Energy conversion

1 Energy "generation" always means conversion!

Energy "generation" always means energy conversion. Generation in the sense of "increasing" the energy content of a closed system is not possible according to the general principle of the conservation of energy and the first law of thermodynamics. When laymen use the term "energy production" and "energy generation," they always mean the conversion of an unusable form of energy to useful energy. In order to remind students of this fact, these terms are placed in quotation marks when used here or in other media files related to these topics (i.e., energy "generation" and energy "production").

To give an example, in a coal-fired power plant the stored chemical energy of coal is first converted to heat through combustion. This heat is converted to mechanical energy with a turbine and then to electrical energy with an electric power generator. The electrical energy can be distributed and used in the form of electric power. Coal and other energy sources that cannot be used directly are known as "primary energy sources." The forms of energy in which the energy is distributed are known as "secondary energy sources." These are usually electric power and district heating. The end consumers or their appliances and machines such as stoves or drills then convert the electric power to heat or mechanical energy.

In other words, there is no such thing as the "generation" of energy. On the contrary, the conversion from one form of energy to another is usually accompanied by losses. In terms of efficiency, one also speaks of the "degradation" of part of the energy used.

2 Efficiency and energy efficiency in particular

Conversion from one form of energy to another is subject to certain energy losses relative to the wanted useful energy. The reasons for this are twofold. First, there are **technical constraints**. For example, it is possible only in theory to convert mechanical energy 100 percent to electrical energy by means of an electric power generator. Because of the electrical resistance of the coils in the generator and their associated heating, 100 percent conversion is not technically possible. There are also heat losses due to friction in the bearings of the machines. Nevertheless, with cooling modern electric motors and generators achieve up to approximately 99 percent efficiency. This means that the efficiency of these machines can be increased to almost 100 percent through suitable technical measures. The conversion of electrical energy to heat using an immersion heater also reaches nearly 100 percent in a well-insulated container. However, there are also **natural constraints** for certain conversion processes: The second law of thermodynamics does not allow complete conversion, especially regarding the conversion of thermal energy to mechanical energy.

2.1 Efficiency, the ratio of "useful work to expenditure"

The concept of "efficiency" was introduced in order to have a comparable quantity as a measure for the losses occurring in energy "generation." The efficiency designates the proportion of useful energy gained (E_{Useful}) to expended energy (E_{Exp}) and is abbreviated in engineering as the letter η (Greek "eta"). The closer efficiency comes to the value 1 or 100 percent, the better (more efficient) energy conversion is.

$$\eta = \text{useful energy/expended energy} = E_{Useful}/E_{Exp}$$

An efficiency of 1 is never achieved in practice for the above reasons.

2.2 Efficiency of heat engines

Processes in which mechanical work is generated from heat have great significance in technology. These processes can be used to drive motorized vehicles or in a generator for conversion to electrical energy. The ideal heat engine is described by the so-called Carnot cycle. This cycle has the theoretically maximum possible efficiency. The maximum proportion of the heat input that can be converted to mechanical work can be derived from the Carnot cycle. It is calculated as the ratio of the difference between maximum temperature (T_2) and minimum temperature (T_1) to maximum temperature (T_2) in the overall process. (Note: The formula for efficiency is derived via heat and work. If the gas equation is used, it is possible to convert the equation to T.)
There are a host of cyclic processes in real life, but they all have a lower efficiency than the theoretically ideal Carnot process:

Cyclic process	Machine	Efficiency
Carnot	Theoretically ideal heat engine	$\eta_{ideal} = 1 - \frac{T_1}{T_2} < 1$
Stirling	Stirling engine	η_{real} = 20 % to 50 %
Diesel	Diesel engine	η_{real} = 40 % to 50 % (stationary)
Otto	Otto engine	η_{real} = 30 % to 38 %
Rankine cycle	Steam turbine, steam engine	η_{real} = 30 % to 50 %
Joule process	Gas turbine	η_{real} = 30 % to 40 %
Combined cycle power plant (CCPP)	Combined gas and steam turbines	η_{real} = up to 61.5 %

Heat pump as a special case: For the inverse heat engine, the “heat pump,” a “coefficient of performance” (COP) has been defined as an inverse efficiency, so to speak. This coefficient of performance is therefore greater than 1. The maximum coefficient of performance of a heat pump is L = 6, and the usual figure is between 3 and 5. This means that 6 kWh of heat can be obtained by using 1 kWh of electric power.

2.3 Measures for increasing energy efficiency

In order to make more effective use of our fossil fuel resources, constant efforts are made to optimize the efficiency, that is, the efficiency of conversion. Although it is not possible to change natural laws (efficiency < 100 percent), particularly in thermal power processes, it is, however, possible to increase the efficiency:

- **Combined heat and power:**
  Combined heat and power is the term used for the combined generation of electricity and heat in which the naturally occurring waste heat from a power plant (gas and/or steam turbine) is used for district heating purposes. The average efficiency of a combined cycle power plant is between 51 percent and 58 percent. A first combined cycle power plant with an efficiency of over 60 percent is currently in the test phase. If the waste heat is used for district heating, total efficiencies of up to 90 percent are achieved (for example, the biomass combined cycle power plant in Vienna).
- **Gasification of coal, bitumen, heavy oil, wood:**
  The burning of solid fuels is less well suited for the operation of power plants with gas turbines (due to corrosion, abrasion). By gasifying the solid fuel and cleaning the resulting synthesis gas, one obtains a relatively clean gas with low pollutant content. This burns very well and also at higher temperatures than the corresponding solid fuels. Higher temperature means higher efficiency of the gas turbine (see above). If steam is also generated with the waste heat from the gas turbine and a steam turbine is operated downstream, the combined efficiencies add up to more than 60 percent. Apart from the increase in efficiency, the waste gas with this modern technology contains considerably fewer pollutants and thus has less impact on the environment.
- **Optimized rotor blades on gas turbines:**
  A gas turbine consists of several rows of blades against which the hot combustion gas flowing through the turbine pushes. A portion of the gas passes unused through the gap between the blades and the turbine wall. Thanks to intelligent design, Siemens succeeded in making this gap smaller, thereby reducing the loss. This results in an increase in the efficiency of the gas turbine of about 0.2 percentage points. That might not sound like very much, but in large-scale power plants, it represents a big saving in primary energy.
- **Optimized strength and corrosion resistance of the turbine blades:**
  Today, gas turbines operate with combustion gases of up to 1,500 °C at a pressure of more than 20 bar and achieve efficiencies of greater than 40 percent. Under these conditions, the metal turbine blades could melt or corrode. There is also the danger that the blades may break up, since the acceleration forces acting on them are up to 10,000 times greater than the gravitational acceleration. The blades of the first stage therefore consist of extremely strong monocrystalline superalloys coated on the surface with corrosion-resistant, low-thermal-conductivity, high-melting-point ceramics.

