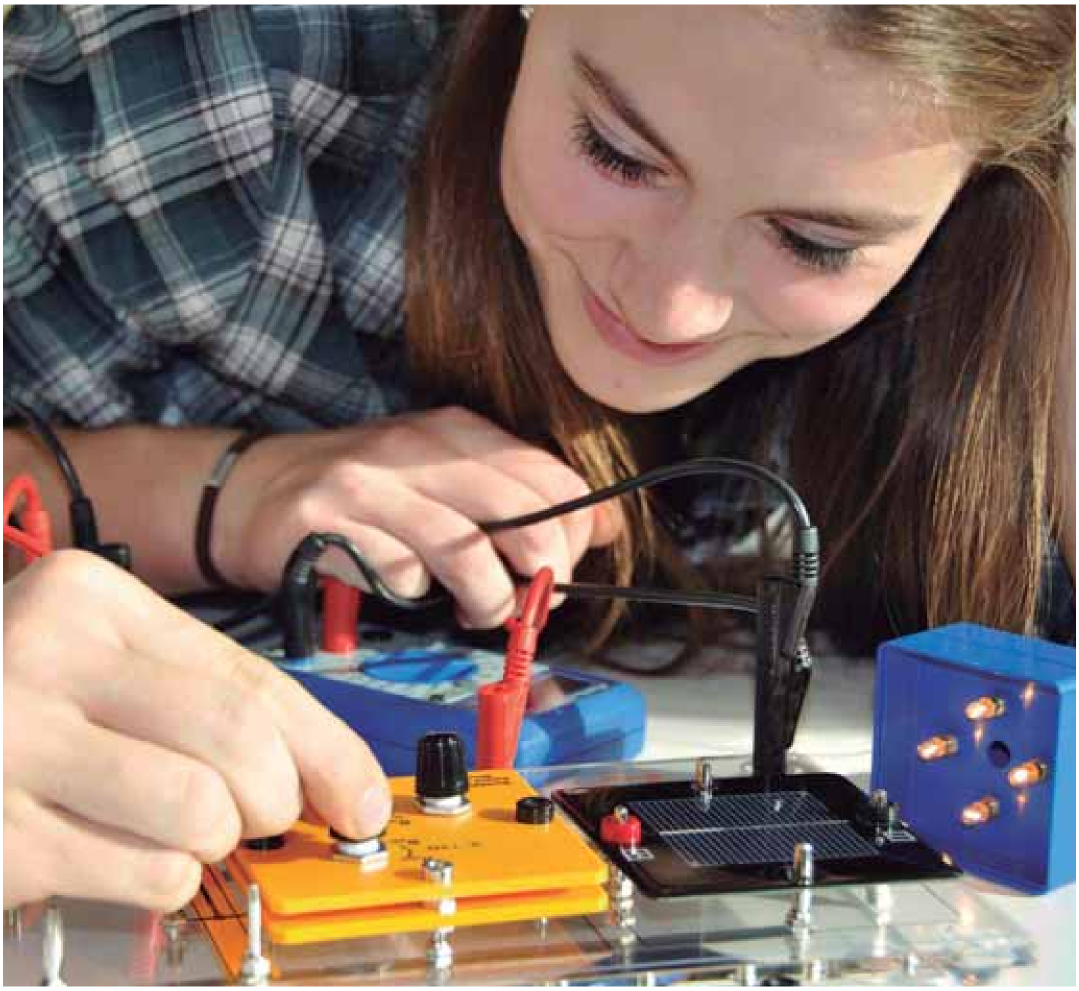
