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# Experiments with the solar module SUSE 4.3RB

**Solar module with 6 solar cells in series connection with 2 test jacks at each cell**

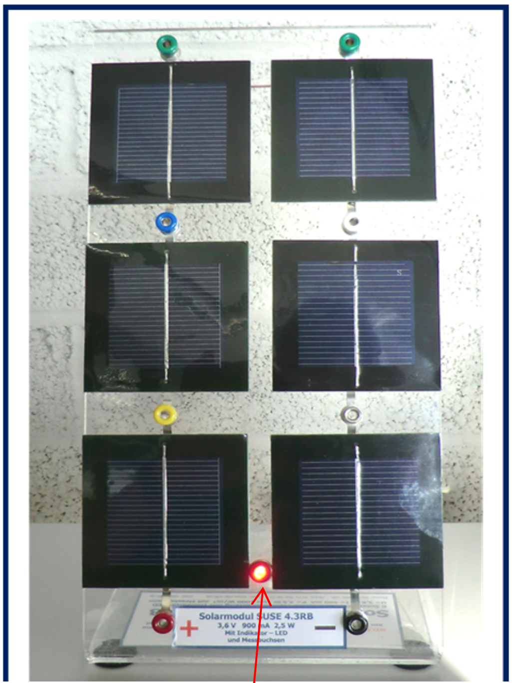
**3.6 V / 900 mA / 2.5 W** with S = 1000 W/m², T = 25°C, AM 1.5 **Operating display by indicator LED**

**Learning station C3**

## 23 pages of experiments available with SUSE 4.3 RB



## A Basic information and technical data




Red glowing indicator LED

White numbers: No. of the solar cells

The solar module **SUSE 4.3RB** is a high-quality 3.6 V – 0.9 A – 2.5 W solar module on a stable plexiglass base plate (480 x 160 x 6 mm) with 6 solar cells in series connection with test jack pairs. In series connection the module produces a open circuit voltage of **3.6 V**, a short-circuit current of **0.9 A**, and a maximum power of **2.5 W** (with 1000 W/m²). Each solar cell has its own test jack pair for electrical measurements, the total voltage is available at the red-black jack pair. To further increase the voltage several modules can also be connected in series. **The module features an indicator LED, that shows operational readiness.** The indicator LED glows brightly even inside a room and signalizes the energy readiness this way. The 6 jack pairs in front of and behind each solar cell are color-coded and form the electrical connections for each single solar cell.

With this module electrical devices (radio, solar vehicles,...) can be operated, that are designed for 3-4 V DC, with the experimentation manual for **SUSE 4.3RB** many experiments about the solar cell and photovoltaics system technology can be conducted.

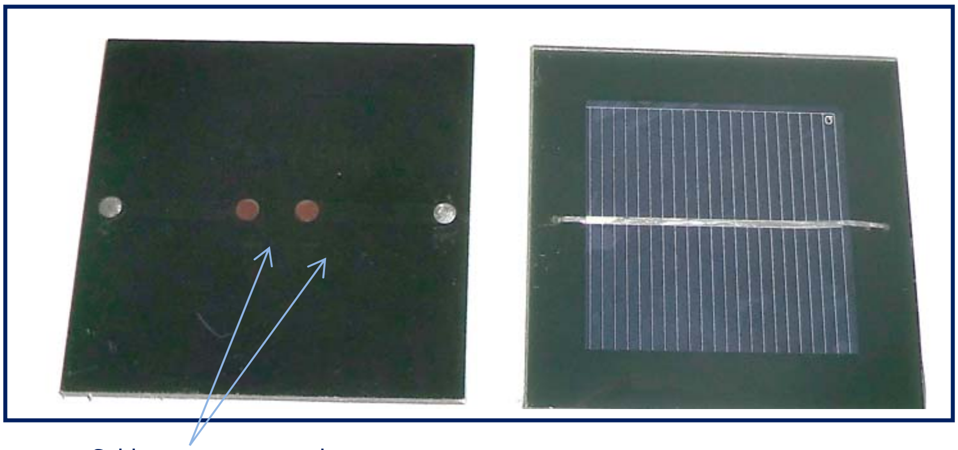
| Jack assignment: | positive | negative |
|---|---|---|
| Solar cell 1 | red | yellow |
| Solar cell 2 | yellow | blue |
| Solar cell 3 | blue | green |
| Solar cell 4 | green | white |
| Solar cell 5 | white | silver |
| Solar cell 6 | silver | black |
| Series connection of 6 solar cells | red | black |

### Technical data:

**Solar module:** Plexiglass base plate 480 x 160 x 6 mm, bent to 75°
**Solar cells:** 6 solar cells SUSEmod2 in series connection with 2 jacks 4mm each for banana plugs/lab wires
**Electrical data of the series connection** with an irradiance S of 1000 W/m², T = 25°C, AM 1.5:
Open circuit voltage $V_{oc}$= 3.6 V Short-circuit current $I_{sc}$= 900 mA Power P = 2.5 W
**Indicator LED: red glowing LED, connected permanently to positive and negative poles of the series connection over series resistor**

**Technical data of the solar cells: SUSEmod2 – a powerful and robust solar module**

**Back side** **Front side**



Cell size 52 x 52 mm
Frame size 75 x 75 mm

Solder contacts + and -

The NILS-ISFH solar module **SUSEmod2** includes a multicrystalline solar cell 52x52 mm. The solar cell is embedded break-proof in a plastic plate of the dimensions 75 x 75 mm. The top surface above the solar cell is laminated super-transparently with plastic. On the back side there are 2 solder contacts for soldering on the positive and negative conductors (hookup wire).

