1. Dependence of power on the area of the solar cell

Introduction

Solar cells are available in different sizes. With this experiment the dependence of the characteristic values voltage, current and power on the solar cell area should be investigated.

Learning Objects

Measure the voltage and the current and determine the power of a solar cell with different active areas!

What relationship between the area and these three measured values can you identify?

Concepts

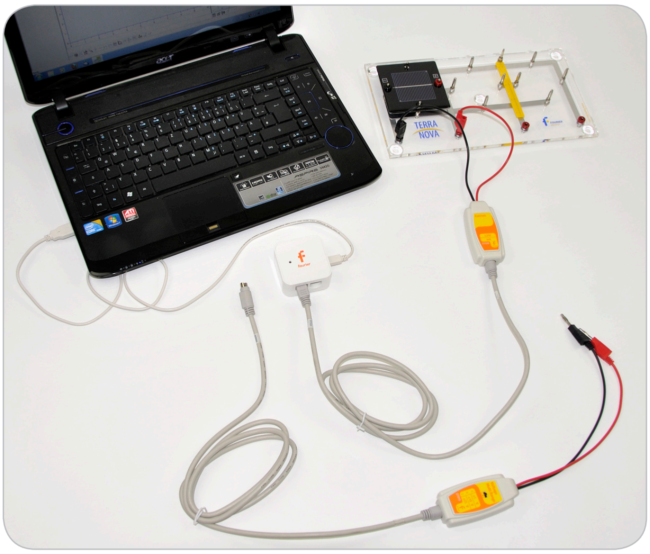
Principles of electrical circuits
Voltage and current

Time Frame

1 lesson

Equipment

1. Main board
2. 1 large solar cell
3. 3 solar cells cover sheets
4. 1 voltage sensor
5. 1 current sensor
6. NOVA LINK



Equipment Setup Procedure

1. Launch MuliLab.
2. Connect the USBLink to the USB port on the computer. The green LED will turn on when the USBLink is successfully connected to the computer.
3. Plug the solar cell onto the main board (left position).
4. For current measurement connect the current sensor parallel to the solar cell and to I/O 1 port of the USBLink.
5. For voltage measurement connect the voltage sensor parallel to the solar cell and to I/O 1 port of the USBLink.
6. Be aware not to connect both sensors at the same time

MultiLab Setup

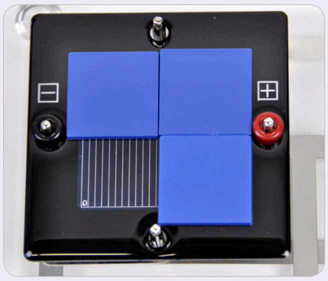
1. Click .
2. Click **Next**.
3. Set **Select rate** to **Manual**.
4. Set **Select recording mode** to **Add**.
5. Click **Next**.
6. Set **by samples** to **50**.
7. Click **Finish**.

Notes

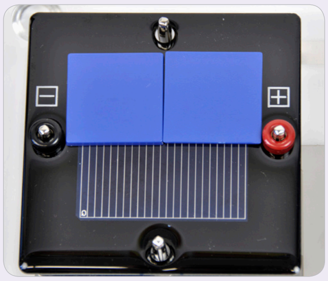
The calculated power of the solar cell is higher than the real maximum power, because voltage V and current I are not measured at Maximum Power Point (MPP) but at open circuit voltage Voc and short circuit current Isc. This procedure makes the experiment much easier but nevertheless the qualitative results will be true.

Experimental Procedure

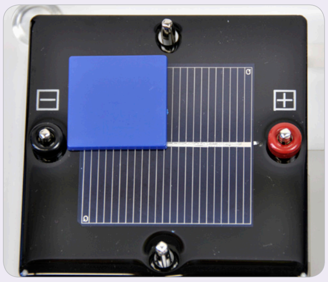
1. Connect the current sensor as described in the equipment setup.
2. Put all 3 covers onto the solar cell.



3. Click .
4. Take one cover away from the solar cell, so that there are two covers left



5. Repeat step 2 to 3 until no cover is on the solar cell.

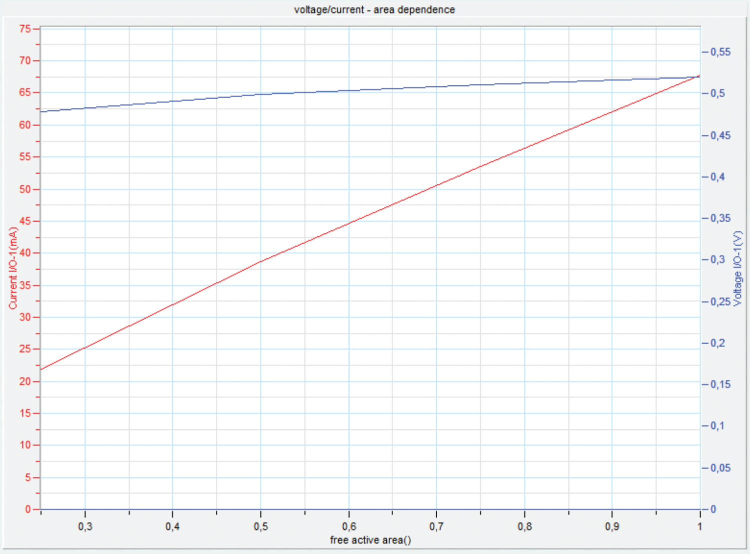


6. Click .
7. Connect the voltage sensor as described under "Equipment Setup Procedure".
8. Repeat point1 to 4.
9. Click .

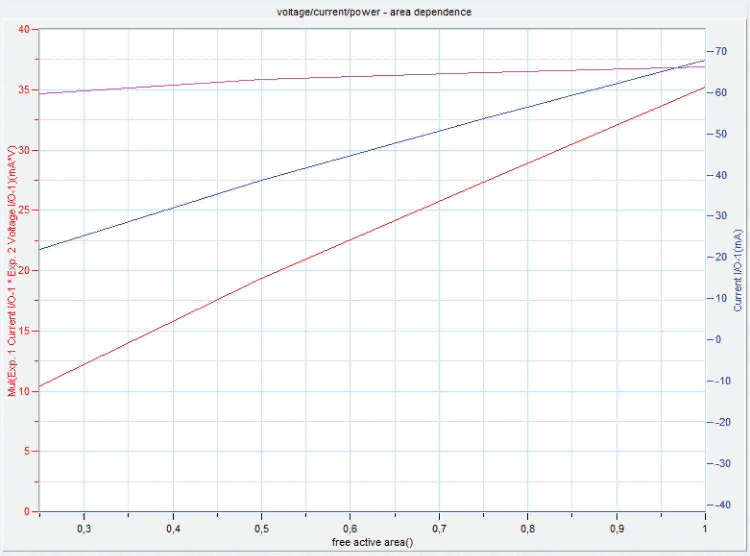
Data Analysis

1. Click f_x.
2. Click **Functions**.
3. Set **Functions** to **Multiply**.
4. Set **G1** and **G2** to voltage and current measurement data.
5. Click **Ok**.
6. Go to **Table** > **Add manual column**.
7. Set **Column name** to **free active area**.
8. Click **Ok**.
9. Click .
10. Add the columns of free active area, the current and voltage measurement and of the calculated power function.
11. Click **Ok**.
12. Click .
13. Click .
14. Set **X-axis** to **free active area**.
15. Set **Y-axis** to the measured current and voltage data points.
16. Set the **Graph title** to "**Voltage / Current / Power - Area Dependence**".
17. Click **Ok**.

Expected Results



The voltage stays nearly constant. In contrast, the current increases with the active area.
It is directly proportional to the solar cell area.



Because power P is the product of voltage and current,
it also increases with active area and is also directly proportional to the solar cell area.

Questions

1. How does the voltage V depend on the solar cell active area size?
2. How does the current I depend on the solar cell active area size?
3. What can therefore be conclusion for the power P?
4. Advanced: Give an explanation for this behavior!
5. Advanced: In the experiment kit only relative small solar cells are included. In practice mostly so called 6-inch solar cells are used. They have a size of 156mm x 156mm. Apply a linear fit to your data and calculate the current and power of a 6-inch solar cell under the conditions of your experiment.

Answers

1. The voltage is constant. It is independent of the solar cell area.
2. The current increases linearly with larger active area.
3. Because power P is the product of voltage V and current I, it also increases linearly with the active area size.
4. The voltage of the solar cell does not change because it is a material constant. It mainly depends on the solar cell material but only slightly on illumination density (it depends on the illumination density by a logarithmic law). The solar cells in this kit are made of silicon and therefore have a voltage of 0,5V under sun light.
5. The reason that the current on the other hand increases with area is the following: The larger the area of the solar cell the more photons (light particles) are collected by the solar cell. Each photon can excite one electron. This means that with larger area more photons are collected and more electrons are excited. And more electrons means more current.

Further Suggestions

You can also compare the two different kinds of solar modules included in the kit.
The larger one has a size of 52mm x 52mm and the smaller one of 52mm x 26mm.

2. Dependence of power on angle of incidence

Introduction

Solar modules are mostly mounted on roofs in a fixed position. During the day, when the sun is "moving" across the sky, the angle of incidence of sunlight changes. In this experiment the dependency of the solar cell power on the angle of incidence should be investigated.

Learning Objects

Measure the short-circuit current and the open-circuit voltage of the solar cell depending on the angle of incidence of the light

Concepts

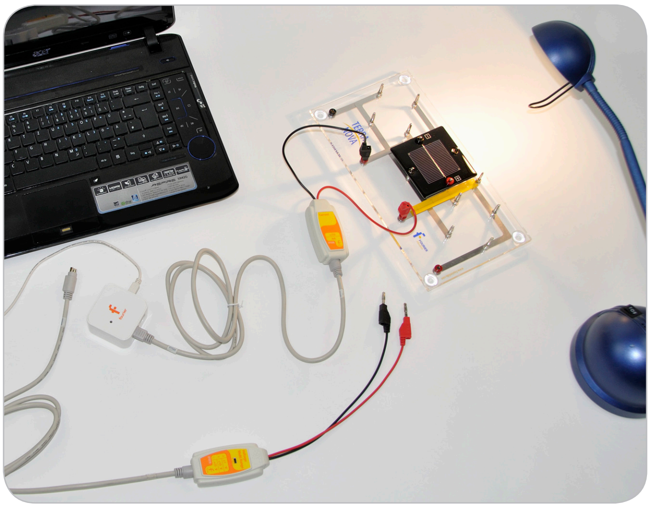
Principles of electrical circuits
Voltage and current

Time Frame

1 lesson

Equipment

1. Main board
2. 1 large solar cell
3. 1 current sensor
4. 1 voltage sensor
5. Desk light or equivalent (if you do not conduct the experiment in sunlight)
6. NOVA LINK



Equipment Setup Procedure

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. For voltage-measurement connect the voltage sensor to I/O-1 port of the NOVA LINK.
4. For current-measurement connect the current sensor to I/O-1 port of the NOVA LINK.
5. Plug the large solar cell onto the middle position of the main board.

MultiLab Setup

1. Click [gear icon].
2. Click **Next**.
3. Set **Select rate** to **Manual**.
4. Set **Select recording mode** to **Add**.
5. Click **Next**.
6. Set **by samples** to **50**.
7. Click **Finish**.

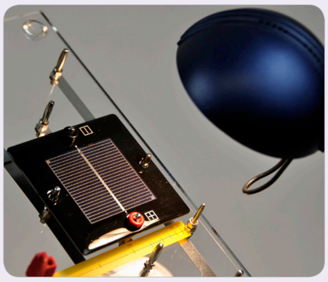
Notes

For this experiment the shadow bar and the angle scale of the base unit has to be used. It allows measuring the angle of incidence very easily. But this requires either to measure in direct sunlight or to use only one main light source in the room. Diffused light has to be avoided!

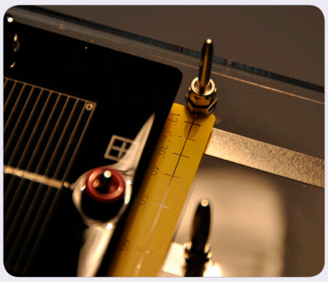
If you do the experiment in sunlight you have to use either a current sensor with a range of at least 1A or you use the small solar cell instead of the large one.

Experimental Procedure

1. Connect the voltage sensor parallel to the solar cell.
2. Align the main board to the sun or the main light source so that the angle. between the base unit and the incident light is 90° - this means the angle of incidence is 0°. Use the shadow bar of the main board for alignment: There should be no shadow visible.



3. Click [start icon].
4. Change the angle of the main board so that the shadow is parallel to the angle scale and reaches the 10° line.



5. Now change the angle to the values of 20°,30°,40°,50°,60°,70° and 75° and for each angle click [start icon].
6. Click [stop icon].
7. Exchange the voltage sensor by the current sensor and repeat step 1 to 4.
8. Click [save icon] to save your data.