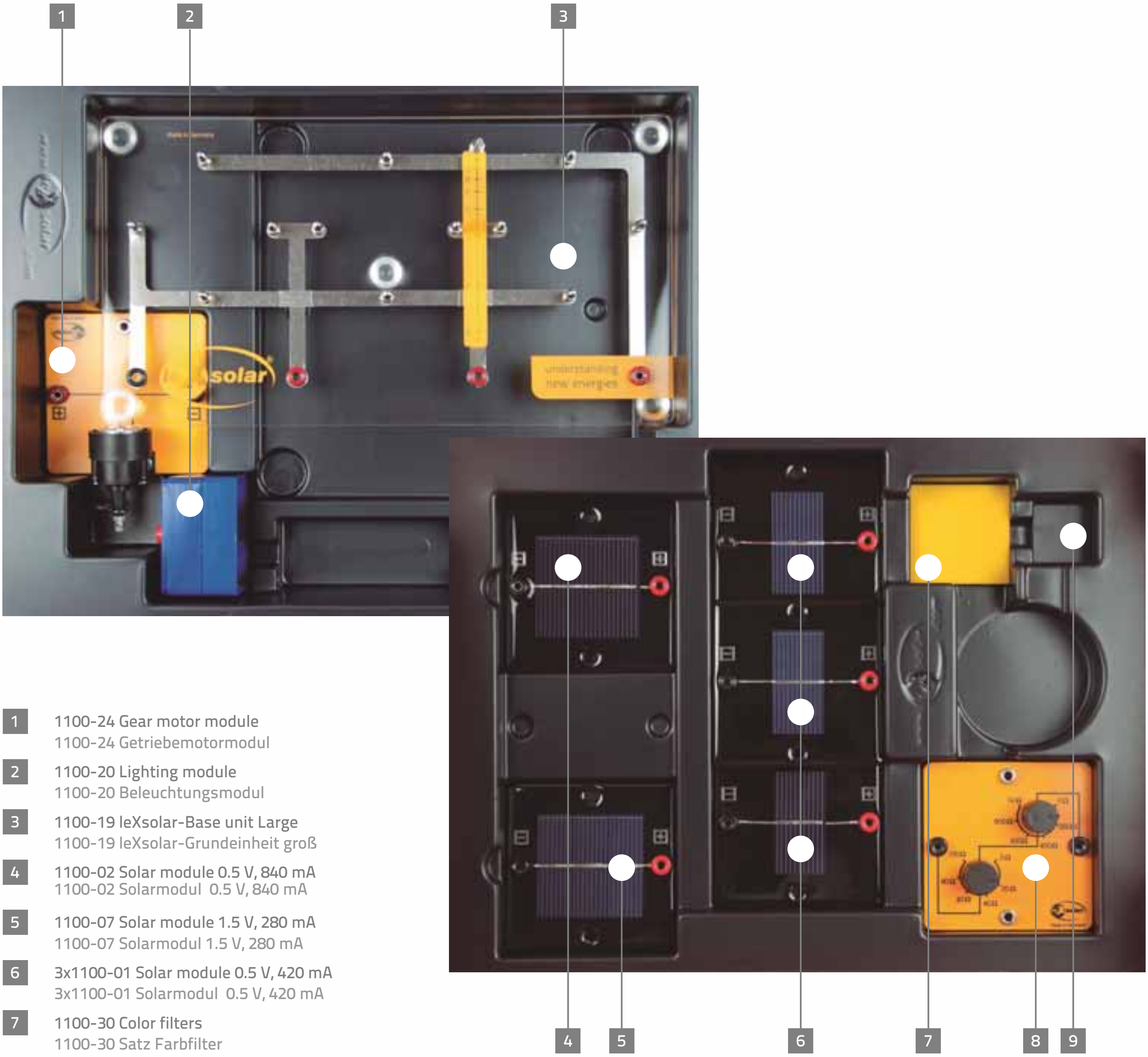
leXsolar-PV Large



