1 Energy and the society

The universe is made of space and time, matter and energy. Space and time refer to where and when things happen. Matter refers to what things are made of, and **energy** is the reason why things change, e.g. position, shape, state between solid, liquid, or gas; this is why energy is so important.

This chapter introduces the basic terms used to describe the flow of energy in the energy system, and then describes the flow of energy today including some general statistical data, a historical review of the technologies used, and future challenges and options.

1.1 The energy system today

1.1.1 Overview

At the beginning of the evolution of humankind, humans could only use the energy from their body. Throughout history, more sources of energy were found, and this allowed doing more useful things. However, the basic types of use of energy have not changed: energy, as it is finally used, called **useful energy** (Fig. 1-1), comprises mechanical work, heat / cold, and light.

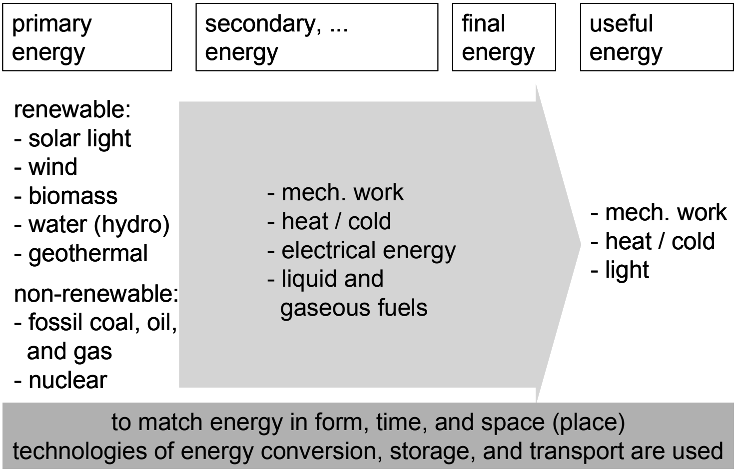


Fig. 1-1 Flow of energy in the energy system - overview

Where does the useful energy come from?

Primary energy, which is energy as it is found in nature, is the initial source (Fig. 1-1). Primary energy can be non-renewable or renewable. Examples of non-renewable energies are energy contained in fossil coal, oil, and gas, and nuclear fuels. The fossil sources are called non-renewable as they need millions of years to build up and are thus not renewed at a useful time scale, and nuclear fuels are not renewable at all. Examples of renewable energies are solar light, wind, biomass (the counterpart of fossil sources on a short time scale), water (also called hydro from the Greek expression for water) as ocean tides and river flow, and geothermal energy.

The demand of useful energy in most cases does not match the available supply of primary energy regarding the energy form, but also regarding the time and the place where useful energy is needed. Therefore, steps of energy conversion, storage, and transport are set up between the primary energies and useful energies (Fig. 1-1).

As soon as primary energy has undergone a conversion process, it is called **secondary energy** (Fig. 1-1). If additional steps are accounted for separately, they are sometimes called **tertiary energy** etc. Reasons for conversion are to get the required type of useful energy, and to get more convenient energy forms for storage and for transport. Examples are electrical energy, refined or synthetic fuels; they are also called **energy carriers** and are secondary energy. Electricity is one of the most common energy carriers, generated by conversion from various primary energy sources such as coal, oil, gas, and wind, being easy to transport, and suitable for all types of use as mechanical work, heat / cold, and light. The storage of energy as electrical energy is however comparatively difficult for large amounts of energy, and therefore energy storage is today mostly by liquid and gaseous energy carriers which are more easy to store.

Final energy, sometimes called **end energy**, is defined as the energy as it arrives at the user (Fig. 1-1). At the user, the final energy is converted to useful energy, for example, electrical energy is converted to light.

Depending on the type of user, energy sectors are defined, the most common ones being the building sector, industrial sector, transport sector, and service sector; agriculture and fishing are often not named separately as their relative size has become small in many countries.

Fig. 1-1 suggests a straight connection between primary energy and useful energy. However, there are several exceptions. First, not all primary energy is put into the system for the purpose of useful energy; there is also a **non-energetic use**, for example when in industry a material is shaped or produced like polymers by a chemical reaction or metals by electrolysis. Second, there are of course **energy losses** during conversion, storage, and transport, such that by far not all primary energy is finally ending up as useful energy. Because of conversion losses and other losses, the amount of useful energy is significantly smaller than the amount of final energy or of primary energy used for getting it. This is shown in so-called Sankey diagrams (Fig. 1-2). Fig. 1-1 thus shows a very simplified overview of the energy system.

