

Electric current and energy – Basic physics principles and models

1 Atomic model

Knowledge of the structure of substances is required for understanding electrical conductivity phenomena.

All substances are made of **atoms**. Each atom consists of a positively charged atomic nucleus at the center surrounded by negative charges, the **electrons**. The nucleus is composed of positively charged and electrically neutral particles (protons and neutrons). Viewed from the outside, an atom is electrically neutral; the number of electrons in the “shell” corresponds to the number of protons in the nucleus. Although strong attraction forces exist between the particles with different charges, the electrons in the shell do not combine with the protons in the nucleus. Fig. 1 shows a schematic atomic model. It shows electrons moving in different orbits around the nucleus. This movement is extremely fast and prevents the electrons from falling into the nucleus, thus ensuring the atom’s stability.

This model with fixed electron orbits is outdated, although you still find it in many books. In a more abstract and viable model, the electrons occupy only very specific energy levels in the atom due to their wavelike properties. The inner electrons close to the nucleus are bound very tightly, and by contrast the outer electrons can be separated from the atom with less energy expenditure. Removing an electron from the atom results in an unbound (“free”) electron and a positively charged atom (an ion).

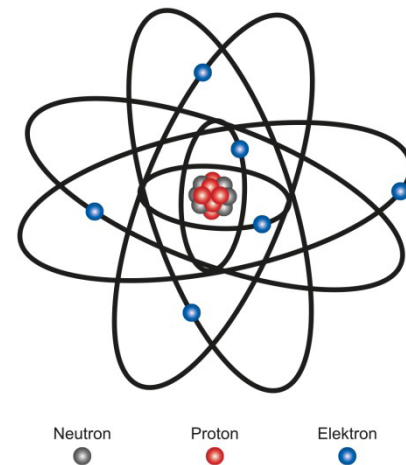


Fig. 1: Schematic atomic model.

2 Electrical conductivity

In a substance, countless atoms are connected together. The outer electrons of the atoms play an important role in bonding. Depending on the substance class (for example, metals, salts, carbon compounds), there are different types of bonds. They significantly determine the substance properties (for example, stability, color, electrical conductivity).

In principle, a substance needs **free charge carriers** to be electrically conductive. Negatively charged **electrons** or **ions** (positively or negatively charged atoms) are possible charge carriers.

In a **metal**, the free electrons are responsible for the fact that electric current can flow. The metal atoms are arranged in a regular lattice structure. The outer electrons are no longer bound to certain atoms, but move throughout the entire metal as “electron gas”. Like the temperature-dependent movement of the particles of a gas, their movement is chaotic; the electrons are constantly changing their direction due to collisions with atoms and other electrons (Fig. 2).

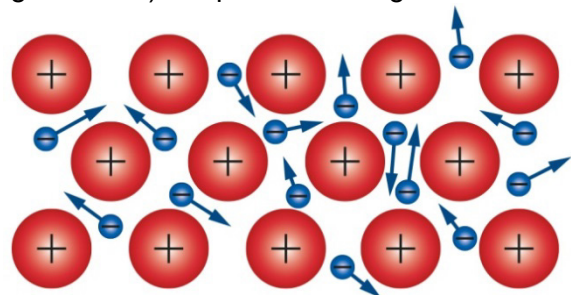


Fig. 2: Model of the electron gas in a metal.

Substances that do not contain any free charge carriers and therefore do not conduct current, such as plastic, glass, ceramic, or table salt, are called **insulators**. Table salt crystals consist of a regular arrangement of positively charged sodium ions and negatively charged chlorine ions. Only when the salt is heated to a high temperature or dissolved in water do the ions become mobile, giving rise to ion conduction. The current is carried by both the positive and the negative ions, which move in opposite directions.

Another important group of substances in electrical engineering and electronics is **semiconductors**. In semiconductors, the number of free charge carriers depends on the level of purity of the substance. The purity can be influenced over a wide range by the addition of impurity atoms (doping) and through external influences (for example, temperature, light). Unlike the mechanism of electronic conduction in metals, positive charges (electron holes) can contribute to the current in semiconductors. Components with complex functions can be produced through the combination of semiconductor materials with various conduction properties. Without the group of semiconductors, modern information and communication technology (computers, mobile phones, Internet, and much more) would not be possible. These components are also playing an increasingly important role as energy converters. Experimento | 8+ goes into more detail about this with the LEDs as high-efficiency light sources and with the use of the sun's radiant energy in solar cells.