**Module:** Plastic base plate square 75 x 75 mm with super-transparent surface, mechanically very robust
**Solar cell:** Polycrystalline solar cell 52 x 52 mm, square

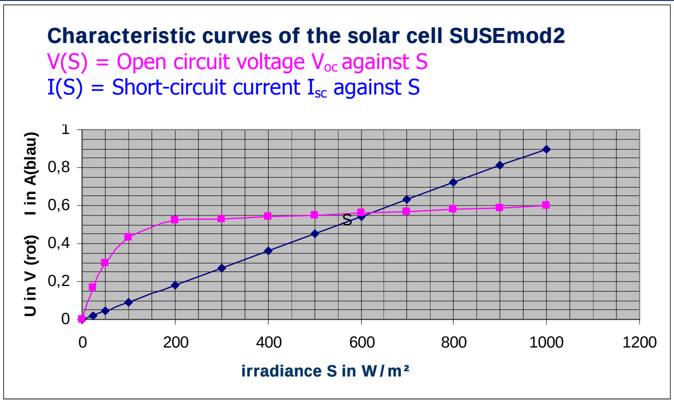
**Laminated inside the module there is a multicrystalline solar cell 52 x 52 mm, square, surface acid-textured**

**Technical data with an irradiance of 1000 W/m², T = 25°C, AM = 1.5 Tolerance 3 %**

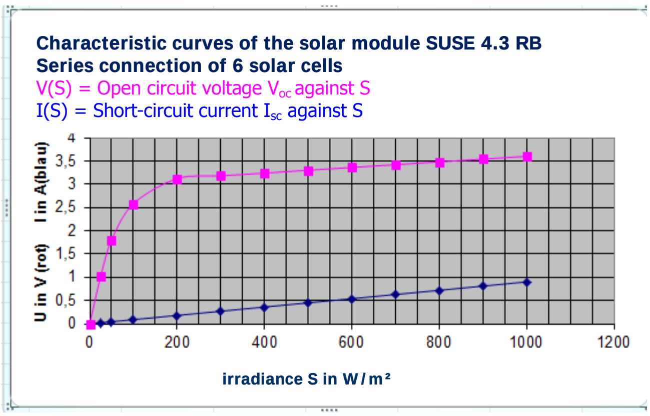
| Physical value | Symbol | Numerical value | Physical unit | Annotations |
|---|---|---|---|---|
| Dimensions | | 52 x 52 x 0.22 | mm | Square cell |
| Open circuit voltage | $V_{oc}$ | 0.61 | V | Typical for silicon |
| Short-circuit current | $I_{sc}$ | 0.90 | A | Proportional to light intensity |
| El. power | P | 0.42 | W | At solar spectrum, AM 1.5 |
| Efficiency factor | η | 16.0 | % | |
| Filling factor | FF | 77.5 | % | |
| Current density | j | 33.3 | mA/cm² | j is a quality feature |
| Thermal behavior Open circuit voltage $V_{oc}$ | | - 0.36 | % /K | The voltage decreases with warming by 0.36% per 1° C = 1K |
| Thermal behavior Short-circuit current $I_{sc}$ | | + 0.06 | % /K | The short-circuit current increases by 0.06 % per 1°C = 1K |

**Characteristic curves of the solar cells inside the module, characteristic curves of the module with 6 solar cells**

## 1. Dependence of the open circuit voltage and the short-circuit current on the light intensity (irradiance S in W / m²)




**Characteristic curves of one solar cell**

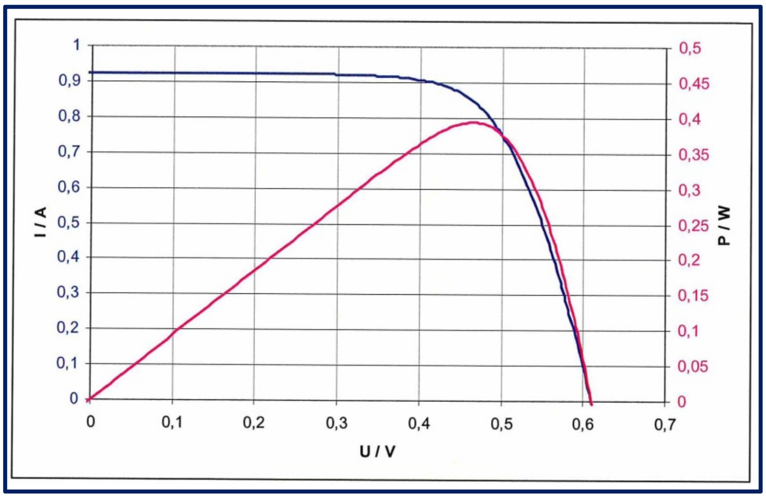



**Characteristic curves of the solar module SUSE 4.3 RB = 6 cells in series connection**

The open circuit voltage (exp. Function!) is 0 in total darkness, strongly increases with low irradiances and then just slightly increases further up to the maximum value 0.6 V with 1000 W/m² (bright sunshine with blue sky, solar cell positioned towards the sun).

The short circuit current is a linear function through the origin and increases in a linear fashion from 0 in total darkness up to 0.9 A with 1000 W/m².

