A5 Properties of solar cells – Voltage, current and power

If the subexperiments for investigating the electrical properties of solar cells are conducted in the suggested order, they form a learning unit that is very good for students to verify hands-on the basic knowledge of electricity they have previously learned. The fact that solar electricity is currently a hot topic will certainly help motivate the students. These experiments also provide an excellent opportunity to discuss the topics of renewable energy and energy transition, as long as the students have the relevant prior knowledge. The materials and apparatus supplied are sufficient to allow four groups of students to conduct the experiments simultaneously.

1 Main question

Solar cells are used in numerous small electronic devices and toys as well as on the roofs of houses and in large-scale power plants. The underlying question of the experiments is: What must be taken into account when solar cells are interconnected? How do voltage, current, and power output behave in different combinations and under different lighting conditions? And last but not least, how can this be measured? In this way, the experiments impart basic knowledge that is equally important for craft projects with solar cells and for large-scale application.

2 Integrating the experiment into the teaching context

2.1 Basic principles

The following prior knowledge and previous experience are necessary for working through the experiments:

- Knowledge on series and parallel circuits of batteries and resistors
- Experience in using a multimeter
- Knowledge of the basic electricity terms (current, voltage, resistance, power)
- Experience in plotting graphs
- Knowledge of the concept of internal resistance

2.2 Relevance to the curriculum

Experiments on solar cells can be conducted during lessons on electricity. They can also be meaningful in the context of energy, a subject that meanwhile plays a role for all age groups. Students need only very elementary knowledge on electrical circuits for subexperiment 1. Subexperiments 2 and 3 are suitable for age groups starting from about 12 years. By comparison, subexperiments 4 to 6 require a higher level of abstract and theoretical thinking and are therefore recommended for students aged 14 and up.

Topics and terms: accumulator, battery, current – voltage characteristic curve, direct current voltage source, electrical circuit, electricity, energy supply, interconnection of solar modules, internal resistance, load resistance, measurement curve, no-load voltage, parallel circuit, potentiometer, resistance, series circuit, shading, short-circuit current, solar cell, solar motor, threshold voltage (of the diode), using measuring instruments, voltage drop

2.3 Skills

2.3.1 Subject-specific skills

The students will learn …

- to describe how a solar cell works.
- to systematically investigate the factors that influence the performance of a solar cell.
- to systematically set up and conduct experiments with solar cells.
- to explain the terms short-circuit current and no-load voltage.
- to describe and compare the performance of solar cells connected in series and in parallel.
- to evaluate series and parallel circuits of solar cells with respect to their importance in practical applications.
- to describe the importance of internal resistance of a solar cell for practical applications.

2.3.2 The students will learn the following main points based on subexperiment 6

The students will learn …

- to explain the meaning of a maximum power point (MPP).
- to plot measured values on a graph and interpret them.
- to plan an experiment to investigate the change in internal resistance depending on the lighting of a solar cell.

2.4 Explaining the experiment in the teaching context

Solar cells convert radiant energy of the sun into electrical energy. This process is manifested by a voltage generated across the solar cell. The solar cells used in these experiments will reach a maximum value of approximately 0.55 volts (no-load voltage). If the solar cell is short-circuited, a maximum current of approximately 0.11 A will flow (short-circuit current). (In contrast, an alkaline manganese AA cell temporarily has a short-circuit current of up to 80 A.)

Students are used to dealing with standard alkaline manganese AA batteries. In contrast to this type of battery, the voltage in solar cells drops noticeably if a load (e.g., a small light or a solar motor) is installed in the electrical circuit. The difference is due to the internal resistance of the solar cell, which is relatively high compared with the resistance of these loads. If current is flowing, a considerable portion of the voltage in the solar cell drops due to this internal resistance. In addition, unlike with charged batteries, the internal resistance of solar cells is not constant, but depends on the illuminance.

As a result, the conditions for interconnecting solar cells are simple, as long as no loads are installed in the electrical circuit. However, the correlations become considerably more complex when a load is involved and the lighting conditions are not optimal. The complex correlations must be taken into account in order to gain insight into the specific application of solar cells in practice. If the primary objective is to analyze solar cells as electrical components and to integrate them into the context of traditional electricity lessons, then the more theoretically relevant investigations of solar cells without loads are more important. The subexperiments take both needs equally into account and present the different perspectives.

