A1 Electric current from solar cells – Let's build a dye-sensitized solar cell

This experiment is particularly suitable for an introduction to solar cells, since unlike experiments with premade silicon cells, students can experience hands-on the working principle behind solar cells. With the experiments in chemistry class, students can verify their knowledge from the Bohr model of the atom (electron energy levels and excitation) and also apply their knowledge of redox chemistry. In biology class, the experiments with the dye-sensitized solar cell can best be used to introduce or illustrate the topic of photosynthesis. The materials supplied for this experiment allow four groups of students to work at the same time. The experiments are not really difficult, but require attention to detail. Experienced students can easily conduct all three subexperiments in the allowed time of approx. 45 min. For inexperienced students, teachers should schedule more time or possibly skip subexperiments 2 and 3. The experiment also lends itself very well to use during a project day on renewable energy.

1 Main question

For decades, scientists have been researching the conversion of solar energy to chemical energy according to the principle of photosynthesis. The silicon-based solar cell has been used since 1958. In 1992, Michael Grätzel applied for a patent for a dye-sensitized solar cell, which converts the energy of sunlight into electrical energy with the aid of dyes. Because Grätzel invented the dye-sensitized solar cell, it is also known as a Grätzel cell. If this cell is successful on a large scale, it would be the most cost-effective method of extracting electricity from sunlight.
The experiments suggested in this unit address the following questions:

- How is a dye-sensitized solar cell built and how does it work?
- How can the power output of a dye-sensitized solar cell be determined and improved?
- What processes of a dye-sensitized solar cell and photosynthesis are comparable?

2 Integrating the experiment into the teaching context

2.1 Basic principles

A dye-sensitized solar cell makes it possible to convert the radiant energy of light into electrical energy. The involved processes of energy conversion and electron transfer are part of the basic concepts of science education.
The students can understand energy conversion and electron transfer experimentally and examine the influence of different materials and conditions on the cell's power output.
The dye-sensitized solar cell can be used as a functional model for photosynthesis.

2.2 Relevance to the curriculum

For age groups up to 14 years, the way a dye-sensitized solar cell works should be handled only qualitatively or semiquantitatively. As a qualitative two-electrode model, the dye-sensitized solar cell is well suited for explaining all processes of solar cells. Furthermore, the cell can already be used with the 13-to-16-year age group as a functional model for better understanding of photosynthesis (conversion of light energy into electrical or chemical energy).

If the students are familiar with the energy level model, the electron donor-acceptor principle, and the basic electricity terms (voltage, current, and power), the individual reaction steps in the dye-sensitized solar cell can be discussed in more detail and the influence of different materials and conditions on the cell's power output can be determined quantitatively.
The dye-sensitized solar cell lends itself superbly to interdisciplinary lessons in biology, chemistry, and physics within the following topics:

- Renewable energy and energy conversion (solar energy to electrical energy)
- Energy level model (photons boost electrons to higher energy levels)
- Light and absorption spectra (wavelength and energy of emitted and absorbed light)
- Electricity (semiconductors, voltage, current, parallel and series connections, power output depending on the materials and circuits)
- Redox reactions (electron transfer)
- Photosynthesis (conversion of solar energy to chemical energy)

Topics and terms: absorption spectra, electron loss, electron gain, electrolyte, electron transfer, energy level model, electron donor-acceptor principle, dye, dye-sensitized solar cell, semiconductor, light, light energy, light spectrum, reduction of iodine to iodide, radiant energy, UV radiation, wavelength

2.3 Skills

The students will …

- come to understand the structure of a dye-sensitized solar cell and how the cell works.
- build a dye-sensitized solar cell themselves and determine the influence of different materials and conditions on its power output experimentally.
- describe comparable reaction steps in the dye-sensitized solar cell and in photosynthesis.

2.4 Explaining the experiment in the teaching context

The subexperiments can be conducted at different difficulty levels according to the students' prior knowledge:

- Structure of a dye-sensitized solar cell and experimental proof of conversion of light energy to electrical energy. The students will recognize that electrodes made of two different materials, one with the property "electron loss upon exposure to light" and one with "electron gain", are needed for the conversion process to occur.
- Researched-based experimentation in order to test the influence of different materials and conditions on the cell's power output and to understand the individual partial reactions in the cell.
- Interdisciplinary approach incorporating a comparison of how a dye-sensitized solar cell, photosynthesis, and a conventional solar cell work.

2.4.1 Building a dye-sensitized solar cell

A dye-sensitized solar cell makes it possible to convert solar energy to electrical energy using plant pigments for light absorption according to the principle of photosynthesis.
The cell’s supporting substrate consists of two coated glass plates (anode and cathode), each with a layer of transparent conducting oxide (TCO) on one side.
At the negative pole (anode), the TCO layer is additionally coated with titanium dioxide and immersed in an anthocyanin pigment.
At the positive pole (cathode), the conductivity of the TCO layer is increased through the application of a thin graphite layer.
Before the two conductive sides of the anode and cathode are joined together, two drops of iodine tincture (iodine/potassium iodide solution) are placed on the anode.