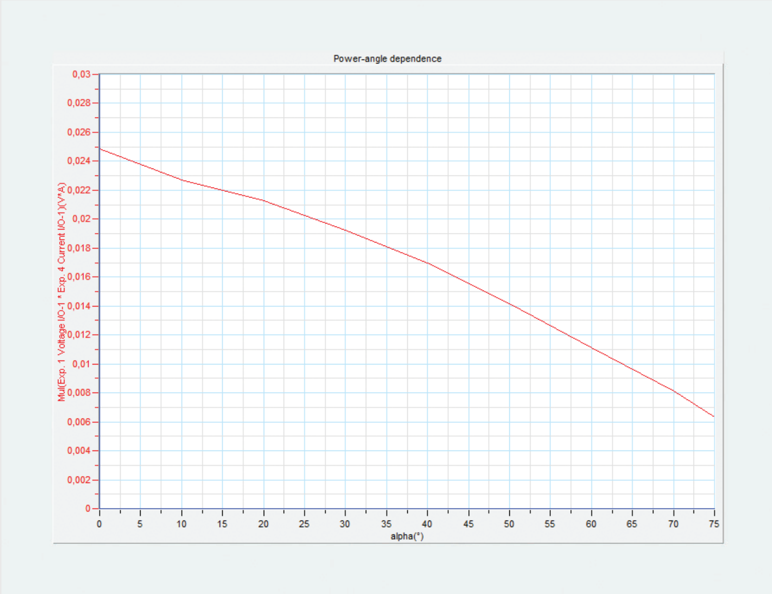
Data Analysis

1. Click **Table** > **Add manual column**.
2. Fill in the field for Column title : "**Angle**".
3. Click Ok.
4. Click f_x.
5. Click **Functions**.
6. Set **Functions** to **Multiply**.
7. Set **G1** and **G2** to the voltage and current measurement data.
8. Click **Ok**.
9. Click .
10. Add the columns of the current and voltage measurement, of the calculated power function and the column **angle**.
11. Set the name of the table to Overview.
12. Click Ok.
13. Fill the column angle with the correct numbers.
14. Click .

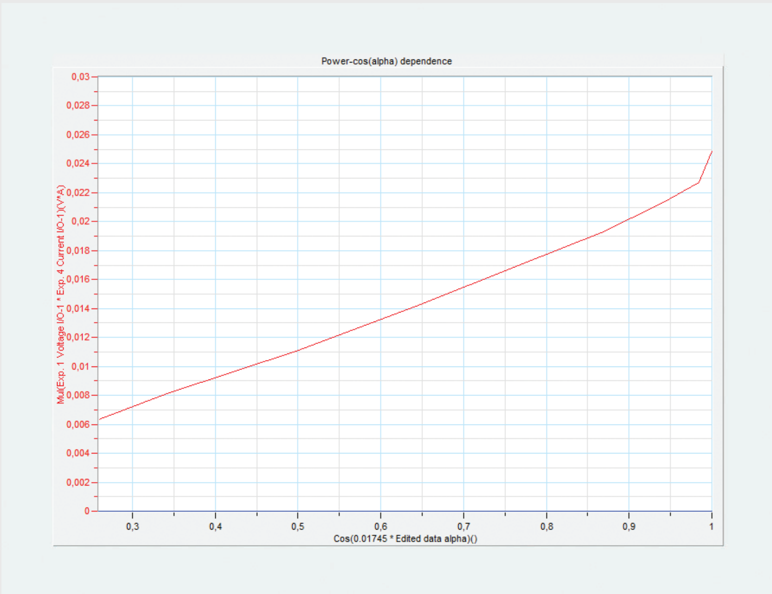
Plotting power vs. cosin (alpha)

1. Click f_x.
2. Click **Functions**.
3. In the tab **Functions** select **Cosine**.
4. Set G1 to **angle**.
5. Set B to **0.01745** (pi/180°).
6. Click **Ok**.
7. Click and add the cosine function as column.
8. Click .
9. Set the **X-axis** to the **Cos function**.
10. Set **Y-axis** to current and **the calculated cosine function**.

Expected Results



With increasing angle of incidence the power of the solar cell in decreasing.



If the power is plotted against the cosine of the angle a linear behavior can be found.

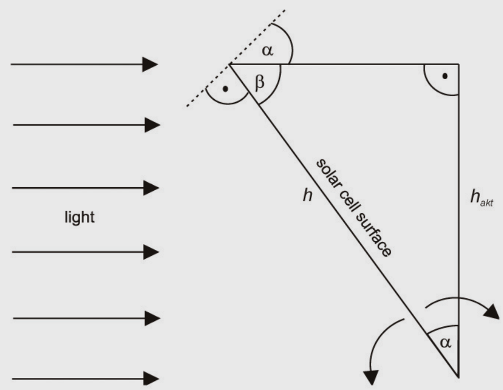
Questions

1. How do the current and the voltage depend on the angle of incidence?
2. What is the exact mathematical relation between the power and the cosin function of the angle?
3. Advanced: Explain this behavior geometrically.

Answers

1. The voltage is independent of the angle of incidence.
   The current is decreasing with increasing angle of incidence.
2. The current is directly proportional to the cosine of the angle.
3. The behavior can be explained by Lambert's law.

As explained in experiment 1, the photocurrent is proportional to the illuminated area of the solar cell. However, the area which is actually exposed to the incident light depends on the angle of the surface to the light. This fact can easily be demonstrated to the students by turning a sheet of paper in a beam of light and watching the shaded area. Only the part of the light which was taken out of the incident light beam (causing the shadow) can be converted into current by a solar cell.
In principle the explanation for this experiment is the same as for experiment 1. The only difference is that between the angle of incidence of light and the actual illuminated surface of the solar cell (Aact) there is no linear correlation. Hence, there can't be a linear connection between power and angle of incidence. The following geometrical relations show the actual connection:
The height of the cell be h, the width b and the surface area A. (compare with the figure). If the cell is turned into the light, the effective (and therefore active) height is reduced to hact. It follows that:
$h_{act} = h \cdot cos a.$
Since the active width is constant, the following applies for the active surface:
$A_{act} = h_{act} \cdot b = b \cdot h \cdot cos a = A \cdot cos a.$
As shown in Experiment 1:
$P \sim A_{act}.$
It follows that:
$P \sim cos a.$
Since the open circuit voltage of the solar cell mainly depends on the material but only to a small extend on the illumination, the following connections follow:
$I_{SC} \sim cos a$
$V_{OC} = const.$
The power shows almost the same dependence on the angle of incidence as the current.



Further Suggestions

As described in the explanation above, show the students how the shaded area of a sheet of paper behaves if it is introduced into the light beam of a beamer or an overhead projector.

3. Series and parallel connection of solar cells (qualitative)

Introduction

Individual solar cells can only be manufactured up to a size of about 6 inch by 6 inch (156mm x 156mm). Hence, to achieve large photovoltaic power plants it is necessary to connect many solar cells together. But how should solar cells be connected to each other? In this experiment series and parallel connection of solar cells can be compared in a qualitative way.

Also the problem of partly shaded solar modules can be introduced qualitatively.

Learning Objects

Investigate the differences between series and parallel connected solar cells by using the buzzer module.

Concepts

Principles of electrical circuits

Voltage and current

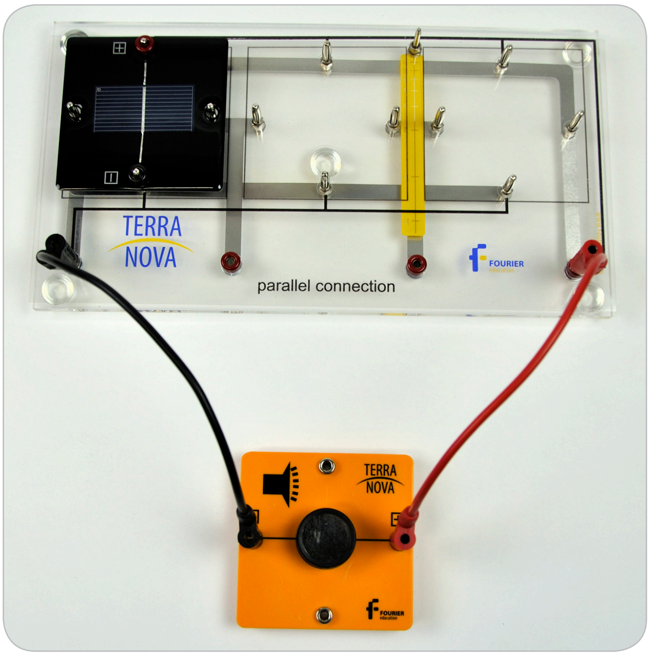
Students do not necessarily have to know the concepts of series and parallel connection but these terms can be introduced to them with this experiment.

Time Frame

1 lesson

Equipment

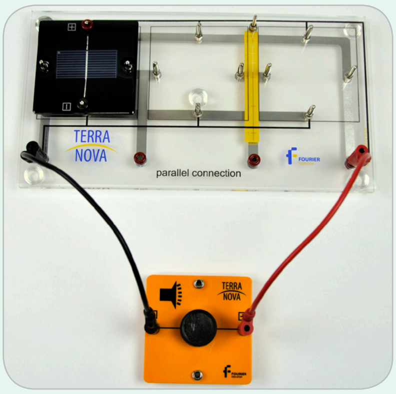
1. Main board
2. 3 small solar cells
3. 1 buzzer module
4. 2 cover sheets
5. 2 cables (not included in the kit)

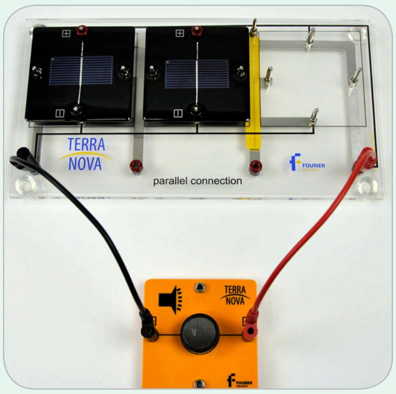


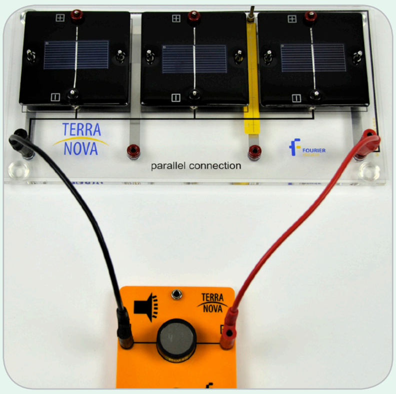
Equipment Setup Procedure

Experimental Procedure

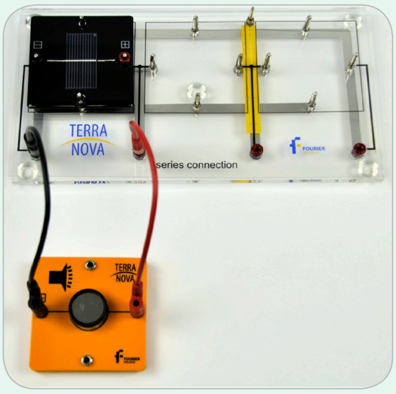
1. Measurement with parallel-connected solar cells
   a) Operate the buzzer with one solar cell, as well as two and three solar cells connected in parallel
   b) You can try different illumination conditions (e.g. sun light, desk lamp, room light)

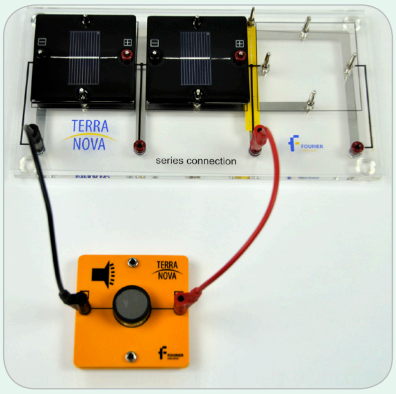






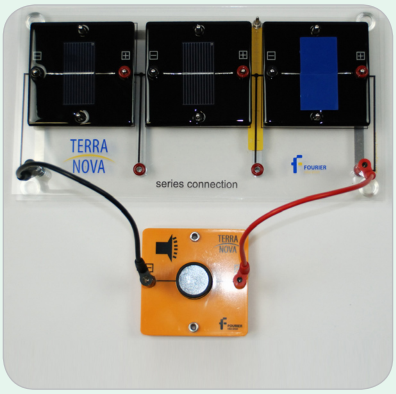
2. Measurement with series-connected solar cells
   a) Operate the buzzer with one solar cell, as well as two and three solar cells connected in series.
   b) You can try different illumination conditions (e.g. sun light, desk lamp, room light).



