Renewable energy

This guideline provides a comprehensive introduction to the subject of “renewable energies.” The various renewable energies are listed in the order in which they were historically used by humans. The following criteria are discussed for each form of energy:

- **Explanation**
  Definition and explanation of the energy source, including historical aspects if applicable.
- **Availability and substitution potential**
  How many of these energy sources are available worldwide, and how are they distributed geographically? What proportion of the fossil and nuclear energy sources used to date would be replaced by these renewable energy sources, and over what time frame?
- **Technologies used**
  and the most important scientific background information on them.
- **Disadvantages and limits**

In addition, there is also a chapter on energy storage, which is particularly important for renewable energies.

1 What are renewable energies?

To renew literally means “to make like new.” A renewable energy source is a source which “regenerates itself” on its own, so to speak. This doesn’t exist yet, strictly speaking, because energy can neither be created nor destroyed, nor regenerated, but only converted.
Nevertheless, the custom of referring to particular energy sources as “renewable” is correct. That is because the energy sources are inexhaustible by human standards; more energy than humans can use will continue flowing for an extremely long time. From this perspective, it doesn’t matter, for example, whether wood is burned since trees grow back thanks to sunlight; or whether heat from sunlight is extracted from the ground using a heat pump since it will be resupplied by the sun; or whether a photovoltaic power plant continuously converts radiation to electrical energy, because the sun will shine for another five billion years.
The term “renewable energy sources” was coined in contrast to fossil and nuclear energy sources, which will be used up by people in a foreseeable period of time. Renewable energy sources, on the other hand, are nearly inexhaustible in human terms.

1.1 What renewable energy sources are there?

Renewable energy sources include the following:

- Sunlight (photovoltaics)
- Solar heat (solar thermal energy including geothermal sources near the surface)
- Biomass (plants, wood, biogases)
- Water (hydropower)
- Wind
- Geothermal energy (deep geothermal energy)

1.2 Do renewable energy sources have mainly advantages or disadvantages?

One advantage of renewable energies that is often cited, in addition to their inexhaustibility, is the fact that they are distributed evenly across the globe. In contrast to fossil and nuclear energy sources such as coal, oil, natural gas, and uranium, this seems to be true. But when we look more closely, we see, for example, that hydropower and wind are also not available to the same extent around the globe. And sunshine cannot be used economically as solar thermal energy in many regions either, at least not for generating electric power. So this advantage is a relative one at best! However, the use of renewable energies can offer a clear advantage for the respective national economy, since it reduces dependency on energy imports. For example, in 2005, the degree of dependency on imported petroleum in the European Union (EU) was around 80 percent, and in the United States around 66 percent (sources: EU Green Paper on Energy Security and the German Foreign Office).

One of the disadvantages of renewable energies that is often mentioned is their low “power density.” This is true to a certain extent since the sunlight from millions of years ago is now being used, as it were, in an accumulated, concentrated form as oil, natural gas, or carbon. In order to generate 3.5 MWh of electrical energy, for example, a coal-fired power plant needs around 1 tonne of carbon, but a photovoltaic power plant covering at least one hectare in Central Europe needs one average sunny day. But on the other hand, the economic use of, for example, the fossil energy source coal or the nuclear energy source uranium requires very large, centralized power plants. In contrast, wind and photovoltaic systems can also be used economically in relatively small, decentralized plants. For example, if the facades of large office buildings and factories were also used, nearly the entire energy requirement of a Central European country could be met with photovoltaic power alone. With a non-subsidized electricity production price starting at 7 eurocents/kWh, photovoltaic power is now (2016) less expensive than gas turbine power. Onshore wind power from new, optimally placed wind turbines has already become the cheapest power source, at 4.5 eurocents/kWh.
The fluctuating availability of renewable energy sources such as water, wind, and sun in comparison with traditional energy sources such as coal, oil, gas, and uranium is also a disadvantage. These irregularities in power generation must be compensated for by expanding the power supply grid and building energy stores.

2 Finite availability of resources

2.1 How large is the share of renewable energy sources today?

In 2014, around 22 percent of the worldwide consumption of primary energy sources was already covered by renewable sources. Of this, biomass still accounts for the largest share of renewable energy. However, in 2005, the proportion of electric power generated using renewable hydropower was actually 16 percent worldwide. The consumption of fossil and renewable energy sources is divided very differently across industry, transportation, and private households. For instance, in 2001 oil accounted for 28 percent of total energy consumption in the United States, but the share for transportation was 70 percent.

2.2 How long will fossil and nuclear resources last?

An optimistic estimate from 2005 indicates that, according to International Energy Agency (IEA) figures, worldwide stores of non-renewable energy sources will last around 190 years for coal, around 40 years for oil, around 60 years for natural gas, and around 100 years for uranium. Further statistics and overviews are provided in the “An overview of energy sources” media file (information sheet).
According to studies conducted by the IEA in 2007, however, world energy consumption is set to rise again by around 60 percent by the year 2030 – a fact which had not been taken into account. Skeptics therefore assume that the above resources will not last anywhere close to this, especially since it is uncertain whether it will actually be economically viable to exploit deposits that have not yet been used. This is because when the technical efforts to obtain fossil energy sources increase, the costs and thus consumer prices also rise. Whether industries and end consumers can pay the

prices, though, is questionable. For example, an economic crisis already occurred in 2007 due to increased prices for steel and coal, but it was hardly noticed because of the subsequent financial crisis.

2.3 How is climate change affecting energy resources?

The burning of fossil energy sources (coal, oil, and natural gas) releases carbon dioxide (CO_2), which contributes to the increase in the greenhouse effect and thus to global warming. Politicians are therefore making efforts at the international level to restrict the use of fossil fuels or to use these fuels more efficiently and to replace them in the medium and long term with renewable energy sources. That's because the sun, wind, water, and geothermal sources do not release carbon dioxide when used, or are at least CO_2 neutral, like biomass. This CO_2 neutrality also applies theoretically to nuclear energy, but then there is the problem of radioactive waste. In any case, time is running out much more quickly than is generally realized. Thermal power plants make use of traditional energy sources, both fossil and nuclear, and they require cooling equipment. River water is generally used for cooling at the moment, because although cooling with air or seawater is technically possible, it is more complicated and more expensive. However, as cheap river water becomes increasingly scarce due to climate change, large thermal power plants using traditional cooling technology will be left standing idle. During the hot summer of 2006, for example, nearly all French nuclear reactors remained idle and France had to purchase renewable electricity from Germany for up to 2 euros/kWh. During the dry summer of 2015, most lignite-fired power plants in Poland also stood idle, and renewable electricity from Germany came to the rescue again.
As a result of climate change, the use of traditional energy sources in thermal, nuclear, and run-of-river power plants will become increasingly expensive. The use of renewable energy sources, by contrast, will become increasingly economical.