3 Steam engines

The steam engine converts **heat to mechanical work** using the working medium water. It was the first heat engine in the world and originally had an efficiency of less than 1 percent. It was this low efficiency that motivated researchers and engineers to develop heat engines with ever better efficiencies. Siemens played a significant role in the development of modern steam turbines and holds numerous patents today in the field of steam generation and turbine technology.

3.1 The world’s first heat engine

In 1690, the Frenchman Denis Papin invented the **steam digester** with safety valve. This was based on the principle that the boiling point of water rises with increasing pressure and as a result cooking times are reduced. It was also Papin who hit upon the ingenious idea of utilizing this effect in reverse. Higher temperature produces increased pressure that can be used to perform work. Pumps built according to Papin's **piston steam engine principle** were used from about 1700 onward and further improved by the Englishman Thomas Savery. In 1712, Thomas Newcomen in England built the first continuously operating steam engine, which was used in coal mines. It had the disadvantage that it consumed almost as much coal as was mined using it. It was not until 1765–1781 that the Scottish instrument maker James Watt successfully developed a piston steam engine of modern form.

The principle of Watt's steam engine:
Steam is produced in a boiler and injected into the working cylinder first above and then below the piston. In a subsequent condenser, the steam is condensed and additionally generates negative pressure. The condensed water can then be pumped back to the boiler. The upward and downward motion of the piston is converted to the rotary motion of a flywheel by means of rods and cams.
The consumers, for example pumps, spinning and weaving machines, and machine tools, are connected to its axle via gears or drive belts.
With Watt's steam engine, a drive unit for **railway** locomotives was also found. The first means of mass transport in the world could be developed. The physical unit of power was named the "watt" in honor of the inventor.

Note: An information module with animated displays of all steam engine types is available on the media portal.

3.2 Why is water used as the working medium?

In actual fact, a gas would be adequate as the working medium since pressure and volume of a gas are a function of its temperature ($p \cdot V = n \cdot R \cdot T$). If you have a closed system made up of a cylinder and moving piston, volume work $p \cdot V$ can be performed according to the Carnot cycle by adding heat. However, this principle was originally very difficult to realize technically with gases. It was not until 1816 that the Scottish pastor Stirling invented the engine named after him using air as the working gas. (Note: Several media files related to the Carnot cycle and the Stirling engine are available on the media portal).
Steam has advantages: If you heat water (H_2O) to above 100 °C at normal atmospheric pressure, it turns into "steam" or, strictly speaking, gaseous water. In this case, it must be pointed out that the process of "vaporization" should scientifically be termed a "transition to the gaseous phase." However, since the individual H_2O molecules of the gaseous water are invisible to human beings, vaporized water is also invisible. What we call "steam" in everyday language is in fact a fog consisting of condensed (in other words, liquid) water in the form of fine droplets. In steam engineering, "steam" can also mean "two-phase areas." That has to do with the critical point in the p-T diagram of water. Since gaseous water has a larger volume than liquid water, it tries to expand. If it can't expand, for example, in the steam boiler of the engine, the pressure increases. As a result, though, the temperature at which water vaporizes increases. This produces even hotter water vapor, which generates even more pressure, etc. This process ends at a "critical" temperature at which gaseous and liquid state are no longer distinguishable. In practice, piston steam engines, because of their temperature range, usually operate with supersaturated steam, i.e., a mixture of gaseous water and liquid water droplets. At the higher "supercritical" temperatures of modern steam turbines, the "steam" consists only of gaseous water. The appeal of water as a working medium for the inventors of the steam engine was that relatively large amounts of high-energy steam

can be generated from relatively little liquid water. On the other hand, considerably larger amounts would be needed of a substance that was gaseous at room temperature and normal atmospheric pressure.

Steam has disadvantages: In the steam engine, the thermal energy input is initially used only to vaporize the water and only the excess portion to heat the steam. After performing work in the engine, the “spent steam,” i.e., gaseous water, leaves the engine. In the piston steam engines of locomotives, for example, the steam condenses outside the engine and the vaporization heat is released as unused condensation heat. This heat cannot be used for performing mechanical work in engines of this type. The theoretical efficiency of a piston steam engine in locomotives is lower by the amount of the condensation heat. In modern steam turbines, there are scarcely any losses due to condensation heat. These steam turbines operate at extremely high inlet steam temperatures and pressures (for example, 600 °C and 270 bar). The condensation process integrated in the turbine outlet (cooling to 30 °C at 30 mbar) contributes to the power due to negative pressure. As a result, the temperature and pressure differences between the inlet and outlet steam are increased and the efficiency is improved in this way.

3.3 Teaching notes on the Stirling engine

The Stirling engine uses air or another inert (chemically non-reactive) gas as the working medium. This gas does not pass through the engine, but remains permanently within its closed working space. In that respect, the Stirling engine corresponds considerably better to the theoretical Carnot engine than the steam engine. The special characteristic of all heat engines, namely that the heat employed cannot be converted 100 percent to work, is not immediately apparent with a steam engine. The steam engine does not appear to be anything other than a mechanical working machine in which the force of the steam is converted to the force of the piston. The fact that steam has pressure and can exert force can be seen simply from a mechanical consideration of the “aeolipile,” a rotating sphere filled with steam described by Hero of Alexandria around 120 BC, or a model steam engine. Since these steam engines do not have a cooling unit, the natural restriction of the conversion of heat to mechanical work is concealed “at first sight.” On the other hand, the Stirling engine with its cooling unit provides a visible demonstration of the laws of thermodynamics acting in the case of heat engines. A small model Stirling engine of two-cylinder V-construction with a glass cylinder provides a really effective way of illustrating the thermodynamic implications of the heat engine. For this reason several media files dealing with the subject of the Stirling engine (a video, experimentation instructions, and an information module) are available on the media portal. In view of the energy and climate problems, however, the significance of the cooling unit for the efficiency of heat engines should also become clear in science and technology lessons.

4 Turbines

A turbine (Latin *turbare*, literal translation: to agitate, to throw into confusion) is a continuous-flow machine that converts the internal energy of a mass flow (liquid or gas) to mechanical rotational energy. The term turbine is also used to distinguish these machines from open systems with the mass flowing freely against them, such as water wheels. Unlike the water wheel, the shape of a turbine and its guiding mechanisms (guide blades or jets) force the mass flow to take the path that will impart the most energy to the rotor blades.