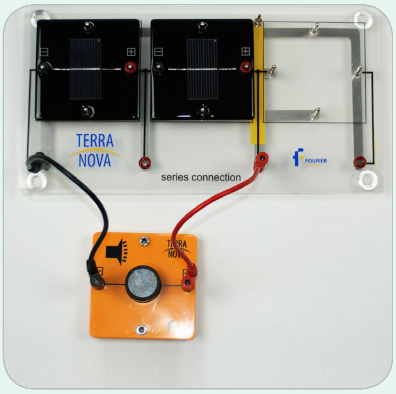


3. Partly shading of solar modules Set up the following circuits and compare the buzzer's sound level:

a) Three solar cells connected in series to the buzzer with one solar cell completely shaded by the solar cell covers.



b) Two solar cells connected in series to the buzzer.



Notes

This experiment can be conducted as preparation for Experiment 4. It allows a very easy understanding of series and parallel connection. It is applicable for students from 12 years.

Data Analysis

1. The buzzer does not work with parallel connected solar cells.
2. The buzzer only works with at least two solar cells connected in series.
3. Comparing the two circuits:
   a) The buzzer does not work.
   b) The buzzer gives a gentle tone.

Questions

1. What behavior of the buzzer do you observe with series connected solar cells?
2. What behavior of the buzzer do you observe with parallel connected solar cells?
3. What could be the reason for this behavior?
4. What is the result of your comparison of the two circuits? What is the conclusion from that?

Answers

1. The buzzer does not work with parallel connected solar cells.
2. The buzzer only works with at least two solar cells connected in series.
3. The buzzer needs a certain threshold voltage to operate. This threshold is larger than the voltage of one individual solar cell. Because the voltage of two solar cells connected in series is sufficient one can conclude that in series connection voltage is added. In parallel connection the voltage stays constant independent of the number of solar cells. So the buzzer does not work.
4. Comparing the two circuits:
   a) The buzzer does not work.
   b) The buzzer gives a gentle tone.
   Shading a solar cell in series connection has negative impact on total power. Obviously the shaded solar cell blocks the current of the other cells. Partial Shading of solar modules should therefore be avoided.

Further Suggestions

This experiment can be used as easy preparation for experiment 4 and 9 where the same effects are studied in a quantitative way using data loggers.

4. Series and parallel connected solar cells

Introduction

In Experiment 1 we have seen that the voltage of a solar cell is around 0,5V and this value cannot be increased by increasing the solar cell area. But such low voltages cannot be used for practical applications. So the question is: How can we achieve higher voltages with solar cells? In this experiment series and parallel connection of solar cells should be compared to determine the best solution for that problem.

Learning Objects

Determine the behavior of the total voltage and the total current of series- and parallel-connected solar cells!

Concepts

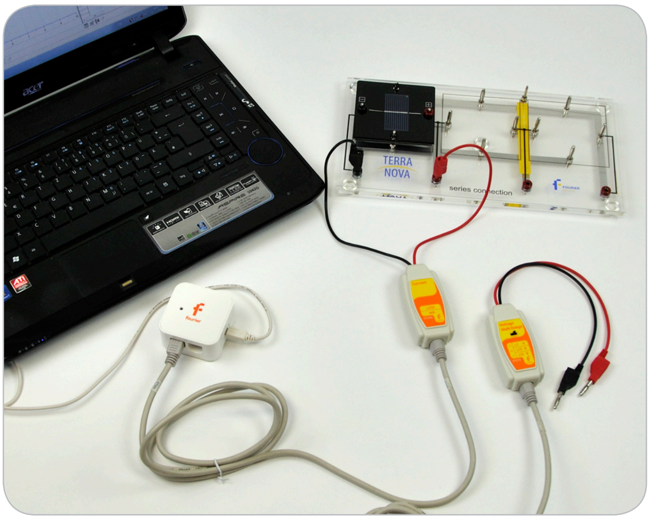
Principles of electrical circuits
Voltage and current
Students do not necessarily have to know the concepts of series and parallel connection but these terms can be introduced to them with this experiment

Time Frame

1 -2 lesson

Equipment

1. Main board
2. 3 small solar cells
3. 1 voltage sensor
4. 1 current sensor
5. NOVA LINK

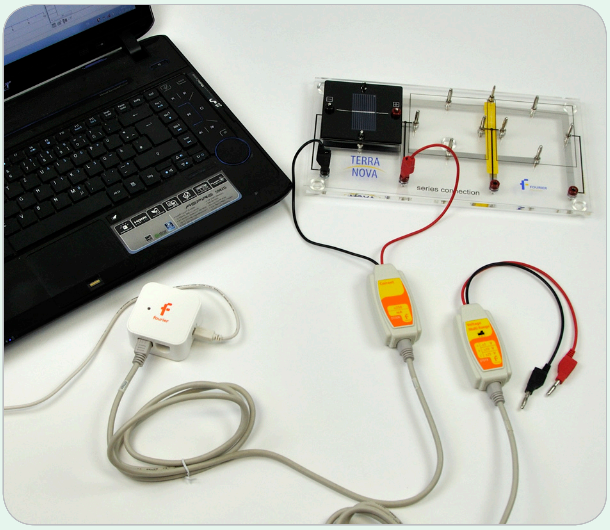


Equipment Setup Procedure

1. Launch MuliLab
2. Connect the NOVA LINK to the USB port on the computer.
   The green LED will turn on when the NOVA LINK is successfully connected to the computer

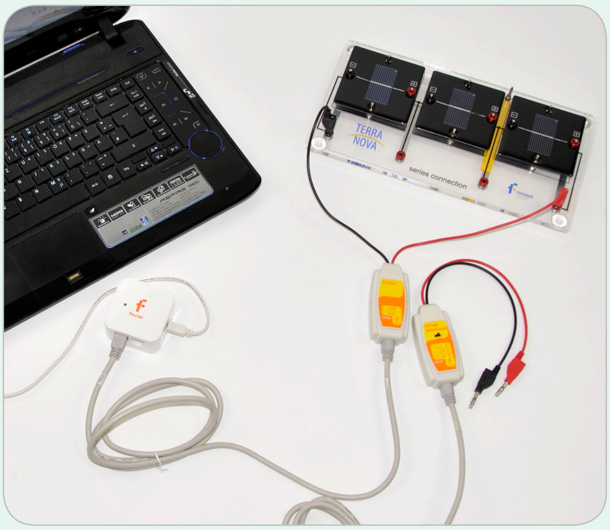
Setup 1:
Measurement with series-connected solar cells

1. Plug 1 small solar cells in series on the main board.
2. Set the voltage sensor to position "B".
3. For voltage measurement connect the voltage sensor to I/O -1 port of the NOVA LINK.
4. For current measurement connect the current sensor to I/O-1 port of the NOVA LINK.
5. Do not connect voltage sensor and current sensor at the same time with the solar cells.
6. Please note that in all pictures only the current sensor is connected – for the voltage measurement it has to be exchanged by the voltage sensor of course.



Setup 2:
Measurement with parallel-connected solar cells

1. Plug 1 small solar cell in parallel on the main board.
2. Set the voltage sensor to position A .
3. For voltage measurement connects the voltage sensor to I/O -1 port of the NOVA LINK.
4. For current measurement connect the current sensor to I/O-1 port of the NOVA LINK.
5. Do not connect voltage sensor and current sensor at the same time with the solar cells.
6. Please note that in all pictures only the current sensor is connected – for the voltage measurement it has to be exchanged by the voltage sensor of course.



MultiLab Setup

1. Click .
2. Click **Next**.
3. Set **Select rate** to **Manual**.
4. Set **Select recording mode** to **Add**.
5. Click **Next**.
6. Set **by samples** to **50**.
7. Click **Finish**.

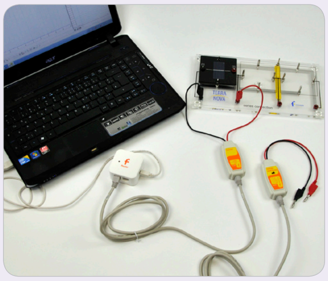
Notes

Pay attention to a homogeneous illumination of all modules, otherwise the voltage in the series setup and the current in the parallel setup will not show a linear increase with the numbers of solar cells.

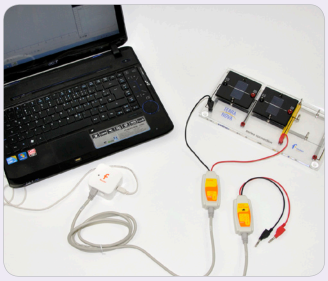
Experimental Procedure

Series connected solar cells (setup 1) - voltage measurement:

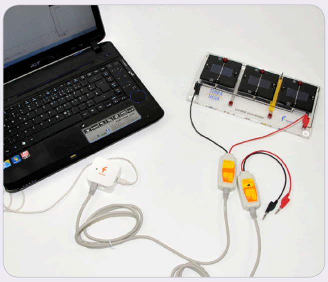
1. Connect the voltage sensor in series to one solar cell



2. Click .
3. Connect the voltage sensor in series to two solar cells



4. Click .
5. Connect the voltage sensor in series to all solar cells



6. Click .
7. Click .
8. Click to save your data.
9. Disconnect the voltage sensor.

Series connected solar cells (setup 1) - current measurement:

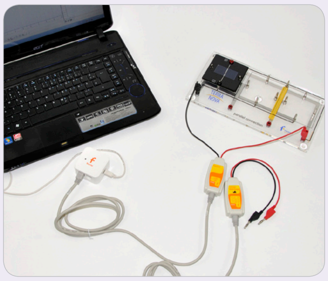
1. Connect the current sensor in series to one solar cell.
2. Click .
3. Connect the current sensor in series to two solar cells.
4. Click .
5. Connect the current sensor in series to all solar cells
6. Click .
7. Click .
8. Click to save your data.
9. Disconnect the voltage sensor.

Continue next page...

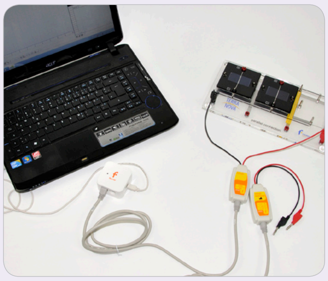
Experimental Procedure

Parallel connected solar cells (setup 2) - voltage measurement:

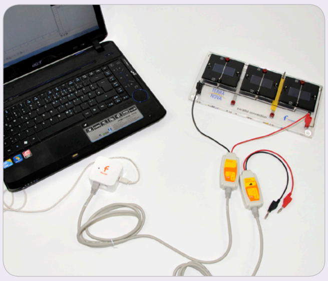
1. Connect the voltage sensor in series to one solar cell



2. Click .
3. Connect the voltage sensor in series to two solar cells



4. Click .
5. Connect the voltage sensor in series to all solar cells



6. Click .
7. Click .
8. Click to save your data.
9. Disconnect the voltage sensor.

series connected solar cells (setup 1) - current measurement:

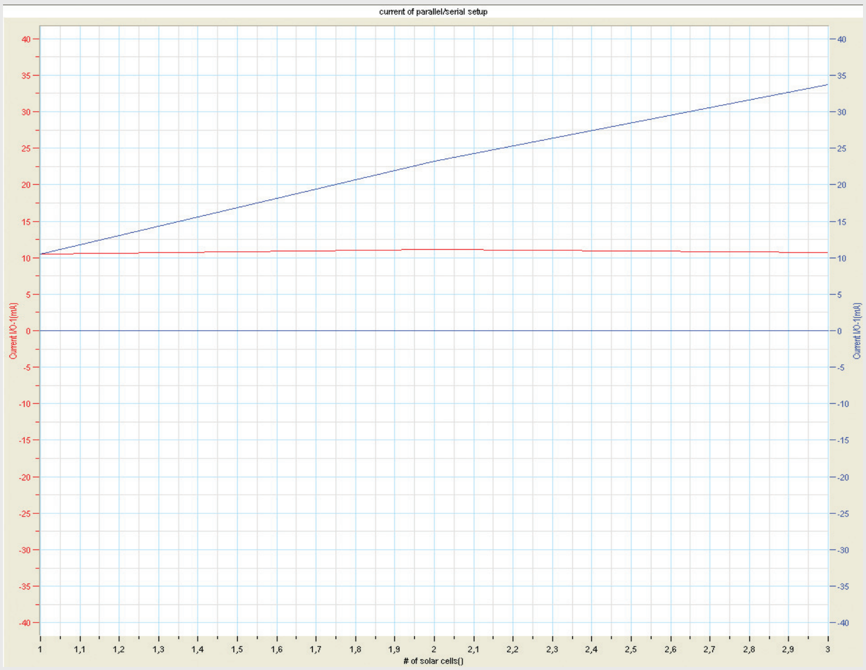
1. Connect the current sensor in series to one solar cell.
2. Click .
3. Connect the current sensor in series to two solar cells.
4. Click .
5. Connect the current sensor in series to all solar cells
6. Click .
7. Click .
8. Click to save your data.
9. Disconnect the current sensor.