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

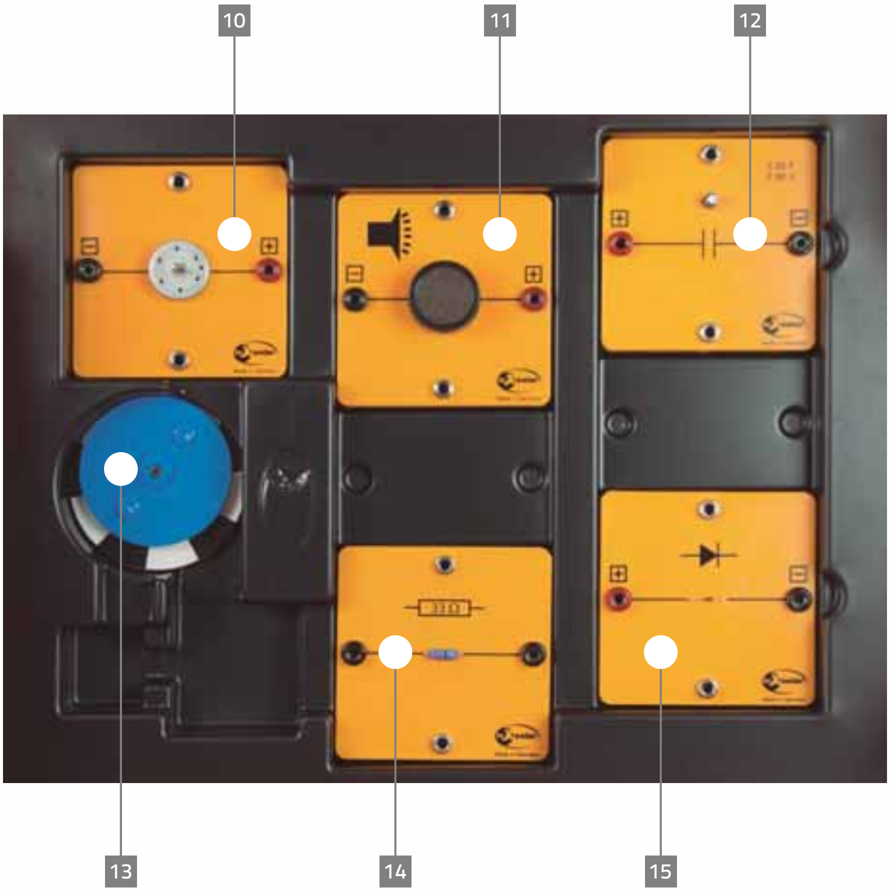
CE RoHS2

Layout diagram leXsolar-PV Large

Item-No.1103

Bestückungsplan leXsolar-PV Large

Art.-Nr.1103



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

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.

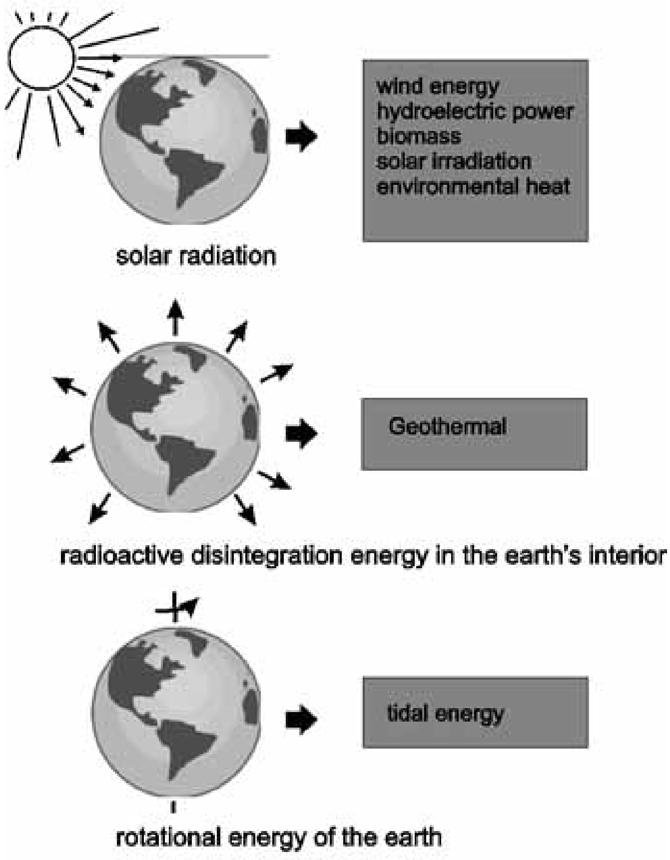


Figure 1.1: The sources of renewable energies.