A turbine in its simplest form consists of a shaft on which a rotor with a large number of blades is fitted. Depending on the type of turbine, several rotors can be placed one behind the other. If possible, the entire **energy** of a flowing medium (water, steam, gas) should be converted **to mechanical rotational energy** of the turbine. If the turbine shaft drives a generator, the mechanical energy of the turbine can be converted to electrical energy (electric power).

We differentiate between:

- Steam turbine
- Gas turbine
- Water turbine

While the laws of fluid mechanics apply in the case of water turbines, the laws of thermodynamics apply additionally in the case of steam and gas turbines. Steam and gas turbines are typical heat engines.

4.1 Steam turbine instead of steam engine

Like the steam engine, the steam turbine also converts **thermal energy to mechanical energy**. On the one hand, the steam turbine is designed based on fluid mechanics calculations. On the other hand, since they are heat engines, they must also be optimized in terms of thermodynamics.

4.1.1 Design differences compared with the piston steam engine

Compared with the piston engine, the steam turbine's main design difference is the direct conversion of the steam energy to rotational motion. With the piston engine, in contrast, the linear motion of the piston has to be converted first to rotary motion via a connecting rod. The inlet and discharge of steam into and from the working cylinder of the piston engine is relatively slow, which in turn limits the pressure and temperature of the steam. For this reason, the classic piston steam engine attains an efficiency of only up to 20 percent compared with up to 50 percent for modern steam turbine-based power plants. Siemens AG is currently developing, for example, steam turbine power plants with an efficiency of over 50 percent. This is made possible by technology operating at 700 °C and 300 bar at the turbine inlet.

For technical reasons, the classic piston steam engine can hardly be designed for rotary speeds of more than about 600 rpm. The steam turbine, on the other hand, effortlessly attains the high rotational speeds – 1,500 and 1,800 rpm with two-pole electric power generators and 3,000 or 3,600 rpm with single-pole generators – that are necessary for generating alternating current at 50 Hz or 60 Hz. The power output of the steam turbine also has no upper limit. The technically feasible power output of the piston steam engine is about 12 MW, whereas modern steam turbines now attain outputs of up to 2,000 MW and are constantly being further developed. For this reason, only steam turbines are still used today in practice.

4.1.2 How do steam turbines work?

Theoretically, steam turbines with only a single row of blades would be possible. However, they would have to run exceedingly fast in order to absorb the greatest possible amount of energy from the steam as it flows past at extremely high speed. Such high rotational speeds are not easy to implement technically nor are they desirable for the generation of electric power. Instead, the energy is transferred in several stages at a lower rotational speed (max. 3,000 or 3,600 rpm). Several rotors ("stages") sit one behind the other along the shaft so that the energy of the flowing steam can be transferred gradually. Since the flow pressure drops as the steam passes through the turbine, the rotors become increasingly large in the later stages in order to keep the force acting on the blades constant (force = pressure times area). The lower the steam pressure, the lower the force on the blades. A fixed stator is positioned between each pair of rotors. The purpose of this is to deflect the steam back to the best angle of incidence for impinging on the blades so that its energy is used most effectively. The extremely high efficiency of modern steam turbines is made possible by inlet temperatures of over 600 °C at a pressure of 270 bar and outlet temperatures of about 32 °C at a pressure of approx. 0.03 bar. The low outlet values have the effect of improving the thermodynamic efficiency, since the condenser at the outlet is an integrated component of the entire turbine. The negative pressure caused by condensation thus improves the pressure difference between the inlet and outlet of the turbine.

4.2 Gas turbines

If hot gas from the combustion of a gas-air mixture is used instead of water vapor as the working medium for the turbine, we have a “gas turbine.”

4.2.1 Why gas turbines?

The main advantage compared with a steam turbine is the more compact construction and the possibility of ramping the power output up and down quickly since steam does not have to be generated first. The steam for steam turbines is generated, for example, by means of lignite, coal, or heavy oil, the use of which is accompanied by exhaust gases containing pollutants or else involves expensive scrubbing of the flue gas. In this respect too, gas turbines operated with natural gas or synthesis gas are considerably less problematic. Originally, the efficiency and the power output of the gas turbine were considerably lower than those of steam turbines. Now, however, gas turbines achieve power outputs of up to 400 MW at a current efficiency of 40.1 percent. In practice, this means that gas turbines are preferred today for use wherever power plants or power plant blocks of medium power output are used to cover peak loads.

In modern large-scale power plants, gas and steam turbines are used in combination to an increasing extent. The waste heat from the gas turbine is used to generate steam for a steam turbine, thereby boosting the overall efficiency to as much as 61.5 percent.

Note: In countries with a high proportion of renewable electricity (in Germany, approximately 32 percent at the end of 2015), the gas turbine power plants are being used less and less to cover peak loads (usually midday). This is because nonsubsidized photovoltaic power now costs approximately 7 to 9 eurocents/kWh and wind power costs start at approximately 4.5 eurocents/kWh, whereas gas turbine power costs up to 10 eurocents/kWh.

4.2.2 How do gas turbines work?

Air at a temperature of about 15 °C and at normal pressure is compressed to 17 bar in a compressor and is thereby heated to a temperature of about 400 °C. This compressed air is mixed with natural gas in the combustion chamber of the turbine, where it burns at approximately 1,500 °C. This hot gas at high pressure now flows through the turbine blades and gives off so much energy to the blades that the pressure of the outlet gas drops back to normal pressure and the temperature to about 600 °C. The thermodynamic efficiency of the gas turbine can be calculated from this data. For calculating the overall efficiency, the energy expended for the compression process must also be taken into account.
The laws of fluid mechanics apply to the calculation of the turbine geometry. In contrast with the steam turbine, in the case of the gas turbine, it must be borne in mind that the density of the gas is

comparatively low. The blades are therefore deflected less by impact (impulse). Instead, it is the high speed of the gas stream that provides the main effect. The gas has different speeds at the front and back of a rotor blade. This results in a pressure difference (see Bernoulli equation), leading to transverse motion of the blade with respect to the direction of flow of the gas stream. The turbine starts to rotate.
At this point, reference could be made to the significance of mathematics in the calculation of the flow in the turbine (differential equations, finite elements method).