Data Analysis

1. Click **Table** > **Add manual column**.
2. In the field **Column title fill in**: # of solar cells.
3. Click Ok.
4. Click .
5. Add all measurement data of the serial connected setup and the new column # **of solar cells** to **current columns**.
6. Write "**Serial Connected Setup**" in the field for the table name.
7. Click **Ok**.
8. Fill the column **# of solar cells** with the correct values according to your measurement (1 to 3).
9. Click .
10. Click .
11. Add all measurement data of the parallel connection and the new column **# of solar cells** to **current columns**.
12. Write "**Parallel Connected Setup**" in the field for the table name.
13. Click **Ok**.
14. Fill the column **# of solar cells** with the correct values according to your measurement (1 to 3).
15. Click .
16. Click .
17. Type "**Comparison of voltage of parallel/ serial setup**" in the field for the graph title.
18. Select **# of solar cells** as x-axis.
19. Select the datasets of the voltages for parallel and serial setup in the field for the y-axis .
20. Click **Ok**.
21. Click .
22. Click .
23. Type Comparison of current of parallel/serial setup in the field for the graph title.
24. Select # of solar cells as x-axis the.
25. Select the datasets of the current for parallel and serial setup in the field for the y-axis.
26. Click .

Expected Results

Red: serial setup / blue: parallel setup



Red: serial setup / blue: parallel setup

Questions

1. What behavior of the voltage do you see in graph 1?
2. What behavior of the current do you see in graph 2?
3. How could you explain the behavior of the voltage and current in the parallel setup?
4. How could you explain the behavior of the voltage and current in the serial setup?

Answers

1. In the serial setup an increase of the voltage with increasing number of solar cells can be seen.
   In the parallel setup the voltage stays constant with increasing number of solar cells.
2. In the serial setup the current stays constant with increasing number of solar cells.
   In the parallel setup the voltage increases with increasing number of solar cells.
3. The behavior in the parallel connection can be explained with Kirchhoff's point rule.
   According to that the overall current is the sum of the currents through the individual components.
4. The behavior can be explained with Kirchhoff's laws. The solar cells can be considered as separate voltage-sources and according to Kirchhoff's mesh rule these voltages have do add in series connection. Because the current only has one route through the circuit it stays constant. The highest current you can get from your solar module is the current of the solar cell with the lowest current.

Further Suggestions

Go to a photovoltaic power plant and investigate the modules there.
How many solar cells are connected in series in one module?
What should therefore be the voltage of such a module?
(In most cases commercially available modules feature nominal voltage in the range of 12...48 V.)

Let the students ask the operator at which current the plant is running
and how many modules are connected in series and in parallel.

5. Dependence of power on illumination

Introduction

Over the day, when the sun is "moving" across the sky, the illumination density on earth is changing. Therefore, also the power of solar cells is changing. In this experiment this relation should be observed.

Learning Objects

Measure the voltage and the current and determine the power of a solar cell under different illumination densities!

What relationship between the illumination and these three measured values can you identify?

Concepts

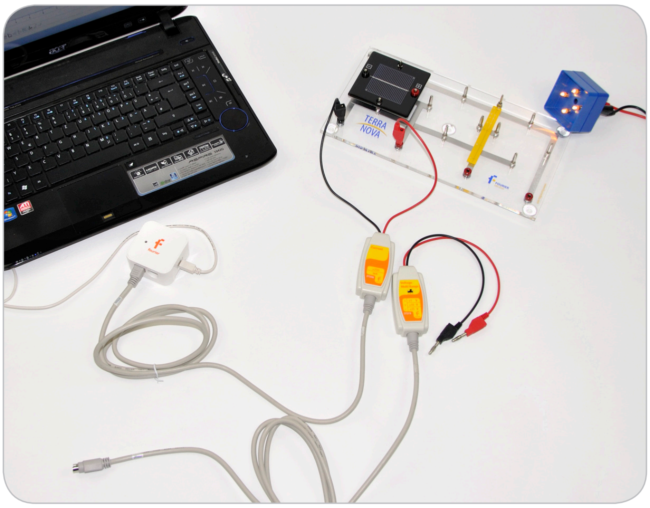
Principles of electrical circuits
Voltage and current

Time Frame

1 lesson

Equipment

1. Main board
2. 1 large solar cell
3. 1 voltage sensor
4. 1 current sensor
5. NOVA LINK
6. Illumination module and power supply (at 12V)



Equipment Setup Procedure

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Plug the solar cell onto the main board.
4. For current measurement connect the current sensor parallel to the solar cell and connect the current sensor to I/O-1 port of the NOVA LINK.
5. For voltage measurement connect the voltage sensor parallel to the solar cell and connect the voltage sensor to I/O-1 port of the NOVA LINK.
6. Be aware not to connect both sensors at the same time.
7. Connect the illumination module to the power supply.

MultiLab Setup

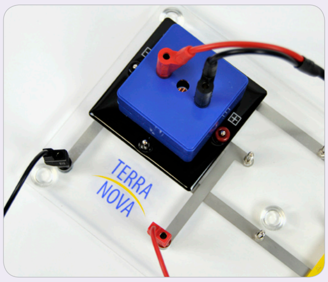
1. Click .
2. Click **Next**.
3. Set **Select rate** to **Manual**.
4. Set **Select recording mode** to **Add**.
5. Click **Next**.
6. Set **by samples** to **50**.
7. Click **Finish**.

Notes

The calculated power of the solar cell is higher than the real maximum power, because voltage V and current I are not measured at Maximum Power Point (MPP) but at open circuit voltage VOC and short circuit current Isc. This procedure makes the experiment much easier but nevertheless the qualitative results will be true.

Experimental Procedure

1. Connect the current sensor as described in the setup procedure.
2. Screw one bulb into the illumination module (only one should glow) and put it onto the solar cell.

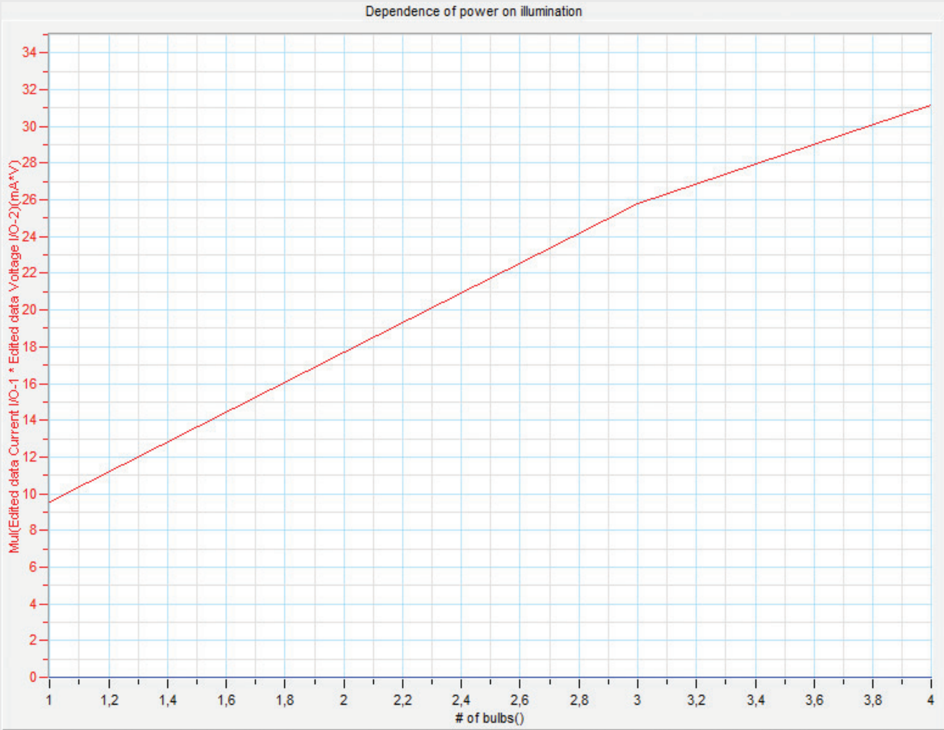


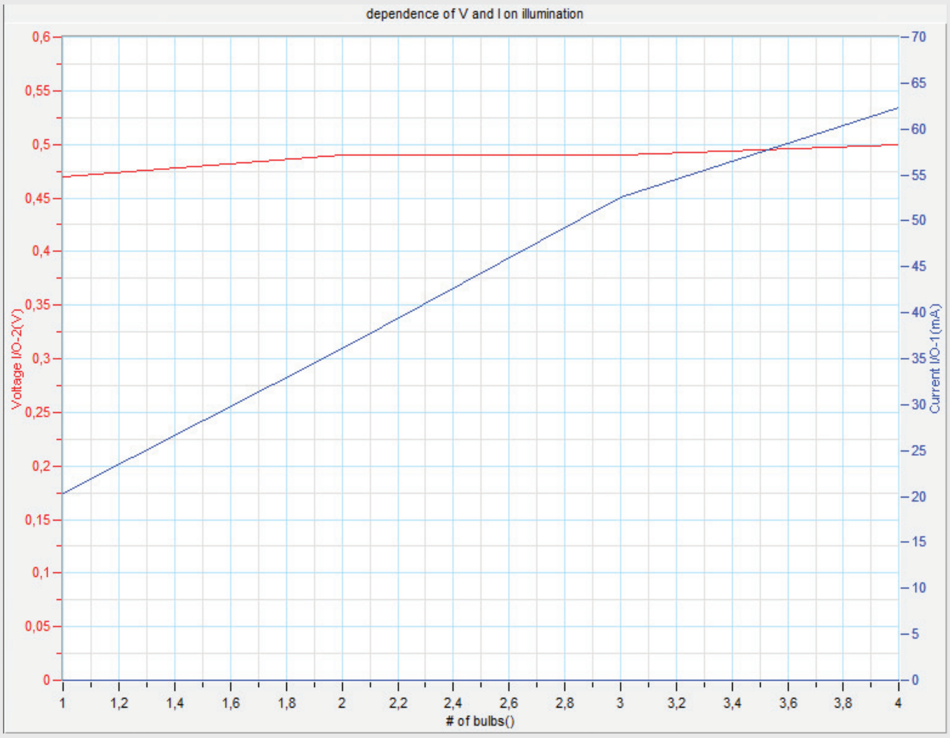
3. Click .
4. Screw one more bulb into the illumination module and put it again onto the solar cell.
5. Repeat step 2 to 3 till all bulbs are screwed into the illumination module.
6. Click .
7. Connect the voltage sensor as described under "Experiment Setup Procedure".
8. Repeat point 9.1 to 9.4.
9. Click .
10. Click to save your data.

Data Analysis

1. Click f_x .
2. Click **Functions**.
3. Set **Functions** to **Multiply**.
4. Select your voltage and current measurement dataset as **G1** and **G2**, respectively.
5. Click **Ok**.
6. Go to **Table** > **Add manual column**.
7. Set **Column name** to **# of bulbs**.
8. Click **Ok**.
9. Click .
10. Add the columns: #of bulbs, the current measurement, the voltage measurement and the calculated power function.
11. Click Ok.
12. Click .
13. Click .
14. Set **X-axis** to **# of bulbs**.
15. Set **Y-axis** to the measured current and voltage data points.
16. Set the **Graph title** to "**Voltage/Current/Power - Area Dependence**".
17. Click **Ok**.

Expected Results





The voltage stays nearly constant. In contrast, the current increases with higher illumination intensities. Therefore, power P also increases with higher illumination intensities.

Questions

1. How does the voltage depend on the illumination intensity?
2. How does the current depend on the illumination intensity?
3. From 1 and 2 what can be concluded concerning power?
4. Explain the behavior!

Answers

1. The voltage is nearly constant. There is only a weak dependence between illumination intensity and the Voc. (A detailed investigation would lead to a logarithmic relations between illumination intensity and voltage.)
2. The current increases linearly with illumination intensity.
3. Because power P is the product of voltage V and current I, it also increases linearly with the light intensity.
4. The voltage is only dependent on the material as we already have seen in Experiment 1. It only changes slightly with illumination intensity (according to a logarithmic law). With increasing illumination intensity the number of photons hitting the solar is increasing. As we already have seen in the explanation of experiment 1 this results in a higher number of excited electrons. This results in a higher current.

Further Suggestions

Compare the measured values with data obtained under direct sunlight / a desk lamp / in normal room light!

6. IV-characteristics of a solar cell

Introduction

The range of possible loads for a solar cell can vary much. The question is: Does the output power of the solar cell depend on the load? What are practical consequences for such a dependency? These questions can be answered by measuring the current a solar cell is generating in dependence of the voltage that is produced by the solar cell. The according diagram is called IV-characteristics which should be measured in this experiment.

Learning Objects

Measure the I-V-characteristics of a solar cell and determine its maximum power point (MPP).