3 The sun as the origin of all energy on Earth

Apart from deep geothermal energy, the sun, or its radiation, is the origin of all renewable energy sources on Earth. This applies to the biomass formed via photosynthesis from the sun's rays, to the water cycle brought about by the heat of the sun and the resulting hydropower, and to the winds created by solar heat. In addition, solar radiation can be used directly as heat (solar thermal energy) or via photovoltaics as electrical energy. The energy radiated by the sun is by far the greatest source of renewable energy. Each year, the sun radiates an average energy volume worldwide of approximately $1.56 \cdot 10^{18}$ kWh ($5.6 \cdot 10^{24}$ J) onto Earth's surface. This is more than 10,000 times the world demand for primary energy. In the ranking of renewable energies, solar energy is followed by geothermal energy (deep geothermal energy) and tidal energy (effects of the moon and the rotation of Earth).

4 Biomass

The oldest of any of the energy sources used by humans is biomass. Traditionally, ever since the discovery of fire, humans initially used renewable biomass only in the form of wood; later, in the plains where wood was scarce, they also used the dung of their domestic animals as fuel.

4.1 What is biomass?

With primary biomass products, plants are used to convert solar radiation to organic matter via the process of photosynthesis. Biomass thus represents stored solar energy. The main advantage of using biomass energy is the reduction of carbon dioxide emissions into the atmosphere: wood and other biogenic energy sources initially drew the carbon dioxide stored in them from the atmosphere as they were growing. After these sources are burned, the carbon dioxide formed is re-integrated completely if renewable vegetation is used sustainably.

4.2 Availability and substitution potential of biomass

Of the solar energy shining onto Earth, only around 0.01 percent is stored on Earth in the long term. Nature stores over 99.9 percent of this 0.01 percent in the form of biomass via photosynthesis. However, “only” about 10 percent of the worldwide primary energy requirement is currently covered by this biomass. It might seem possible to increase this amount, but if examined more closely, biomass does not represent an additional viable source of renewable energy, in global terms. See also the chapter on “Disadvantages and limits of biomass” below.

4.3 Technologies used with biomass

Biodiesel
Plant-based oils, especially canola oil and palm oil, can replace traditional fossil diesel fuel relatively cheaply. However, the quality of untreated plant-based oils is inadequate with regard to shelf life and suitability for winter use; they are therefore still subsequently converted chemically to substances that can be better used for technical purposes. In many regions of the world, including in Germany, large-scale plants have since been built for this purpose. (For chemistry teachers: The production of biodiesel in the classroom is a great example of esterification or transesterification. You will need canola oil from the supermarket, methanol, and sodium hydroxide.)

Wood gasification
If wood is dry-distilled or carbonized with the addition of water, gases that burn well are produced. This process was used to manufacture a substitute for gasoline during and after World War II for the operation of cars and trucks. Modern high-tech processes such as the integrated gasification process (IG) are not only used in large power plants for carbon and heavy oil gasification, but are also suitable for the gasification of wood and other organic substances. The advantage is that they produce an extremely pure mixture of hydrogen and carbon monoxide, which can be substituted for natural gas in the operation of highly efficient gas turbines, and which produces better exhaust gas values than a conventional power plant with direct combustion with steam boiler firing.

Biogas
Organic waste materials containing carbohydrates and cellulose, like manure, slurry, and straw, as well as grains, like corn and wheat, are broken down in the absence of air (anaerobically) into methane by particular bacteria. The biogas thus generated can be used directly on-site with diesel engines to generate electrical energy. After being purified, the biogas can also be fed into the public gas network. For the process to run efficiently, concentrations, temperatures, pH values, and other factors must be controlled very precisely. Now there are sophisticated technologies for biogas plants of all size classes.

4.4 Disadvantages and limits of biomass

Biomass is not necessarily more environmentally friendly than fossil energy sources. Bioenergies are limited, for example, by the surface areas available and the growth conditions required by the energy crops. The competition between food and energy crops then has negative consequences for the agricultural structure. For example, incentives paid for imports of palm oil from tropical

cultivation areas lead locally to climatic damage and the disruption of regional economic patterns, which causes the balance of trade to deteriorate and weakens domestic agriculture. In the cultivation and processing of biomass, environmental pollution such as overfertilization, acidification, and erosion caused by the mechanical processing of soil used for agricultural purposes are negative factors in the ecological balance. In addition, there is the environmental pollution due to herbicides, fungicides, and pesticides. The shortage of freshwater and the steppization and desertification of large areas are currently increasing worldwide, but this is caused only partly by climate change. These processes are significantly intensified by logging and slash-and-burn clearing of rainforests and, more recently, especially for the cultivation of sugar cane and oil crops for the production of bioalcohol and biodiesel as “renewable” fuels. Admittedly, some biofuels produce less than two-thirds of the greenhouse gases produced by gasoline or diesel. In Central Europe or the United States, however, nitrogen-based fertilizers used in the increased cultivation of rapeseed, for example, leads to increased emissions of the extremely strong greenhouse gas nitrous oxide (N_2O), which is 310 times more potent than CO_2! In tropical countries, for example, the slash-and-burn clearing of rainforest areas produces large quantities of CO_2, which in turn causes increased air pollution through soot and other hazardous exhaust gases like nitric oxides, aerosols, and dioxins and results in a loss of biological diversity of flora and fauna.
In regions where forestry is a major industry and the waste products have been left unused until now, or where unused fallow land is available, the increased use of biomass may make ecological and economic sense. Because hundreds of millions of people worldwide still suffer from malnutrition and the world’s population is still growing, biomass will have to be used in the medium and long term especially for food production, and will not be available as a potential substitute for traditional energy sources.

5 Water

Hydropower is also a form of solar energy stored in nature. After all, it ultimately comes from the cycle of evaporation and precipitation brought about by the sun. Here, we are just considering the directly used mechanical “hydropower” as an energy source. Water is also used to store heat (district heating, geothermal energy). In contrast, when electrical energy is stored in the form of hydrogen through the electrolysis of water, it is hydrogen rather than water that is the energy source.