The experiments of the Energy module focus on electronic conduction in metals. Ion conduction plays a role in the study of water's conductivity (see experiment A2).

3 Electric current and voltage

Although electrons move very quickly inside a metal wire, current that can be measured from the outside does not flow because inside the wire, as many electrons flow in one direction as flow in the opposite direction.

Electric current is however the movement of charge carriers in a common direction.

This “directed” movement requires an external “drive” – an **electric voltage**.

Current does not flow without voltage, or in other words, voltage gives rise to current.

Fig. 3 illustrates the current in a conductor as a directed movement of the conduction electrons. This schematic representation shows only the additional average electron velocity elicited by the applied voltage. The much stronger random movement of the electron gas is not shown here (see Fig. 2).

For the students' initial encounter with the concept of “voltage” as part of the introduction to electric circuits, it is sufficient to assume the voltage is a given variable (“Voltage is what is indicated on the battery or what a voltmeter displays”). It is measured in **volts** (abbreviated V).

The electric voltage of a battery comes about when a surplus of electrons exists at the negative pole and a shortage exists at the positive pole. If the poles are conductively connected, electrons flow from the negative pole to the positive pole through the conductor. This current would very quickly equalize the charge difference between the poles, but the battery continues to provide additional charge carriers. Inside the battery, chemical processes take place that maintain the charge difference and thus also the electric voltage. The reactions are complex and cannot be explained here in detail. Ultimately, the chemical processes inside the battery transport electrons from the positive pole to the negative pole. When the chemical substances are “used up”, the battery is “dead”. Electric voltage cannot be built up and the current comes to a standstill.

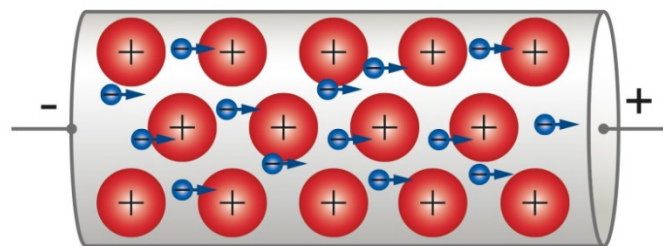


Fig. 3: Model of electric current in a metallic conductor.

A vivid cause-and-effect model – the perception of the voltage as the cause that effects a current in the conductor – is viable. The amount of voltage, its numerical value, is a measure of the power of the drive. The higher the voltage, the more electrons flow through the conductor in the same amount of time, and the greater the power of the current. These types of simple comparative observations should definitely be made during class because they help to more clearly define and differentiate the concepts of voltage and current. These observations can be built upon for future reinforcement and abstraction processes.

4 Electric circuit

A closed **circuit** must always be present to operate electrical devices like incandescent lamps or electric motors: The electrons flow from the battery's negative pole to the device via a conducting connection and back to the voltage source's positive pole via another conductor. The chemical processes inside the battery close the circuit.

It is not immediately apparent to the students that a closed circuit is present. First, only the two external connections from the battery to the device are visible and tangible; the internal processes of the battery, which close the circuit, remain inaccessible and go unnoticed. Second, the circuit model conflicts with intuitive everyday perceptions, which may be difficult to dispel. Many people (not only children) associate a rather "energetic" image with electricity: It is generated and consumed. They assume that electricity/current is stored in the battery, flows to the device via the cable, and is "consumed" there. The term "consumer" used in everyday language for electrical devices reflects this perception. The consumption idea should be discussed in class and scrutinized in terms of both substance and energy. No charge carriers are lost in the "consumer", and no energy is consumed (for energy conversion, see below). To keep from overwhelming the students, the teacher should initially limit the lesson to the aspects related to substances and the closed loop of the electric charge (circuit) (experiments A1 to A4). The energy perspective is examined separately (experiment A5); it requires additional conceptual clarification.