4.3 Water turbines

The water turbine converts the mechanical energy of water, i.e., the potential energy of high heads of water or the kinetic energy of flowing water, **to the rotational motion** of a turbine. In hydroelectric plants, this drives a generator for producing electrical energy.
Water flows as a relatively dense mass of liquid that unlike gas cannot be compressed. For this reason and because the speed of the stream of particles is comparatively low (compared with the gas flow in gas turbines), water turbines generally get by with only one rotor. Calculation of the energy transferred from the water to the turbine is relatively simple. It is the difference between the sums of the potential and kinetic energy of the water before and after the turbine.
However, the fluid mechanics calculation of the turbine design is highly complex when it comes to transferring as near to 100 percent of the energy of the water as possible to the turbine. Depending on the volume of water and the height of drop of the available water, significant differences are necessary in the design, form, and function of the turbines. To date, three main types of water turbine have become established.

4.3.1 Pelton turbine

The Pelton turbine is used with relatively small water volumes (mass m) and very high heights of drop (up to 1,800 m). It has a rotor with bucket-shaped blades and no stator (see Francis turbine). The water is focused through nozzles directly onto the buckets.
The transmission of energy could be calculated directly as the transmission of the momentum
($\Delta p = m \cdot \Delta v$, v: velocity)
of the impinging water volume. The Pelton turbine is an impulse turbine with equal hydrostatic pressure at the inlet and outlet. The efficiency of Pelton turbines when used optimally is between 85 percent and 93 percent.

4.3.2 Kaplan turbine

The Kaplan turbine is used with relatively low heights of drop (usually around 10 m), for example, in a run-of-river power plant, and medium to very large volumes of water. The water flows parallel to the turbine axis onto a rotor shaped like a propeller. The fixed stator mounted axially around the shaft in front of the rotor has a lamellar form. The lamellas are adjusted so that the water flow impinges on the propeller parallel to the axis. The Kaplan turbine is a reaction turbine; it is acted on primarily by the water pressure which is lower after the turbine than before. The efficiency of Kaplan turbines when used optimally is between 85 percent and 95 percent.

4.3.3 Francis turbine

The Francis turbine is used with a relatively high height of drop (typically around 100 m) and large to extremely large water volumes, for example, with reservoirs with high dams. The rotor is in the form of curved blades. The water flow is introduced perpendicularly to the axis direction and the fixed stator mounted around the rotor deflects the water exactly in the direction of the rotor blades. The blades of the stator can be adjusted so that optimum efficiency can always be achieved depending on water volume and velocity. The Francis turbine is a reaction turbine; it is acted on primarily by the water pressure, which is lower after the turbine than before. The efficiency of Francis turbines when used optimally is about 90 to 95 percent.

4.3.4 Physics of the Kaplan and Francis turbine

The **continuity equation** applies to the stationary flow (i.e., constant over time) of a non-compressible (constant density) and nonviscous fluid (no internal friction). It states that the volume flow through the cross-sectional area of the fluid is constant. This means that the same amount of water flows faster through narrow pipes than through wide ones. The derived **Bernoulli equation** states that the sum of hydrostatic and hydrodynamic pressure in a flowing liquid is constant. It can be deduced from this that the hydrostatic pressure drops when the flow velocity of a fluid increases. As far as water turbines are concerned, this therefore means that for reaction turbines (Francis, Kaplan), the hydrostatic pressure at the rotor inlet is greater than at the outlet.
Incidentally, the outlet of a Kaplan or Francis turbine is known technically as a “suction pipe.” This means that, as with a water jet pump, the residual kinetic energy of the water causes a suction effect that is added to the pressure before the turbine.

Note: Several media files on the subject of water turbines and hydroelectric plants are available on the media portal.

5 Engines

Engine is the general term used for a machine that performs mechanical work by converting another form of energy (for example, mechanical, chemical, electrical, or thermal energy). By this definition, all **heat engines** including piston steam engines and gas and steam turbines would be engines. Traditionally, though, it has become established convention that only **combustion engines** (for example, Otto, diesel engine), the **hot air engine** (Stirling engine, see above), and **electric motors** are known by this term.
The subject of electric motors is dealt with briefly below. A separate information sheet on the subject of “Engines and heat engines in particular” is available on the media portal.
The **electric motor** converts electrical energy to the mechanical energy of a shaft. The mechanical work results from the Lorentz force that acts on moving charges in a magnetic field. Depending on the design, the electric motor can also act as a generator. For this reason, combinations of combustion engine and electric motor are used increasingly often today in so-called hybrid vehicles. The braking energy and possibly also the idling energy are converted to electric energy and stored in batteries, which in turn drive the electric motor (especially when starting and accelerating). Other media in this connection are available on the media portal, for example, the “Electric motor and electric power generator” experimentation instructions and the partially animated “Electric motor and Lorentz force” and “Hybrid systems for energy conversion” information modules.

6 Electricity generators

The generator converts mechanical energy to electrical energy.
The generator is thus an inverted electric motor. If you rotate a coil in a magnetic field, a voltage is induced in it that moves the charges in the coil wire. The direction of this induced current is always such that its magnetic field opposes the cause of induction (i.e., the motion) (Lenz’s law). The direction of the current therefore changes periodically with the magnetic field, and an alternating cur-

rent is produced. A pulsating direct current is obtained if the current is tapped via a commutator (pole reverser). The induction law acting in the case of the generator is one of the three physical bases for electric machines. The two others are the Lorentz force (for example, electric motor) and Ampere's law (for example, electromagnet).
Historically, the construction of high-power generators posed a technical problem since in the early days of electrification, this was not possible with permanent magnet rotors. It was not until the discovery of the dynamoelectric principle (by Werner von Siemens in 1866) that generators could be built with electromagnets. Even today, when the construction of permanent magnet generators of up to 8 MW is possible, this principle is still indispensable in large-scale power plants for generators with rated powers of several hundred MWs up to more than 1,600 MW.

7 Nuclear reactors

In a nuclear reactor, the binding energy between the particles of the atomic nucleus is converted to thermal energy.
This energy is released in the nuclear reactor by nuclear fission. The principle of nuclear fission through bombardment of uranium (U) with neutrons was discovered experimentally in 1938 by Otto Hahn and Fritz Strassmann. Lise Meitner, the former assistant of Albert Einstein, was able to explain the effect theoretically and prove that the released energy can be calculated as the mass defect in accordance with Einstein's formula ($E = mc^2$) since the sum of the masses in the nucleus (neutron and protons) before fission is somewhat greater than the sum of the masses of the decay products.

Note: The topic of nuclear fusion is not addressed in this guideline, as it deals only with technically established methods of energy conversion. However, some media on nuclear fusion are also available on the media portal.