## 2. The I(V) and the P(V) characteristic curve of one solar cell with S = 1000 W/m², T = 25°C, AM 1.5



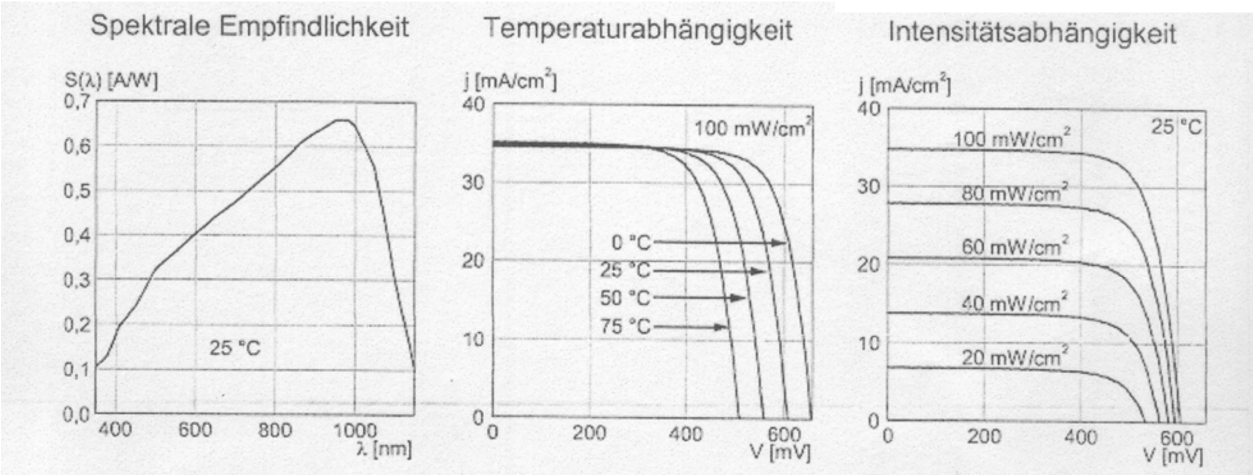

The **blue characteristic curve** shows the dependency of the short-circuit current on the open circuit voltage with an irradiance of 1000 W/m² and a temperature of 25°C.

The **red graph** shows the electric power of the solar cell (each product of V*I of the blue curve) plotted against V with the Maximum Power Point MPP at the maximum of this curve at about 0.4 W.

With the photovoltaics measuring module SUSE 5.15 these curves can be gathered experimentally.

## 2. Additional data of the solar cell

**2A Spectral Sensivity** **2B Temperature dependency** **2C Intensity dependency**




**In the figures of the current-voltage characteristic curves the current is shown per unit of area.**
**The absolute values are obtained by multiplication of the cell area with the according current values.**

**2A** The **graph on the left** shows the **spectral sensitivity** against the wavelength of the light, the maximum sensitivity is at about 950 nm in near infrared, dependent on the semiconductor band gap of silicon (Si).

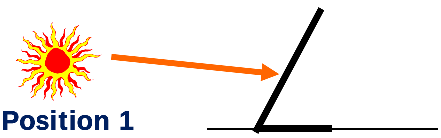
**2B** The **graph in the middle** shows the **j(V) characteristic curve against temperature**, it is recognizable, that the open circuit voltage decreases, if the temperature increases, the short-circuit current just slightly increases with warming (j is the current density = short-circuit current in mA per cm² cell area).

**2C** The **graph on the right** shows the **intensity dependency** of the **j(V) characteristic curves** (1000 W/m² corresponds to the bright sunshine in summer with a blue, cloudless sky, 0 W/m² is absolute darkness).

**The temperature dependencies (2B) V(T) and I(T) and the current density (2C) j(S) can be verified in experiments in this manual.**

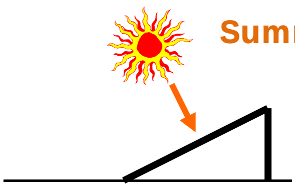
**Because of the 75° angle the solar module can be positioned differently for the operation in the summer or winter half-year:**

**Winter: Low solar altitude**



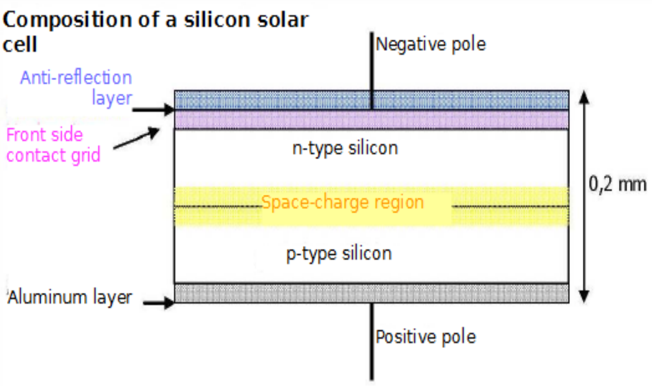
**Position 1**

**Summer** **High solar altitude**



**Position 2**

# Composition and function of a silicon solar cell II from class level 8/9




A solar cell is a large-scale silicon semiconductor diode, the n-type layer is the top surface of the solar cell, here the light enters, the blue color arises from the **transparent** (!) thin anti-reflection layer. **The n-type side is the negative pole of the solar cell!** The thin silver conductors serve as electrical conductors for the collection of the current. **The p-type layer is the lower surface of the solar cell**, normally it is coated razor-thin with aluminum and therefor appears gray. Applied silver conductors support the soldering of wires. Here the **positive pole of the solar cell is located. The inner photoelectric effect of separation of charge takes place at the p-n-junction.**

## How does a solar cell work? Level II

### 1. Electrical voltage $V_{oc}$

An Si solar cell provides a **typical voltage of 0.6....0.62 V** in open circuit operation (= voltage without a connected load). The exact value of the **open circuit voltage $V_{oc}$** depends on the semiconductor material and structure, the temperature, and the irradiance S, but is **independent from the area.**

The open circuit is just slightly dependent on the light intensity from a certain minimum light intensity on, observable in the V(S) characteristic curve. In research there is intensive work going on to obtain higher open-circuit voltages, a current value of research solar cells is 0.65 V.

### 2. Electrical current $I_{sc}$

The maximum electric current $I_{sc}$ (= short-circuit current), that a solar cell can deliver, depends on 3 factors:

- **Area of the solar cell:** The bigger the area, the higher is I (proportional)!
- **Intensity of the incoming light radiation:** The higher the light intensity S, the higher is I (proportional)!
- **Quality of the solar cell** (very good solar cells: $I_{sc}$ = 33-40 mA/cm²!)

The **cause of the current** are the **free electrons emerging from impacting light quanta** per unit of time in the barrier (p-n-junction), that diffuse towards the (n-type) upper surface of the solar cell because of an internal electric field and reach the (p-type) lower surface via the external electric circuit. This process is called „**internal photoelectric effect**“, explained by Einstein in 1905.