Concepts

Principles of electrical circuits

Characteristic values of solar cells

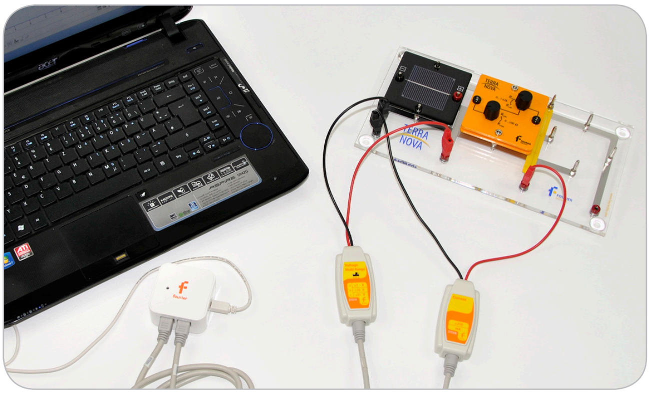
Maximum Power Point (MPP) and Fill Factor (FF) of a solar cell

Time Frame

2 lesson

Equipment

1. Main board
2. 1 large solar cell
3. 1 potentiometer module
4. 1 current sensor
5. 1 voltage sensor
6. NOVA LINK



Equipment Setup Procedure

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.
5. Plug the large solar cell and the potentiometer module on the main board so that both are connected in series.
6. Connect the voltage sensor parallel to the solar cell (and set the range to A if you have a triple-range sensor).
7. Connect the current sensor in series to the solar cell and the potentiometer module so that the electrical circuit is closed.

MultiLab Setup

1. Click .
2. Click **Next**.
3. Click **X–axis** display properties.
4. Set Select measurement to Voltage.
5. Click **Ok**.
6. Set **Select rate** to **Manual**.
7. Set **Select recording mode** to **Add**.
8. Click **Next**.
9. Set **by samples** to **50**.
10. Click **Finish**.

Notes

The light intensity should not be too high to get a well-defined I-V-curve. Direct sunlight is not recommended. Alternatively the illumination module driven at 6V can be used.

Experimental Procedure

During the experiment the illumination of the solar cell should stay constant!

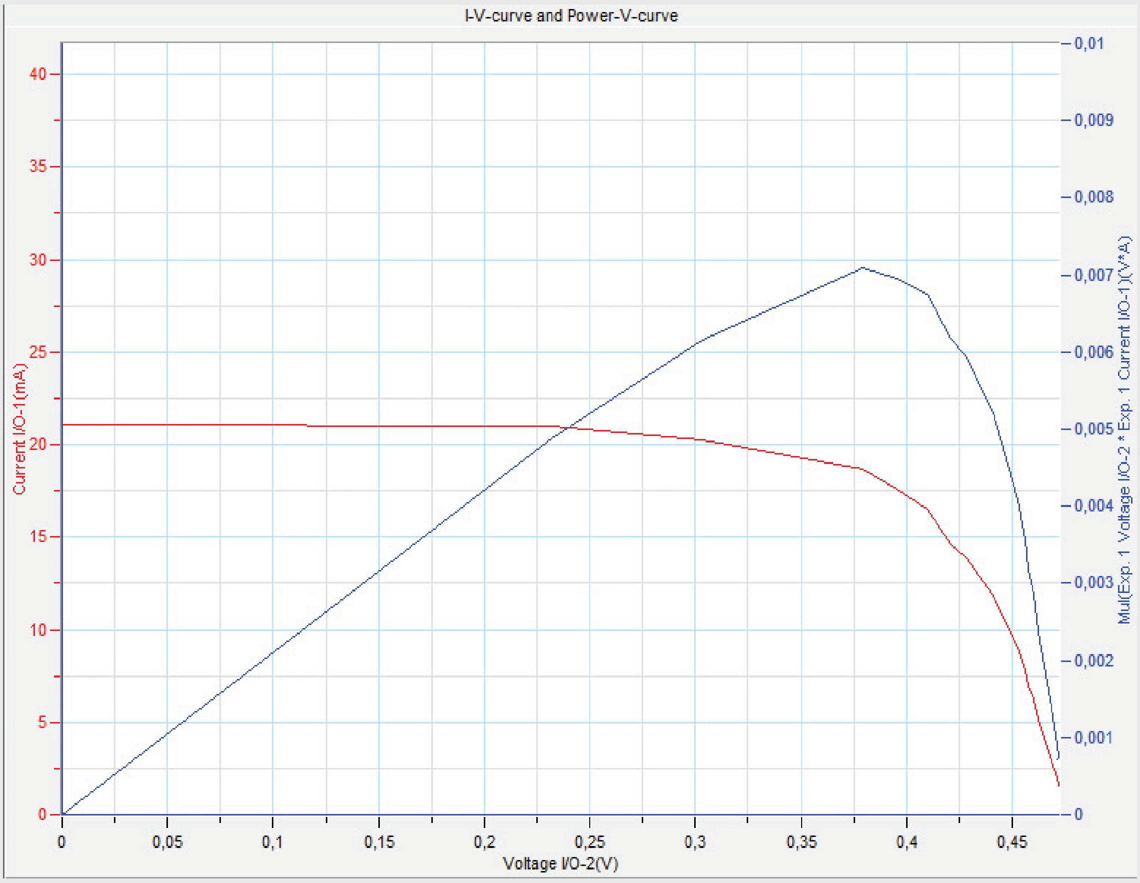
1. Set the potentiometer to the lowest resistance (turn both knobs to Rmin).
2. Click .
3. Turn the knob of the 100Ω-potentiometer clockwise in small steps – as more steps as more accurate will the result be.
4. Click .
5. When you reach the maximum position of the potentiometer start turning the knob of the 1kΩ-potentiometer (in quarter turns).
6. Click .
7. Click .
8. Click to save your data.

Data Analysis

Power Calculation

1. Click f_x .
2. Click **Functions**.
3. Set **Functions** to **Multiply**.
4. Select your voltage and current measurement dataset as **G1** and **G2**, respectively.
5. Click **Ok**.
6. Click .
7. Add the calculated function to **Current columns** (Attention: Do not change the order!).
8. Set the **Table name** to "**Power**".
9. Click **Ok**.
10. Click .

Expected Results



The voltage stays nearly constant. In contrast, the current increases with higher illumination intensities. Therefore, power P also increases with higher illumination intensities.

Questions

1. Read the following characteristic values from your measurement using using the first cursor :

Isc	Uoc	IMPP	UMPP	PMPP	FF

The fill factor (FF) is defined as FF=Uoc*Isc / UMPP*IMPP.

2. At which working point should a solar cell be used for energy generation and why? How can this be realized?
3. What would be the optimal load for the solar cell in the experiment?

Answers

1.

Isc	Uoc	IMPP	UMPP	PMPP	FF
21 mA	0,48 V	18mA	0,38V	6,8mW	67%

2. The solar cell should be used at its MPP. Only there the maximal power of the solar cell can be extracted. The easiest way to realize this, is to use a load with a resistance of RMPP=UMPP/IMPP. But the next experiments will show that the MPP is not constant. Therfore, this answer is only valid for the special conditions of this experiment.
3. In the experiment RMPP=0,38V/18mA=21Ω.

Further Suggestions

Compare the IV-characteristics of different voltage sources (e.g. a battery or a power supply) to the measured one of the solar cell.

7. IV-characteristics under varying illumination intensity

Introduction

In Experiment 6 we have seen that a solar cell should always be driven at MPP. Otherwise one can not get the maximal power out of the solar cell. In this experiment the variation of the MPP with illumination intensity should be investigated. This is a very practical question because illumination intensity is varying all over the day for real photovoltaic power plants.

Learning Objects

Measure the I-V-curve and determine the maximum power point (MPP) of the solar cell at different illumination intensities!

Concepts

Principles of electrical circuits

Characteristic values of solar cells

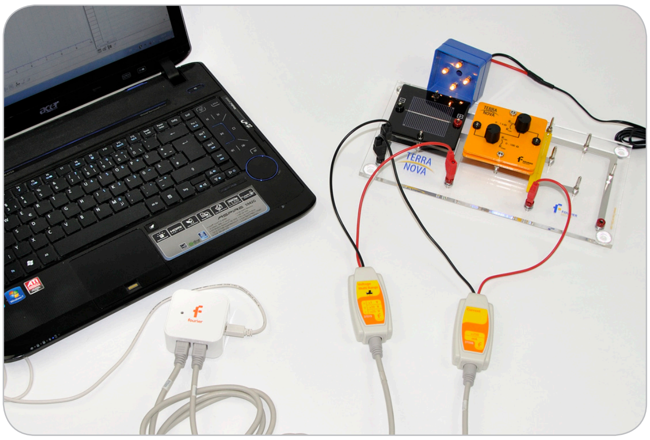
IV-characteristics of solar cells (experiment 6)

Time Frame

2 lesson

Equipment

1. Main board
2. 1 large solar cell
3. 1 current sensor
4. 1 voltage sensor
5. NOVA LINK
6. 1 potentiometer module
7. Illumination module connected to power supply (9V)



Equipment Setup Procedure

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.
5. Plug the large solar cell and the potentiometer module on the main board so that both are connected in series.
6. Connect the voltage sensor parallel to the solar cell (and set the range to a if you have a triple-range sensor).
7. Connect the current sensor in series to the solar cell and the potentiometer module so that the electrical circuit is closed.

MultiLab Setup

1. Click .
2. Click **X – axis display properties**.
3. Set **Select measurement** to **Voltage**.
4. Click **Ok**.
5. Click **Next**.
6. Set **Select rate** to **Manual**.
7. Set **Select recording mode** to **Add**.
8. Click **Next**.
9. Set **by samples** to **50**.
10. Click **Finish**.

Notes

In this experiment the IV-characteristics of a solar cell under different illumination intensities should be compared. The light intensity should not be too high to get a better I-V-curve. Do not use higher voltages than 9V for the illumination module!

Experimental Procedure

1. Unscrew all lamps of the illumination module except for one (only one should glow).
2. Connect the illumination module to the power supply and put it onto the solar cell.
3. Set the potentiometer to the lowest resistance (turn both knobs to Rmin).
4. Click .
5. Turn the knob of the 100Ω-potentiometer clockwise in small steps – as more steps as more accurate will the result be.
6. Click after each step.
7. When you reach the maximum position of the potentiometer start turning the knob of the 1kΩ-potentiometer (in quarter turns).
8. Click after each step.
9. When reaching the maximum position Click .
10. Screw one more bulb into the illumination module and start with 3.