7.1 Basic principle of nuclear fission in a reactor

Although there are a number of different technical designs of nuclear reactors, the basic principle is always the same:
Start of the decay process by bombarding the fuel with neutrons: Nuclear fission is excited in a fuel (fuel rods, for example, with ^{235}U) by bombardment with neutrons. The starting neutrons originate, for example, from a beryllium source, which releases neutrons from natural decay when bombarded with alpha particles ($^{4}He^{2+}$ nuclei). The atomic nuclei of the fuel are split by the neutron bombardment and release neutrons themselves. For each bombarding neutron that causes fission of a nucleus, several neutrons are created, so the process can continue as a chain reaction. In the atom bomb, this chain reaction runs out of control with an avalanche effect causing an explosion, whereas in a reactor, it runs as a controlled chain reaction for producing heat.

Moderation, i.e., slowing the neutrons: Most of the neutrons occurring during fission are so fast that they have “no time” to interact when they strike other atomic nuclei. The chain reaction would therefore come to a stop. In order to slow the neutrons down to a suitable speed (about 2,000 m/s), so-called moderators are needed such as water (H_2O), heavy water (D_2O, in which normally heavy hydrogen is replaced by deuterium), or graphite.

Controlling the decay: The number of neutrons and hence the rate of nuclear fissioning can be regulated with neutron-absorbing control substances such as cadmium (Cd), silver (Ag), boron (B), or indium (In). This is done by means of control rods that can be inserted between the fuel rods.

Boron in the form of boric acid is also added to the water in the primary cooling circuit for this purpose. Overall, the interaction between moderation and controlling is selected such that the neutron balance ("criticality") is minimally higher than 1. That means that on average, slightly more than one neutron of suitable speed is created with each fission, which just maintains the chain reaction in the reactor.

Extraction of useful heat: In nuclear fission, 86 percent of the energy is released as the kinetic energy of neutrons and fission products. This energy is transferred to the fuel rods themselves, to the moderators and regulators, and ultimately to the cooling water in the form of thermal energy. This is used to generate steam to drive a turbine.

Cooling of the steam turbine process: As with every heat engine, a portion of a steam turbine's input heat must also be dissipated unused via cooling (cooling towers). Otherwise, the low temperature point would rise too high and efficiency would drop. For this "external" cooling circuit, the Isar 2 nuclear power plant in Germany, for example, needs 42,000 l/s of cooling water from the Isar River; the now decommissioned Biblis B nuclear power plant extracted 210,000 m^3/h from the Main River.

7.2 Different technical designs of nuclear reactors

All types of reactors used commercially worldwide in electric power generation operate with retarded ("thermal") neutrons. The most commonly used type are water-cooled reactors in which the coolant doubles as the "moderator" with which the neutrons are slowed down. A distinction is made between:

- Light water reactors (pressurized and boiling water reactors), which need enriched uranium as fuel.
- Heavy water reactors, which can be operated with natural, non-enriched uranium.

There are also gas-cooled reactors (CO_2 or helium) in which graphite is used as the moderator. In the United Kingdom, the "Magnox" and "AGR" types are in commercial service, while high-temperature reactors have been built only as test and prototype reactors. Reactors that operate with fast, non-retarded neutrons, so-called fast breeder reactors, are under development.
In addition to the main types mentioned, there are also various other types that have no great significance at present.

The **pressurized water reactor** is a light water reactor since it operates with normal ("light") water (H_2O, i.e., without deuterium). Its special feature is the very high pressure of up to 160 bar in the primary circuit in the reactor core so that the water heats up to 325 °C without vaporizing. The actual steam at 280 °C and about 65 bar used to drive the turbine is generated in the secondary circuit by means of heat exchange using steam generators. The spent steam is condensed through the external cooling water circuit and then fed back to the steam generator. The overall efficiency referring to electric power generation is about 35 percent. Pressurized water reactors account for about 50 percent of all nuclear reactors worldwide. There is now a new generation of pressurized water reactors, which was developed by Areva as the European Pressurized Water Reactor (EPR) and designed to meet even higher safety standards. With a quadruple cooling circuit, quadruple redundancy, physical separation of all safety control circuits, a foundation protected against core meltdown, and a containment made of 2.6 m thick steel-reinforced concrete to protect against attacks and aircraft crashes, it is classified as one of the safest reactors in the world. However, no EPRs are operating yet today. One reactor in Flamanville, France, and one in Olkiluoto, Finland, have been under construction since 2005 and 2007, respectively. The costs in Finland have exploded from EUR 3 billion originally to EUR 9 billion. Today it is assumed that the construction of a new 1 GW EPR will cost approximately EUR 12 billion.

The **boiling water reactor** is also a light water reactor (H_2O). Its special feature is that the pressure vessel in the reactor is only filled with water to approximately two-thirds of capacity. As a result of the heat resulting from nuclear fission, part of the water vaporizes there at 286 °C and 71 bar. The turbine is driven directly with this steam. (This is one of the disadvantages of this reactor type: the radioactive steam contaminates the turbine and would leak into the turbine hall in the event of an accident.) The spent water vapor is condensed through the external cooling water circuit and then fed back directly to the reactor pressure vessel. The boiling water reactor therefore does not have a secondary cooling circuit. The overall efficiency referring to electric power generation is about 35 percent. Pressurized water reactors account for about 30 percent of all nuclear reactors worldwide.

The **heavy water reactor** (HWR) uses heavy water (D_2O) as the coolant and moderator in the primary circuit. The advantage of this type of reactor is that natural, unenriched uranium can be used as fuel. This means that the fuel elements are cheaper to produce. Since the neutrons are less intensively absorbed in heavy water, D_2O as the moderator creates more neutrons of suitable speed than H_2O. The disadvantage is that heavy water is very expensive and also the construction of heavy water reactors is more complicated. For this reason, this reactor type accounts for only about 9 percent of all nuclear reactors worldwide.

High temperature reactors (HTR) are constructed in various designs. In the **pebble bed reactor**, which was developed in Germany, an extremely high service temperature of up to 950 °C can be achieved in the primary circuit. This is made possible by using helium as the coolant and heat-resistant graphite as the moderator and as the base material for the spherical fuel elements (pebbles). Graphite pebbles the size of tennis balls with embedded fuel pellets of uranium or uranium/thorium are used instead of rods. The advantage is that if the cooling system fails, the power output automatically falls practically to zero as a result of rising fuel temperature, making a core meltdown impossible. As a result, the pebble bed reactor enjoys a high level of inherent safety. However, because of its comparatively high costs, this type never progressed beyond the construction of a few prototypes (in Germany, among other countries).