5.1 What is hydropower?

Hydropower, or water power, is the term used to describe the energy of flowing water that is converted to mechanical or electrical energy via turbines and the generators connected to them. Over 2,000 years ago, people in Mesopotamia (present-day Iraq), Egypt, and other places were already using hydropower in the form of scoop wheels for irrigation. Later, mills for grinding grain were developed. From the Middle Ages until the beginning of the 19th century, all ironworks worked as water-powered hammer mills. Iron and steel could not yet be smelted in liquid form in blast furnaces; instead, they were laboriously “hammered out” from solid lumps of iron dross (“blooms”). Therefore, historically, the mechanical energy was initially used directly in mills and hammer mills. Only with the gradual widespread use of electricity in the late 20th century was hydropower increasingly converted to electrical energy using turbines and generators.

5.2 Availability and substitution potential of hydropower

In 2014, hydropower accounted for 16.6 percent of global power generation – the other renewable energy sources (including biogenic substances) combined made a contribution of 6.2 percent. At the moment, the only renewable energy source making any appreciable contribution to supplying the Earth's population is hydropower. The other renewable forms of energy, such as sun, wind, geothermal energy, and biomass, contribute around 2.1 percent combined. In 2005, hydroelectric plants generated around 16 percent of the electrical energy generated worldwide, which is almost the same amount as nuclear power. The speed at which a plant can be started up and shut down, its long service life, and its low operating costs due to the low level of maintenance and servicing are further positive aspects. According to present estimates, the proportion of electric power generated by hydropower could be further increased by a few percentage points with run-of-river power plants. However, natural limitations such as earthquake safety and climate change mean that no more major increases are likely.
It's still too early to say whether the newly developed shaft hydroelectric plants will facilitate further expansion of hydropower in regions such as Central Europe, where further expansion has previously made little sense. These new power plants barely spoil the landscape and are relatively inexpensive.
On the other hand, ocean power plants, like current and wave power plants, theoretically offer great potential, although the associated technology is still in the pilot phase.

5.3 Technologies used with hydropower

A distinction is made between different types of hydroelectric plants, depending on their design. The following is a short overview:

Run-of-river power plants
With a run-of-river power plant, a river is dammed up for a few meters and electric power is produced as continuously as possible with the water flowing through the power plant to cover the base load. Generally speaking, Kaplan or tubular turbines are used.

Buoy generator
With a buoy generator, the turbine is located in a pipe that is suspended directly in the water; the turbine converts the kinetic energy of the water to electrical energy. There is no need for dams, and the landscape and water levels are not changed. Initial pilot projects are running in Austria. However, the output is low – each buoy would cover the consumption of only about 30 households.

Storage power plants with a dam
With a storage power plant, the water is stored for a lengthy period of time. Depending on the quantity of water, the power plant is used continuously or temporarily to cover peak load. In power plants with a high dam (valley dam), that is, where the pressure and water volume are high (for example, Itaipú, Cahora Bassa, Three Gorges Dam), the Francis turbine is generally used. With lesser quantities of water and a relatively large height of drop, the Pelton turbine is used.

Pumped storage power plant
With a pumped storage power plant, surplus electric power is used to pump water to a higher reservoir so that peak-load power can be generated later. At the moment, pumped storage power plants represent the only fully developed, economically viable technology for temporarily storing large quantities of electrical energy in the form of other energies.

Tidal power plant
A tidal power plant uses the mechanical energy from the constant change of ebb and flow. From a teaching viewpoint, this type of power plant is interesting, since the energy ultimately comes from the slowdown in Earth's rotation, rather than from the moon as many people think.

Wave power plant
Wave power plants use the kinetic energy of the mass of water, which is converted from solar energy to more or less continuous waves via winds. The first pilot plants have been running since 2007. One solution works with turbines. Another method aims to convert the fluctuations in the waves to mechanical rotational energy and then to electric power using a type of pendulum. The technologies are promising but have not yet been fully developed.

Ocean current power plant
Because of differences in temperature and salt concentrations, in many areas there are constant ocean currents whose kinetic energy could also be used. Initial pilot projects ("Seaflow") using extremely slow-running underwater propellers are being tested.

5.4 Disadvantages and limits of hydropower

When electric power is obtained from hydropower, no natural resources are consumed, no pollutants are emitted, and only small amounts of waste heat are produced. Additionally, hydropower is very efficient (up to 95 percent). In many cases, the regulation of water courses using dams also has indirect advantages for irrigation, raising the groundwater level, the creation of leisure areas, fish farming, shipping, flood protection, and drinking water supplies.
But hydropower does have some disadvantages. In many cases, power generation is irregular, for example, if the water level of rivers drops because of inadequate precipitation. Climate changes could accentuate these fluctuations. The effects on the landscape and on the habitats of humans and animals are also often massive. The damming of flowing water brings about changes in the flow dynamics and the intertidal zones. The speed of the flow is greatly reduced, which, because of the disturbance of the bed-load balance, leads to sediment deposits above the dam and erosion below. Further consequences are the fragmentation of the habitat of many water-based species and changes in the structure and diversity of the flora and fauna in the water and on the riverbank. The quality of the water can deteriorate, for example, due to oxygen depletion, temperature fluctuations, change in current conditions, and eutrophy (overfertilization caused by standing of the water in the reservoir) and restrict the habitat of migratory fish. Long-standing human habitats are also often lost. There is also increasing debate about the danger of flood disasters caused by earthquakes or landslides. Often, long distances between usable hydroelectric plant locations and the consumer centers mean that transport costs account for a relatively high proportion of the price of the electric power.

6 Wind

6.1 What is wind energy?

Because the wavelengths of sunlight that can be absorbed by the molecules of the atmosphere are filtered out in the upper strata, the air near the ground is not directly heated by the sun. Not until Earth's surface (and water) is heated by direct and indirect radiation are the layers of air above it heated, which lifts the air and causes it to flow upward. At the same time, air flows back in horizontally from less heated areas; this cross flow is described as wind. The kinetic energy of the linear air movement of the wind can now be converted to linear movement by sails or to rotational movement via wind turbines. People have been using wind energy to drive windmills for around 2,000 years.