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

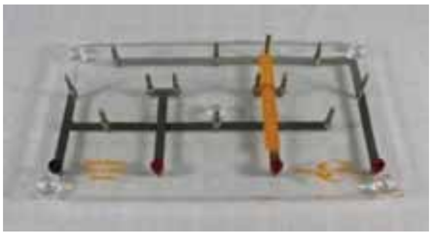
1.3.1 The semiconductor crystal

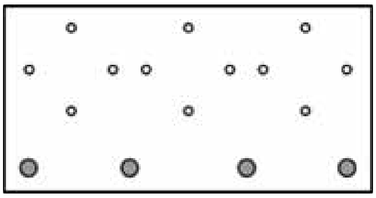
Silicon is the commonly used semiconducting material for the fabrication of solar cells. In the table of elements it appears in the fourth main group which means that a silicon atom has four valence electrons. Those valence electrons are responsible for the formation of stable bonds between neighboring 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.

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.

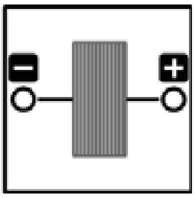
Base unit 1100-19





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.

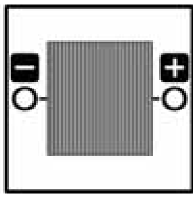
Solar module 1100-01 0,5V 420 mA



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

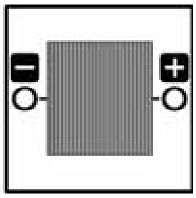
 

The specifications about open circuit voltage and short circuit current can be found on the back surface.

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

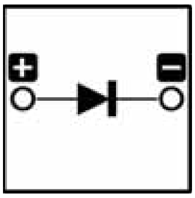
This solar module is a serial connection of three solar cells.

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)

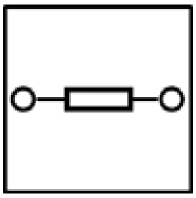
Diode module 1100-21



Specifications:

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

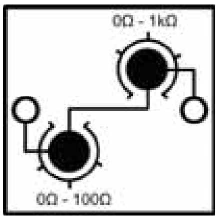
Resistor module 1100-22



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.

1. Understanding the leXsolar base unit

Task

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

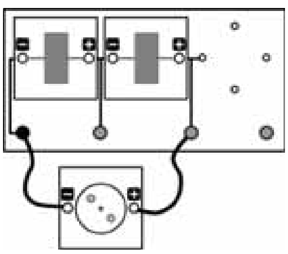
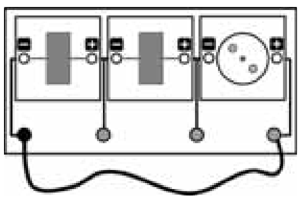
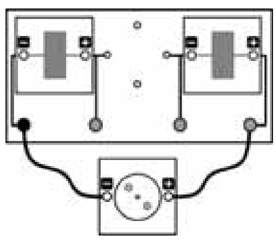
Required devices

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

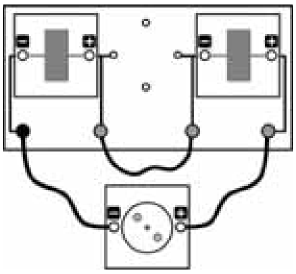
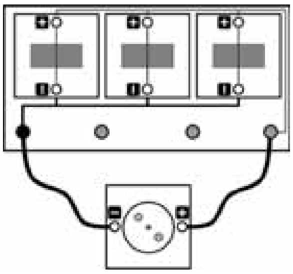
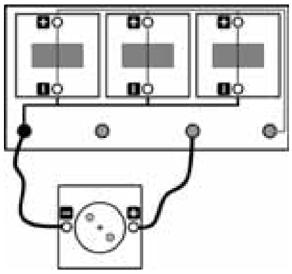
Procedure:

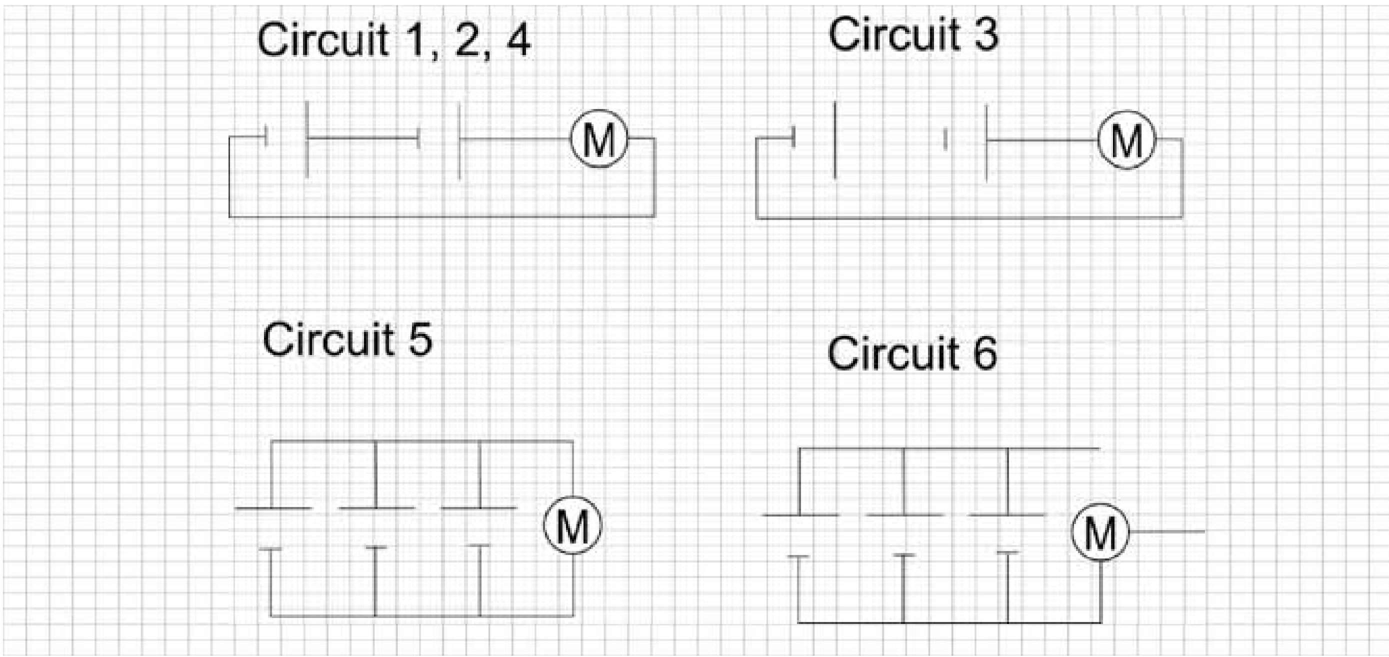
1. Set up the circuits 1 – 6 and check each time, if the motor rotates.
2. Examine the base unit for each circuit and draw the circuit diagram. Decide, whether it is a series or parallel connection.
3. Describe the energy conversions and the physical processes during the experiment with circuit 1.

Evaluation

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

1. Understanding the leXsolar base unit

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



3.

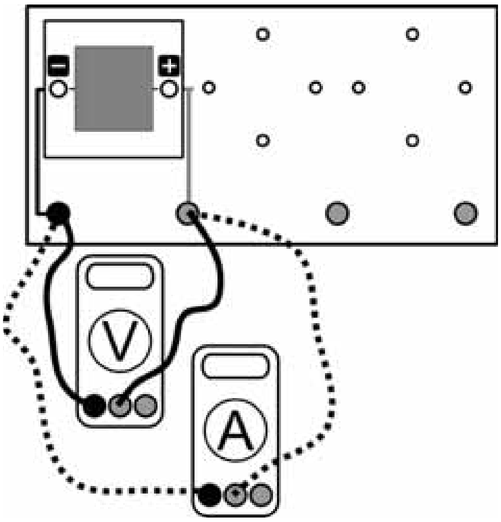
Light energy is converted in electric energy in circuit 1. The motor convert electric energy into rotational energy. To do this process, electrons use the light energy to leave the atomic bond and leave a hole. Due to the intrinsic electric field in the depletion region of the solar cell, the electrons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

4. Dependence of solar cell power on its area

Task

Measure the voltage and the current and determine the power of a solar cell with different active areas! Name the relation between the area and the three measured values.