If current is extracted from the solar cell, the voltage V decreases. The exact relationship between voltage and current is depicted in the V-I characteristic curve of a solar cell, explained in the file of level III. The **maximum power** is only reached in one certain point, viz. at a certain voltage and current, this point is called **MPP = Maximum Power Point**, important in practice! The **efficiency factor of a solar cell** is about **16 – 21 %**, viz. Just 16-21% of the incoming light is converted into electric energy, dependent on the solar cell type.

Additional info files with explanations of the function of a solar cell for other levels are available at SUNdidactics.

# The experiments

**The possibilities for experiments with the solar module SUSE 4.3RB are very manifold and extensive, it is not possible to conduct all experiments in one session. The responsible teacher can choose from the available offers. Of course all experiments can also be thoroughly worked in stages.**

## B SUSE 4.3RB as a solar power supply for devices

**With the solar module SUSE 4.3RB SUSE experimental devices can be operated**, 3.6 V DC are applied at the red-black jack pair (with bright sunshine, illumination on the basic device SUSE 4.0 or with a halogen flood light 120 W):

- LED module SUSE 4.15 (red, green, blue, white, rainbow)
- LED module SUSE 4.20IRRB
- Solar radio SUSE 4.36
- One or several solar motors SUSE 4.16
- Solar crane SUSE 4.37
- Solar filling station for the SUSE solar vehicle 1.2
- Solar filling station for the SUSE solar vehicle 4 (only 4 solar cells are used (black-blue))
- Cell phone charger SUSE 4.17 with 3-4 modules SUSE 4.3 RB in series connection

The devices are connected to the red-black jack pair with the right polarity. For the operation a sufficient light intensity is necessary, outdoors during the day (bright sunshine or even clouded sky) or illumination with a halogen flood light 120 W or by placing the module on the illuminated plate of an overhead projector.

**Different voltages can be picked off for the operation of devices:**

**Jack assignment and voltage (with S = 1000 W/m²):**

| Negative jack | Positive jack | Voltage V in V |
|---|---|---|
| black | silver | 0.6 |
| black | white | 1.2 |
| black | green | 1.8 |
| black | blue | 2.4 |
| black | yellow | 3.0 |
| black | red | 3.6 |

## C Experiments with one solar cell Pages 7 - 14

Use **one** of the 6 solar cells in the module!

# The experiments

$V_{oc}$ = **Open circuit voltage = the electric voltage V of a solar cell without a load**

**Experiments: The solar cell as an energy converter from radiation energy to electric energy**

## 1. The open circuit voltage $V_{oc}$ of the solar cell

Use a multimeter in the measurement range of **20 V DC** and connect the voltmeter to both of the poles (red-black) of the illuminated solar cell with 2 lab wires.

The value should be between 0.55 and 0.61 V in the sunlight, with a clouded sky 0.5-0.55 V, independent of the area! With equal irradiance all solar cells should approximately have the same voltage, the standard test value would be 0.6 V. Small differences are quality differences. **The open circuit voltage is dependent on the light intensity, the temperature, the composition and the material of the solar cell. In our solar cell the material is silicon.**

**The measurements:**

| **Measurement location** | Outdoors with sunshine, positioned towards the sun or overhead projector | Outdoors with sunshine in the shadows | Outdoors with cloudy sky | In illuminated room on the desk |
|---|---|---|---|---|
| **Open circuit voltage V in V** | | | | |
| **Open circuit voltage V in V**<br>a)Solar cell covered 50% by black cardboard or aluminum foil<br>b) Solar cell covered completely by sheet protector | a<br><br>b | No measurements | | |

**What do you notice in the measurements for the open circuit voltage? Express it here:**

## 2. The short-circuit current $I_{sc}$ of the solar cell

In contrast to other current sources (battery, power supply...) solar cells may be short-circuited, the short-circuit current actually is a very important parameter of solar cells.

For the current measurement use a multimeter in the measurement range of 10 A DC, that is connected to + and – of the solar cell.
**Only for measurements indoors** use the measurement range of 200 mA or 20 mA!

The value of the short-circuit current is ***directly proportional to the cell area and to the light intensity***/irradiance, standard test value: With this solar cell with an area of 28.6 cm² the current should be 0.9 A with a light intensity of 1000 W/m².

### The measurements:

| **Measurement location** | Outdoors with sunshine, positioned towards the sun or overhead projector | Outdoors with sunshine in the shadows | Outdoors with cloudy sky | In illuminated room |
|---|---|---|---|---|
| **Short-circuit current $I_{sc}$ in A**<br><br>**$I_{sc}$ in mA** (convert) | | | | |
| **Short-circuit current $I_{sc}$ in A**<br>a)Solar cell covered 50% by black cardboard or aluminum foil<br>b) Solar cell covered completely by sheet protector | a<br><br><br><br>b | No measurements | | |

What do you notice in the current measurements for the short-circuit current? Note your observations/explanations **here:**

## 3. The electric power of the solar cell $P_E$ in W (Watt)

**Here no new measurements are necessary, calculations with the two already determined measurement values $V_{oc}$ and $I_{sc}$**

Simplified approach: P is open circuit voltage x short-circuit current x 0.8, so P should ideally be about 0.54 W with an irradiation of 1000 W/m², if the cell has an area of 27.04 cm². The factor 0.8 is explained with the characteristic curve and the MPP of the solar cell.

### The measurements:

| **Measurement location** | Outdoors with sunshine, positioned towards the sun or overhead projector | Outdoors with sunshine in the shadows | Outdoors with cloudy sky | In illuminated room |
|---|---|---|---|---|
| **Short-circuit current $I_{sc}$ in A** Transfer values | | | | |
| **Open circuit voltage $V_{oc}$ in V** Transfer values | | | | |
| **Power P** $U_{oc}$ x $I_{sc}$ x 0.8 **in W** | | | | |
| **Power P** $U_{oc}$ x $I_{sc}$ x 0.8 **in mW** | | | | |

## 4. The quality of the solar cell

That's the current density j in mA/cm².

