B6 Renewable energies – Sun, water, wind, hydrogen, and fuel cell

The sequence of subexperiments on photovoltaics, hydropower, wind power, and hydrogen technology provides a highly topical introduction to renewable energies. However, the subexperiments require a lot of time and cover a wide range of content. For this reason, the experiments are particularly useful as a project or for a project day on the subject of energy transition. Due to the large scope, it is also highly unlikely that the students will be able to work through the underlying scientific topics during the experiment. Provided that they have certain basic knowledge, however, the students can optimally verify their current knowledge of physics and chemistry based on the subexperiments. Alternatively, the individual subexperiments can also be used as an introduction to one of the basic scientific topics, based on a real-world technical application. Since the kit includes only two of some apparatus, we recommend that you divide the class into groups and have the groups conduct different subexperiments.

1 Main question

The decrease in workable, affordable reserves of coal, oil, and natural gas (fossil fuels), the extremely risky use of nuclear energy, climate change, and increasing environmental awareness have made it necessary to accelerate the implementation of suitable renewable energies. Renewable energies are sustainable, since in contrast to fossil fuels (coal, natural gas, and oil), they are available in virtually unlimited volumes through the use of solar energy. Well-known examples of renewable energies are directly used solar energy (solar thermal energy and photovoltaics), biomass (e.g., wood, biogas, bioethanol), wind energy, hydropower, and geothermal energy. Aside from biomass, costs arise only for the equipment; the energy sources themselves are free.

In this experimentation unit, students will have the opportunity to take a good look at the problematic nature of the existing energy supply and to recognize renewable energies as a possible alternative solution.

They should come to understand the variety of meaning of the term **energy**, especially the four central ideas: energy conversion, energy transport, conservation of energy, and energy degradation. The various forms of renewable energies should be covered in the experiments based on selected examples (solar energy, hydropower, wind energy).

For instance, students will become acquainted with a process for storing and transporting energy based on the example of converting electrical energy to chemical energy (hydrogen). It will probably be many years before drivers will be able to “fill up” with hydrogen at filling stations instead of with the current fossil fuels. But hydrogen is already being tested today in practical applications as a stationary storage system for wind and solar energy.

2 Integrating the experiment into the teaching context

2.1 Basic principles

The full scope of energy is not always covered in science class, although biological and physical processes and chemical reactions always involve the conversion of energy. In everyday life, people don’t often think about the availability of energy sources (electricity, fuels, food, etc.) until there’s suddenly no more supply.

Ideally, students will recognize that the proportion of renewable energies in the global energy supply must increase in order to compensate for the declining reserves of fossil fuels and to make the increasing energy consumption more environmentally compatible.
Students know about the production of renewable energies through wind power plants, hydroelectric plants, or solar power plants from experience. In contrast, they know less about how these renewable energies can be converted into a highly versatile energy form such as hydrogen, which can then be used, for example, to power gas turbines or fuel cells.
Knowledge of the energy level model, the principle of electrolysis, and basic electricity terms (voltage, current, and power) is helpful for successfully conducting and analyzing the individual subexperiments.

2.2 Relevance to the curriculum

In the age group up to 15 years, students will be provided with an overview of the fossil fuels and renewable energy sources used in everyday life and in technology, and the energy forms produced from them (e.g., electrical energy, thermal energy, kinetic energy, chemical energy). They should come to understand that the primarily used energy forms can be converted to other energy forms as needed, whereby a certain "energy loss" (energy degradation) is to be expected. Energy is not lost in such a conversion, but a certain portion thereof is converted to an energy form other than the desired form. (For example, in an incandescent lamp, only about 5% of the electrical energy is converted to light energy, and the other 95% is converted to thermal energy.)
In the age group of 16 years and up, the quantitative aspect of energy conversion can be covered in addition to the qualitative aspect. For instance, the power output of solar cells and fuel cells can be calculated, or the efficiency of generators determined.
Although the technical emphasis of this subject is related to physics, aspects of the chemistry curriculum are also covered with "hydrogen technology".

Topics and terms: biomass (e.g., wood, biogas, bioethanol), conventional load, current, definition of energy (energy is the capacity of a system to perform work, or energy is stored work), energy consumption, energy conversion, energy level model, energy supply, gas turbines, geothermal energy, height of drop of water, hydropower, load, methane, parallel circuit, peak-load current, photovoltaics, power, series circuit, solar cells, solar thermal energy, sustainability, tidal power plant, turbine, voltage, water turbine, waterwheel, wind energy, work

2.3 Skills

After conducting the subexperiments, the students should …

- know how to use silicon-based solar cells.
- recognize how solar cells connected in series and in parallel influence the voltage and the current.
- recognize the influence of wind force on the power of a wind turbine.
- be able to calculate the power of water turbines and wind turbines.
- understand the production of hydrogen during the electrolysis of a soda solution.
- recognize the chemical energy released in an oxyhydrogen reaction.
- understand the conversion of the chemical energy stored in hydrogen and oxygen into electrical energy (in a fuel cell).
- be able to develop a simple concept for hydrogen technology.
- communicate the results they obtained with the other groups.