Even if the students recognized in the experiments that two conducting connections are necessary between a voltage source and an electrical device for the device to operate, this does not automatically imply that they have fully grasped the circuit model. The students often use a sort of two-component model as an intermediate stage. In this model, two different types of electricity come from the positive and negative poles. They are transported to the device via the two cables, come together there, and their "consumption" drives the device. To disprove the consumption model and support the circuit model, the teacher can use an additional ammeter to demonstrate that the current is identical before and after the alleged "consumer" and that the direction of the current before and after the "consumer" is in line with the circuit model. The experiments themselves are not sufficient to convince the children of the circuit concept. In addition to support during the experiments, the teacher must also provide comprehensive conceptual support to develop and reinforce a viable circuit model. It is important that the students learn to successfully apply the circuit concept (for example, in the setup of more complex circuits or in troubleshooting). In this way, the model is gradually reinforced and internalized.

5 Electrical resistance

The “strength” of the electric current in a circuit depends on the applied voltage. In addition, the current “strength” depends on the quality of the connected devices and the connecting cables. For a given voltage, a stronger current flows through a thick copper wire than through a thin wire. An iron wire does not conduct as well as a copper wire of the same diameter and length. A stronger current flows through an incandescent lamp than through an equally bright LED. The property of substances and electrical devices to oppose the passage of current is called **resistance**. For a given voltage, the lower the resistance of a device or conductor, the stronger the current through the device or conductor. Good conductors (copper, gold) have low resistance. At very low temperatures, the resistance of some conductors disappears completely, making them superconductors. The resistance of an insulator is (nearly) infinite.

Current and resistance are discussed only qualitatively in the materials to give the teachers freedom in planning the lesson. Depending on the students’ learning progress and the teacher’s conceptual confidence, advanced quantitative observations can be made that can be built upon during subsequent lessons. Beyond the comparative formulations (“the higher the voltage, ...”) many students can grasp basic proportional correlations: “A doubling of the voltage results in a doubling of the current.” The idea of proportionality between current and voltage is already stated in Ohm’s law without having to deal with a formula. This formulation paves the way for future quantitative formulations linking voltage, current, and resistance.

6 Analogies and models on current

Because we cannot see current, attempts are often made to explain the concept of current to students using analogies and to illustrate the concept using the simplest and easiest-to-grasp models. An analogy is basically understood as the correlation of objects or processes with regard to certain characteristics. In physics, analogies are helpful to the extent that they make it possible to use experiences and knowledge from a familiar phenomenon to understand a new, unfamiliar, or less accessible phenomenon. Models are also based on similarity relations, but they have an even wider range of functions than analogies. Children are familiar with models, for example, a dollhouse or a model train set. Unlike these toy models, which for the most part strive to represent reality accurately, the purpose of physical models is to describe the interdependencies of processes as accurately as possible.

Analogies and models should be both factual and age-appropriate to be effective. However, acceptance of analogies and/or models is very individual, which is why there is no single solution for practical implementation in the lessons. What is important is that they fit the children’s conceptual world. The range of experience (foundation range) underlying the models and analogies should be sufficiently familiar and the relationships to the target range should be comprehensible. Nonetheless, comprehension of the model should not complicate comprehension of the phenomenon to be explained. Also, the phenomenon being modeled (the reality) should not be confused with the model itself. Teachers should encourage and help develop models, but to avoid possible misconceptions, they should reflect upon the limits of modeling.

These guidelines result in narrow limits in the application of models and analogies in the introductory lesson. In the materials for Experimento | 8+, we intentionally refrained from the explicit presentation of certain models to stay within the scope of the experimentation instructions and to give teachers freedom in selecting an adequate modeling level for their group of students. The topics of current and energy cannot be taught without the aid of simple models.

7 Teaching an energy concept that can be built upon

The topic of energy is at the center of sociopolitical discussions more than any other field. Energy moves, changes, enables, and drives all dynamic processes in the natural and man-made worlds. Societal development is also driven by energy. In Germany and globally, this development vitally depends on the successful transformation of energy systems. Advancements in technology must balance the conflicting demands of security of supply, efficiency, and sustainability. In light of these multifaceted challenges, educational processes are focusing more and more on the topic of energy. There is now broad consensus that the topic of energy should be incorporated into introductory curricula. However, the extent to which curricula should focus on a sustainable physical energy concept is still contentiously debated.