**No new measurements are necessary here, calculation with both of the already determined measurement values $V_{oc}$ and $I_{sc}$**

The current density j indicates how much short-circuit current a 1 cm² piece of the solar cell produces, the more, the better! **For that purpose the irradiation has to be 1000 W/m²** (international standard value), because with a lower irradiation <1000 W/m² the current density j of course is also lower! So we take the value from the bright sunshine or overhead projector.

This is how we calculate the current density j:

$$j = \frac{\text{short-circuit current in mA}}{\text{cell area in cm}^2} = \text{..................}\ \text{mA/cm}^2$$

**with 1000 W/m² irradiation!**

Our solar cell is a square with a side length of 5.2 cm, its area A is.................cm².

**The current density of the used solar cell is.........................mA/cm².**

**The quality of the solar cell is.........................................................**

Very good – good – medium - bad

**Very good: > 34 mA/cm² Good: 28-33 mA/cm² Medium: 24....28 mA/cm²**
**Bad: < 24 mA/cm²**
**With an irradiance of 1000 W/m²!! Maximum possible theoretical value: 44 mA/cm²**

## 5. Determination of the efficiency factor of a solar cell

Example: Overhead projector or sunlight with the irradiance 1000 W/m²

**5.1** Conversion of the light power 1000 W/m² or 0.1 W/cm²,respectively, to the real area of the solar cell:

**The cell has an area of 27.04 cm², it receives with 1000 W/m² a <u>light power</u> of 27.04 cm² * 0.1 W/m² = $P_L$ = 2.704 W**

**5.2** The electric power of the measured cell in exercise 3 was **$P_E$ = 0.432 W**

**5.3.** Efficiency factor in % = electric power : light power * 100

$$\text{Efficiency factor} = \frac{P_E}{P_L} * 100 = \text{..........................} \%$$

**The efficiency factor of the used solar cell is..........................%**

**Efficiency factors of solar cells:** Monocrystalline cells: 16 - 21 % Polycrystalline cells: 14 – 20 %

**Experimental exercise:**

**Determine the efficiency factor of the module's solar cell with an irradiation by a halogen spot light 120 – 150 W, distance approx. 30 cm. The light intensity (irradiance) is < 1000 W/m² and is determined with the equation from experiment 6.**
**Method:**

1. Measurement of the open circuit voltage $V_{oc}$ and the short-circuit current $I_{sc}$:

   $V_{oc}$ = ..........................V   $I_{sc}$ = ..........................A

2. With the equation P = $V_{oc}$ * $I_{sc}$ * 0.8 the electric power P of the solar cell is determined:

   $P_E$ = ..................*.....................*0.8 = ..........................W (I)
   $V_{oc}$ $I_{sc}$

3. With the equation from exp. 6 the irradiance of the light in W/m² is determined:

$$S_x = \frac{I_{mes} \text{ (in A)} * 1000}{0.9 \text{ A}}$$

| |
|---|
| $I_{mes}$ is the short-circuit current measured in 1.) here<br>$S_x$ is the irradiance of the light in W/m² |

**$S_x$ = ...............................W/m²**

$S_x$ is the light power per 1 m², but because the solar cell area is just 27.04 cm², we have to calculate this part for our solar cell by dividing the value by 10,000 (because 1 m² is 10,000 cm²) and then multiplying with 27.04 cm², that is the real light power $P_L$ on the solar cell:

$$P_L = S_x * \frac{27.04\ cm^2}{10\,000\ \frac{cm^2}{m^2}} \quad (II)$$

The efficiency factor is obtained by dividing the electric power $P_E$ by the light power and multiplying that value with 100 to get a percentage:

Efficiency factor $\eta = \frac{P_E}{P_L} * 100 = \text{------------------------} * 100 = \ldots\ldots\ldots\ldots\ldots\ldots\%$

If measured/calculated correctly, the efficiency factor should be approximately 16%.

## 6. Measurements of the light intensity (irradiance) in W/m²

**The brightness (intensity) of the light is called irradiance S and is measured in W/m² (Watts per m²).**

With the calibrated solar cell used here the **light intensity in W/m²** can be determined exactly in front of a halogen spot light, on an overhead projector, or outdoors.

**1000 W/m² is the intensity of the light radiation of the sun with cloudless sky in the summer and the international standard measurement value for solar cells.**

**Short-circuit current $I_{sc}$ of the solar cell with an irradiation of 1000 W/m²**

**$I_{SC}$= .........0.9...................A = ......900...............mA**

### Measurement of the irradiance S of light (light intensity) in W/m²:

Because the short-circuit current $I_{sc}$ of a solar cell is proportional to the irradiance S, it holds:

$$\frac{I_{sc}\text{ in A}}{1000\text{ W/m}^2} = \frac{I_{mes}\text{ in A}}{S_x\text{ in W/m}^2}$$

or solved for $S_x$: $$S_x = \frac{I_{mes}\text{ (in A)} * 1000\text{ W/m}^2}{0.9\text{ A}}$$

It is: $I_{sc}$ in A the calibrated short-circuit current at 1000 W/m² **= 0.9 A**
$I_{mes}$ in A the measured short-circuit current at the irradiance $S_x$
$S_x$ in W/m² the measured irradiance of the light radiation

### Measurements outdoors and with light sources:

| Light radiation | Short-circuit current $I_{sc}$ in A | Irradiance $S_x$ in W/m² |
|---|---|---|
| Bright sunshine, measured directly towards the sun | | |
| Bright sunshine, measured in the shadows | | |

| | | |
|---|---|---|
| Clouded sky | | |
| Very gloomy weather | | |
| On the plate of an overhead projector | | |
| 10 cm **above the surface** of an overhead projector | | |
| 40 cm in front of halogen spot lamp 35 W<br><br>(Spot light SUSE 5.16) | | |
| 40 cm in front of halogen spot lamp 150 W | | |
| Indoors, directed towards the window | | |