2.4 Explaining the experiment in the teaching context

In physics, energy is defined as “the capacity of a system to perform work” or as “stored work”.
A visual description for students is “a system has energy when it can lift, move, or heat something, or make something light up.”
The terms type of energy, energy conversion, energy transport, energy storage, and energy degradation play a key role when this subject is covered.
Humans, animals, and plants needs energy to live, and technology doesn’t work without energy.
The international unit for energy is the joule (J). The following applies for conversions:
1 joule = 1 J = 1 Newton-meter = 1 Nm = 1 watt-second = 1 Ws = 0.239 kilocalories (kcal).
One joule is equal to the energy that is needed to do the following:

- Lift a mass of 100 g by (approximately) one meter.

$$E_{pot} = m \cdot g \cdot \Delta h = 0.1\,\text{kg} \cdot 9.81\frac{\text{N}}{\text{kg}} \cdot 1\,\text{m} = 0.981\,\text{J}$$

- Produce one watt of power for one second (e.g., power for one heart beat).

$$E = P \cdot t = 1\,\text{W} \cdot 1\,\text{s} = 1\,\text{Ws} = 1\,\text{J}$$

- Heat one gram of water (at 15°C) by 0.239°C.

$$E = c \cdot m \cdot \Delta T = 4.18\frac{\text{J}}{\text{g} \cdot {}^\circ\text{C}} \cdot 1\,\text{g} \cdot 0.239^\circ\text{C} = 1\,\text{J}$$

The students can develop an idea of the energy requirement in technical areas, such as their daily energy expenditure or the energy content of food. The daily energy consumption of a student is approx. 10,000 kilojoules (kJ), which roughly corresponds to the energy need to do the following:

- Run a 1,000-watt device for 2.8 hours.
- Heat 30 liters of water from 20°C to 100°C.

Note: Even though the terms energy generation and energy consumption are used constantly in economic senses, the students must know that these terms are wrong from a physics and technology viewpoint. Energy can neither be generated nor consumed, but only converted from one form to another: In subexperiment 1, radiant energy is converted to electrical energy and then into mechanical energy (motor). In subexperiments 2 and 3, mechanical energy is converted to electrical energy and then back into mechanical energy. In subexperiment 4, electrical energy is converted into chemical energy and then back into electrical energy.

2.4.1 Subexperiment 1: Electrical energy from the radiant energy of light

Students will measure voltage and current at the solar cells. Power (P) is calculated from the measured voltage (V) and the current (I):
Power P = Voltage V · Current I
In this subexperiment, possible measured values follow:

Number of cells	Circuit	Voltage [V]	Current [A]	Power [W]
1	–	0.5	0.2	0.1
2	Series circuit	1.0	0.2	0.2
2	Parallel circuit	0.5	0.4	0.2

Note: The power calculated from the no-load voltage and short-circuit current is a typical parameter for a solar cell, but it does not correspond to actual power under load, thus when a load is connected. The solar motor used is also not suitable for determining the maximum possible power of the solar cell. To determine this information, the load resistance and recording of the current and voltage values would have to be varied. This should be pointed out to the students to prevent misunderstandings. (To determine the real power of a solar cell, there is a subexperiment in Experiment A5 entitled "Properties of solar cells – Voltage, current and power".)

The measurements clearly indicate that the highest voltage occurs in a series circuit; this is comparable to the connecting of batteries in series to provide a higher voltage. The highest current is achieved with a parallel circuit.
In this measurement, the power achieved with two cells, for example, is always equal, since the change in the current and in the voltage practically offset each other.
The solar motor starts to rotate when a voltage of approx. 0.4 volts and a current of approx. 0.014 ampere are reached. These values can be achieved with one to three solar cells (connected in series), depending on the light intensity.

Tip: As an extension of the experiment, the students could also use a burning mirror to intensify the light or to concentrate the light on the solar cell.

2.4.2 Subexperiment 2: Electrical energy from hydropower

In this experiment setup, the potential energy of water is converted into electrical energy, whereby measured values of, for example, 0.4 volts and 0.025 ampere are expected for a duration of 8 seconds. The converted electrical energy is calculated from the power P and the time t:

$$\text{Energy } E = \text{Power } P \cdot \text{Time } t$$

Voltage [V]	Current [A]	Power [W]	Time [t]	Energy [Ws]
0.4	0.025	0.01	8	0.08

(See also the note on the problematic nature of determining power in Section 2.4.1.)