The concept of energy is too complex for a simple definition. It is counterintuitive to think that energy can be neither generated nor destroyed. In all processes that have been scientifically explored to date, energy is only converted from one form of energy to another. The total amount of energy remains unchanged. Energy is indestructible. On the other hand, matter can be converted to or generated from energy. Having emerged only relatively recently in the development of science, a universal concept of energy is associated with abstract principles of symmetry and conservation. How can a scientific structural concept that highlights the peak of theoretical development be sensibly integrated into the early stages of learning at school? To what extent can curricula sustainably convey the topics that play a role in current times (for example, saving energy, reducing the “energy consumption” of household appliances, utilizing renewable energies, developing a sustainable energy supply)?

Even today, these questions have still not been sufficiently clarified for the elementary school level. The materials for Experimento | 8+ offer experimental aids for teaching. They create a variety of learning opportunities. Nevertheless, the teacher should play an active role in cultivating the students’ knowledge base.

Despite its abstract nature as a physical variable of conservation and balance, energy manifests itself in extremely concrete forms that permeate our lives in numerous ways. For elementary school children, a didactic approach should incorporate a variety of energetic phenomena and should reflect on their meaning in our world. In didactics there is a general consensus regarding a cumulative model of learning about energy that can serve as an orienting guideline. Its structure is illustrated in Fig. 4. It starts with energy phenomena and their qualitative description. The various facets of the energy concept are developed on this foundation; initially, energy conversion and energy transport are processes that describe changes. As a continuation of this systematic model, the next stages deal with the destruction and conservation of energy, theoretical concepts that underlie the conversion processes and describe it qualitatively and quantitatively but which do not play a role in teaching until grades 5 to 8. The introductory lesson is generally limited to the first two stages shown in Fig. 4. However, the teacher should be in a position to adequately respond to additional questions the students may have. Also, the teacher should be cognizant of the long-term goals, namely of being able to build upon the knowledge introduced in early grade levels.

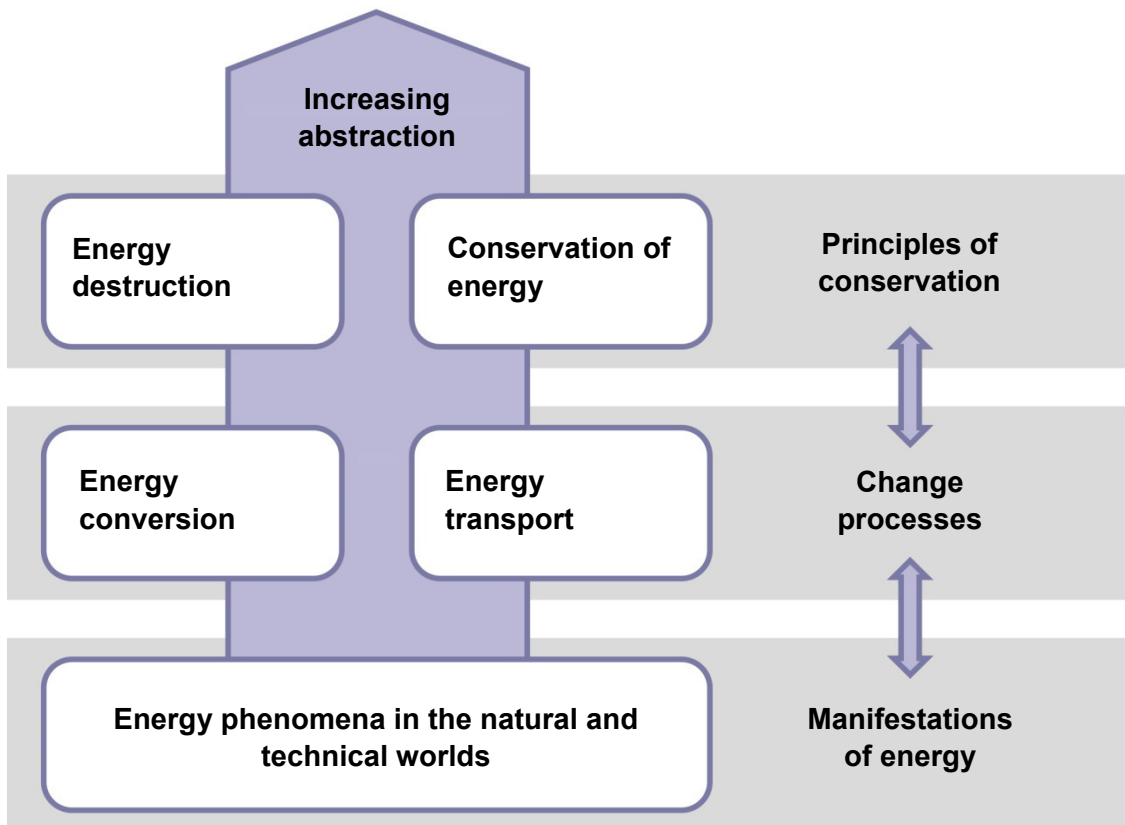


Fig. 4: Model of stages for developing the energy concept in class.