The **breeder reactor** is not only intended to “generate” energy, but its main purpose is to create additional fissionable material. Nonfissionable materials are converted to fissionable materials by bombardment with neutrons and can then be used as nuclear fuel. This is possible for nonfissionable ^{238}U, from which fissionable plutonium (^{239}Pu) is produced or “bred.” And ^{232}Th can also be bred from ^{233}U. These processes can also be realized in thermal reactors with limited yield. The hallmark of the breeder reactor, then, is that due to the fact that it operates with fast neutrons, it can produce more fissile material than it uses itself. However, breeder reactors are technically extremely complex, in part because they are cooled with sodium (Na). The yield of a few percent ^{239}Pu per breeding process is also relatively low and processing of the material produced is an elaborate business. Since the fear of a uranium shortage that provided the impetus for the development of breeder reactors in the 1960s proved unfounded and no shortage is expected in the near future either, there is no commercial interest in breeder reactors with the present state-of-the-art. The few breeder reactors worldwide are therefore operated only for research purposes.

The transmutation reactor: In recent years, there has been interest in using breeder reactors for another application, namely the transmutation of long-life fission products and transuranium elements into short-life radioisotopes. Energy that is released during transmutation could be used to generate electricity. In addition, transmutation would "shorten" the duration of the final disposal of radioactive waste from nuclear power plants (a few hundred years instead of many thousands of years). Research must first demonstrate the extent to which this technology can really solve the final disposal problem. However, the costs are so high that progress is not being made in realizing a transmutation reactor. The MYRRHA project (Multi-purpose Hybrid Research Reactor for High-tech Applications) planned for 2014 in Belgium is not expected to be commissioned until in 2023.

8 Fuel cells

8.1 Electrical energy instead of heat

Hydrogen and oxygen burn at room temperature, releasing heat and emitting practically 100 percent water. This water can be decomposed back into hydrogen and oxygen by applying heat at temperatures above 3,000 °C. In terms of energy, what happens here is that chemical energy is converted to thermal energy and conversely thermal to chemical energy. However, ultimately all chemical reactions are based on the interaction or exchange of electrons of the atoms involved. From this emerged the idea of suppressing the direct flow of electrons in the chemical reaction between the hydrogen and oxygen atoms and directing the electrons through an external operating circuit instead. This electricity flow, in other words electrical energy, would then be available instead of heat.

8.2 The operating principle of the fuel cell

For the cold combustion of hydrogen, a primary element (electrochemical cell) is built in which one electrode consists of hydrogen (H) and the other of oxygen (O). Since gases are insulators, a technical trick is used – platinum electrodes with hydrogen or oxygen circulating around them. Platinum (Pt) itself does not react but has the property of splitting H_2 molecules catalytically into atoms and then releasing them. The O atoms are also catalytically split by Pt into atoms and adsorb on its surface.

Negative pole:	$2\ H_2$		→	$4\ H^+ + \mathbf{4e^-}$
Positive pole:	O_2	$+ \mathbf{4e^-}$	→	$2\ O^{2-}$
Overall:	$2\ H_2$	$+ O_2$	→	$2\ H_2O$

At the negative pole, the released H atoms emerge from the Pt surface in the form of H^+ ions (protons) and pass through an electrolyte or a proton-permeable membrane to the positive pole. One electron remains in the electrode per H atom and these electrons flow via the external circuit to the positive pole.

At the positive pole, the O atoms each absorb two electrons at the surface of the Pt and become O^{2-} ions, in the process of which two positive charges are created in the electrode. Two of the H^+ ions that have passed through the electrolyte/membrane to the positive pole encounter one O^{2-} ion and react together to form H_2O. After flowing through the external circuit to the positive pole, the electrons recombine there with the positive charges. Overall, the same reaction takes place as in the case of combustion, merely that the electrons in the fuel cell flowed via the external circuit.

Note: Several media files related to fuel cells and hydrogen technologies are available on the media portal.

8.3 Technical problems with high-power current cells

If hydrogen gas, Pt electrodes, and a polymer electrolyte membrane (PEM) are available, a fuel cell of this type can be built in minutes in any school laboratory (see suggestion for experiment on the media portal). However, these PEM fuel cells that operate at room temperature are comparatively expensive and have only relatively low power outputs of up to about 500 kW. The Pt electrode surface areas and membranes necessary for higher power outputs would be so large that it would make these cells unaffordable.
Researchers are currently working feverishly on replacing the expensive platinum with other less expensive catalyst materials. For instance, organometalic compounds are being field-tested. If this succeeds, hydrogen could be combined with a fuel cell to produce an alternative to battery-powered electric cars.
Fuel cells of up to 100 MW are therefore usually built in the form of high-temperature solid electrolyte fuel cells (also known technically as solid oxide fuel cells (SOFC) or solid ceramic fuel cells). In the SOFC, both electrodes consist of a high-temperature ion- and electron-conducting oxide. The electrolyte membrane consists of an oxide that is selectively permeable for oxygen ions. That makes for a rugged and relatively cheap design. However, one drawback is the operating temperature of over 800 °C, since the oxide materials do not display the necessary properties until they reach this temperature. There are also other technologies at the development stage, so it is not yet clear which will become the established technology in the long term.
Meanwhile, smaller block-unit heating power plants using SOFC technology generating up to 20 kW of heat output are available as heating systems for single-family homes or smaller multiple-family buildings.

9 Synthetic gas generators

Solid fuels such as coal, lignite, bitumen, heavy heating oil, refinery residues, and wood or fuels containing added solids are not well suited, or not suited at all, for operating gas turbines. In order to be usable for this application, they are therefore converted to “synthesis gas” (“gasified”). This synthesis gas, a mixture consisting mainly of carbon monoxide (CO) and hydrogen (H_2), is referred to as such because historically in World War II, it was used as the starting material for the synthesis of other chemical compounds, for example, methanol and gasoline. “Gasification” in the synthesis gas process, unlike the carburetor in the Otto engine, is not a change of phase but a chemical reaction. Nor is one form of energy converted to another in the process of synthesis gas production. Chemical energy is stored in both the solid as well as the gasified fuel, although in the form of different compounds. Gaseous compounds are created from solid carbon or from solid or liquid carbon compounds through reaction with a small amount of oxygen and water (the chemical process involves partial oxidation of the coal and reduction of the water). In a typical process of this type, approximately 31 percent hydrogen (H_2), 56 percent carbon monoxide (CO), 5 percent nitrogen (N_2), 4 percent carbon dioxide (CO_2), and 4 percent water (H_2O) are typically obtained from mineral coal. This gas mixture has a considerably lower calorific value than natural gas. The remaining gaseous impurities such as sulfur and halogen compounds as well as all solid mineral components can be removed from the synthesis gas almost 100 percent during production with relatively little effort.
Today, synthesis gas is used for operating combined cycle power plants. In this case, one speaks of an IGCC power plant (integrated gasification combined cycle). Although the synthesis gas produced would also be suitable for generating steam in a steam power plant, the efficiency would be less than with the combined cycle power plant. The high-purity synthesis gas is, on the other hand,

exceptionally well suited for operating the gas turbine stage of the combined cycle power plant and has similarly good exhaust gas values as pure, sulfur-free natural gas.
Today, synthesis gas from the gasification of biomass (for example, straw, wood, sewage sludge) is being used for renewable energy. Modern wood-burning stoves for single-family homes also work with wood gasification, since then the exhaust gas is practically free of dust, soot, and odors.