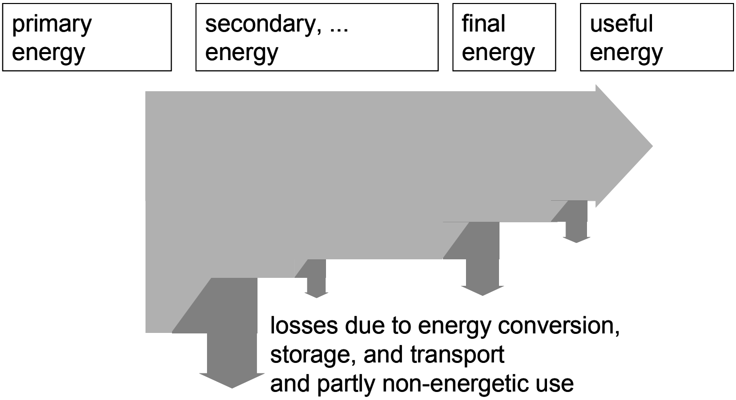


Fig. 1-2 Flow of energy described by a Sankey diagram

When looking at the energy system in more detail, it becomes clear that the **energy system** is a complex network of energy conversion, storage and transport technologies to supply useful energy. After discussing the essentials and the different technologies of energy conversion, storage, and transport, this will finally be discussed in detail in chapter 6.

1.1.2 Statistical data

Statistical data on the energy system and supply chain are usually available for every country. Detailed data for the European Union (EU) and its member countries are available from Eurostat, for example in its publication “EU Energy in figures – Statistical Pocketbook 2014” (EU 2014). For the world, a renowned data source is the **International Energy Agency (IEA)**, which annually publishes its “World Energy Outlook” (WEO) and its “Key World Energy Statistics”.

As it is convenient to count the use of the non-renewable energy resources, statistical data often cover the primary energy. Fig. 1-3 shows, as an example, the world total primary energy supply from 1971 to 2012 by fuel in million tons of oil equivalent, Mtoe, and their fraction in 2012, as published in the “Key World Energy Statistics 2014” (IEA 2014a).

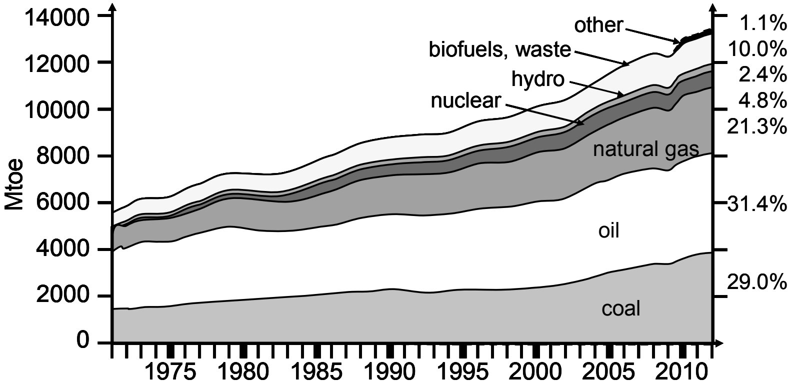


Fig. 1-3 World total primary energy supply from 1971 to 2012 by fuel in million tons of oil equivalent, Mtoe (data from IEA 2014a)

Also available are often data on the final energy, as this is what the consumer has to pay for.

When discussing the energy system, and potential energy savings or increases in energy efficiency, it is important to keep in mind that the real demand of the user is the useful energy, and not primary or final energy. The primary energy is only the initial effort, and if some amount of useful energy is delivered in an inefficient way the necessary quantity of primary energy increases (Fig. 1-2); the inefficient way then seems to be relatively more important when looking at primary energy data, as it is associated with a larger amount of primary energy. The same argument holds in a similar way for the final energy. Another important point is that an amount of useful energy that is saved by less consumption leads to a larger saving in primary energy.

2 Energy essentials

This chapter contains the essentials on energy that are necessary for the discussion of the different technologies and the whole energy system in the following chapters. It serves as a short introduction for those not working in the field of energy, as a summary for those who do, and in general as a reference when reading the following chapters.