The materials for Experimento | 8+ encourage students to explore the processes of conversion of electrical energy and to learn further about the importance of energy in the natural and man-made (technical) worlds. They are oriented toward the research cycle and promote the acquisition of experiential procedural knowledge (**knowledge of how** something works). Extensive assistance from the teacher is required for the building of conceptual knowledge (**knowledge of what** the point is) and reflection (**knowledge of why** something happens). The teacher should support the students in linking the various facets of energy and in developing sustainable model concepts, based on Fig. 4, which can be gradually combined into a comprehensive energy concept.

Describing energy phenomena

At a phenomenological level, the following aspects should be addressed in the context of the experiments, described by the students, and studied in more depth in terms of their interaction:

- Description of the effects of energy: Energy is necessary to generate current, light, heat, and movement and to lift bodies.
- Conversely, energy is found in current, light, heat, moving bodies, and lifted bodies. Fuels (heating oil, gasoline) and food also contain energy.
- The containment of energy in a substance or a system results in the energy source model, which is helpful during the observation of transport and conversion processes.
- Naming of various energy sources or manifestations of energy that occur in everyday energy conversion processes.
Typical forms of energy are: chemical energy, electrical energy, thermal energy (heat), magnetic energy, mechanical energy (potential and kinetic energy), nuclear energy, and radiant energy.
Typical energy sources are: light (radiant energy), oil (chemical energy), wind (kinetic energy of air), water (kinetic energy or thermal energy), etc.
- Description of energy transport processes: Energy can be transported from one location to another by transporting the energy sources (e.g., oil in a tanker, natural gas in a gas line).
- However, energy can also be transported without transporting matter; for instance, the sun's energy comes through empty space to the Earth as radiant energy (light, heat radiation).
- Clear definition of the special role of electrical energy: It can be used conveniently in many ways and transported relatively easily via power lines.

Energy can be transported as electricity across great distances very conveniently and with relatively low loss. However, electricity is not identical to energy. Clearly separating the terms electricity and energy conceptually is a major challenge because “electricity” and “electrical energy” are largely used synonymously in everyday life. It makes sense to draw upon mechanical models on energy conversion to clarify the correlations. However, with this approach, vague everyday perceptions may need clarifying as well. In mechanics, force is frequently mixed up with energy. A clear delineation between energy and force proves difficult. Initially, during the lesson, choosing the correct terminology can be tricky, but the correct vocabulary should be emphasized.

In everyday life, energy is frequently associated with vitalistic ideas. For many people, not just students, “biological” energy is something completely different from “physical” energy. Some people may resist the idea that the same energy conversion processes that occur in inanimate natural and technical systems also play a role in living organisms. In this respect, it is important to include the energy conversion process in organisms in the discussion. In health education, it is also very important to discuss the energy content of foods (their “caloric value”).

Conversion and conservation of energy

With this background information, it makes sense to link energy conversion processes with the students' physical experiences. For instance, the bicycle dynamo is well suited for physically experiencing the cost of converting kinetic energy into electrical energy. If the dynamo circuit is closed, then you must pedal much harder than with an interrupted circuit.

The conversion of the two basic mechanical forms of energy (kinetic energy, potential energy) can also be well anchored in experience and then generalized:

- When riding a bicycle, you must push the pedals forcefully and perform work with your leg muscles to ride faster and faster. You gain kinetic energy in the process.
- The performed work corresponds to the increase in kinetic energy.
- If you ride uphill, you gain potential energy as you get higher.
- The potential energy is converted to kinetic energy when you ride downhill.