6.2 Availability and substitution potential of wind energy

As a CO_2-free source of electric power, wind energy not only makes an important contribution to active climate protection, it also conserves our stores of fossil fuels. In 2014, CO_2 emissions were already reduced by 40 million tonnes through wind power. In 2015, China alone built wind power plants with a total capacity of over 30 GW, which corresponds to the capacity of up to 15 nuclear power plants. Even if only relatively windy areas and large wind farms (for example, offshore wind farms) can be regarded as economically viable, there are still plenty of potential locations. Because of the relatively modular technology used, these wind farms do not take long to build, in contrast to other major power plants. In just a few years, a small portion of the energy requirement worldwide has been covered through the use of wind power, as we can see in China. In Germany, however, the expansion of wind power had to be restricted in 2016 because there aren't enough power lines and people want to avoid a sudden cut in jobs in the fossil fuel field, especially as concerns lignite. However, regarding the availability of wind power, it must be kept in mind that because of the varying wind conditions, on average only approximately 25 to 50 percent of the installed wind generation capacity is available for the current electric power supply.

6.3 Technologies used with wind power

At the moment, there is basically only one fully developed wind turbine technology: "lift-type wind turbines," usually with three-blade propellers, aligned vertically to the direction of the wind. The latest generation of wind turbines works without gears with multipole generators, balancing out the fluctuations in wind-related voltage and frequency using modern power converter technology. These technologies are explained in the "How a wind power plant works" medium (interactive information module).

6.4 Disadvantages and limits of wind energy

In most cases, concerns about wind farm locations are related to concerns about protecting nature as well as for aesthetic reasons. However, ever since the beginning of the industrial era, humans have been living in an increasingly densely populated industrial landscape with a highly developed infrastructure. Artificial structures – structures created by humans – determine and influence the landscape. Roads, rails, airports, large power plants, waste incinerators, chemical factories, and all sorts of power poles over 60 m high are now regarded as perfectly normal. Our landscape has been molded by people from time immemorial, and so any adverse effects from wind turbines should be viewed relative to the impact and, more specifically, relative to the major advantages that wind energy offers ecologically. Some people also complain about the shadows thrown, noise pollution, and the danger to birds and bats. However, careful planning of the locations as well as regulations concerning distances can reduce these disadvantages.

The restriction of locations to windy areas, the fluctuating supply of wind energy, inadequate grid development, and the continuing lack of facilities for the temporary storage of electrical power are currently the major barriers to wind energy.

7 Solar heat (solar thermal energy)

In physics and biophysics, light is defined as the visible portion of the electromagnetic spectrum. However, with solar thermal energy and photovoltaics, the invisible portions of solar radiation are also partly used. In addition, a distinction is made between heat and light in physics, chemistry, and energy conversion technology. Depending on the absorption material used, solar thermal technology uses the complete spectrum of solar radiation: the invisible UV range (under 400 nm), the visible range up to 800 nm, and the invisible range of the near (over 800 nm) to far infrared (up to approximately 12,000 nm). With an ideal solar thermal absorber, approximately 1 percent of the thermal energy would come from UV light, approximately 50 percent from visible light, and approximately 49 percent from infrared light.

7.1 What is solar heat or solar thermal energy?

Way back in the Stone Age, before fire was discovered, cavemen used the heat of the sun stored in rocks to protect against the cold in the night or during cold weather. But how does heat get from solar radiation into the rock? When the electromagnetic solar radiation hits a body, some of it is reflected and some is absorbed. With an ideal, black object, the degree of absorption would be 100 percent. The absorbed radiation is converted into the movement of the tiniest particles in the object (atoms or molecules). The heat content of the object rises, and so does its temperature. An ideal, black object absorbs both visible and invisible light, that is, ultraviolet (below approximately 400 nm) and infrared (above approximately 800 nm). When we talk about solar thermal energy, we generally mean the long-wave range of solar radiation.

Be careful using the term "heat radiation"!
The term "heat radiation" is frequently used incorrectly or in a misleading manner. It's correct that all bodies that are warmer than 0 K radiate energy. When heat is the cause of the radiation, it is correct to use the term "heat radiation." But watch out; when the heat is radiated, energy has been converted from heat (movement of the tiniest particles in the material) to radiant energy (electromagnetic waves). When radiation hits a body and causes it to warm up, the radiant energy is also converted to thermal energy. Thus, there is no such thing as radiation that transports heat and is therefore called "heat radiation," but only thermal energy or radiant energy.

7.2 Availability and substitution potential of solar thermal energy

In 2013, private households in Germany consumed 2,603 petajoules (PJ) of energy, which equates to 723 billion kWh. This accounted for 28 percent of total final energy consumption in Germany. Private household energy use can be broken down as follows: approximately 69 percent for heating, 15 percent for hot water, 6 percent for cooking, 4 percent for refrigeration and cooling applications, 4 percent for information and communication technologies, 2 percent for lighting, and less than 1 percent for other electrical devices and appliances.
It stands to reason that the solar heat being received today could be used for heating rooms and water instead of relying on fossil solar energy such as coal, heating oil, or natural gas. In large parts of the temperate and cooler regions of Earth, solar thermal energy would be sufficient for this. In Central Europe, solar irradiation per year is approximately 1,000 kWh/m^2. The heating requirement in a house with traditional insulation is approximately 200 kWh/m^2 per year, and in a well-insulated "low-energy house" approximately 30 kWh/m^2 per year. If all heating and water heating in German households were converted to solar thermal energy, the energy consumption and thus the CO_2 emissions of each household could be cut by up to 70 percent, and total CO_2

emissions in Germany could be cut by up to 20 percent! Solar thermal energy therefore has tremendous potential as an energy substitute!

7.3 Technologies used with solar thermal energy

Solar radiation can be “collected” or captured with collectors and stored temporarily in heat stores, generally water tanks. It is also possible to use the solar heat stored in the soil, groundwater, or surface water with heat pumps. Structural measures are also suitable for absorbing and storing solar heat in the body of the building itself.

7.3.1 Using solar heat directly with collectors

The most important part of the collector is the absorber, which converts the radiant energy of the sun to heat and passes it on to a liquid heat transfer medium. This liquid is pumped through the entire cycle, passing on its heat to a heat store such as the boiler in a central heating system or the hot water supply boiler. If the temperature of the collector is approximately 60°C, several days without sunshine can be also be covered if the heat store is large enough (approximately 2,000 l water). In order to reduce absorber losses to the surroundings, good heat insulation is essential. Collector systems are classified according to the efficiency of the absorption and the insulation technology used.

Simple absorbers
Simple absorbers generally consist of black plastic bodies without any additional insulation. In southern countries, a black barrel is often simply placed on the roof of the house. In Central Europe, this is enough in summer for showering or heating a swimming pool.