2.4.1 Subexperiment 1: First investigations with the solar cell

This subexperiment provides an initial basis for further experiments. It should remove any nervousness the students may feel toward handling the materials used in the experiments. For this reason, we incorporated the investigation of the effect of covering the solar cells with materials of varying transparency as an entertaining, exploratory component. Other influencing factors can also be examined. In this experiment, the solar motor serves as an indicator that electricity is being generated. While it doesn't allow for highly accurate results, it does support the entertaining nature of the experiment.
Important note: When a lamp is used as the light source, the ruler should be used to make sure that the distance of this light source from the solar cell is kept constant.
In the first part of the experiment, the students should also recognize that, like a battery, a solar cell is a source of direct current voltage whose polarity is easy to determine.
An interesting complement to subexperiment 1 would be to have the students take quantitative measurements of the current and voltage at different angles of incidence of the light. However, this is difficult to accomplish with the relatively small solar cells. For this purpose, we recommend building devices that make it easier to position the solar cell at defined angles.

Transfer
The orientation of a roof to the sun plays a key role in answering the question of whether it is recommendable to install solar cells on the roof of a house.
A film of dirt impairs the efficiency of solar cells, meaning that solar cells must be cleaned.

2.4.2 Subexperiment 2: Short-circuit current and no-load voltage at different distances from the lamp

The core of this subexperiment is examining how current and voltage change as the distance of the solar cell from the lamp changes. This experiment thus introduces a quantitative description of solar cells and the terms no-load voltage and short-circuit current. The basic measurement principle will be used again in subexperiment 4. The measurement curves make it clear that the current responds much more sensitively to changes in the lighting than the voltage. Figures 1 and 2 serve as a guide with regard to the measurement results to be expected and the accuracy. Furthermore, they provide an insight into the distances between the solar cell and the lamp (20 W halogen) that make sense for taking the measurements (see Fig. 1 and Fig. 2).

Transfer
The varying distance from the lamp is equivalent to the varying intensity of the light. The result can be transferred to the first subexperiment. When the light is shaded, the current in particular drops off dramatically. The teacher should refer to the inverse-square law: "the illuminance is proportional to the inverse square of the distance from the light source" (Fig. 2).

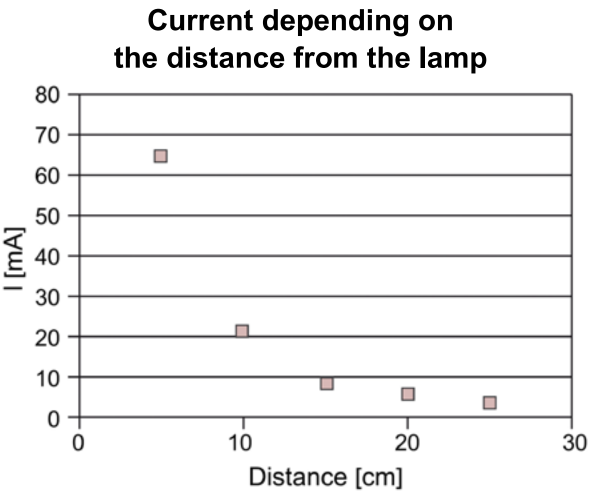


Fig. 1: The current has dropped off dramatically at just a distance of 10 cm.

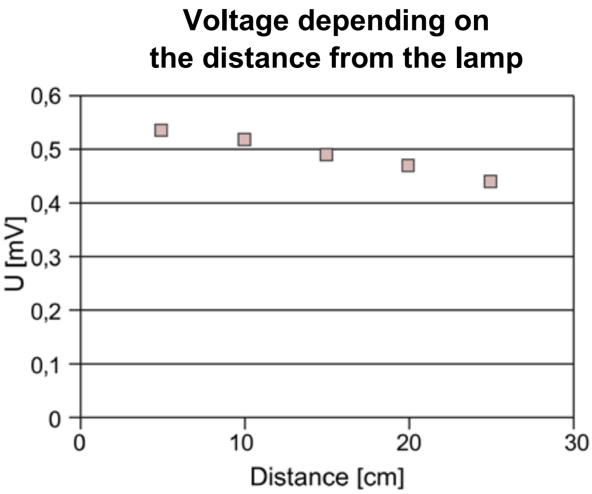


Fig. 2: The voltage decays only moderately as the distance from the lamp increases. The curve shape is approximately linear.