In addition to the verbal description of the processes, a visual depiction in the form of energy conversion chains is useful. The depiction is easily remembered and expanded, and it supports the formation of abstract ideas. In the conversion chains, the forms of energy involved are shown as boxes, and the conversion processes are symbolized as arrows. Fig. 5 shows a simplified illustration of riding uphill. It incorporates the energy from food (chemical energy) that is necessary for the muscle activity into the energy conversion chain. As learning progresses, these illustrations of the energy conversion chains can be made more precise, e.g., the muscles give off heat to the environment. Resistance processes (friction on the tires, air resistance) drain kinetic energy, which is also given off to the environment as heat. We recommend that energy conversion charts be created for the discussed conversion processes and for the experiments.

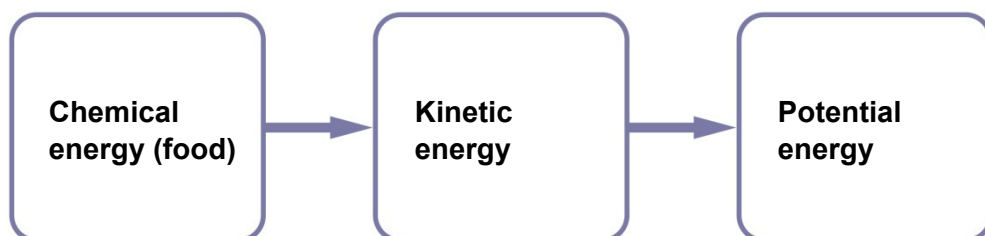


Fig. 5: Simplified energy conversion chain for riding a bicycle uphill.

Useful energy and energy efficiency

Energy is not created from nothing, and similarly it is not consumed and does not disappear without a trace. Despite what we know, the origin and the nature of energy in the entire universe still remains a huge, unsolved scientific puzzle even today. The conservation of energy as an empirical principle can only be told to the students. At the elementary school level, the focus is on the fact that any use of energy builds upon energy already present. The term "power generation" used in everyday language is also a type of energy conversion, like the "energy consumption" in electrical devices, which are sometimes colloquially referred to as "consumers" or are listed as such in some technical illustrations. The term "consumer" should be avoided as much as possible, and the reason why its meaning is misleading should be discussed. Instead of talking about power generation, the teacher can use the more neutral wording of "provision of energy" or talk about an energy source. However, the teacher should remember that correct usage of language does not necessarily imply an understanding of the material. When the students are capable of associating adequate models with the terms, their misconceptions will also gradually disappear.

In addition to useful energy, energy conversion also results in a certain portion of energy that's of no further use. When an incandescent lamp is operated, electrical energy is converted to light (useful energy). At the same time, the heated filament gives off energy as heat that dissipates unused into the environment. Fig. 6 uses arrows of different widths to visualize the respective amounts of energy that are transformed during the conversion processes.

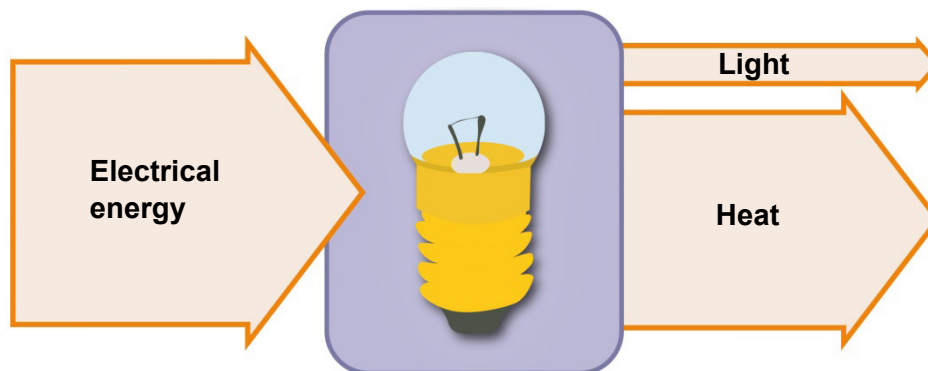


Fig. 1: Energy conversion in an incandescent lamp.

The electrical energy used is equal to the sum of the useful energy and the unused energy losses during the conversion. For an incandescent lamp, less than 10% of the electrical energy is converted to light. For an LED light, on the other hand, the portion of unused energy is lower. Its energy efficiency is higher, but it also is more expensive to purchase. When you purchase an electrical appliance, you should make sure that the useful energy arrow is as large as possible compared to the loss arrow and that the purchase price is reasonable relative to the saved energy costs. The categorization into different energy efficiency classes for electrical appliances provides a starting point (A+++ stands for a particularly efficient appliance, B, C...G for decreasing efficiency).