Data Analysis

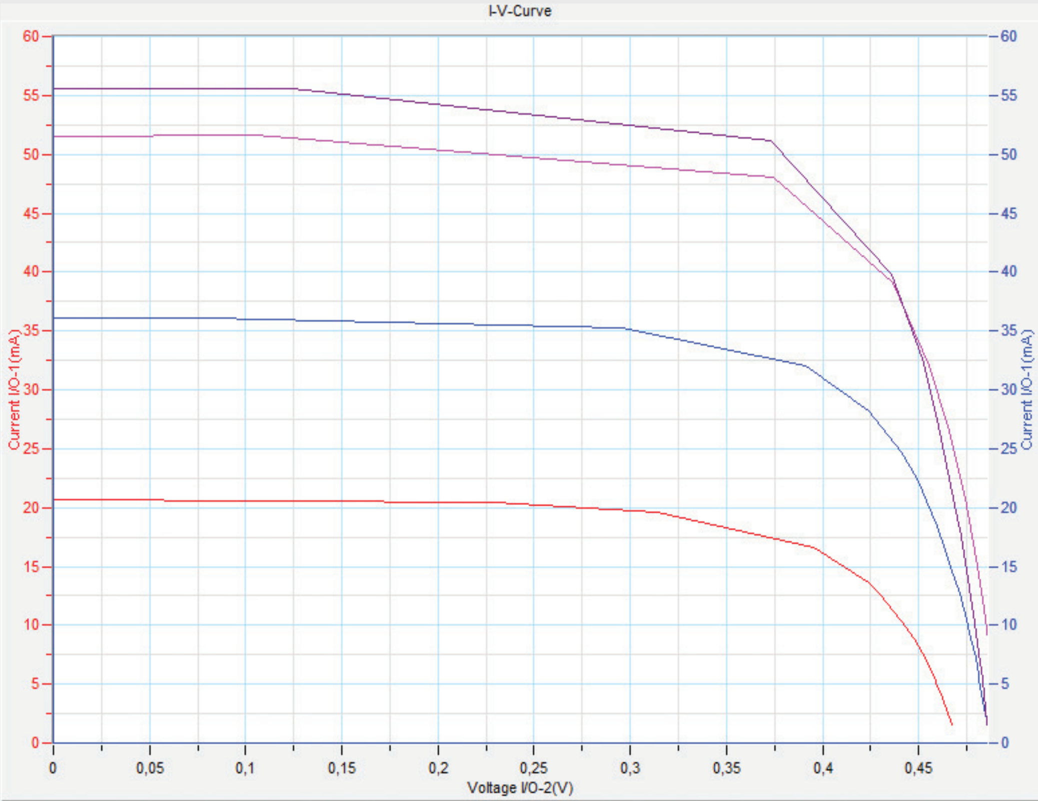
I-V-curve

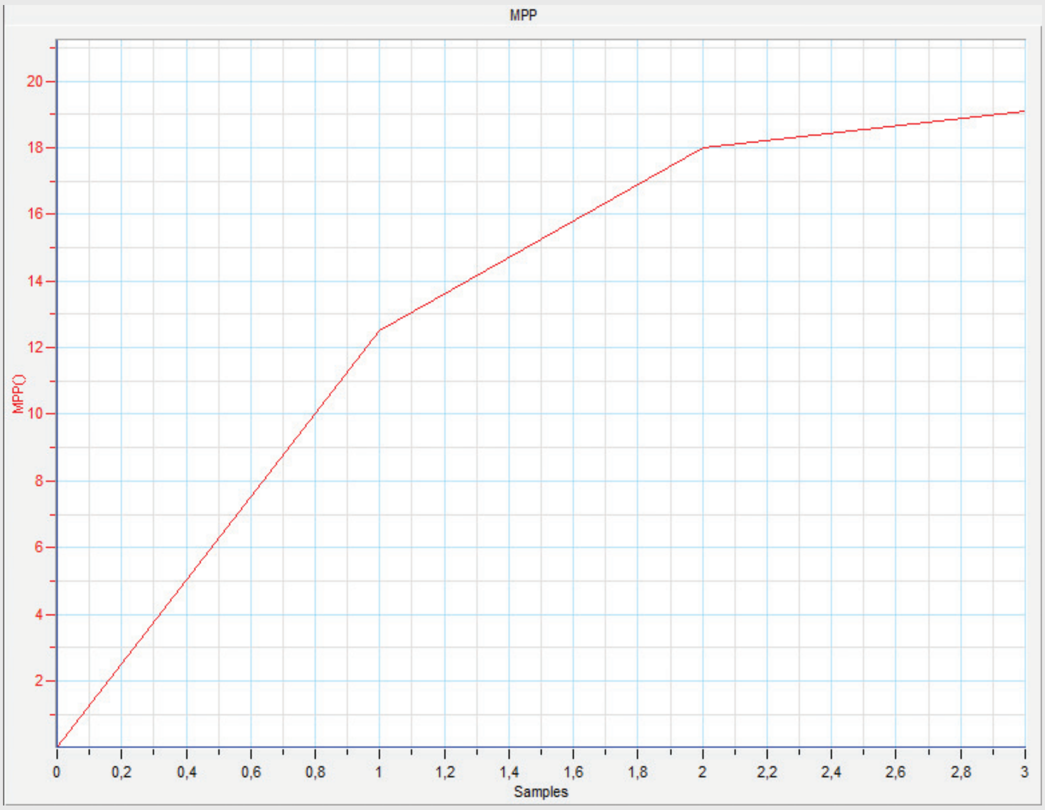
1. Click .
2. Set **X-Axis** to **Voltage**.
3. Set **Y-Axis** to all measured currents.
4. Set **Graph title** to "**I-V-Curve**".
5. Click **Ok**.
6. Find the highest measured current in your data and copy the value to the clipboard.
7. Click (in plots).
8. Select the first current dataset.
9. Deselect Autoscale.
10. Set Min: to 0 and Max: insert the highest measured current from the clipboard
11. Repeat the last three steps for all current datasets.
12. Click Ok.
13. Click .

Power calculation

1. Click f_x .
2. Click **Functions**.
3. Set **Functions** to **Multiply**.
4. Select the first measured voltage and current dataset as **G1** and **G2**, respectively.
5. Click **Ok**.
6. Repeat these steps for the next 3 measurements.
7. Click .
8. Add all calculated functions to Current columns (Attention: Do not change the order!).
9. Set the Table name to Power.
10. Click ok.
11. Click .

Expected Results





Questions

1. Describe the differences of the four I-V-characteristics with your own words.
   Which characteristic values stay constant and which are varying?
2. What is the practical consequence for the fact that the MPP changes with illumination intensity?

Answers

1. The principal shape of the IV-characteristics does not change with illumination intensity.
   But as already seen in Experiment 5, the short circuit current is increasing with illumination intensity.
   That is why the IV-characteristics scales in y-direction whilst Voc stays almost constant.
2. During the day the MPP is changing permanently because the illumination intensity is not constant over the day. Therefore a permanent MPP-tracking has to be realized to always get the maximal power out of the solar cell. This can be done with a so called MPP-tracker. In PV power plants this is realized by the inverter module that converts the DC current of the solar modules into AC power for feed-in to the power network.

8. IV-characteristics of a solar module

Introduction

In practice only solar modules consisting of many individual solar cells connected in series are used (compare experiment 3). Therefore, in this experiment the IV-characteristics of a solar module – not an individual solar cell – should be measured.

Learning Objects

Measure the I-V-characteristics of a solar module and determine its maximum power point (MPP).

Concepts

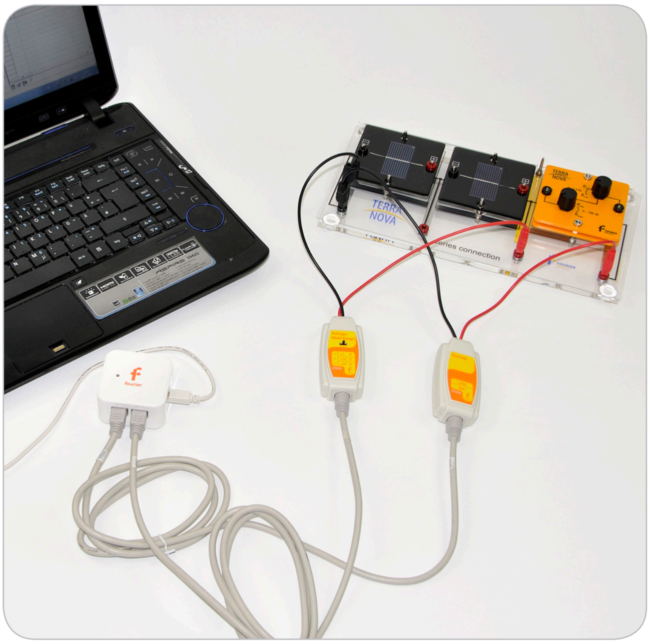
Principles of electrical circuits
Characteristic values of solar cells
IV-characteristics (experiment 6)

Time Frame

1 lesson

Equipment

1. Main board
2. 2 small solar cell
3. 1 current sensor
4. 1 voltage sensor
5. NOVA LINK
6. 1 potentiometer module



Equipment Setup Procedure

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.
5. Plug the 2 small solar cells and the potentiometer module on the main board so that all are connected in series.
6. Connect the voltage sensor parallel to both solar cells (and set the range to B if you have a triple-range sensor).
7. Connect the current sensor in series to the solar cells and the potentiometer module so that the electrical circuit is closed

MultiLab Setup

1. Click .
2. Click **X – axis display properties**.
3. Set **Select measurement** to **Voltage**.
4. Click **Ok**.
5. Click **Next**.
6. Set **Select rate** to **Manual**.
7. Set **Select recording mode** to **Add**.
8. Click **Next**.
9. Set **by samples** to **50**.
10. Click **Finish**.

Notes

The light intensity should not be too high to get a well-defined I-V-curve. Direct sunlight is not recommended

Experimental Procedure

1. Set the potentiometer to the lowest resistance (turn both knobs to Rmin).
2. Click .
3. Turn the knob of the 100Ω-potentiometer clockwise in small steps – as more steps as more accurate will the result be.
4. After each step click .
5. When you reach the maximum position of the potentiometer start turning the knob of the 1kΩ-potentiometer (in quarter turns).
6. After each step click .
7. When reaching the maximum position Click .
8. Click to save your data.

Data Analysis

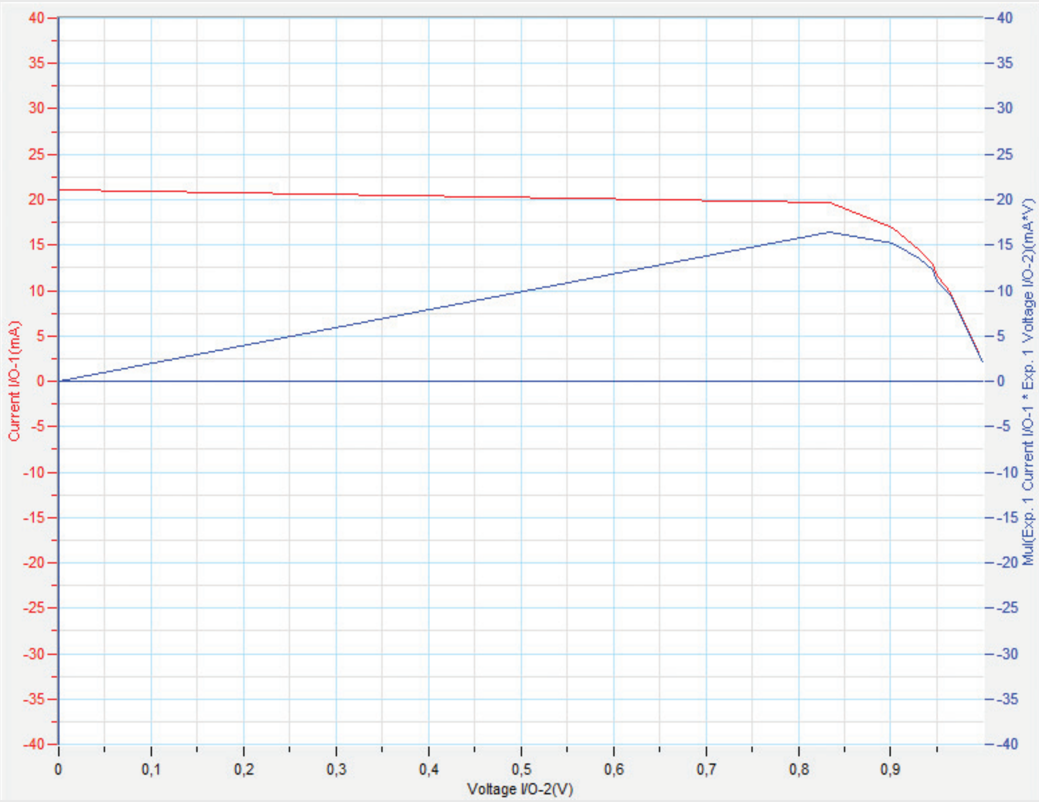
I-V-curve

1. Click .
2. Set X-Axis to Voltage.
3. Select the measured current dataset as **Y-Axis**.
4. Set **Graph title** to "**I-V-Curve**".
5. Click Ok.
6. Click .

Power calculation

7. Click f_x .
8. Click **Functions**.
9. Set **Functions** to **Multiply**.
10. Select the first measured voltage and current dataset as **G1** and **G2**, respectively.
11. Click **Ok**.
12. Click .
13. Add all calculated functions to Current columns (Attention: Do not change the order!).
14. Set the Table name to "**Power**".
15. Click ok.
16. Click .

Expected Results



Questions

1. Fill the table, using the first cursor , with the values from the measurement.
   The fill factor (FF) is defined as FF=Uoc*Isc / UMPP*IMPP.

Isc	Uoc	IMPP	UMPP	PMPP	FF

2. What is the qualitative difference of the IV-curve compared with that of Experiment 6 and why? How do the characteristic values differ especially the fill factor?

Answers

1.

Isc	Uoc	IMPP	UMPP	PMPP	FF
22mA	1V	20mA	0,85V	17mW	77%

2. The Voc has doubled compared to experiment 6 because the voltages add in series connections (compare Experiment 4). The IV-characteristics is therefore scaled in x-direction. The fill factor is also increasing for series connected solar cells. This means series connections are advantageous concerning fill factor.

Further Suggestions

You can also measure the IV-characteristics of a solar module consisting of 3 solar cells. In this case, the potentiometer module has to be connected to the base unit in series by external cables. You will achieve an IV-characteristics scaled in x-direction. The Voc will be three times the Voc of a single solar cell and fill factor will increase again.

9. Partly shaded solar modules

Introduction

In large PV power plants it often comes to situations where parts of the plant are shaded. This can for example happen if a tree is situated near the PV power plant and during the day it casts a cloud over the solar modules. In this experiment we want to investigate the impact of such a partly shading of solar modules.

Furthermore the concept of so called bypass-diodes is introduced in this experiment.

Learning Objects

How do the total voltage and total current of three series/parallel-connected solar cells change when one of the cells is shaded?

How do these values change if a solar cell with a parallel-connected diode is shaded?