Flat plate collectors
Flat plate collectors consist of a copper or aluminum absorber that looks like a flat radiator placed on an insulating layer of mineral wool or rigid foam in a flat casing. The surface of the absorber is coated with a blue-black titanium compound that is able to absorb over 90 percent of the radiation. The special characteristic of this coating is that it gives off only approximately 10 percent of the heat, because it reflects around 80 percent of the heat back into the absorber at the boundary with the copper or aluminum. Covering the casing with a pane of glass considerably reduces heat loss through the air (conduction, convection, and wind). The temperature in the absorber reaches up to 90°C under full solar irradiation. If the storage container is large enough, collectors of this type with a collector surface of approximately 5 m^2 are sufficient in Central Europe to heat water in a single-family house for around nine months of the year. With a surface area of approximately 32 m^2, heating of the house can also be covered for the same period of time.

Evacuated flat plate collectors
Evacuated flat plate collectors have the same design as the normal flat plate collector, except that, in addition, air is evacuated from the casing (vacuum). The loss of heat to the surroundings is therefore lower, and in theory, temperatures of up to approximately 200°C could be reached when the pump is idle. If not covered by snow, a collector of this type can supply part of a household’s heat requirement even in winter.

Evacuated tube collectors
As with the evacuated flat plate collector, in the evacuated tube collector the absorber is made from specially coated copper. But in contrast, the absorbers are copper tubes, each in an

evacuated glass tube. A parabolic reflector is attached to the underside of the glass tube so that the copper absorber tube is at the focal point. Collectors of this type are up to four times more efficient than flat plate collectors and can reach stagnation temperatures of over 300°C. Initial pilot projects in Germany show that they can fully cover hot water and heating requirements all year round in low-energy houses. However, there are doubts about the economic viability of such extreme solutions, since the investment required is much higher than it is for other types of collectors.

7.3.2 Using solar heat indirectly with heat pumps

In large areas of Europe, North America, and Japan, the temperature of the soil and the groundwater never falls below approximately 7°C, even in the winter. Even the surface water in rivers and lakes falls below 4°C only when they are completely frozen. These temperatures are the result of warming from the sun's rays and the large heat storage capacity of the water and the soil. Heat can be conveyed from a low-temperature reservoir (for example, groundwater) to a high-temperature reservoir (for example, heating boiler) with heat pumps (inverse heat engines). If the temperature of the groundwater is, for example, 7°C and the heating boiler temperature is approximately 40°C, then approximately 4 kW of thermal heat can be obtained using 1 kW of operating energy from the heat pump. Suitable heat sources are river water, groundwater (boreholes to a depth of approximately 15 m), geothermal energy (laying of pipes over a large area at a depth of at least 1.5 m), the air, and also thermal solar collectors. Even if the heat pump is operated using electric power, this can be an ecologically and economically viable solution. However, amortization of at least 15 years is likely, which is worthwhile only with extremely long-lasting heat pumps.

7.3.3 Using solar heat through architectural measures

Solar heat is traditionally also used to regulate the temperature in living areas. This is done using architecture that meets these needs, in the form of low-energy or passive houses. In cold climates, windows, doors, and sunrooms preferably face toward the midday sun. Ideally, they should be shaded by canopies or blinds so that the overhead sun in summer does not shine into the house. In contrast, the flat rays of the low-lying sun in the transitional seasons and in winter will shine inside. The interior walls and floors are made from materials that store the heat well, such as brick, concrete, or certain natural stones. If the mass of these materials is large enough, sufficient heat is stored in them to keep the entire house pleasantly warm at night and on cloudy days. If, like in a low-energy house, the windows and outer walls of the house are extremely well insulated, in areas with many days of sunshine, up to 80 percent of heating energy can be saved in this way. Instead of having an annual energy requirement of over 200 kWh/m^2, like a traditionally heated house, the low-energy house needs only approximately 40 kWh/m^2. A "passive house," which has even better insulation and better heat stores, can actually save up to 95 percent of energy.
A new trend is "energy-plus houses," which generate more energy than they consume over the course of a year. With a combination of optimal orientation of a house's glass surfaces toward the south (in the northern hemisphere), heat-storing building materials, heat pump heating with ice storage, thermal solar collectors, and photovoltaics, cost-efficient energy-plus houses can already be built today. One way to achieve cost-effective construction is to forgo heat insulation methods. (For example, a 35-cm-thick aerated concrete exterior wall costs only about 1/3 compared to a "normal" wall with added plastic foam insulation. Even though wooden construction, which is highly praised for its energy savings, uses the wood's relatively good insulating property, its capacity to store heat is low. That's why the interior temperature of wooden houses drops quite a lot at night.)

7.3.4 Thermal solar power plants

For quite some time, many power plants for generating electric power from solar heat were built. However, this is worthwhile only in areas with strong, continuous sunshine – in Europe, for example, in southern Spain, in the desert regions of Arabia and Africa, in the desert regions of the southern United States, in Central America, and in Australia. Two types of thermal solar power plants have emerged:

- Smaller solar power plants have a large, round concave reflector (dish), with the working cylinder of a Stirling engine located at the focal point and the generator placed directly on the Stirling engine. Currently, the most efficient power plant of this kind is the EuroDish-Stirling type plant.
- Large solar power plants with the capacity of large coal-fired power plants work with long rows of parabolic reflectors with an absorber tube containing the working medium running through the focal point (“parabolic trough power plant”). The hot working medium produces steam via a heat exchanger that is then used to operate large steam turbines and generators. With appropriate heat stores (molten salt), large solar thermal power plants can continue to run for up to seven hours at full load even without sunshine. That’s a huge advantage over photovoltaic and wind power!

Since the price for photovoltaic modules has dropped from 4 euros/W originally in 2005 to below 0.40 euro/W (2016), power generation with solar thermal power plants has become comparatively more expensive. Therefore, the construction of new solar thermal power plants has greatly decreased worldwide.

7.4 Disadvantages and limits of solar thermal energy

One disadvantage is that there is insufficient solar heat (too few sunny days) available in all the populated regions of the globe. Another disadvantage is the relatively high investment costs for the required technology, which could be more than twice the cost of traditional natural gas or oil heating systems in private households. In addition, there are generally the costs for improving a building’s heat insulation. However, because of the tougher statutory requirements and the massive rises in oil and gas prices, amortization periods have already been halved in the last decade, from 15–30 years to 8–15 years. The major advantages of solar thermal energy are that it produces neither waste nor emissions and, in areas of the globe with suitable climatic conditions, almost unlimited amounts of solar energy are available. Solar power plants admittedly require large areas of land, but these are available anyway in deserts. The problem of transporting the electric power across thousands of miles is technologically feasible in many cases, but the economic viability of this transportation is generally a disadvantage.