Renewable energy

The term “renewable energy” should also be discussed in the context of energy conversion and energy conservation. It is unclear to many people that renewable energies also require an energy source to provide replenishment. The common renewable energies can ultimately be traced back to the sun’s energy. This fact is immediately clear with photovoltaics and solar thermal energy since in these cases the solar radiation is converted directly to current or heat. Chemical energy is used in biomass. It stems from the energy-rich substances that were formed in plants during photosynthesis. For this process, the plants need water, which they absorb from the soil via their roots; carbon dioxide from the air, which they absorb via their leaves; and light from the sun, which is absorbed in the leaf pigments and drives the chemical processes with its energy. However, people often have the misconception that the energy of the substances stored in the plants comes from the soil nutrients. Our bodies also live on the basis of renewable energy that comes from the sun and has passed through many conversion chains before we take it in through our food.

Hydroelectric and wind power plants are ultimately driven by the sun. A discussion of the water cycle and wind currents driven by the sun is very well-suited for elementary school children. It provides students with their first basic sustainable insights into global connections. Insightful learning is supported by drawing diagrams of the underlying cycles of substances and by linking these diagrams with energy flow diagrams.

8 Circuit models and the direction of energy transport

The conceptual separation of electricity and energy can be supported through suitable models. Two examples are presented.

The first example, the **water model**, is frequently used during class. It illustrates the closed circuit by means of a water circuit. A pump drives the water stream. The drive component builds up a pressure difference, which corresponds to the voltage source. The liquid stream drives a turbine (waterwheel), which corresponds to an electrical device in the circuit. The water flows in a circle, but the energy flows only in one direction – from the pump to the turbine. Fig. 7 shows the “one-way street” of the energy in contrast to the closed water circuit. The electric current flows similarly in a closed circuit, and the energy flows only in one direction – from the energy source (e.g., generator, battery) to the electrical device (e.g., motor, lamp).