The students should recognize that as the height of drop of the water increases, the voltage and the current increase, and thus the electrical power is greater.
This is because as the height of drop and the volume of the water increase, the potential energy of the water and thus the electrical energy generated from the water also increase.
The students should describe the principle of a storage power plant, in which water is pumped higher when there is an energy surplus, and the energy is converted back to electrical energy by the water turbine when there is a demand for energy. (Sources for further study of hydroelectric power plants are available in Section 3, "Additional information on the experiment".)

2.4.3 Subexperiment 3: Electrical energy from wind power

The students will blow on a propeller attached to an electric motor, which serves as a generator. Possible results in this subexperiment are as follows:

Voltage [V]	Current [A]	Power [W]
3.1	0.030	0.093

The light-emitting diode, which is used here as a load, visibly lights up starting from a voltage of 1.8 volts. The students should recognize that the power of a wind turbine depends on the form and surface area of the propeller and on the wind force.

2.4.4 Subexperiment 4: Conversion of electrical energy into chemical energy and vice versa

By conducting the subexperiments, the students should recognize that hydrogen (at the negative pole) and oxygen (at the positive pole) are produced in a 2:1 ratio. When ignited, pure hydrogen explodes weakly with a dull sound; in contrast, a mixture of hydrogen and oxygen (volume ratio 2:1) produces a bang (oxyhydrogen gas).
If hydrogen electrolysis is performed not only with the 9-volt accumulator, but also with the solar cells, the following becomes clear: Starting from approx. 2.2 volts (five solar cells connected in series), gas begins to visibly form in the electrolytic cell. The electrical energy of the accumulator or the solar cells has been converted into chemical energy (hydrogen and oxygen).
The graphite electrodes of the electrolytic cell become saturated with hydrogen and oxygen, and can then be used themselves as a source of electricity: If the students connect a motor to the electrolytic cell in place of the battery or solar cell, the motor works as a fuel cell, since the reverse reaction of hydrogen and oxygen into water produces electric current.
If this hydrogen technology were used, electric current from renewable sources of energy could be converted into hydrogen on site by electrolytic cells. This hydrogen could then be fed into the natural gas network, for example, and transported to consumers. Hydrogen is also currently being tested directly at inland wind farms. In times of wind surplus, the electricity is used to generate hydrogen and is stored on site in tanks. When the air is calm, the chemical energy of the hydrogen can be converted back into electrical power by fuel cells.
Researchers are currently testing the first pilot plants for producing methane from the hydrogen obtained through excess renewable electricity through the catalysis of CO_2. This process has been known for 70 years. With this renewable methane, the natural gas network could be used both to store and to distribute energy! In the distant future, gas turbines for extracting the peak-load current would then no longer be run with fossil fuel, but with renewable fuel.

The hydrogen fuel cell was discovered based on the experiment setup shown. In contrast, in our experiment we use graphite electrodes instead of platinum electrodes and do without a membrane to divide the fuel cell into two parts. We do not use pure water as the electrolyte, but a saturated sodium carbonate solution. It is possible to do without the membrane for a short period of non-continuous operation. We need the sodium carbonate solution to reduce the water's decomposition voltage. This is explained in detail in the teacher instructions for experiment "B7 Capacitor, hydrogen, redox flow – We store renewable energy."

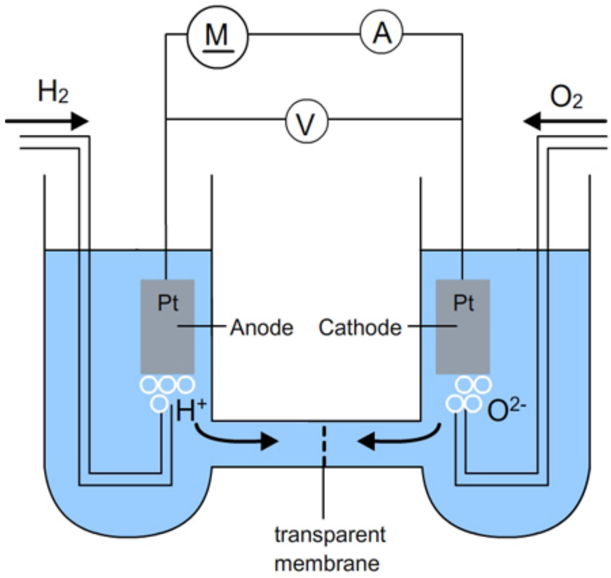

Fig. 1: The original principle of the hydrogen fuel cell.

2.5 Experimental variations

Since the apparatus supplied in the experiment kit are sufficient for only four groups, groups 1 and 2 should conduct subexperiments 1 and 2, and groups 3 and 4 should conduct subexperiments 3 and 4.
If there is sufficient time, the groups can trade apparatus and conduct the subexperiments of the other groups. The important aspect is the communication and comparison of results among the groups. If the students are unable to handle the calculations, they should be required to describe the phenomenon only.

