A5 Properties of solar cells – Voltage, current and power

Note: This answer sheet will go into the analyses for the individual subexperiments only if experience shows that there could be particular difficulties.

1 First investigations with the solar cell

1.5 Analysis

List the factors that influence the power output of a solar cell.

Note:
The factors that influence the power output are:
a) illuminance
b) distance of the light source from the solar cell
c) angle of incidence of the light

The illuminance plays a role because electricity is ultimately generated by the light rays (or light particles, photons) striking the individual atoms of the solar cell. This means only the atoms that are illuminated will contribute to electricity generation. The cell's power output is better when the cell is illuminated as well as possible, i.e., the illuminance is as great as possible.
During the experiment with an incandescent lamp, the illuminance will be greatest when the distance to the solar cell is the shortest. The distance to the light source influences electricity production, because the illuminance is proportional to the inverse square of the distance from the light source. This means that the closer you move the lamp to the solar cell (e.g., reducing the distance by half), the higher the light intensity becomes (e.g., when the distance is cut in half, the intensity quadruples). With sunlight, however, we cannot measure this effect of distance, because due to the immense distance between the Earth and the sun, the brightness is practically equal at the same time at every location with direct solar radiation on the same longitude and latitude.
However, the solar cell's power output worsens when the light rays do not strike the solar cell perpendicularly. This angle dependency is based on the angle dependency of the solar radiation. According to the law of nature, if the sunlight shines perpendicularly, the energy input of the radiation is highest. This is why a solar cell that is aligned perpendicular to the sun's radiation will also have the highest power output.

1.6 Questions

How should solar cells be mounted to houses so that they can be used most effectively?

Answer: When solar cells are aligned on houses, the angle of the solar cells relative to the sun in particular must be taken into account, because solar cells generate widely varying power output depending on the angle of incidence (non-linear relation between angle and output). In a horizon system, the altitude of the sun is determined by the azimuth angle and the angle of elevation. The azimuth indicates the directional angle of the sun, and is measured in a clockwise direction from the north on the horizontal plane. The angle of elevation is the angle at which the observer sees the sun above the hori-

zon. Ideally, the solar modules should be flexibly mounted to automatically track the position of the sun so that the light always strikes them perpendicularly. By contrast, if they use a fixed mounting system, a precise southern orientation is normally the best. By facing south, the solar module receives light at an angle from the east and west in the mornings and evenings and receives the full irradiation power at midday when the sun is at its highest point. However, the angle of tilt that is best on average throughout the year depends on the latitude. In central Germany, for example, this optimal angle of tilt is approx. 35°.
In individual cases, however, the climate- and weather-related characteristics of the location must be taken into account. This means that if, for example, in a certain region the sun shines only in the morning and the sky is usually overcast in the afternoon, then the solar cells should be aligned more toward the rising sun.

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

2.5 Analysis

a) How does the distance and thus the illuminance affect measured current and voltage?

Note: The current should drop proportionally to the square of the increase in distance, meaning that the measuring points should form a parabola on the graph where current is entered relative to the distance from the lamp. The voltage should drop approximately in a linear fashion, meaning that the measuring points should lie along a straight line.

b) What changes to a greater extent when you change the lighting conditions: the current or the voltage?

Note: The measurement curves make it clear that the current responds much more sensitively to changes in the illuminance than the voltage.

2.6 Questions

You can use a solar cell to measure the lighting conditions at a location. Which variable is better for this purpose, the current or the voltage? Explain your answer.

Answer: Since the current is considerably more sensitive to changing light conditions, it is better suited for determining the lighting conditions.

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

3.5 Analysis

When you use two solar cells, twice the electrical energy is generated from the light. Actually, you would expect that the solar motor would clearly rotate faster with two solar cells than with one, regardless of the type of connection. Why is it that a different amount of the energy flows to the motor depending on the connection? (Tip: internal resistance of the solar cell.)

Note: Depending on the connection, more or less electrical energy is "lost" in the form of heat at the internal resistance of the solar cells. This energy is then unavailable to the motor. If you use a solar motor with a starting voltage of less than 0.5 volt, and if you connect the solar cells in parallel, the internal resistance will be reduced to the extent that the solar motor will normally run faster with this connection.

3.6 Questions

a) Why does the solar cell's power output differ for parallel and series connections?

Answer: If we consider the solar cells without (!) a load, that is, without a connected "consumer," the following applies in theory: Two cells connected in parallel provide the same voltage and twice the current, and conversely, two cells connected in series produce twice the voltage and the same current. The power output as a product of the voltage and current would thus remain constant. (See result of subexperiment 4.) This suggests the erroneous belief that it does not matter whether we operate the motor in a parallel or series connection.