Concepts

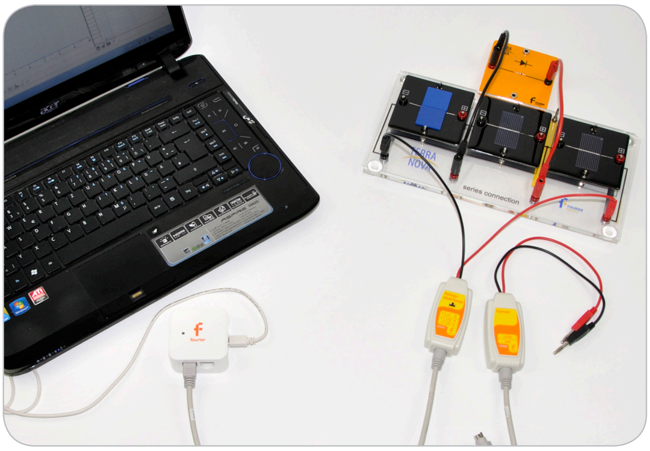
Functionality of a diode
Principles of electrical circuits

Time Frame

1 lesson

Equipment

1. Main board
2. 3 small solar cells
3. Diode module
4. 1 current sensor
5. 1 voltage sensor
6. NOVA LINK
7. 4 covers for the solar cells

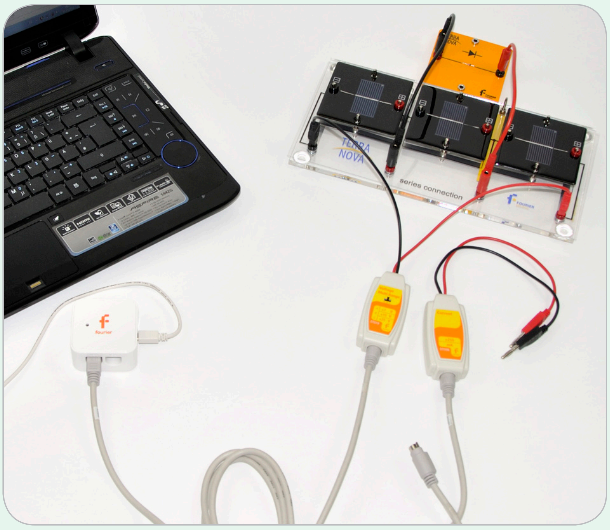


Equipment Setup Procedure

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer.
   The green LED will turn on when the NOVA LINK is successfully connected to the computer.

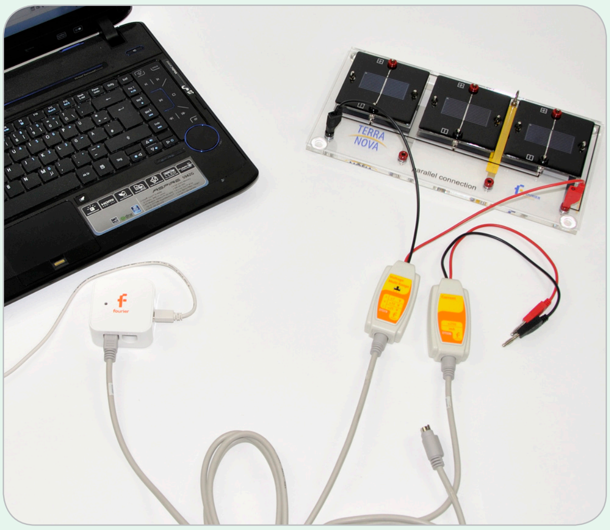
Setup 1:
Measurement with series-connected solar cells

1. Plug 3 small solar cells in series on the main board.
2. Connect the diode parallel to one solar cell.
3. For current-measurements connect the current sensor parallel to all solar cells and connect the current sensor to I/O-1 port of the NOVA LINK.
4. For voltage-measurements connect the voltage sensor parallel to all solar cells and connect the voltage sensor to I/O-1 port of the NOVA LINK.
5. If you have a triple range voltage sensor set it to position B.
6. Do not connect voltage sensor and current sensor at the same time with the solar cells.



Setup 2:
Measurement with parallel-connected solar cells

1. Plug 3 small solar cells parallel on the main board.
2. For current measurements connect the current sensor parallel to all solar cells and connect the current sensor to I/O-1 port of the NOVA LINK.
3. For voltage measurements connect the voltage sensor parallel to all solar cells and connect the voltage sensor to I/O-1 port of the NOVA LINK.
4. If you have a triple range voltage sensor set it to position A.
5. Do not connect voltage sensor and current sensor at the same time with the solar cells.
6. Note that in all pictures only the current sensor is shown! For voltage. measurements it has to be exchanges by the voltage sensor.



MultiLab Setup

1. Click ⚙.
2. Click **Ok**.
3. Click **Next**.
4. Set **Select rate** to **Manual**.
5. Set **Select recording mode** to **Add**.
6. Click **Next**.
7. Set **by samples** to **50**.
8. Click **Finish**.

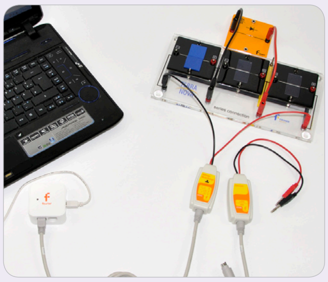
Notes

An often made mistake is that students use the diode in wrong polarity. It has to be connected reverse biased to the solar cell.

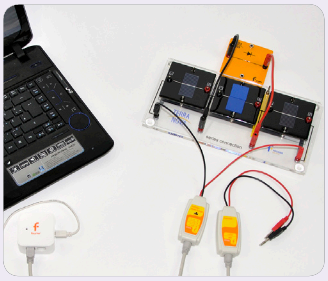
Experimental Procedure

Procedure for Setup 1

1. Connect the voltage sensor as described in setup 1
2. Click .
3. Shade one of the solar cells where no diode is connected in parallel using the blue covers.



4. Click .
5. Shade the solar cells where the diode is connected in parallel .



6. Click .
7. Click .
8. Connect the current sensor as described in setup 1.
9. Click .
10. Shade one of the solar cells where no diode is connected in parallel using the blue covers.
11. Click .
12. Shade the solar cells where the diode is connected in parallel.
13. Click .
14. Click .
15. Click to save your data.
16. Click f_x .
17. Click **Functions**.
18. Set **Functions** to **Multiply**.
19. Select the voltage and current measurement datasets as **G1** and **G2**, respectively.
20. Click **Ok**.
21. Click .
22. Add the columns **Voltage, Current** and the **calculated function** to the table.
23. Set the name of the table to series connected solar cells with parallel connected diode.
24. Click Ok.
25. Click .
26. Click .
27. Set the graph title to series connected solar cells with parallel connected diode.
28. Select the datasets: current, voltage and the calculated function of the power as Y-axis
29. Click Ok.
30. Click .

Experimental Procedure

Procedure for setup 2

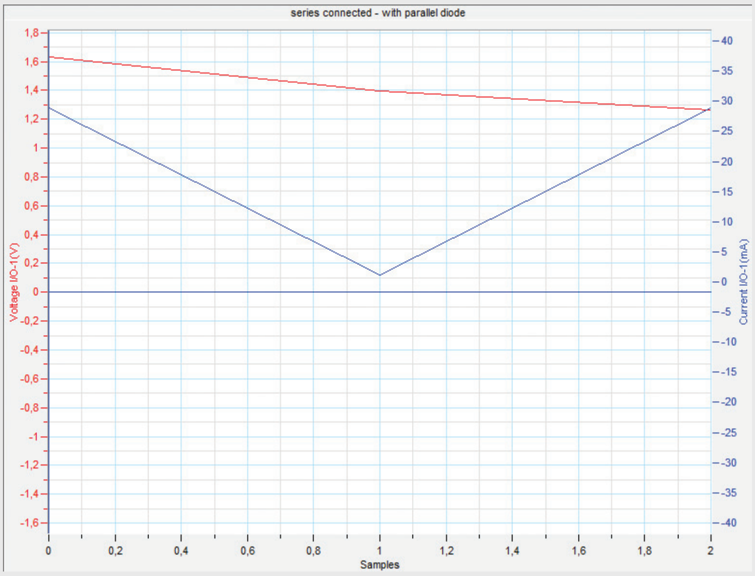
1. Connect the voltage sensor as described in setup 2
2. Click .
3. Shade one of the solar cells.
4. Click .
5. Shade two solar cells.
6. Click .
7. Click .
8. Connect the current sensor as described in setup 2.
9. Click .
10. Shade one of the solar cells.
11. Click .
12. Shade two solar cells.
13. Click .
14. Click .
15. Click to save your data.
16. Click f_x.
17. Click **Functions**.
18. Set **Functions** to **Multiply**.
19. Select the voltage and current measurement datasets as **G1** and **G2**, respectively.
20. Click **Ok**.
21. Click .
22. Add the columns **Voltage, Current** and the **calculated function** to the table.
23. Set the name of the table to "**Parallel Connected Solar Cells**"
24. Click Ok.
25. Click .
26. Click .
27. Set the graph title to "**Parallel Connected Solar Cells**" .
28. select the datasets: current, voltage and the calculated function of the power as Y-axis
29. Click Ok.
30. Click .
31. Click to save your data.

Data Analysis

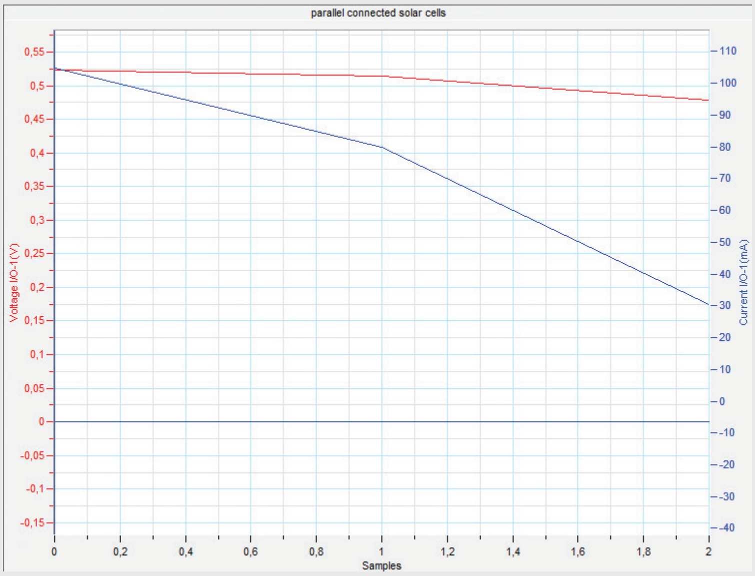
I-V-curve

1. Click .
2. Select the current datasets of the measurement with parallel and series connected solar cells as Y-axis.
3. Click Ok.
4. Click .
5. Select the voltage datasets of the measurement with parallel and series connected solar cells as Y-axis.
6. Click Ok .
7. Click
8. Select the power datasets of the measurement with parallel and series connected solar cells as Y-axis.
9. 10. Click Ok.

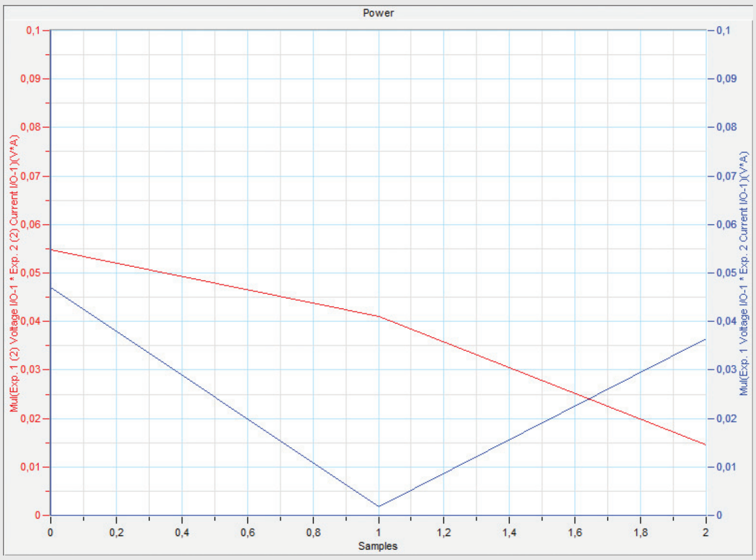
Expected Results



Sample 0: nothing shaded;
Sample 1: solar cell w/o bypass diode is shaded;
Sample 2: solar cell with bypass diode shaded



Sample 0: nothing shaded;
Sample 1: 1 solar cell shaded;
Sample 2: two solar cells shaded



Questions

1. What differences in the behavior of the voltage and the current of series connected solar cells do you observe? Compare the two cases: 1. Shaded solar cell has no diode connected in parallel and 2. Shaded solar cell has a diode connected in parallel.
2. What is the reason for your findings?
3. Do the same comparison as in 1 for parallel connected solar cells.
4. What is the overall conclusion?