2.4.3 Subexperiment 3: What happens when you connect solar cells in series or in parallel?

This subexperiment focuses on the question of how solar cells should be interconnected in order to boost the performance of a connected device (in this case, a solar motor). The result depends greatly on the distance of the solar cells from the lamp when the experiment is conducted. If the solar cells are relatively close to the lamp, a parallel circuit yields a considerably higher motor speed; for a greater distance, a series circuit is better. In the suggested variation, the students will take the measurements with the solar cells relatively close to the lamp. The solar cell will then work close to its optimal power range. This roughly corresponds to the conditions for direct sunlight. The experiment shows that under these conditions and with this solar motor as the load, a parallel circuit is considerably better than a series circuit. That’s because as the illuminance decreases, the current output of the solar cell decreases and its internal resistance increases. (In the experiment with the halogen lamp, the illuminance decreases by the square of the distance from the light source).
This contradicts the typical experience when batteries are interconnected. The observation doesn’t become clear until the solar cell is modeled as a voltage source with internal resistance: When the solar cells are connected in series, the internal resistance doubles, while it is halved when the solar cells are connected in parallel. However, the internal resistance of a solar cell is greater than 20 Ω (see subexperiment 6), thus approximately half the motor resistance. By comparison, alkaline manganese AA batteries for example have very low internal resistance in the range of 0.1 Ω, which is barely noticeable in comparison with the resistance of customary loads, such as toys or music devices. Connecting two (not overloaded) batteries in series therefore results in twice the voltage and twice the power.

Transfer
Connecting solar cells in parallel ensures that sufficient current will be provided, and is a requirement of many technical applications. By comparison, connecting solar cells in series offers the possibility of providing the necessary minimum voltage for a certain purpose (e.g., approx. 2 volts is needed to charge an accumulator cell). Moreover, connection in parallel offers the possibility of compensating for the shading of individual cells within the modules (see subexperiment 5). Both types of connection are used in technology when solar cells are interconnected to form solar modules. If solar toys are powered with several solar cells, a parallel circuit or a combination of parallel and series circuits can be used depending on the motor.

2.4.4 Subexperiment 4: Current and voltage with solar cells connected in series and in parallel

In this subexperiment, students will investigate the connection of solar cells in series and in parallel under the idealized condition of not having a load connected, which makes the conditions relatively simple. The no-load voltage is doubled with connection in series, while the short-circuit current is doubled with connection in parallel. It seems reasonable to interpret the product of the short-circuit current multiplied by the no-load voltage as the power output. However, since measurements taken with a short circuit and no load are fundamentally different from those taken under normal operating conditions, the values cannot be used to calculate the power output. Subexperiment 6 will provide an explanation of the power output of solar cells.

Transfer
When solar cells are interconnected to form larger solar modules, different currents and voltages can be generated by combining series and parallel circuits in various ways. For example, a complete module built from approx. 1008 basic 0.5-volt/200-mA cells will generate 24 volts and 100 watts.