**What do you notice? Explain here:**

## 7. Measurements of the temperature dependence of V,I,P

Voltage, current and power of solar cells are dependent on temperature, the voltage strongly decreases with warming of the solar cell, the current slightly increases, the power as a product of both values therefor decreases. Though photovoltaic complexes on roofs or other fundaments deliver the highest power in the summer with intensive solar radiation, but it strongly increases, if the solar cells grow warm. In the summer cell temperatures of 60° – 80° C are possible. Ideal conditions are found in outer space, there the irradiation is intensive with very low temperatures (< -50°C).
The characteristic curves 2B on page 4 show this effect. With our own measurements we want to verify this effect.

### 7.1 Measurements without temperature measurement at the solar cell

**Requirements:** Bright sunshine without clouds or irradiation by halogen flood light 120 W, for example on basic device SUSE 4.0
**Accessories:** 1 multimeter for the measurement of voltage and current, 2 lab wires, calculator or calculator app on smartphone.

We place the solar module SUSE 4.3RB in the refrigerator or in a dark, cool place in the room and let it cool down. After the cooling we go into the sunlight, position the module towards the sun and measure $V_{oc}$ and $I_{sc}$ in time lags for 5 minutes **on one solar cell** and enter the values into the table. During measurement breaks we calculate P and enter the power in the according column. After positioning the module we immediately start the measurements.

| **Time in s** | **Open circuit voltage $V_{oc}$ in V** | **Short-circuit current $I_{sc}$ in A** | **Power P $= V_{oc} * I_{sc} * 0.8$** |
|---|---|---|---|
| 0 | | | |
| 30 | | | |
| 60 | | | |
| 90 | | | |
| 120 | | | |
| 180 | | | |
| 240 | | | |
| 300 | | | |

**What do you notice? Explain here, compare to figure 2B:**

### 7.2 Measurements with temperature measurement at the solar cell

**Requirements:** Bright sunshine without clouds or irradiation by halogen flood light 120 W, for example on basic device SUSE 4.0
**Accessories:** 1 multimeter for the measurement of voltage, current and temperature, 2 lab wires, calculator or calculator app on smartphone

We attach the wire with the temperature sensor of the multimeter to the black border of a solar cell and look to it that the actual solar cell in the module is kept free. Afterwards we place the solar module SUSE 4.3B in the refrigerator or in a dark, cool place in the room and let it cool down. After the cooling we go into the sunlight, position the module towards the sun and measure T, $V_{oc}$ and $I_{sc}$ in time lags for 5 minutes **on one solar cell** and enter the values into the table. During measurement breaks we calculate P and enter the power in the according column. After positioning the module we immediately start the measurements.

| **Time in s** | **Temperature T in °C** | **Open circuit voltage $V_{oc}$ in V** | **Short-circuit current $I_{sc}$ in A** | **Power P = $V_{oc}$ * $I_{sc}$ * 0.8** |
|---|---|---|---|---|
| 0 | | | | |
| 30 | | | | |
| 60 | | | | |
| 90 | | | | |
| 120 | | | | |
| 180 | | | | |
| 240 | | | | |
| 300 | | | | |

**What do you notice? Explain here, compare to figure 2B:**

## D Experiments with solar cells in series connection Pages 15 -19

**Before practice first some theory**

To increase the voltage a high number (mostly 36 or 72 cells) of solar cells are connected in series in industrially manufactured solar modules. In doing so the single voltages of the cells add up to the module voltage.
A solar cell typically has a voltage of 0.6 V under illumination. If now **several solar cells are connected to each other, the voltage values add up, the current does not change in series connection.**
**(Exception: The cells are illuminated with different light intensities or shadowed, then the weakest cell determines the current in the series connection).** That can become a problem in practice, if in a photovoltaic power system on a roof with several hundred or even over 1000 solar cells in series connection just one solar cell is shadowed, e.g. by a shadow of the building, the chimney, a tree or if the solar cell is covered by a leaf flying around. The shadowed single cell now has a lower current, that lowers and determines the total current of all solar cells. Therefor the power of the whole complex decreases dramatically.

**Experiment D1:**

**In the solar module SUSE 4.3RB the solar cells already are connected in series internally.** Each solar cell has its own positive and negative jacks, the connection to the whole series connection is the red-black jack pair.
We measure the **open circuit voltage $V_{oc}$** (that is the electric voltage of a solar cell in open circuit without a connected load) and the **short-circuit current $I_{sc}$** (that is the current, which the solar cell delivers – in short-circuit measured via an amperemeter) of all 6 single solar cells of the module **SUSE 4.3RB** with 4 different light sources (1: On the basic device **SUSE 4.0**, 2: if no basic device SUSE 4.0 is available, in front of a 120 W halogen spot lamp (flood light), 3: On the plate of an overhead projector, 4: Outdoors with natural sunlight or in the light of the clouded sky).