8 Sunlight (photovoltaics)

Photovoltaics refers to the direct conversion of sunlight to electrical energy using solar cells. Direct conversion is a fascinating possibility at first glance, since the indirect conversion of solar energy via heat engines always creates unused waste heat, according to the second law of thermodynamics. However, photovoltaics could theoretically achieve an efficiency of nearly 100 percent.

8.1 What is photovoltaics?

If light hits metals, electrons are released on the surface. This “external” photo effect can be used only in a vacuum to generate small electric currents and is not suitable for generating electrical energy. This is done using the “inner” photo effect, which can basically be described as a two-electrode process. At the positive electrode (doped semiconductor), the light removes electrons from the valence band through excitation, leaving behind holes (positive charges). These electrons pass through a non-conductive separating film into the conduction band of the negative electrode and charge this negatively. From the negative electrode, the electrons can then flow back via the outer operating circuit to the positive pole (charge flow = $V \cdot Q = E_{el}$).
Back in 1883, Charles Fritts developed the world’s first photocell from the semiconductor selenium. However, it was not used to generate power; instead, it was used for decades in photography to measure lighting. In 1954, Chapin, Fuller, and Pearson produced the first silicon solar cell with an efficiency of approximately 5 percent. Initially, these solar cells were used only in the aerospace industry. It was only from the 1980s onward that solar cells were also used in everyday products (calculators, watches). The use of photovoltaics in power-plant-type systems has been taken up only in the last ten years. Due to the drop in prices, the completely modular technology, and the wide variety of possible applications (roofs, facades, fields), photovoltaics likely has the greatest potential for expansion in the long term.
The efficiency of current photocells is still relatively low at the moment. The best mass-produced solar cells (as of 2016) deliver approximately 24 percent efficiency. The reason is that, due to the quantization of energy, there is no continuous absorption spectrum available for sunlight in the substances currently used for solar cells. Instead, absorption takes place in relatively narrow energy bands that correspond only to a few wavelengths of the light spectrum. Efforts are currently being made, by combining solar cell layers of various materials or by using additional layers of fluorescent dyes, to increase the absorption bandwidth and thus improve the efficiency in the direction of the theoretically possible level of 100 percent.

8.2 Availability and substitution potential of photovoltaics

According to information from the Renewable Energy Agency, the proportion of renewable energy sources in the power mix in Germany was approximately 32.5 percent at the end of 2015 (compared to 12 percent in 2006). The proportion of photovoltaic power was approximately 6.5 percent (compared to 0.3 percent in 2006). By comparison, in the United States, the proportion of renewable energies in the power mix was approximately 12 percent in 2014 and photovoltaics had a share of only approximately 0.5 percent (source: U.S. Energy Information Administration, EIA).
Technically, approximately 80 percent of Earth’s land surface is suitable for solar power generation. In Germany, for example, with the current level of efficiency of solar cells, approximately 1 percent of the land surface would be enough to cover the entire demand for electrical energy. With approximately 10 percent of Germany’s surface area, the entire energy requirement including transportation and heating could even be covered. If mainly roofs and the fronts of buildings were used for this, almost no undeveloped landscape would be lost. In comparison with agriculture, photovoltaics is extremely efficient: one hectare of a photovoltaic field delivers ten times more energy than one hectare of a corn field!
There remains the question of the service life and disposal of the solar cells. In a silicon cell, the efficiency does decrease during the cell’s service life, but remains economically viable for up to 30 years with the technology used today (the efficiency does not fall below 80 percent); this period will probably be extended to 50 years in the future. Any pollutants (from the doping) are bound

permanently to the silicon, which means that disposal is unproblematic. With the other types of solar cells, long-term trials still have to be carried out to determine service life. Some types also contain greater quantities of pollutants (such as Cd, Te, Se) and have to be disposed of as hazardous waste.
Based on the example of photovoltaics, it's clear that the subsidization of this technology was very worthwhile (primarily Germany and China were the pioneers around the world in this field). Since 2005, the price of photovoltaic modules has dropped to approximately one-tenth. This means that in sunny regions with intensive solar radiation, like California, southern Spain, and northern Africa, the electricity production costs in 2016 from photovoltaics were already lower than from fossil energy sources. In Central Europe, in 2016 the electricity production costs of large plants (at approximately 7 eurocents/kWh) were already lower than the costs of electricity from gas turbines. As early as 2013, the New Lens Scenarios study of Royal Dutch Shell, one of the world's largest oil companies, declared photovoltaics as the world's most important primary energy source of the future.

8.3 Technologies used with photovoltaics

Depending on the material, crystallization condition, and layer thickness, the following types of solar cells can be described as the most important:

- Thick-film silicon cells
- Thin-film silicon cells
- Gallium arsenide cells (GaAs)
- Cadmium telluride cells (CdTe)
- Copper indium selenide (CIS)
- Organic solar cells
- Dye-sensitized solar cells.

Further details of these solar cell types are found in the "Energy conversion" guideline.

8.4 Disadvantages and limits of photovoltaics

The main advantage of photovoltaics is the possibility of generating electrical energy worldwide, largely irrespective of location. It is used, for example, in India in previously non-electrified rural areas for developing local electric power supplies. An unfavorable eco-balance is often cited as a disadvantage. However, even though a high level of energy is needed to actually produce the solar cells currently used, and toxic heavy metals are sometimes required for production, the overall eco-balance is positive. The proportion of pollutants, for example, in the finished silicon cells, is so low that disposal is not a problem. The often cited toxic boron and arsenic content of silicon cells lies in the parts-per-million (ppm) range. In addition, these substances are permanently bound to the silicon and wouldn't separate even if the discarded solar cells were thrown in a landfill. And with a service life of over 30 years for tried-and-tested types of solar cells, this apparent ecological disadvantage is negligible in comparison with the ecological benefits. The energetic amortization of solar cells has become very favorable at up to 12 months.
A major disadvantage of photovoltaics is the fluctuating photovoltaic current, which can be unstable at night, in bad weather, or due to seasonal fluctuations. While solar heat can be buffered relatively easily, this is rarely done anymore with electrical energy (see chapter 10, "Energy storage").

9 Geothermal energy

Geothermal energy is another renewable, that is, practically “inexhaustible,” energy.