The chapter begins with discussing energy as a quantity, including some examples relating to common experience. Then, the different energy forms, which are the basis for energy conversion, storage, and transport, and their origins, are introduced. Following, the essentials of the processes of energy conversion, storage, and transport and their main characteristics are described. Finally, energy quality, which affects the exchange of energy by heat and work, is introduced.

2.1 Energy quantity and form

Energy has a quantity, meaning an amount, and comes in different energy forms. It also has a quality, which is discussed in section 2.3. These terms and their origin are important basics for the understanding of the following chapters on energy conversion, energy storage, and energy transport.

2.1.1 Quantity

2.1.1.1 Units

It is common to say “a lot of” energy or “little” energy is used, meaning a large or small amount. This shows that energy has a **quantity**. Different units are in use for it. Throughout this book the **International System of Units**, abbreviated **SI** (from the French: Le Système International d'Unités), is used. In this system, the unit for energy is **Joule**, **J** (section 7.2). Large amounts are usually written using prefixes (section 7.1), for example kJ = 10^3 J. Units from older unit systems, still found in literature, are for example the **Calorie**, **cal**, with 1 cal = 4.187 J (≈ 4.2 J), and the **British thermal unit**, **BTU**, with 1 BTU = 1.05986 kJ (≈ 1.1 kJ).

A quantity of energy per time, for example converted, stored, transported, used etc. is called **power**.

$$\text{power} = \frac{\text{quantity of energy}}{\text{time}} .$$ **Eq. 2-1**

Its SI unit is $J \cdot s^{-1}$, which is also called **Watt**, **W**. If a power of 1 kW lasts for 1 h, the amount of energy is 1 kWh, written kilowatt-hour; this is a commonly used unit, with 1 kWh = $3.6 \cdot 10^6$ J (because 1 h = 3600 s). Section 7.3 contains tables for the conversion between different units.

2.1.1.2 Typical values - illustrating examples

It is generally helpful to remember typical values and illustrating examples to get an idea of the scale and magnitude of things. They are usually found in well-known situations and applications. For the discussion here, the human body, cars, household appliances and power plants were chosen.

An example familiar to everybody is the human body, and with respect to energy its metabolism and nutrition. In this field, the Calorie (a non-SI unit) is still widely used as unit for an energy quantity. The Calorie (from the Latin word Calor = heat) is defined as the energy needed to heat 1 g of water from 14.5 °C to 15.5 °C; for 1 kg of water consequently 1 kcal is necessary, which in SI units is 4.187 kJ. The human metabolism has a basic energy need per day of about 1500 kcal, approximately equal to 6000 kJ; this corresponds to an average power of 250 kJ/h, which is about 70 W. When sleeping, the metabolic rate is equal to this basic energy need. When being active, the energy need rises above the basic need. When doing hard work or sports activities, the metabolic rate can rise to about 1000 W (about 13 times the basic need!) for an hour or so, with about ¼ and thus 250 W of mechanical work and the rest as heat (which is removed largely by sweating). The daily energy need reflects that a day includes time for sleeping as well as of different activity levels: when doing light activities it is in the order of 2000 kcal or about 8000 kJ, when doing hard work it is in the order of 3500 kcal or about 14000 kJ (more than 2 times the base energy need).

Cars are another common example of everyday life. The power of a car engine was for a long time given in the unit **horsepower**, **hp**. This unit was introduced in the 18th century to compare the power of the newly developed steam engines to the well-known draft power of horses, as familiar example at that time. Due to its success, it came in use also for other types of machines developed later, for example for the combustion engines used in cars.

The metric definition of 1 hp is the power needed to lift 75 kg, as average weight of a person, by 1 m in 1 s. Then, 1 hp = 750 W (section 2.1.2.1 has the whole calculation) is about three times the mechanical power of a hard working man. The power of car engines today is often larger than 100 hp, meaning larger than 75 kW, and thus corresponds to the power of about 300 hard working people! What about energy consumption? Gasoline has an energy content of about 33000 kJ/l (Diekmann and Heinloth 1997), which is about 8000 kcal/l. A car consuming just 1 l of gasoline consumes thus the daily energy need of 4 people doing light work, or about that of a family with kids! This shows the connection of the availability of food and biofuels if produced from food sources.