2.4.5 Subexperiment 5: How do solar cells connected in series or in parallel behave when shaded?

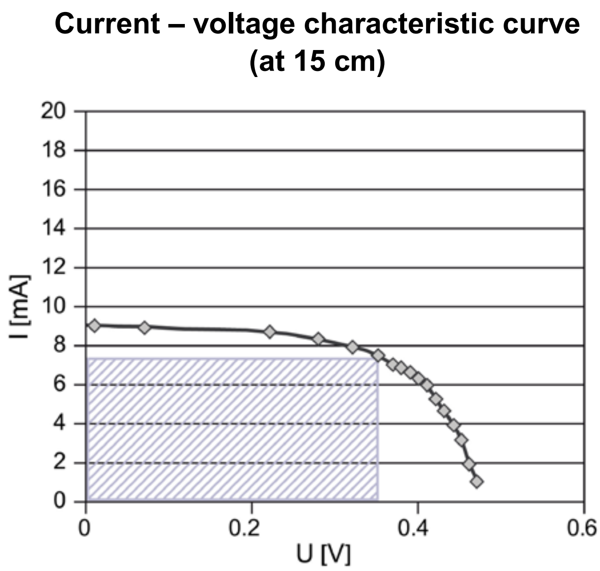
In this subexperiment, the students will focus on the question of how partial shading of solar cells affects the current and voltage of two solar cells connected in series or parallel. They will simulate shading in two ways: by covering half of both cells and by completely covering one of the two cells. This table gives sample values:

	Parallel circuit		Series circuit	
	U [V]	**I [mA]**	**U [V]**	**I [mA]**
Uncovered	0.52	38	1.03	19
Both half covered	0.49	23	0.97	12.5
One completely covered	0.49	23	0.93	3.8

Transfer
When solar modules are built, solar cells are connected in series and the series are connected in parallel. This design can compensate for varying shading on different cells and for the failure of individual cells.
However, the teacher should point out that in large solar modules, series circuits also pose risks if cells are shaded or fail. Specifically, if a single cell in a long series is shaded, it stops producing electricity and acts as a resistor, causing the total voltage of the series to drop. This can fry the cell. Therefore, individual cells are normally bridged with bypass diodes, which are completely normal switching diodes. These diodes are connected in parallel with the cells so that they are inactive when exposed to light (because the series voltage is lower than the diodes' threshold voltage). If a cell is shaded or defective, the diodes complete the circuit and the current conducted by the other cells in the series can flow through the diodes.

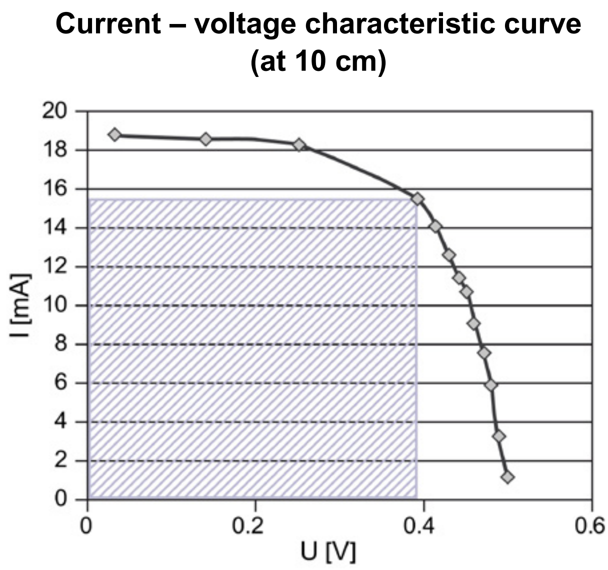
2.4.6 Subexperiment 6: Optimizing the power output of solar cells

In this subexperiment, the term maximum power point (MPP) will be introduced and illustrated to the students. The MPP denotes the point along the current – voltage characteristic curve where the solar cell‘s power output is highest. The current – voltage characteristic curve and the MPP distinguish the features of a solar cell (see the data sheet for a typical solar cell under Additional information on the experiment). To be able to plot the current – voltage characteristic curve, during the experiment the students will measure the current through and voltage across a variable resistor. For purposes of simplification, the maximum power is determined from the measured values (and not from the measurement curve).
The model of a solar cell as a constant voltage source with internal resistance can be used to show that the power at the load is highest when the load’s resistance is equal to the solar cell’s internal resistance. (In high-achieving learning groups, this can be proven using simulation software, if available.) If this is taken as a given, the solar cell’s internal resistance can also be determined via the MPP. Fig. 3 and Fig. 4 provide an impression of the measured values to be expected.



Maximum power P = 2.6 mW
Internal resistance R = 47 Ω

Fig. 3: Current – voltage characteristic curve for a measurement at a distance of 15 cm from the lamp. The shaded rectangle symbolizes the power.