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 following media packages relevant to the individual aspects of renewable energies are available on the Medial Portal:

- Renewable energies – The future is sunny!
- Water and wind – Traditional energy sources rediscovered
- Solar thermal energy and photovoltaics – Energy forms with a future
- Hydrogen – The energy source of the future?

4 Notes on conducting the subexperiments

4.1 Facilities

No special facilities are necessary.

4.2 Time required

	Preparation and execution, analysis, questions
Subexperiments 1 and 2:	Up to 120 min.
Subexperiments 3 and 4:	Up to 120 min.
All subexperiments as a whole	Up to 240 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.
For these experiments, watch out for the following potential dangers and make your students aware of them:

- Working with a flame can result in burns or fires. Before a lighter is used for the first time, the teacher must check that it is working properly and, above all, adjust the flame height.
- Care must be taken to ensure that the accumulator is not short-circuited. This results in a risk of explosion and fire.
- Test tubes made of plastic (PP) must be used for the oxyhydrogen test; do not use glass test tubes!
- The students must wear safety goggles during subexperiment 4. Point out to the students the first aid measures they must follow if sodium carbonate or soda solution splashes into their eyes or onto their skin (rinsing immediately with water is sufficient).

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

Hazard Statements: H319
Precautionary Statements: P260, P305, P351, P338

4.4 Apparatus and materials

Required materials that are not supplied:

- Bucket or large bowl as a collecting container
- Cardboard strips for mounting the solar cells
- Clock (a watch is sufficient)
- Ruler
- Tap water
- If the available sunlight is insufficient, desk lamps or similar light sources with at least 20-watt halogen light bulbs should be provided.
- When subexperiment 2 is conducted for the first time, a tea light and one lighter must be taken from the experiment kit for each group of students so that they can bend the propellers to function as waterwheels.
- For subexperiment 4: One lighter per student group (if possible, a gas igniter) or matches

Supplied:
Depending on the subexperiment, the apparatus and materials supplied are sufficient to allow **two** or **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.
Safety-relevant materials and apparatus must be tested for proper functioning before being handed out to the students.
For **subexperiments 1 to 3**, which **four** groups of students can conduct simultaneously, the following materials included in the kit are needed **one** group of students:

Material	Quantity
Connecting cable, alligator clip to alligator clip	5x
Digital multimeter	1x
Dual propeller for small solar motor	1x
LED, red (clear case), 1.7 V	1x
Measuring cable assembly, banana plug to alligator clip, red and black for each	1x
Plant clip	1x
Plastic cup (clear), 500 ml	1x
Propeller (for large solar motor)	1x
Rubber band	2x
Solar cell, 0.5 V/150 mA	2x
Solar motor, large, iron armature, 0.4 V/25 mA	1x
Solar motor, small, bell-type armature, 0.1 V/2 mA	1x
Syringe (conical tip), 100 ml	1x
Tape	1x

Fig. 2: Apparatus and materials supplied for one group of students for subexperiments 1 to 3.

For **subexperiment 4**, which maximum **two** groups of students can conduct simultaneously, the following **additional** materials included in the kit are needed **one** group of students:

Material	Quantity
Accumulator, 9 V*	1x
Electrolytic cell**	1x
One-way cock (to fit 7/4mm tube and Luer lock)	2x
Safety goggles	1x***
Silicone tube, 7/4mm, 3.5 m (to fit Luer lock)	1x for entire class The first time the subexperiment is conducted, cut one 3.5-cm piece for each group, which can then be reused.
Syringe, Luer lock, 10 ml (as collecting container)	3x
Test tube, plastic (polypropylene), mini	1x
Washing soda (sodium carbonate), package****	1x

*The accumulators must be fully charged, and should be recharged immediately after use. A charger is included in the experiment kit.
**The electrolytic cell is supplied as a set of parts (cup, two graphite electrodes, two pieces of copper cable, two sections of tube) and must be assembled by the first group of students (instructions in students' file).
***A total of 16 pairs of safety goggles are supplied for all students in all groups. If more than 16 students participate in the experiments, additional pairs may need to be provided by the school.
****Note: A package of soda is included in the experiment kit. However, it doesn't appear to make much sense to have the students make the necessary soda solution for the experiment.
In addition, the solution can be reused. Therefore, the teacher should make about 500 ml of

saturated sodium carbonate solution in preparation for subexperiment 4. At the maximum, 217 g of sodium carbonate will dissolve in a liter of water at 20°C. The solution should be provided in a well-sealed container. After they have conducted the subexperiments, the students can pour the sodium carbonate solution back into the sealable container for future use.

Fig. 3: Apparatus and materials supplied for one group of students for subexperiment 4.

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.