With the multimeter (Measurement range for the voltage 20 V DC, current in the range 10 A DC) measure the **open circuit voltage $V_{oc}$** and the **short-circuit current $I_{sc}$** for each cell individually. Enter the measurement values into the following table.

| **Solar cell No.** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| Open circuit voltage **$V_{oc}$ in V** | **Enter the open circuit voltage $V_{oc}$ into the following table elements** | | | | | |
| On basic device SUSE 4.0 | | | | | | |
| 40 cm in front of 120 W flood light | | | | | | |
| On the plate of an overhead projector | | | | | | |
| Outdoors with bright sunshine (module positioned towards the sun) | | | | | | |
| Outdoors with clouded sky | | | | | | |

| Short-circuit current **$I_{sc}$ in A** | **Enter the short-circuit current $I_{sc}$ into the following table elements** | | | | | |
|---|---|---|---|---|---|---|
| On basic device SUSE 4.0 | | | | | | |
| 40 cm in front of 120 W flood light | | | | | | |
| On the plate of an overhead projector | | | | | | |
| Outdoors with bright sunshine (module positioned towards the sun) | | | | | | |
| Outdoors with clouded sky | | | | | | |

### Experiment D2: Series connection of solar cells

Use the natural sunlight, the basic device SUSE 4.0 or the flood light 120 W in 40 cm distance as a light source.
Now measure the open circuit voltage/short-circuit current of solar cell 1 by connecting the measuring instrument to the positive pole of cell 1 and to the jack in the connection plug 1: Voltage measurement in the measurement range 20 V DC, current measurement in the measurement range 10 A DC.

**Solar cell 1:**

$V_{oc}$ = ..........................V $I_{sc}$ = ..............................A

**Solar cells 1 + 2 in series connection**
Now measure the open circuit voltage/short-circuit current of solar cell 1+2 by connecting the measuring instrument to the positive pole of cell 1 and to the jack in the connection plug 2:

**Solar cells 1+2:**

$V_{oc}$ = ..........................V $I_{sc}$ = ..............................A

Now connect cell 1 to cell 2 and 3 and measure $V_{oc}$ and $I_{sc}$:

**Solar cells 1 + 2 + 3 in series connection**

Now measure the open circuit voltage/short-circuit current of solar cell 1+2+3 by connecting the measuring instrument to the positive pole of cell 1 and to the jack in the connection plug 3:

**Solar cells 1+2+3:**

$V_{oc}$ =..........................V $I_{sc}$ = ..............................A

..........continue the experiment up to 1+2+3+4+5+6 and enter the results into the table.Now determine the irradiance S of the incoming light from the short-circuit current as explained in experiment 6!

## Series connection of solar cells

| | Open circuit voltage $V_{oc}$ in V | Short-circuit current $I_{sc}$ in A | Irradiance S in W/m² |
|---|---|---|---|
| Cell 1 | | | |
| Cells 1 + 2 | | | |
| Cells 1+2+3 | | | |
| Cells 1+2+3+4 | | | |
| Cells 1+2+3+4+5 | | | |
| Cells 1+2+3+4+5+6 | | | |

**Which principles do you notice? Express the findings here:**

## Experiment D3: Shadowing of solar cells in series connection

### Before practice first some theory

The **series connection** of solar cells has an **essential disadvantage**. If just **one cell** of a series connection is covered by shadowing (by a fallen leaf, dirt, a bird sitting on it...) and therefor does not deliver any or just an insufficient voltage/current, the whole module is out of order or impaired, because the weakest link in the chain determines the total output.

If several solar modules are connected in series, **a single shadowed solar cell can paralyze a whole solar generator. This is why all solar modules have so called bypass diodes, that reroute the current around the failing cells.**

**The experiment:**

Place the module on the basic device SUSE 4.0 or 40 cm in front of the flood light 120 W. Now measure the open circuit voltage and the short-circuit current of the series connection of the 6 solar cells (plug measuring instrument into the red jack and the black jack):

**$V_{oc}$=...........................V $I_{sc}$=....................................A**

Now cover **<u>one cell</u>** of the 6 solar cells lightproof with black cardboard or the like and measure the open circuit voltage and the short-circuit current again:

**$V_{oc}$=...........................V $I_{sc}$=....................................A**

**What do you notice? Explain your result here:**

**Experiment D4:**
Experiments about the series connection of several solar modules SUSE 4.3RB
Accessories: 4 Solar modules SUSE 4.3 RB, multimeter, 2 lab wires

**Before practice first some theory:**

If several solar modules are connected in series to each other to increase the voltage, a solar generator is obtained.
Because each solar module SUSE 4.3RB delivers about 3.6 V of voltage, we can increase the voltage stepwise with a series connection in steps of 3.6 V, so 3.6 V -7.2 V –10.8 V -14.4 V........
With 4 modules a voltage of 14.4 V is obtained, that is suited ideally for 12 V devices (car radio, stereo system, small TV, DVD player...), connect the device to the series connection of 4 modules (negative pole of module 1 and positive pole of module 4), it will work great!

**Experiment D4.1:**

Take 4 modules SUSE 4.3RB and put them side by side into the sunlight or in front of the light of a 500 W flood light. When experimenting with flood lights, look to it that the modules are illuminated evenly.
Now connect module 1 to module 2 in series by connecting the positive pole of module 1 to the negative pole of module 2 with a wire.
The sum voltage now lies between the negative pole of module 1 and the positive pole of module 2. Enter the values into the table and continue the experiment by connecting the modules 3+4 accordingly.

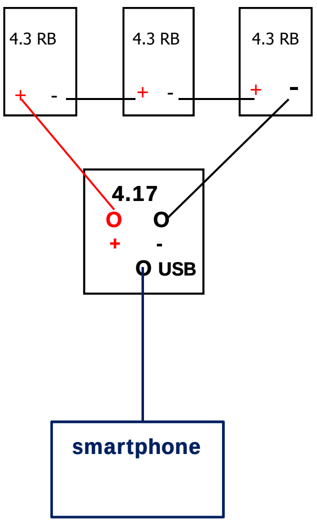
## Series connection of solar modules (S =......................W/m²)

| Series connection of modules | Open circuit voltage $V_{oc}$ in V | Short-circuit current $I_{sc}$ in A |
|---|---|---|
| 1+2 | | |
| 1+2+3 | | |
| 1+2+3+4 | | |

**Which principle do you notice? Express the result here:**

### Experiment D4.2: Charging a smartphone with 3x SUSE 4.3 RB and SUSE 4.17

Connect 3 or 4 solar modules SUSE 4.3 RB in series and connect the positive pole of the first module and the negative pole of the third module to the cell phone charging device **SUSE 4.17**.