Maximum power P = 6.0 mW
Internal resistance R = 25 Ω

Fig. 4: Current – voltage characteristic curve for a measurement at a distance of 10 cm from the lamp. The difference in the curve is obvious. The internal resistance is lower compared with Fig. 3.

As an extension of subexperiment 6, the students can also determine the MPP for series and parallel circuits. They will observe approximately twice the maximum power when they use two solar cells, regardless of the type of connection (at 15 cm from the lamp, from 2.6 mW to 4.8 mW; at 10 cm from the lamp, from 6 mW to 10.5 mW).

Transfer
In large-scale plants, the resistance of the load side can be adjusted electronically according to the lighting conditions in order to optimize the solar cells’ power output.

2.5 Experimental variations

All subexperiments except for subexperiment 2 can also be conducted in sunlight. However, the lighting conditions must be consistently good. The described subexperiments build logically upon one another, but subexperiments can also be skipped without a problem. The order of subexperiments 3 and 4 can also be swapped.
The number of students per group should not be too high (maximum three students per group), since otherwise not all students will have the opportunity to actively participate in the experiments.

3 Additional information on the experiment

You will find additional media for preparing or for further study of this experiment on the Siemens Stiftung Media Portal:
https://medienportal.siemens-stiftung.org

In addition, the media package entitled "Solar thermal energy and photovoltaics – Energy forms with a future" is explicitly devoted to the basic principles and technical applications of the experiment.

4 Notes on conducting the subexperiments

4.1 Facilities

The students can conduct the experiments in any classroom using several desk lamps. Incident sunlight may substantially affect the measurements. Except for subexperiment 2, the measurements can also be taken in sunlight.

4.2 Time required

The following indicated times are an approximate guideline. The time required for analyzing the experiment and answering the questions also includes time for a brief discussion with the teacher.

	Preparation and execution	Analysis, questions
Subexperiment 1	15 min.	15 min.
Subexperiment 2	20 min.	20 min.
Subexperiment 3	15 min.	20 min.
Subexperiment 4	20 min.	20 min.
Subexperiment 5	20 min.	30 min.
Subexperiment 6	30 min.	20 min.

4.3 Safety aspects

The students may conduct the experiments only in the presence and under the supervision of the teacher.
The teacher is to point out to the students that the provided materials may be used only according to the respective instructions.

4.4 Apparatus and materials

Required materials that are not supplied:

- Cardboard for mounting the solar cells
- Desk lamps (halogen lamp, 20 W)
- Materials of varying transparency (e.g., overhead transparency, tracing paper)
- Ruler (30 cm)

Supplied:
The apparatus and materials supplied are sufficient to allow **four** groups of students to conduct the experiments simultaneously.
Depending on the students' level of knowledge, teachers should explain proper wiring and the proper use of multimeters, LEDs, and motors in advance, demonstrating if necessary.
The following materials included in the kit are needed for **one** group of students:

Material	Quantity
Connecting cable, alligator clip/alligator clip	6x
Digital multimeter	2x
Measuring cable assembly, banana plug to alligator clip, red and black for each	2x
Paper, black, DIN A4	1x
Potentiometer, 470 ohms	1x
Propeller (for large solar motor)	1x
Rubber bands for mounting the solar cells	2x
Scissors	1x
Solar cell, 0.5 V/150 mA	2x
Solar motor, large, iron armature, 0.4 V/25 mA	1x

Fig. 5: Apparatus and materials supplied for one group of students.

4.5 Cleanup, disposal, and recycling

All apparatus and nearly all materials from the kit can be reused. Therefore, after the students have completed the respective experiment, they should put the apparatus and materials back in the appropriate boxes and return them to the kit. This practice will ensure that you and your colleagues will find everything again quickly the next time the kit is used.
Apparatus that become dirty during the experiment, such as cups, bowls, spoons, and test tubes, should be cleaned before being returned to the kit. We recommend that you have the students do this immediately after they have completed the experiment.
Also make sure that the apparatus are in working order for the next time. For example, recharge used accumulators immediately (It makes sense to charge the accumulators even if they will not be used for an extended period.).
Materials that cannot be reused, such as used pH test strips and filter paper, should be disposed of properly.
The waste that accumulates during this experiment can be disposed of in the regular trash or poured down the sink.