Answers

1. For the voltage it makes no difference which solar cell is covered, it stays nearly constant. The current in contrast, is much influenced by shading if no diode is connected – it almost goes down to zero. With introducing a diode to the shaded solar cell the current almost recovers to its original value.
2. The reason is that the diode works as a bypass for the current. (That is why this diode is also called bypass diode in photovoltaic technology.) If a solar cell is shaded it produces no current anymore. And as we have seen in experiment 3, the solar cell with the lowest current limits the overall current in series connections. So in the case of shading the overall current goes down to zero. If a bypass diode is introduced the shaded solar cell is not blocking the current anymore and the current of the non-shaded solar cells can flow again – but through the diode now.
3. In parallel connection a bypass diode is not necessary because the solar cell with the lowest current is not limiting the overall current (compare experiment 3). The power just decreased according to the shaded area.
4. As we have already learned in experiment 3, in series connections of solar cells always the cell with the lowest current limits the overall current. If one solar cell is completely shaded the overall current is going to zero. Hence, in series connection partly shading of solar modules is a big problem but with the use of bypass diodes this problem can be solved.
5. In parallel connections there is not such a problem

Further Suggestions

If you have the possibility to visit a PV power plant have a look to the backside of the solar modules. There, a small black box can be found, where also the cables from the modules come out. In this box the bypass diodes are mounted.

10. IV-characteristics of partly shaded solar modules

Introduction

A partly shading of solar modules has severe impact on the power of the module (compare experiment 3 and 9). In this experiment this behavior should be investigated in detail. The IV-characteristics of a partly shaded solar module should be investigated.

Learning Objects

Measure the IV-characteristics of a partly shaded solar module with and without bypass-diode connected in parallel to the shaded solar cell.

Concepts

Principles of electrical circuits

Functionality of a diode

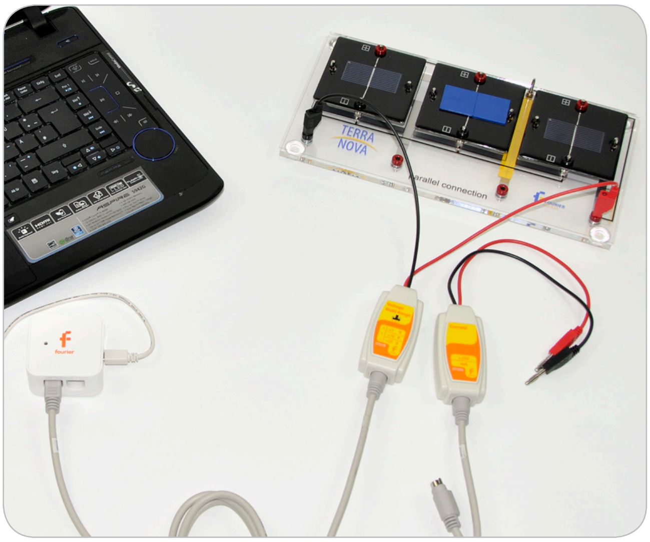
IV-characteristics (experiments 6, 7 or 8)

Time Frame

2 lesson

Equipment

1. Main board
2. 2 small solar cells
3. Diode module
4. 1 cover for the solar cells
5. 1 potentiometer module
6. 1 current sensor
7. 1 voltage sensor
8. NOVA LINK

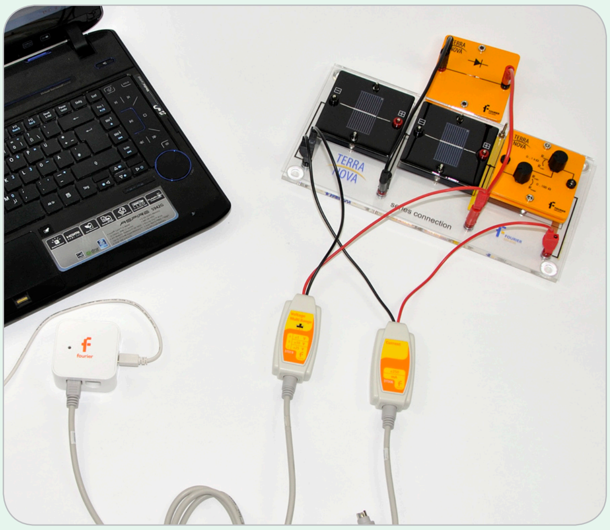


Equipment Setup Procedure

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on. when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.

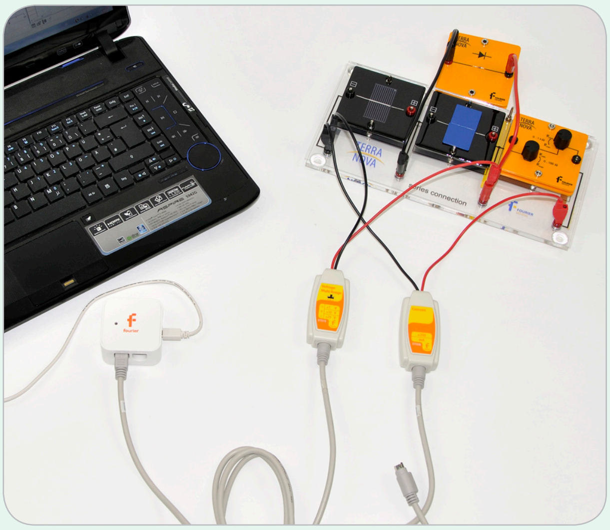
Setup 1:
Measurement of I-V-characteristics of a solar module

1. Plug 2 small solar cells and the potentiometer in series on the main board.
2. Connect the voltage sensor parallel to the solar cells (and set the range to B if you have a triple-range sensor).
3. connect the current sensor in series to the solar cell and the potentiometer module so that the electrical circuit is closed.



Setup 2:
Measurement of the I-V-characteristics of a partly shaded solar module with bypass-diode

1. Plug 2 small solar cells and the potentiometer in series on the main board.
2. Connect the voltage sensor parallel to the solar cells (and set the range to B if you have a triple-range sensor).
3. Connect the current sensor in series to the solar cell and the potentiometer module so that the electrical circuit is closed.
4. Connect the bypass diode in parallel to one of the solar cells. Put the covers on top of this solar cell.



MultiLab Setup

1. Click ⚙.
2. Click **Next**.
3. Set **Select rate** to **Manual**.
4. Set **Select recording mode** to **Add**.
5. Click **Next**.
6. Set **by samples** to **50**.
7. Click **Finish**.

Notes

Setup 1 equals experiment 8 and can therefore be skipped if experiment 8 was already carried out. In this case, the data from experiment 8 should be imported.

Experimental Procedure

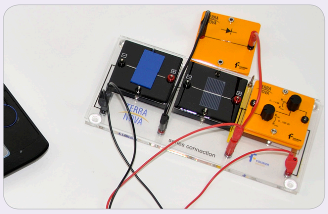
Data Analysis

Procedure for Setup 1

1. Set the potentiometer to the lowest resistance (turn both knobs to Rmin).
2. Click .
3. Turn the knob of the 100Ω-potentiometer clockwise in small steps – as more steps as more accurate will the result be.
4. After each step click .
5. When you reach the maximum position of the potentiometer start turning the knob of the 1kΩ-potentiometer (in quarter turns) .
6. After each step click .
7. When reaching the maximum position click .
8. Click to save your data.
9. Click .
10. Set **X-Axis** to **Voltage**.
11. Select the measured current dataset as **Y-Axis**.
12. Set **Graph title** to **solar module I-V-curve**.
13. Click Ok.
14. Click .

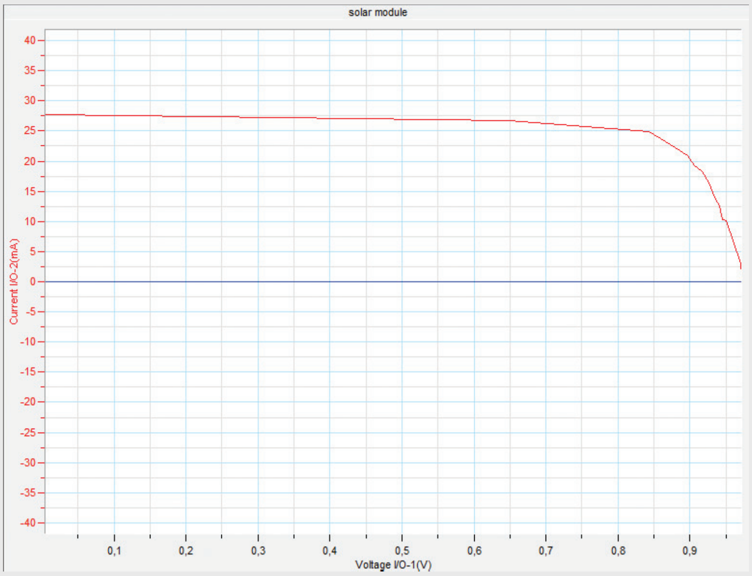
Procedure for Setup 2

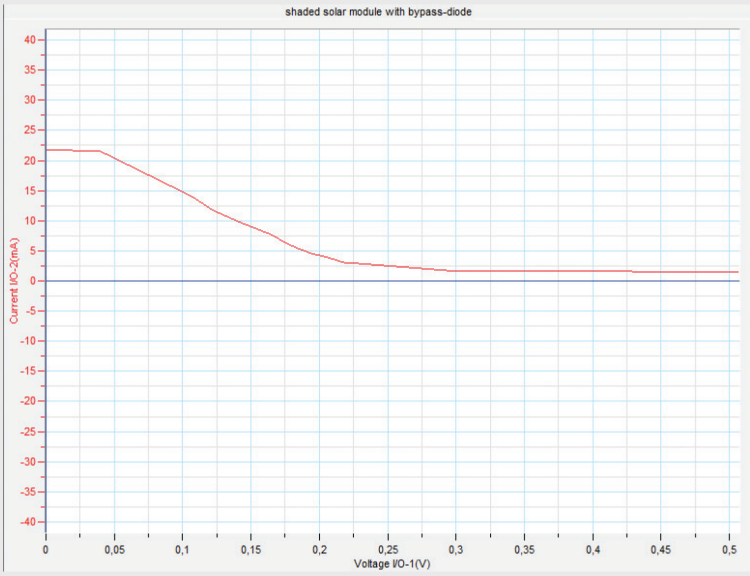
1. Set the potentiometer to the lowest resistance (turn both knobs to Rmin).
2. Click .
3. Turn the knob of the 100Ω-potentiometer clockwise in small steps – as more steps as more accurate will the result be.
4. After each step click .
5. When you reach the maximum position of the potentiometer start turning the knob of the 1kΩ-potentiometer (in quarter turns).
6. After each step click .
7. When reaching the maximum position click .
8. Click to save your data.
9. Click .
10. Set the graph title to "**Solar Module with Bypass Diode**".
11. Set **X-Axis** to **Voltage**.
12. Select the datasets: current and voltage as **Y-axis**.
13. Click **Ok**.
14. Click .
15. Click to save your data.
16. Take the covers away and put them on the other cell (without bypass diode) and repeat the measurments (steps 1 to 8)

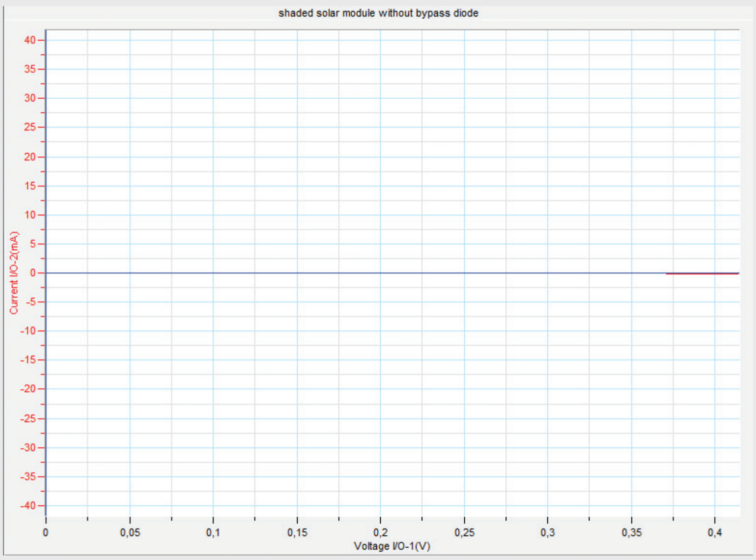


17. Click .
18. Set the graph title to "**Solar Module without Bypass Diode**"
19. Set **X-Axis** to **Voltage**
20. Select the datasets: current and voltage as **Y-axis**
21. Click **Ok**.
22. Click .
23. Click to save your data.

Expected Results







Questions

1. Compare the three measured IV-curves! Describe the qualitative differences with your own words.
2. What can be concluded for the output power of a partly shaded solar module?

Answers

1. The IV-curve of the non-shaded solar module has the "normal" shape as already seen in experiment 8.
   A partly shaded solar module with bypass diode shows a "dented" IV-curve.
   If no bypass diode is used, no current can be measured and the IV-characteristics equals the x-axis.
2. Partly shading reduces the output power to zero if no bypass diode is used. With bypass diode the loss is reduced but still high. Partly shading should always be avoided. In every case bypass diodes should be integrated in solar modules.