Light source: Natural daylight outdoors or indoors the surface of an overhead projector or in front of a 120 W halogen spot light.
At the USB socket of the charging module SUSE 4.17 you can charge your cell phone or smartphone or a 5 V rechargeable battery (Powerbank).

In the module SUSE 4.17 there is a DC-DC converter, that converts the higher voltage of the series connection of several solar modules to exactly 5V DC at a USB jack. Smartphones and tablet PCs are charged with 5V DC.

# Experimental learning stations about solar energy

## Photovoltaics, Solar radiation, Solar heat, Optoelectronics

**Experiments of the learning workshop NILS- ISFH for classes, training, workshops, project days, labs**

Execution in sunlight/daylight outdoors or with halogen spot lights indoors

Levels: 1 (easy) 2(medium) 3(high)

www.sundidactics.de

# Experiment

**How many solar motors can be connected to a solar module?**
**How many LEDs can be connected to a solar module?** **Level 1**

**Learning station**

**A1**

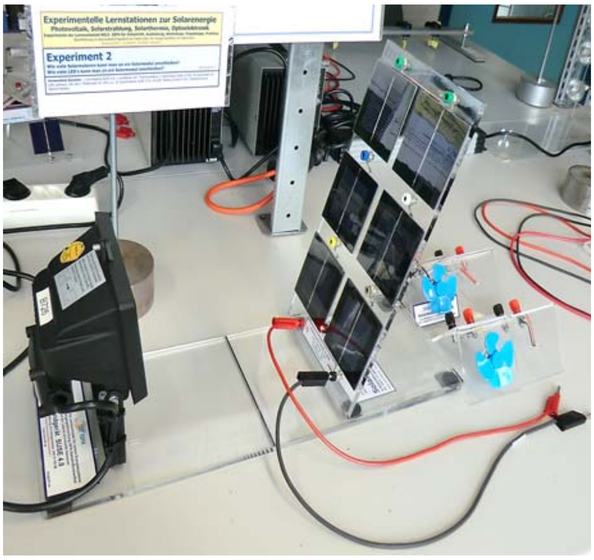
**Elements used:** 1 basic device SUSE 4.0, 1 switchable desk power socket 3x, 1 solar module SUSE 4.3RB, 20 lab wires 1m (10x black, 10x red), 1 multimeter VC 150 or the like, 10 solar motors SUSE 4.16, 10 LED modules (SUSE 4.15), calculator of your cell phone

### Tips for the experiment:

You can conduct the experiment on a table outside in the sunlight or indoors with the halogen flood light. In each case the natural daylight or the halogen lamp of the basic device SUSE 4.0 illuminates the solar module SUSE 4.3 RB, this is where electric energy develops from the light radiation, 6 solar cells are connected in series here, use the jacks red (+ of the 1st solar cell) and black (- of the 6th solar cell).

### Experimental procedure 1:

Connect 1 solar motor to the solar module, if it rotates fast, you can connect a 2nd solar motor additionally, continue this way. Test how many solar motors the solar module can power. You can reason yourself which type of electric circuit to use (parallel or series connection).




Experimental setting: On the base plate SUSE 4.0 the solar module SUSE 4.3RB is placed, behind it to the right there are 2 solar motors SUSE 4.16

### Experimental procedure 2:

Use the LED modules instead of the motors, conduct the experiment again! Mind the correct polarity!

### Experimental procedure 3:

Connect motors and LED modules to the solar module at the same time and observe!

**Note the results here, explain and draw your electric circuit used:**

**Which differences do you notice between a parallel and a series connection? Explain:**

**Professional question:** How could the maximum number of motors or LEDs be calculated with the aid of electric measurements? You can confirm your idea with a multimeter! **Explain here:**

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## Experiment
## We bring light energy from outside into the room

**Level 1-2**

**Learning station**

**A3**

**Elements used:** 1 solar module SUSE 4.3 RB, 1 storage module SUSE 4.12, 1 LED module SUSE 4.15, 4 lab wires 1m (2x red, 2x black), with bad weather: Basic device SUSE 4.0 (Halogen flood light 120 W) and switchable 3x power socket

**Tips for the experiment:**

The natural daylight or the halogen lamp of the basic device SUSE 4.0 illuminates the solar module SUSE 4.3 RB. This is where electric energy develops from the light radiation. 6 solar cells are connected in series here, use the jacks red (+ of the 1$^{st}$ solar cell) and black (- of the 6$^{th}$ solar cell).

The solar storage module SUSE 4.12 can be charged at the solar module and can store electric energy. You can disconnect the storage module after charging, carry it into the darkened room and connect an LED there, it glows!

Setting of the experiment A3: On the base plate SUSE 4.0 the solar module SUSE 4.3RB is located, in front of it there are the storage module SUSE 4.12 and the LED module SUSE 4.15

**Experimental procedure:**

Go outside and direct the solar module towards the sun, if the sky is clouded to the brightest spot of the sky. If the weather is bad, you can also use the halogen flood light of the basic device SUSE 4.0 indoors.

Connect the **solar storage module SUSE 4.12** to the solar module with 2 wires (red/black) and **correct polarity** (+ to + and – to -) and let it charge for about 3 minutes. After charging pull the wires out of the storage module and go inside with the storage module. Connect an LED module SUSE 4.15 with the right polarity to the storage device there.

**Explain the function of this experiment and the different energy conversion processes here. How long does the LED glow? Determine the glowing time with the stopp watch of your cell phone. Can the glowing time also be calculated? Do you have an idea?**

**Continue: Explain the function of this experiment and the different energy conversion processes here.**
**How long does the LED glow? Determine the glowing time with the stopp watch of your cell phone. Can the glowing time also be calculated? Do you have an idea?**

**Additional experiments with SUSE 4.3RB are available at sundidactics.de**