Setup



Required devices

- leXsolar-base unit
- 1 big solar cell
- 1 voltmeter
- 1 amperemeter
- Black covers for solar cells

Primary notes

The power will be calculated with the short circuit current and open circuit voltage in this experiment. This power is a fictive power and is not the maximum power of the solar cell. However, this fictive power is used, because it is sophisticated to ascertain the maximum power without facilities. In this context, the comparison of the fictive powers leads to the same result than the comparison with the maximum power.

Procedure

1. Set up the experiment according to the circuit diagram!
2. Measure successively both the open circuit voltage and short circuit diagram, since both values cannot be measured simultaneously.
3. Repeat this measurement with 1/4, half and 3/4 of the solar cells covered.
4. Record the measured data in a table!

Evaluation

1. Calculate the respective fictive powers *P* of the solar cell according to the measurement!
2. Plot the results in a diagram (x-axes: degree of cover (0, 1/4, 1/2, 1); y-axes: *P*, *I* and *V*)
3. Name the relation between the voltage (current, power) and the area.
4. Explain the behavior of open circuit voltage and short circuit current depending on the degree of cover.

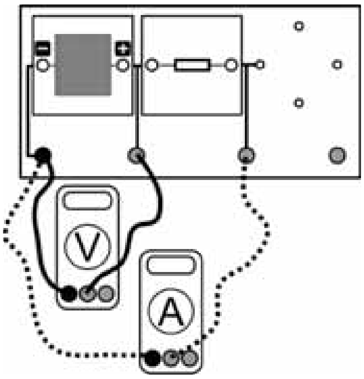
10. The I-V-characteristics of a solar cell

10.1 Dependence of solar cell power on load

Task

Measure the solar cell power depending on the consumer.

Setup



Required devices

- IeXsolar-base unit
- IeXsolar-lightning module
- 1 large solar module (1.5V)
- 1 amperemeter
- 1 voltmeter
- 1 resistor module
- 1 horn module
- 1 Motor module
- 1 PowerModule (9V)

Procedure

1. Set up the experiment according to the circuit diagram. Switch on the lightning module at a voltage of 9V. At first, plug in the resistor module.
2. Measure current and voltage of the solar cell.
3. Repeat the measurement with the horn and motor module. Note your measured values in the table.

Evaluation

1. Calculate the power of the solar cell and the resistance of each consumer.
2. Compare the solar cell power depending on the different consumers. Draw conclusions between resistance and power.

Measured values

	Resistor 33 Ω	Motor module	Horn
V (V)	0.61	1.25	1.44
I (mA)	15.5	13.4	2
$P=V \cdot I$ (mW)	9.4	16.8	2.9
R=V/I (Ω)	39.4	93.3	720

10.1 Dependence of solar cell power on load

Evaluation

2.

The solar cell power differs depending on the consumer despite the same illuminance.

Without further experiments, it is not possible to conclude the exact relation between power and resistance.

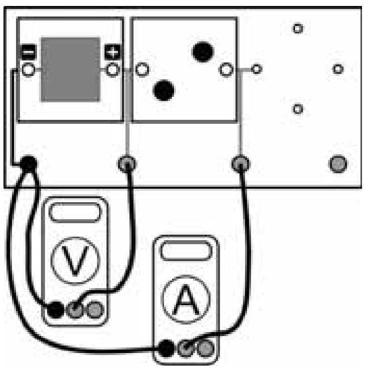
The measured values do not show, the power is high, when the resistance is low or high.