9.1 What is geothermal energy?

Literally, geothermal energy is “heat obtained from the ground.” Because the heat of Earth’s strata exists to a depth of approximately 30 m, primarily as a result of solar radiation and counter-radiation from the atmosphere, this type of heat is classified as solar thermal energy. Sometimes we also talk about “near-surface” geothermal energy. The term “geothermal energy” or, to avoid misunderstandings, “deep geothermal energy” means obtaining heat from Earth’s interior, which has to be extracted by drilling holes several thousand meters deep. This heat is partly residual heat from the time when Earth was formed approximately 4.6 billion years ago, and it partly comes from the natural radioactive decay processes of the long-lasting radioactive isotopes such as ^{235}uranium (U) and ^{238}U, ^{232}thorium, and ^{40}potassium in Earth’s interior, which have been going on for millions of years.

9.2 Availability and substitution potential of geothermal energy

Geothermal energy is a source of energy that can be used over the long term. The heat stored in the upper 3,000 meters of Earth’s crust could theoretically meet the current energy requirement worldwide for the next 100,000 years or more. In this context, deep geothermal energy is actually inexhaustible by human standards despite the slow cooling of Earth’s core. But at present, this geothermal energy can be extracted economically only at a very few points on Earth’s crust containing hotspots at a depth of a few hundred to a few thousand meters. Traditionally, the generation of electric power from geothermal energy is concentrated in countries like Iceland, which have many hotspots near the surface because of their many volcanoes. In countries where this is not the case, the electric power must be generated rather inefficiently with a comparatively low temperature level of 90–150°C. On the other hand, hotspots starting at approximately 45°C are sufficient as a heat source for heating homes and water. If, for example, all the possibilities existing in Germany were to be exploited, the use of geothermal energy could save more than 20 million tonnes of carbon dioxide by 2020. Worldwide in 2005, around 20 GW were installed in plants for generating heat and 8 GW in geothermal power plants for generating electric power (source: RWE). From 1979 to 2005, the United States constructed geothermal power plants with a capacity of approximately 2.6 GW, making it the world leader in this respect. But at the moment, further expansion has come to a standstill, which is probably due to the lack of economic viability of the remaining available sites (see “Disadvantages and limits of geothermal energy”).

9.3 Technologies used with geothermal energy

To open up sources of geothermal energy, a hole is drilled to the depth of the hotspot. If water over 100°C is located there, its own steam pressure may possibly convey it to the surface. If not, it must be pumped. Heat is then removed from the pumped hot water using a heat exchanger, and this heat is then fed into a district heating grid or to a power plant. The cooled water is injected back into Earth’s interior. If the hot stratum in Earth’s interior does not contain any water, cold water could also be injected into the drilled hole from the surface and the resultant steam drawn off.
If the heat obtained geothermically is to be used for heating purposes but its temperature is still too low for this, the temperature can be increased to the required level using a heat pump. If the bore was not too deep, and thus not too expensive, this is economically viable in many cases.

If the geothermal energy is used for power plants, temperatures of 90–150°C are insufficient for the efficient operation of traditional steam turbines. Instead of water, a low-boiling substance, such as perfluoropentane (boiling point 31°C), is used. A Stirling engine could also be used.

9.4 Disadvantages and limits of geothermal energy

The main obstacle to the use of geothermal energy has been the cost. However, since increased energy prices have made geothermal energy competitive, other disadvantages have also appeared. For instance, the use of geothermal energy can lead to regional sinking of the subsoil if hot deep water is removed but not replaced. The hot deep water may also contain salt solutions and toxic heavy metals. If the water cannot be returned completely to the depths of Earth, it must be purified and the residues disposed of as hazardous waste. Drilling more deeply in order to reach optimum temperatures in tectonically active regions has seemed particularly promising. Because these hotspots generally do not contain water, it was hoped that steam could be generated through the injection of water. However, when a geothermal power plant was built near Basel, Switzerland, the injection of water triggered a major earthquake in December 2006. The use of geothermal energy for larger power plants has been viewed with skepticism since then.

10 Energy storage

The supply of renewable energy generally fluctuates a great deal. This is its biggest disadvantage. The energy that comes from the conversion of renewable energy sources therefore has to be stored temporarily in order to cover demand that may fluctuate in the opposite direction. How much and how quickly wind and sun can replace fossil fuels therefore greatly depends on the development of suitable stores.
Energy stores can be classified based on the form of energy stored. The following section lists only the stores that are already of major practical significance, or that have high potential for the future.

10.1 Thermal energy stores

Temperature stores
Temperature stores change their temperature during charging and discharging. Water is a heat store, for example, for heating homes or water. But stone, concrete, and brick can also be good heat stores. These are standard, and are already used on a wide scale for solar heat.

Latent heat stores
Latent heat stores change their state of aggregation or phase state during charging and discharging. The transition from solid to liquid and back is the most suitable. When a substance melts, it absorbs heat, which it gives off again when it solidifies. Paraffins and special plastics are suitable for lower temperatures. For instance, a chemical company developed wallpaper with embedded plastic capsules that absorb heat on hot summer days by melting and give off the heat at night as they solidify – an air-conditioning system that doesn’t consume energy. In contrast, another process uses the heat of solution rather than the heat of fusion. The salt dissolves completely in water at a particular temperature and thus gives off the heat stored in this way when it crystallizes (see experiment instructions on “Storing heat chemically”). The heat of fusion of salts and salt mixtures is ideal for high temperatures of up to several hundred degrees. Surplus wind energy, for example, could be stored in this way via electrical resistance heat in molten salt and used when necessary to generate steam for a steam turbine. On a large scale, molten salt is used, for example, in solar thermal power plants. In the parabolic trough power plants Andasol 1, 2, and

3, the heat stored in the molten salt is enough to operate the 3x50 MW plant for over seven hours without sunshine.

10.2 Stores for mechanical energy

Flywheel
Energy can be stored in the moving mass of a flywheel. However, the energy content is not very high (~500 kJ/kg). The flywheel bearings must be extremely low-friction and the flywheel generally runs in a vacuum. Typical capacities are from 3 kWh to >100 kWh. There have recently been attempts to use flywheels with wind turbines and gas turbines. The principle has been successfully applied for years in small gas turbines used to supply emergency power to hospitals. In the meantime, the light rail operator in Zwickau and the municipal utilities in Munich, for example, use flywheels connected to electric motor generators to compensate for fluctuations in the power supply grid lasting from a few milliseconds to several seconds.