10 Wind turbines

A wind turbine converts the **mechanical kinetic energy of the air to the mechanical rotational energy** of a rotor, which converts this energy to electrical energy via a generator.

10.1 Physics of the wind turbine

Air particles flow past a circular area (perpendicular to the wind direction) with radius r at velocity v in time t.

The mass (m) of the air flowing through is:

$$m = \rho \cdot V = \rho \cdot A \cdot v \cdot t = \rho \cdot \pi \cdot r^2 \cdot v \cdot t$$

ρ: density of the air, V: air volume,
A: swept rotor area ($\pi \cdot r^2$),
v: wind velocity upwind of the wind turbine
w: wind velocity downwind of the wind turbine
c_P: efficiency, t: time

The kinetic energy (E_{kin}) of the wind is:

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 = \frac{\pi}{2} \cdot \rho \cdot r^2 \cdot t \cdot v^3$$

The power (P_{Wind}) of the wind is:

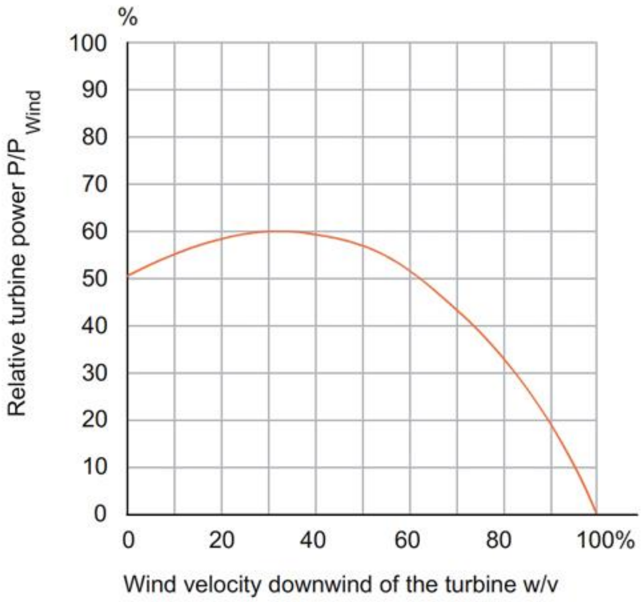
$$P_{Wind} = \frac{E_{kin}}{t} = \frac{\pi}{2} \cdot \rho \cdot r^2 \cdot v^3$$

Power output (P) of the wind turbine:

$$P = c_p \cdot P_{Wind} = c_p \cdot \frac{\pi}{2} \cdot \rho \cdot r^2 \cdot v^3$$

The power therefore increases as the cube of the wind velocity.
In this respect, calculation of the energy balance is no problem. But the question is how to transfer the energy of the wind to the wind turbine most effectively. There are two types of turbines: the resistance force type turbine and the lift-type wind turbine.
In the “resistance force type,” the air flow pushes the rotor blade of the wind turbine away, similar to the way the water acts on the bucket in the Pelton turbine. However, most wind turbines operate as “lift-type wind turbines” because they are more efficient. The principle behind the lift-type wind turbine is the same principle that causes the movement of the blades in the gas turbine (see above). In order to calculate the propeller of a wind turbine optimally, the laws of fluid mechanics must be applied (see the section on “Turbines”). An interesting teaching approach is to consider the problem on the basis of the following chain of thought: Lift at the wing of a glider – Lift at the wing of a powered aircraft – Propulsion at the propeller of a powered aircraft – Rotation of a wind turbine propeller in the air stream.
It is an interesting question as to whether it is possible at all to transfer 100 percent of the wind’s flow energy to the wind turbine. Betz’ law (Albert Betz 1926) states that theoretically a maximum of

59.3 percent of the wind's kinetic energy can be captured. This becomes clear if one considers the following:
The rated power of a wind turbine depends on how much of the kinetic energy of the wind (Ekin = $^1/_2 \cdot m \cdot v^2$) is transferred to the propeller, in other words what braking effect it has on the air. If it has a strong braking effect, the wind speed downwind of the turbine is low. The force applied to the turbine was large but the mass throughput was low. If the wind velocity downwind of the turbine is high, the force was low but the mass throughput was high. An optimum must be found from this, taking into account the conservation of energy and mass.
If power is extracted from the wind by the turbine, the wind is slowed down. Despite the lower speed downstream of the turbine, the same amount of air has to be transported away as flowed against the turbine. However, according to the law of conservation of mass, the mass flow must remain constant. In the case of a free-swept wind turbine, the wind therefore spreads out again downwind of the turbine. The same mass can therefore pass even at reduced speed. If the air mass remained slowed down with the same cross section, the afterflow would be additionally slowed by the wind turbine. The optimum can be found from the derivation of the corresponding functions. The result of the maximization is shown in the form of a graphic.



As the graphic shows, the maximum efficiency of a wind turbine is 59.3 percent, obtained when the wind velocity downwind of the turbine is exactly $^1/_3$ of the wind velocity upwind of the turbine. Modern wind turbines are therefore designed to achieve this "braking" of the wind speed as far as possible. Their efficiency is approximately 50 percent.

10.2 Wind turbine designs

Wind turbines can be differentiated according to the rotor axis position relative to the airflow. Wind turbines with a vertical rotation axis, so-called Darrieus rotors or Savonius rotors, have proven suitable in individual cases but have not been adopted as a widespread solution. The most frequent type today is wind turbines with a horizontal rotation axis. As far as the number of rotor blades is concerned, rotors with one, two, three, four, or even five blades are all possible. Three-bladed turbines (also referred to as three-bladed rotors) are the most commonly used. Because of their symmetry, they can be designed with extremely low oscillation. Although four- or five-blade rotors would possibly achieve higher output and better efficiency, these gains would be incommensurate with the costs for the additional rotor blades. The rotor blades are made of lightweight, high-strength composite materials such as are used in aircraft construction. The stresses they are subject to are enormous. The rotational speed at the tip of the rotor blade is approximately seven times the wind velocity!