The level of current and voltage that is actually generated by the solar cell under load depends on how great the solar cell's internal resistance is compared to the load resistance (= motor). Actually, the internal resistance of a single 150-mA solar cell is very high compared to the internal resistance of most loads. Our solar motor also has a very low internal resistance, and so if the solar cells are connected in series, most of the solar cells' power output will be lost due to their high internal resistance. In contrast, if we connect the solar cells in parallel, the internal resistance is reduced and the solar motor will run at higher performance.

But a word of caution: There are other loads that are "voltage controlled," unlike our solar motor that is "current controlled." This is the case, for instance, with a red LED. It has a nominal power similar to that of our solar motor, but requires at least 1.6 volts. In this case, connecting the solar cells in parallel does no good. Rather, we had to connect four (!) solar cells in series to light up the LED.

Thus, there is no general rule stating which type of connection is better; it also depends on the connected load.

b) How do two AA batteries behave when connected in parallel or in series, compared to solar cells?

Answer: Since the internal resistance of modern alkaline AA batteries is relatively low compared to the load resistance of most loads, you can regard them as constant current and voltage sources. You can thus maximize the voltage using a series connection and the current using a parallel connection, and you will obtain practically the same power output with loads such as small solar motors.

4 Current and voltage with solar cells connected in series and in parallel

4.5 Analysis

Compare the results of this subexperiment with the results of subexperiment 3 (What happens when you connect solar cells in series or in parallel?) and explain the differences.

Note: 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.

4.6 Questions

Why is the product of the short-circuit current multiplied by the no-load voltage not equal to the actual power output of the solar cell?

Answer: 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 a truly meaningful power output. Students need to take measurements under load to determine the “real” power output (what they then do in subexperiment 6). Nevertheless, they can use the power output (from the product the short-circuit current multiplied by the no-load voltage) as a guide value to classify solar cells.

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

5.6 Questions

a) Why are solar cells connected in series for the production of solar modules and then why are the solar modules connected in parallel? Explain your answer.

Answer: When solar modules are built, solar cells are connected in series and the series are connected in parallel. This produces modules that have the necessary voltages and currents for sensible use of the generated electrical energy.

b) The following sentence appears on a website about solar technology: “For a series connection, the weakest module determines the total power output.” What is meant by that? Write a corresponding sentence for a parallel connection.

Answer: When voltage is optimized by connecting several solar modules in series, it is important to avoid a situation in which nearly all of the power output drops at a single module that is shaded. Otherwise, these individual cells would “burn out,” meaning they would be destroyed. This is why protective diodes are connected in parallel with the modules. When a solar module is shaded, the diodes automatically become conductive and bridge the module in this way.
The same principle applies to the interconnection of modules: The module with the weakest output generates the greatest resistance. Since the total resistance in a series connection is the sum of the resistances, the greater resistances play a greater role than the smaller resistances. For a parallel connection, the statement would be “For a parallel connection, the strongest module determines the total output.”
On the one hand, the maximum power output is transferred between the current source and the load when the load’s resistance and the current source’s internal resistance are equal. On the other hand, the solar modules’ output and thus their internal resistance ultimately depend on the sun exposure.
For this reason, the converter unit that is part of every solar system to feed the solar electricity into the public grid is never designed for constant output. Otherwise, this would mean that the load resistance would be constant and solar system’s internal resistance would continually fluctuate with sun exposure. The load resistance and internal resistance would therefore rarely optimally match each other. Modern solar electricity systems therefore have a converter with additional control electronics that automatically adjust the load resistance – and thus the usable power output – to the power output that is available from the solar system at any given moment.

c) Tina would like to participate in a solar competition. She must build a boat that is driven by a fan. She may use a maximum of four solar cells (0.5 volt, 100 mA). The motor has a starting voltage of 0.6 volt and a starting current of 25 mA. How would you advise her to connect the solar cells so that the boat reaches maximum speed? Explain your answer.

Answer: In this case, Tina must connect two solar cells in series (approx. 1 volt) to reach the starting voltage. With two solar cells connected in parallel (200 mA), Tina will definitely have ample starting current, even when sun exposure fluctuates. Therefore, she should connect two solar cells in series twice, and then connect the two series-connected modules in parallel. Because the varying illuminance has a greater effect on the current than on the voltage (see subexperiment 2), this parallel connection will provide additional reliability when the sun shines less brightly.

6 Optimizing the power output of solar cells

6.5 Questions

The maximum power is drawn when a device's resistance is just as high as the solar cell's internal resistance. The internal resistance is not constant, but depends on the lighting. Therefore, in order to draw the maximum power in poor lighting conditions, you must change the resistance. Create an experiment to prove whether a device's resistance must be increased or decreased when the lighting conditions change.

Answer: We work with the same connection as in this subexperiment. We now change the illuminance, turn the resistance on the potentiometer so that the voltage always remains at the maximum level, and then measure the current. We determine the respective resistance from the voltage and the measured current. We will see that at lower illuminance, we need higher resistance to maintain the voltage.