Pumped storage power plant
If there is surplus electrical energy, the power plant takes electrical energy from the power grid and uses it to pump water into a reservoir at a higher level. The electrical energy has thus been buffered as potential energy. When there is a peak in demand, the power plant works “normally” and converts the stored energy back to electrical energy. Pumped storage power plants have been built in Germany since 1923. The German pumped storage power plants in Goldisthal with 1.06 GW of capacity, Markersbach with 1.05 GW, and Schluchsee with 0.95 GW are some of the largest in the world. Today, a total capacity of over 6 GW has been reached, meaning that the failure of several nuclear power plants or large-scale coal-fired power plants can be covered. As a result, Germany experiences power failures of just 20 minutes per year on average, compared with almost 3 hours in the United States. The United States is therefore planning to build the world’s largest pumped storage power plant, with a capacity of 3.2 GW, in Brumley Gap, Virginia. Despite these apparently large storage capacities, the existing pumped storage power plants are now barely adequate for buffering the electrical power produced from traditional energy sources. Because further expansion is hardly economically viable anymore in most countries, including Germany, other storage options for renewable energy sources must be developed.

Compressed air storage plant
Compressed air storage plant technology is already used in combination with gas turbines (two plants completed). Because gas turbines work with highly compressed air anyway, the gas turbine power plant fills a compressed air store before switching off (if there is a surplus of electric power). This store is emptied as the power plant is started up again (at peak demand), getting the gas turbine started quickly and producing additional power without using any fuel. Consideration is now being given to temporarily storing wind and solar energy in compressed air stores and generating electric power, when there is a demand, using solely compressed air turbines, without combustion. If natural caverns or abandoned mine tunnels cannot be used as stores, the construction of large stores is currently not viable economically. And because real gases heat up when compressed, compressed air stores have an efficiency level of only about 60 percent due to heat losses. If this waste heat cannot be used, economic viability is also poor.

10.3 Chemical energy stores

Solid-state batteries
Batteries and rechargeable batteries are electrochemical cells or arrays of such cells. If solid-state electrodes made from metals (or non-metals) with differing electrochemical potentials are combined, one type of atom is oxidized and the other reduced. The electrons exchanged in this process flow via an outer electrical circuit; chemical energy is thus converted to electrical energy. The cell is discharged. Conversely, if an outer voltage is applied to this electrochemical cell, the oxidized atom type is reduced again and the reduced atom type oxidized again. When the battery is charged in this way, electrical energy is stored by being converted to chemical energy. Common rechargeable batteries work with lead (car battery), nickel/cadmium, nickel/metal hydride, or lithium. But they are expensive, their storage capacity is not easily variable, and they have a relatively short life. The solid-state batteries that are currently standard can be charged only a few hundred to a thousand times, depending on the type. This life is too short for storing wind or solar electricity in power plants.

Redox flow cell
A redox flow cell, a type of battery works, as it were, with liquid electrode materials, for example, zinc (Zn) and bromine (Br). Zn is suspended in water, while Br is available in an organo-aqueous emulsion. Two graphite electrodes are used as current collectors. As the Zn powder flows past its electrode, it is oxidized, that is, it gives off electrons and dissolves to form zinc ions (Zn^{2+}). As the Br flows past its electrode, it is reduced, that is, it picks up electrons and dissolves to form bromide ions (Br^{-}). During charging, voltage is applied and the two solutions are pumped past the electrodes again. The process has the advantage that the two charged suspensions or emulsions can be stored in tanks of any size. These liquid electrodes do not show any ageing effects, and an unlimited number of charge and discharge cycles is therefore theoretically possible. Since the process is technically not very complicated and is thus inexpensive, it is ideal, in principle, for storing large quantities of wind or solar electricity. Especially long-lived redox flow cells based on vanadium have recently been developed and are being used in the first major plants.

Hydrogen
Surplus electric power can be used with little technical complexity for the electrolysis (electrochemical decomposition) of water (H_2O) to hydrogen gas (H_2) and oxygen gas (O_2). The chemically pure oxygen created in this way can be sold to industrial companies or simply released into the air. The hydrogen gas is then liquefied and stored in tanks. Tanks for liquid hydrogen are extremely complex and inefficient if they are intended for mobile purposes; in contrast, large stationary tanks can be produced relatively inexpensively with good explosion resistance in line with current state of the art. When electric power is needed, the hydrogen can be converted back to electric power by combustion to form water via gas turbines, diesel engines, or Stirling engines. However, the level of efficiency is not very good, since the heat engines can convert only part (approximately 40 percent) of the heat to mechanical energy. Fuel cell technology is therefore an option. Here, the electrical energy is obtained directly without combustion, at efficiencies of up to 85 percent. Since it ultimately produces only water, which does not affect the environment, energy storage using hydrogen is an ecologically excellent process, especially if the stored hydrogen gas comes from wind or solar electricity. An alternative to pure hydrogen technology would be the catalytic conversion of hydrogen with CO_2 from the air (modified Fischer-Tropsch process) to methanol (CH_3OH) or CH_4. This would produce a universal, CO_2-emission-free fuel that is easy to store and distribute, in contrast to hydrogen, which could also completely replace oil and natural gas.

The advantage of conversion to CH_4 would be that the entire widespread natural gas network could then be used for distribution. And the existing natural gas stores already have a sufficient range at up to three months to compensate for even larger fluctuations in renewable energy production. This process called “power to gas” is already being tested in some pilot plants.

10.4 Electrical energy stores

Capacitor

Capacitors are the only existing devices that can store electrical energy directly. (Strictly speaking, coils store electrical energy as magnetic energy!) Capacitors consist of two large-surface terminals between which there is an electrical insulator. The application of direct current voltage moves the electrons between the terminals. The capacitor is now charged and can release the energy at any time as a charge flow via an outer electrical circuit. Capacitors are practically wear-free and have an almost unlimited life. For technical and economic reasons, however, they are suitable only for storing relatively small quantities of energy. They range from solar clocks to capacitor arrays for storing the braking energy in commuter, subway, and railway trains. Capacitors are not suitable for storing large quantities of energy in wind and solar power plants. This is because the storage capacity of a capacitor depends on the area of its electrodes – which means huge, expensive structures would therefore be needed, as with solid-state batteries.

10.5 Magnetic energy stores

Magnetic coil

Switching on the flow of electrical current through a coil generates a magnetic field. The magnetic energy stored in this field can be removed again as electrical energy when the flow of electrical current through the coil is switched off. If the flow of current through the coil can be established as a resistance-free electrical circuit, a coil is suitable for storing electrical energy. With suitably cooled superconductors and modern control electronics, superconducting coils of this type are already being used for energy storage. However, they are extremely complicated and expensive, and the cooling consumes a relatively large amount of energy. Magnetic coils are therefore not practical as “mass energy stores.”