analogous measurements for parallel-connected solar cells. In order to do this, develop a new circuit diagram in accordance with the diagram of the base unit.
5. Note the measured values in the table.

Evaluation

1. Draw the n-I-diagram (*n*... number of solar cells) for series- and parallel-connected cells. Draw both graphs into one diagram!
2. Draw the n-V-diagram for series- and parallel-connected cells. Draw both graphs into one diagram!
3. Phrase a rule for the total current and total voltage with series- resp. parallel-connected cells.

11.2 Behavior of voltage and current in series and parallel connections of solar cells (quantitative)

Measured values

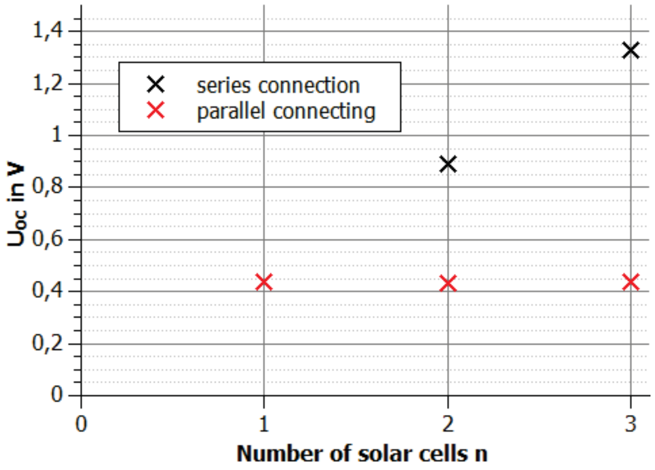
Series connection:

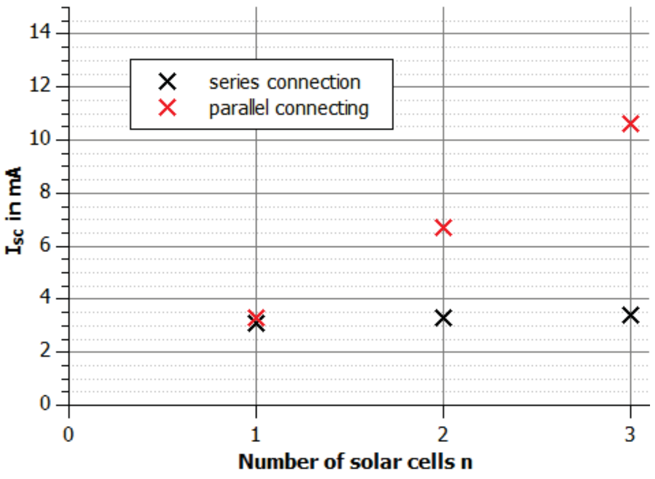
	one solar cell	two solar cells	three solar cells
V_{OC} (V)	0.44	0.89	1.33
I_{SC} (mA)	3.1	3.3	3.4

Parallelschaltung:

	one solar cell	two solar cells	three solar cells
V_{OC} (V)	0.44	0.43	0.44
I_{SC} (mA)	3.3	6.7	10.6

Diagrams





Evaluation

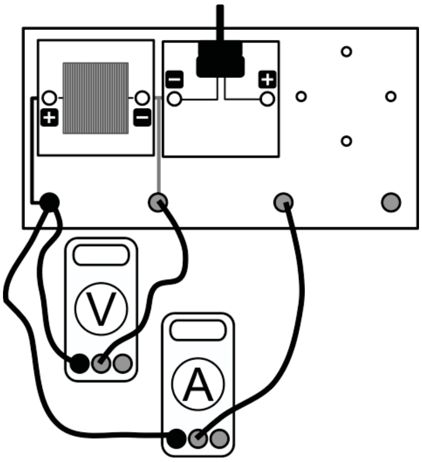
	Behavior of	
	Voltage	Current
Series connection	$V_{tot} = V_1 + V_2 + \ldots + V_n$	$I_{tot} = I_1 = I_2 = \ldots = I_n$
Parallel connection	$V_{tot} = V_1 = V_2 = \ldots = V_n$	$I_{tot} = I_1 + I_2 + \ldots + I_n$

15.1 Determination of efficiency of some energy conversions

Task

Determine the efficiency of conversion from electric to mechanic energy.

Setup



Required devices

- leXsolar-base unit
- leXsolar-lightning module
- gear motor module
- 1 large solar module (1,5 V)
- 1 PowerModule (12V)
- 1 amperemeter
- 1 voltmeter
- Cables
- 1 weight 20g

- *additionally required:*
- Stopwatch, ruler
- String

Procedure

1. Set up the experiment according to the sketch and place the base unit to the edge of the table so that the weight hangs freely at approximately 45 cm on a piece of string! Lay the lightning module on solar module and apply a voltage of 12 V with the PowerModule.
2. Switch on the PowerModule and measure the time it takes for the motor to wind up a marked length of string! At the same time, measure the current and voltage of the solar cell.
3. Modify the circuit so that the current and voltage are measured at the PowerModule. Select the measuring range of 10 A at the amperemeter. Repeat the experiment. Note the measured values in the table.