10.2 The I-V-characteristics and filling factor of a solar cell

Task

Measure the I-V-characteristics of the solar cell.

Setup



Required devices

- IeXsolar-base unit
- 1 large solar cell
- 1 voltmeter
- 1 amperemeter
- IeXsolar-potentiometer module
- IeXsolar-lightning module
- 1 PowerModule (5V)

Procedure

1. Set up the experiment according to the circuit diagram. Connect the lightning module with the PowerModule (5 V) and lay it on the solar cell. All four lamps inside the lightning module should shine. Set the highest resistance at the potentiometer.
2. Make out sensible voltage values and measure the corresponding current. For this purpose, decrease the resistance of the potentiometer.
3. Measure the open circuit voltage and short circuit current without potentiometer, as well.
4. Not the measured values in the table.

Evaluation

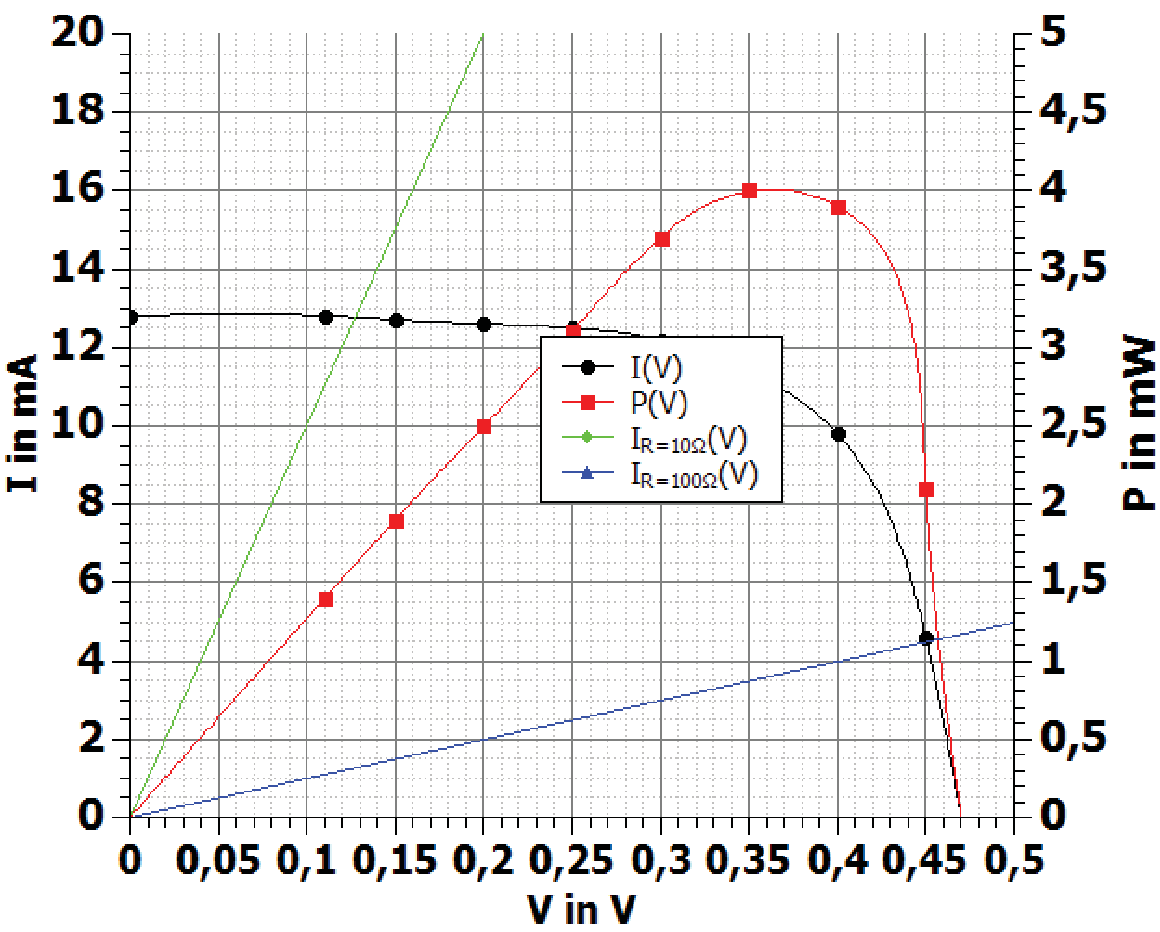
1. Draw the I-V-curve of the solar cell.
2. Calculate the respective power of the solar cell for each data point and plot the V-P-characteristic curve in the same diagram.
3. Describe the curves.
4. Draw the I-V-characteristic of a 10 Ω- and a 100 Ω-resistance into your diagram. Explain the meaning of the intersection points between the characteristic curves of the solar module and the resistances.
5. Draw conclusions about the solar cell power depending on the resistance.
6. The filling factor FF displays the relation between the power at the MPP and the power that is calculated by multiplying the open-circuit voltage with the short-circuit current ($FF = P_{MPP}/V_{oc} \cdot I_{sc}$). Calculate the filling factor.
7. Calculate approximately the efficiency of the solar cell, when it operates at the maximum power point. (Advice: The short circuit current amounts 840 mA at an illuminance of 1000 $\frac{W}{m^2}$ 840 mA. Both quantities are proportionate.)