10.3 Problems of electric power generation with wind turbines

The electric power generator is positioned on the rotor axis or connected via a gearset. In order to generate electricity with a constant frequency, the generator must be operated at a very specific constant speed. For 50–60 Hz power line frequency, for example, that would be 1,500 rpm with a two-pole generator. Maintaining this constant speed, though, would appear almost impossible, given that wind does not blow constantly. These variations in wind velocity can be compensated to a certain extent via control systems for adjusting the rotor blade pitch and the gearset. State-of-the-art wind turbines also operate with generators with up to 36 poles. Depending on the strength of the wind, poles are connected or disconnected so that the entire wind spectrum can be used almost seamlessly. As an alternative, however, gearless permanent magnet generators in combination with feed units using power electronics have been available. Since these generators use power converters to convert the generated alternating current first to direct current and then back to alternating current at constant frequency and voltage, electric power generation is not dependent on the wind velocity or the speed of the generator. Elimination of the gearset means one less wearing part, resulting in smaller and lighter nacelles in wind turbines.

11 Solar cells

A solar cell converts the **radiant energy of the sun** (energy of the electromagnetic waves) **to electrical energy**. This process is also known as photovoltaics.
Solar cells were first used to generate electric power for satellites. The first terrestrial photovoltaic power plants were not built until the 1970s. Today, photovoltaics is seen as one of the most promising energy “generation” technologies of all in the future. Unlike wind power or hydropower, it is far more flexible in terms of location and could potentially be used in almost any region of the world. Photovoltaics has also become very affordable in the interim. In 2005, 1 watt of solar electricity still cost approximately 4 euros, and by 2016 price started at approximately 40 eurocents/W. This means that in 2016, a 5 kWp roof system could generate electricity for approximately 10 eurocents/kWh without subsidies. Newly constructed solar farms in Germany even reached 7 eurocents/kWh in 2016.

11.1 The physics of the solar cell

In principle, photovoltaics can be described as a two-electrode process that can be outlined as follows in a silicon cell:
At the positive electrode (doped semiconductor), the light removes electrons from the valence band through excitation, leaving positive holes (charges). These electrons pass through a nonconductive separating film into the conduction band of the negative electrode (doped semiconductor) and charge this band negatively. The electrons can then flow back from the negative electrode to the positive electrode via the external operating circuit.

Note: Several media files related to solar cells and photovoltaics are available on the media portal.

11.2 Why is the efficiency of solar cells so low?

Because of the quantization of energy, a solar cell cannot absorb energy at all frequencies contained in the light spectrum. Instead, absorption takes place in relatively narrow energy bands that correspond to only a few wavelengths of the light spectrum. The solar cell types listed below are all affected by this disadvantage. At present, attempts are being made to increase the absorption bandwidth and hence the efficiency by combining solar cell layers from various materials or from semiconductors with different doping or by adding layers of fluorescent dyes.

11.3 Solar cell types

There are a number of distinct types at present based on material, crystallization state, and layer thickness, of which the following are the most important.

Thick-film monocrystalline silicon cells
Efficiency in series production up to 26 percent, in the lab up to 40 percent,
very long service life (30 years and longer),
more expensive than polycrystalline or amorphous silicon cells.

Polycrystalline silicon cells
Efficiency in series production up to 19 percent,
very long service life,
production less expensive than monocrystalline cells.

Amorphous thin-film silicon cells
Efficiency in series production up to 10 percent,
very long service life,
production less expensive than monocrystalline and polycrystalline cells.

Cadmium telluride cells (CdTe)
Efficiency in series production up to 14 percent, in the lab over 20 percent,
long service life,
production less expensive than for silicon cells,
Due to cadmium and telluride content, disposal and recycling are more problematic than for silicon cells.

Copper indium (gallium) selenide (CIS, CIGS)
Efficiency in series production up to 14 percent, in the lab over 20 percent,
very thin, semitransparent, suitable for glass façades, good yield even in diffuse light
long service life,
production 50 percent less expensive than for monocrystalline and polycrystalline silicon cells,
disposal could be problematic due to selenium content.

Gallium arsenide cells (GaAs)
Efficiency up to 40 percent (currently not in series production),
long service life,
production more expensive than for silicon cells.

Organic solar cells (from semiconductor plastic)
Efficiency up to 7 percent in series production, over 14 percent in the lab,
very thin and flexible,
up to 40 percent transparency, suitable for glass façades, but service life is too short,
service life 5–10 years,
production cheaper than for all inorganic cells.

Dye-sensitized solar cells
Efficiency up to 15 percent in the lab,
good transparency, suitable for glass façades, but service life is still too short, which is why not yet commercially available,
production would be less expensive than for all other cells.
They are also known as “Graetzel cells” after their inventor.
Dye-sensitized cells use organic dyes as their positive electrode, from which electrons excited by light flow over to a semiconducting titanium oxide electrode (negative counterelectrode).

11.4 Climate footprint, ecological balance, and energy efficiency of solar cells

Some grossly distorted assertions in this regard are circulating.

“More energy is used to manufacture solar cells than they ever produce.”
The correct statement is: The energetic amortization of solar cells today is 12 to 18 months. With a service life of up to 30 years, this isn’t an issue. For that matter, solar cells can also be manufactured using renewable energy.

“Solar cells contain toxic substances that pollute the environment during production, disposal, or recycling.”
The correct statement is: During the manufacture of all types of solar cells, there are production stages that involve hazardous chemical substances. Incidentally, this is also the case for materials used in smartphones, beverage and food packaging, and cars. However, if these substances are used in closed processes as prescribed, the production of solar cells is not any more dangerous than the production of yogurt containers. The same thing applies to disposal and recycling. In particular, disposal of the most frequently used silicon cells is completely harmless. Arsenic and boron, most often cited as harmful doping substances, are present only in the ppm range and are chemically bound, and so even if the silicon cells are disposed of in a landfill, the chemicals cannot seep into the groundwater.

“Solar cells are ridiculously inefficient at only 20 percent efficiency.”
The correct statement is: The efficiency of a car with a combustion engine is ridiculously low at approximately 10 percent (portion of fuel that is converted to movement). Plus there are the fuel costs and the car’s exhaust gases. By contrast, the sun is free of charge and solar cells cause neither exhaust gases nor noise. The same thing also applies in comparison with the agricultural production of energy crops: One hectare of a solar field delivers ten times more energy than one hectare of a corn field. Furthermore, nitrogen-based fertilizers applied to the corn field pollute the groundwater with nitrate and the air with the greenhouse gas nitrous oxide, and on top of that, there’s the pollution from herbicides and pesticides.