Evaluation

Calculate the total efficiency of the following energy conversions:

a) Electric energy of solar module > potential energy weight
b) Electric energy of PowerModule > radiation energy of light bulbs > electric energy of solar module > potential energy of weight

15.1 Determination of efficiency of some energy conversions

Measured values

- with determination of the power at the motor

h (cm)	height by which the weight was lifted	43.5
t (s)	time it took to reach *h*	34
V (V)	voltage of the solar module	1.45
I (mA)	current in the circuit of the solar module	19

- with determination of the power at the lamps

h (cm)	height by which the weight was lifted	43.5
t (s)	time it took to reach *h*	34
V (V)	voltage drop over the lamps	12.1
I (mA)	current in the circuit of the lamps	390

Evaluation

Calculations:

Power of PowerModule	Power of solar module	Power for lifting the weight
$P_{Pow} = U_{Pow} \cdot I_{Pow}$ $P_{Pow} = 12.1\,V \cdot 390\,mA$ $P_{Pow} \approx 4.7\,W$	$P_{solar} = U_{solar} \cdot I_{solar}$ $P_{solar} = 1.45\,V \cdot 19\,mA$ $P_{solar} \approx 27.6\,W$	$P_{lift} = \frac{W_{lift}}{t} = \frac{m \cdot g \cdot h}{t}$ $P_{Hub} = \frac{0.02\,kg \cdot 9.81\,\frac{m}{s^2} \cdot 0.435\,m}{34\,s}$ $P_{Hub} = 2.5\,mW$

Efficiency of power of solar module to power for lifting the weight	Efficiency of power of PowerModule to power for lifting the weight
$\eta_a = \frac{P_{lift}}{P_{solar}}$ $\eta_a = \frac{2.5\,mW}{27.6\,mW}$ $\eta_a = 9\,\%$	$\eta_b = \frac{P_{lift}}{P_{netz}}$ $\eta_b = \frac{2.5\,mW}{4700\,mW}$ $\eta_b = 0.05\,\%$

Results: Energy conversion efficiency of the electric energy of the solar cell to potential energy of the weight amounts to: 9%.

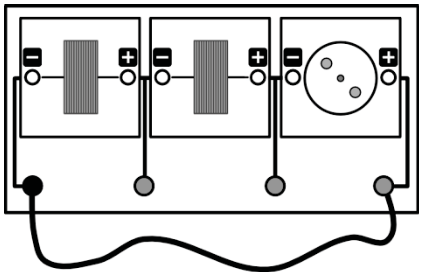
Energy conversion efficiency of the electric energy of the power supply to potential energy of the weight amounts to: 0.05%.

15.2 Rotational direction and speed of a motor

Task

Examine the rotational direction and speed of a motor.

Setup



Required devices

- leXsolar-base unit
- 2 small solar cells
- 1 motor module
- 1 cable

Procedure

1. Set up a series connection out of the two solar cells and the motor.
2. Hold the base unit to the light source until the motor starts rotating. Note the rotational direction and observe the movement.
3. Change the polarity at the motor by turning the motor module 180° on the base unit. Note again the rotational direction.
4. Remove the cable and observe the movement again.

Evaluation

Rotational direction during the first experiment:
☐ clockwise X anti-clockwise
Rotational direction after changing polarity:
X clockwise ☐ anti-clockwise

1. Describe the movement of the disk before and after removing the cable.

At first, the disk accelerates. From a certain point of time, the angular speed is constant. When the cable is removed, the circuit is opened and the rotation stops due to friction.

2. Explain the behavior of the rotational direction during different polarities.

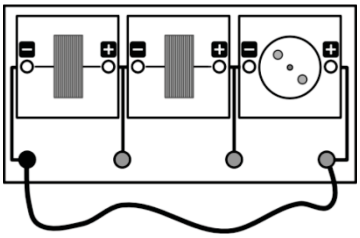
Due to the opposite polarity the current flows in the other direction. So an opposite magnetic field will be created, that moves the rotor in the other direction.

15.3 Starting and running current of a motor

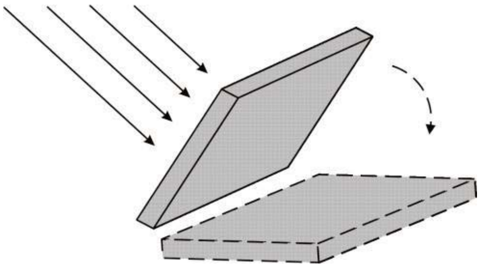
Task

Examine the starting behavior of a motor.

Setup



circuit



Picture 2

Required devices

- IeXsolar-base unit
- 2 small solar cells
- Motor
- 1 cable

Procedure:

1. Set up the experiment according to the circuit diagram.
2. Hold the setup to the light source and wait until the motor starts rotating.
3. Tilt the base unit slowly away from the light source as shown in picture 2 until the motor stops rotating.
4. Now, tilt the base unit slowly towards the light source until start rotating again.

Evaluation

1. Describe the movement of the motor during the experiment.

The motor rotates slowlier until the motor stops rotating. When the base unit is tilted towards the light source, the motor does not start rotating immediately. From a clearly smaller angle of incidence than the motor stops rotating, the motor starts to rotate.

2. Explain this behavior.

Due to the friction the motor needs a higher force to move than during the rotary movement. Thus, the motor needs a clear higher solar cell power, which is generated by a higher illuminance.

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