Fig. 1: Schematic diagram of a dye-sensitized solar cell.

1 Glass plate (light incidence side)
2 Layer of transparent, electrically conductive oxide (e.g., SnO_2)
3 Layer of TiO_2 sensitized with anthocyanin pigment (negative pole)
4 Electrolyte solution of potassium iodide and iodine
5 Layer of transparent, electrically conductive oxide (e.g., SnO_2) and a layer of graphite (positive pole)
6 Second glass plate

2.4.2 Power output of the dye-sensitized solar cell at different light illuminances

Like every solar cell, the dye-sensitized solar cell as invented by Grätzel consists of two electrodes separated by a boundary layer. The first electrode can release electrons when light shines on it, and the second electrode can absorb electrons. The dye-sensitized solar cell shares this principle with all other solar cells, such as silicon-based solar cells. In the case of a dye-sensitized solar cell, however, the electrons flow to the second electrode directly via the external electric circuit when the cell is exposed to light. There, they recombine on the positively charged carriers in the boundary layer between the two electrodes. In this way, the total circuit is closed via the internal circuit of the dye-sensitized solar cell.

2.4.3 Higher voltages through several dye-sensitized solar cells

The way the cell works can be explained in the following interconnected partial steps:

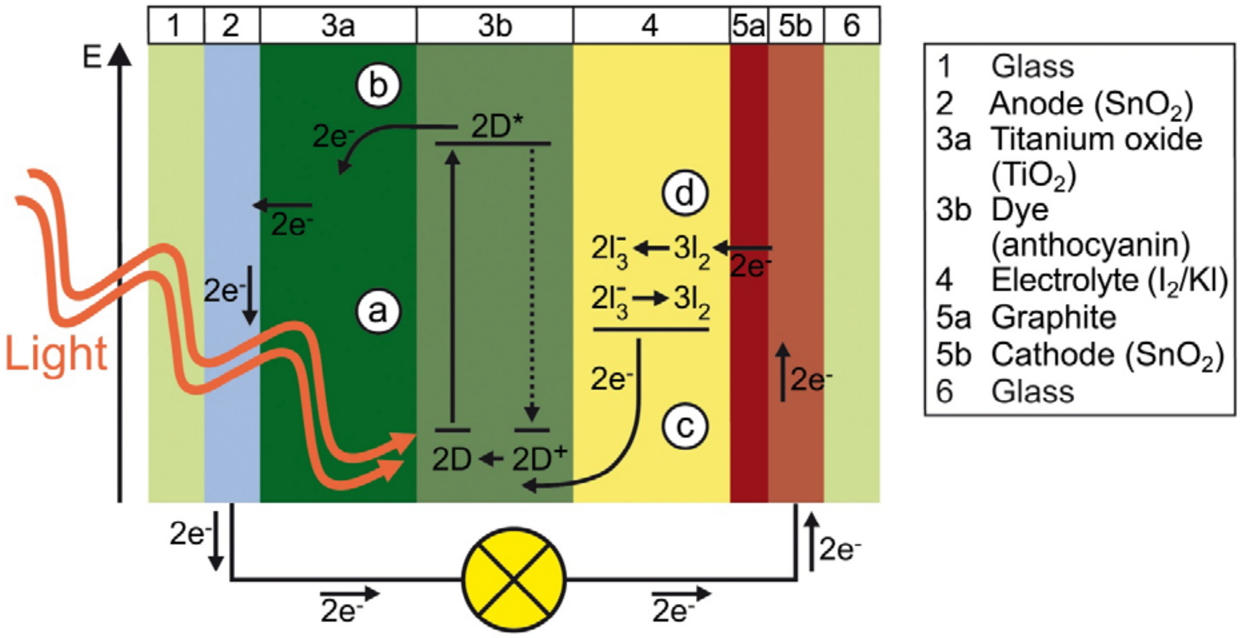

Fig. 2: How a dye-sensitized solar cell works.

- The dye molecules (D) absorb light of a certain wavelength. The absorbed energy excites electrons in the molecule to a higher energy level (D*).
  2 D + light energy → 2 D*
- From this higher energy level, the dye's energy-rich electrons can be transported in the conduction band of the titanium dioxide. The dye molecules are now positively charged and the titanium dioxide is negatively charged.
  $2\ D^* \rightarrow 2\ D^+ + 2e^-$ →→ $2\ TiO_2 + 2\ e^- \rightarrow 2\ TiO_2^-$
- The flow of electrons is possible only because the loss of the electron by the dye molecules is balanced out by the iodide molecules.
  $2\ I_3^- \rightarrow 3\ I_2 + 2e^-$ →→ $2\ D^+ + 2e^- \rightarrow 2\ D$
- The energy-rich electrons flow from the anode to the cathode in an external circuit and can provide energy to any present load. The electrons arriving at the cathode (TCO and graphite layer) reduce iodine molecules to iodide ions once more, thus closing the circuit.
  $3\ I_2 + 2\ e^- \rightarrow 2\ I_3^-$

The arrangement of the individual electron transfer systems allows the electrons to flow in only one direction.
Sample experiment results:

Light source	Voltage in mV	Current in mA	Power in mW
Direct sunlight	400	0.6	0.24
Overhead projector	350	0.4	0.14

2.5 Experimental variations

The students can work in groups and at first familiarize themselves with the structure and functional principle of a dye-sensitized solar cell. In a second step, they can investigate the influence of different dyes on a cell's power output. A goal could be to operate a low-power device (calculator or solar motor) with an appropriate number and arrangement of dye-sensitized solar cells.
During a class project or for learning at stations, the students can work out the structure and functional principles of the dye-sensitized solar cell in groups and then present their results to the entire class.
The individual partial reactions in the cell can also be worked out in expert teams and then consolidated into a complete overview in the learning team.
The interdisciplinary approach to dye-sensitized solar cells can be interesting for students aged 16 and up. The way photosynthesis (biology), the dye-sensitized solar cell (chemistry), and the solar cell (physics) work can each be figured out in expert teams and then presented and compared in the entire learning group.

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

4 Notes on conducting the subexperiments

4.1 Facilities

No special facilities are necessary.
Direct sunlight or a strong source of artificial light must be available.

4.2 Time required

- Approx. 45 min. for building and testing the function of the cell (subexperiments 1, 2, and 3).
- Approx. 90 min. for research-based experimentation with different materials (variants).
- Approx. 15 min. to 45 min. for discussion of the results. Approx. 120 min. in addition for an interdisciplinary approach including photosynthesis.

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.

For these experiments, pay attention to the following potential dangers and make your students aware of them:

- Normally, the teacher should provide the hot water for making the tea.
- The teacher should dispense the drops of iodine tincture on the prepared glass plate. Iodine is harmful to health only if large amounts are absorbed in the body (through ingestion, inhalation, or skin contact). It is still used in medicine in small amounts for disinfection. Anyone suffering from an iodine allergy should always avoid skin contact!

According to the international hazardous substance labeling (GHS): “Caution”

Hazard Statements: H332, H312, H400
Precautionary Statements: P273, P302, P352

4.4 Apparatus and materials

Required materials that are not supplied:

- Make the hibiscus tea:
  It is best for the teacher to prepare a half cup of concentrated (!) hibiscus tea in advance and then let it cool before bringing it to the classroom. It is not possible to store the tea for a few days or weeks, because the dye loses its effect. To make the concentrated tea, pour 100 ml of boiling water over two tea bags. When you remove the bags, squeeze them out well.
- Paper towels
- Optional, depending on the experimental variations: Fruit or fruit juice (e.g., blackberry, raspberry, cherry, currant). The juice of blackberries, elderberries, currants, and other substances containing anthocyanins can be frozen in individual portions.
- Electric kettle
- Beaker or cup
- Overhead transparency marker, felt-tipped pen, fiber-tip pen, or similar
- Desk lamps (halogen lamp, 20 W)

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 from the kit are needed for **one** group of students:

Material	Quantity
Clips (paper clips)	2x
Connecting cable, alligator clip to alligator clip	4x
Digital multimeter	1x
Glass electrode for dye cell (SnO, clear)	1x
Glass electrode for dye cell (TiO_2, white)	1x
Hibiscus tea bag (as dye for solar cell)	1x for entire class
Iodine/potassium iodide solution ("iodine tincture"), dropper bottle	2x for entire class
Measuring cable assembly, banana plug to alligator clip, one red and one black for each	1x
Pencil, soft (6B)	1x
Screw-on lid (for 100-ml cups)	1x
Syringe (conical tip), 5 ml (as pipette)	1x

Fig. 3: 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.

Shelf life and regeneration of completed dye-sensitized solar cells

The instructions are based on the assumption that the supplied iodine/potassium iodide solution will be used. If it has been used up, we recommend that you prepare your own iodine/lithium iodide solution (composition: lithium iodide (LiI) 0.5 mol/l and iodine (I_2) 0.05 mol/l).
If the completed solar cells are stored in a cool, dark place, they may remain functional for at least a week. Strong sources of light, e.g., overhead projectors, cause the cells to dry out more quickly. Dried cells can be reactivated with a drop of electrolyte solution.
For complete regeneration, the students should proceed as follows:
First, rinse the negative electrode (the side with the dyed layer of titanium oxide) with distilled water. Then to decolor it, place it in a bowl with distilled water and place the bowl in the sun (for example, on a windowsill). The ultraviolet radiation of sunlight destroys the organic components of the dye, resulting in decoloration. When the titanium dioxide layer is white, the electrode can be removed from the water, dried with a hairdryer, and then reused.
For cleaning the positive electrode, only the electrolyte must be washed off, and not the graphite. The graphite does not age and remains fully functional. If the experiment is repeated, the students should nevertheless apply a new layer of graphite on the existing layer, to be on the safe side.
Attention: When you are regenerating the two electrodes, you must never rub the electrodes with a towel or a brush. This would destroy the sensitive coatings. To speed up drying, at most you may gently dab the wet electrodes with a soft paper towel or cotton.
The negative and positive electrodes should be stored separately from each other.