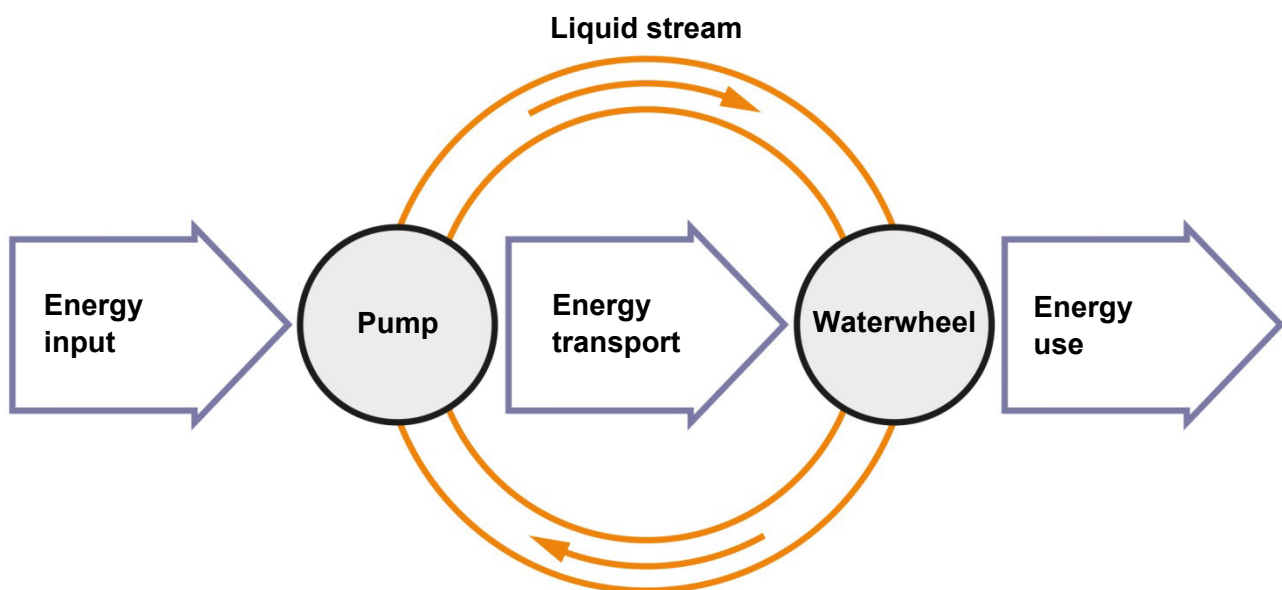


Fig. 7: Water circuit model and the “one-way street” of energy transport

The second model, the **marble track model**, is somewhat more complex. In it, potential energy can be visualized as the height above the entire circuit. An excess of negative charges exists at the negative battery pole. Energy must be spent to transport an electron from the positive to the negative pole. This corresponds mechanically to the lifting of a marble from a lower level to a certain height. There the marble has potential energy. It can roll down a channel, which causes it to lose potential energy and gain kinetic energy. This kinetic energy can be used to operate a device. Fig. 8 shows the model. A lift, representing a drive, transports the marbles upward. A paddle wheel is driven by the marbles and can be used as a motor. The lift corresponds to the electron transport in the battery.

The marble track model and the modeling of the battery as a “lift” are based on the fact that electric voltage is related to potential energy. This representation corresponds to the definition of voltage (electric voltage as a potential difference). Other details can be discussed in this model. One recognizes in the model that energy is “lost” in the cables. The two channels are tilted slightly to be able to transport the marbles against the friction forces. As a result, the paddle wheel motor has less energy than is present directly at the lift. The height difference along the channel corresponds to the voltage drop in an electric line. The voltage drop depends on the line resistance and reduces the useful energy when an electrical device is connected.

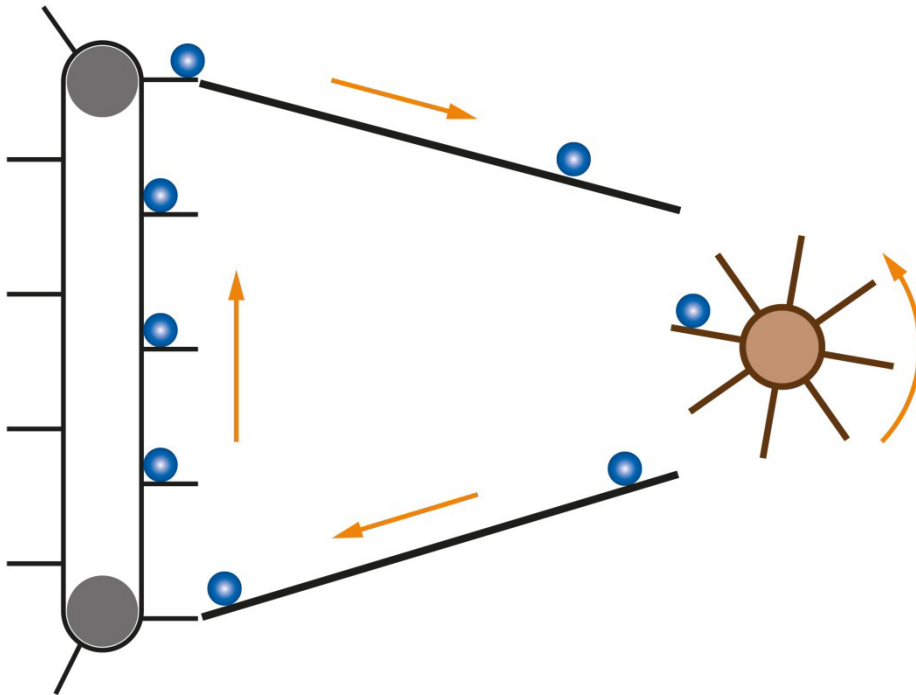


Fig. 8: Marble track model of electric current.

The marble track model is primarily designed to provide theoretical background for the teacher. Depending on the teacher’s own familiarity with the correlations, models with varying levels of sophistication can be used in class. For example, the marble lift as a voltage source model can illustrate the effects of the parallel and series connection of batteries in relation to voltage, current, and the energy converted per unit of time, the electrical power. The teacher is explicitly encouraged to try out different models in class, test the suitability of the models in the context of learning, and exchange experiences among the teaching staff. The teacher can thus optimize the effectiveness of the learning materials and ensure his or her own teaching success.