10.2 The I-V-characteristics and filling factor of a solar cell

Measured values

V (V)	0.47	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.11	0
I (mA)	0	4.6	9.8	11.4	12.2	12.5	12.6	12.7	12.8	12.8
P=*V*·*I* (mW)	0	2.1	3.9	4	3.7	3.1	2.5	1.9	1.4	0

Diagram



Evaluation

3.
The I-V-characteristic curve shows, that the higher the voltage the lower the current. The maximum voltage and current amount to 0.47 V and 12.8 mA. The maximum power has a voltage of 0.35 V and a current of 11.4 mA. The large the difference to this voltage the lower the power, until it is zero.

Evaluation

4.
The point of intersection of both curves illustrate the voltage and the current, the solar cell release to the resistor.

5.
The solar cell power is not only dependent on the illuminance but also on the connected resistance. In this case, the resistance of the maximum power amounts to 30.7 Ω.

6.

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

$$FF = \frac{0.35\ V \cdot 11.4\ mA}{0.47\ V \cdot 12.8\ mA}$$

$$FF = 0.663 = 66.3\ \%$$

7.
Calculation of the radiation power:

$$P_{in} = \frac{P_{in,1000} \cdot I_{SC,exp}}{I_{SC,1000}} \cdot A_{solar\ cell}$$

$$P_{in} = \frac{1000\ \frac{W}{m^2} \cdot 12.8\ mA}{840\ mA} \cdot 0.0036\ m^2$$

$$P_{in} = 0.0548\ W = 54.8\ mW$$

Calculation of the efficiency:

$$\eta = \frac{P_{MPP}}{P_{in}}$$

$$\eta = \frac{4\ mW}{54.8\ mW}$$

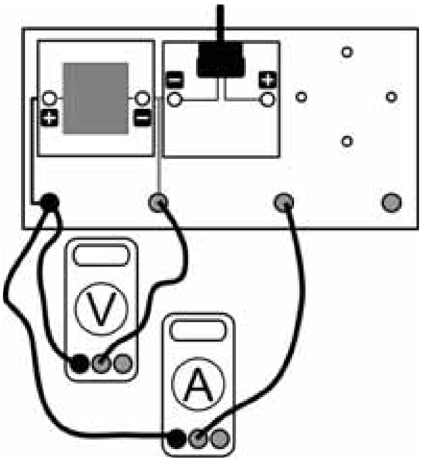
$$\eta = 7.3\%$$

15.1 Determination of efficiency of some energy conversions

Task

Determine the efficiency of conversion from electric to mechanic energy.

Setup



Required devices

- IeXsolar-base unit
- IeXsolar-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%.

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