Even thought this book is on energy, and climate change and environmental pollution are not even side topics, one illustrating example in that area should not be omitted because of its significance. For lakes and rivers, everybody can imagine to some extent what a spill of 1 liter of gasoline or something similar looks like. For the atmosphere, this is not the case as it is a gas and extends to a height of more than 10 km. To help imagination it is suitable to picture the air in the atmosphere as condensed to a liquid. The atmospheric pressure at the earth surface is about 10^5 Pa = 10000 kg/m^2, meaning 10000 kg of air are on top of every m^2 of surface. As liquid air has a density of 870 kg/m^3 (water has a density of 1000 kg/m^3) the corresponding lake of liquid air covering the earth surface, maybe better called ocean, would only be about 11.5 m deep (for water 10 m). This is well within human imagination. When consuming 1 liter of gasoline, for example by driving a car, that liter of gasoline ends up there. And the same for the combustion of coal …, and not only by personal use, but also in power plants ….

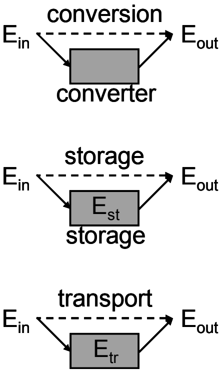
Household appliances, like hair dryers or vacuum cleaners, are other well-known examples. Both have a power typically in the range from 1500 W to 2000 W. This is the power of two horses or six people doing hard work; far less than a car, but still quite impressive for such small devices. More impressive is the case of domestic hot water. A fully opened tap can deliver up to 10 l/min. If the water leaves at 45 °C, while entering the house at 15 °C, its temperature is raised by 30 °C. For this, according to the definition of the Calorie, 30 kcal per kg of water or 30 · 4.2 kJ = 126 kJ are necessary. The corresponding power to get the 10 l/min using that 1l of water weights 1 kg is then 1260 kJ/min = 21 kW. This is equal to the mechanical power of 84 hard working people or 28 horses!

2.2 Types of processes and their characteristics

2.2.1 Types of processes

Energy enters the energy system from different natural sources as primary energy, and finally leaves as useful energy in a different energy form, at a different time, and at a different location (Fig. 1-1). Therefore, processes of energy conversion, storage, and transport are necessary on the way.

Each of these tree types of processes (Fig. 2-7) has energy as input (subscript in) and as output (subscript out); otherwise, they are fundamentally different, and in their pure form complementary. A process of **energy conversion** is characterized by a change of the energy form between input and output, a process of **energy storage** by a change of time between input and output, and a process of **energy transport** by a change of space / location between input and output.



energy		**affecting**
conversion	→	energy form
storage	→	time
transport	→	space / location

Fig. 2-7 Basic types of processes: conversion, storage, and transport

In successive processes, the output of one process is the input of the next process. The three basic process types are the building blocs for any device, machine, plant etc., and finally for the whole energy system, where the initial input is primary energy, and the final output useful energy.

3 Energy conversion

This chapter is the first of three chapters that describe the three basic types of processes: energy conversion, energy storage, and energy transport.

Energy conversion changes energy of one energy form to another energy form. In the energy system, energy conversion is used to balance between supply and demand, such that supplies of other energy forms can satisfy the demand of one energy form. Without energy conversion, the demand for an energy form could only be satisfied if enough supply of the same energy form is available. For example, as the sun is the only natural source of light, without conversion there would be no other way of lighting. Ideally, energy conversion allows the use of any energy form at the supply side.

The chapter begins with necessary basics, followed by the description of the technologies. The description of the technologies of energy conversion starts with processes having a single step of conversion, as they are common in materials and many components. Following are processes with multiple steps, typical for devices, machines, and power plants.

3.1 Basics

Conversion, realized in devices called **converter**, means that something is changed to something else. Conversion is usually with focus on a single aspect, but additional changes in other aspects (desired or not) are common. Energy conversion focuses on the energy form (Fig. 2-7). Ideally, the amount of energy E_{out} is as large as possible.

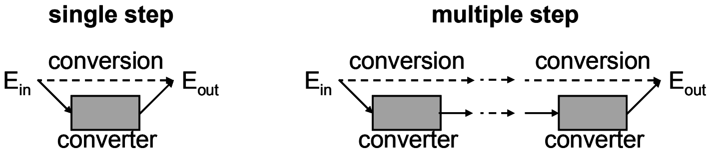


Fig. 3-1 Energy conversion schematic – single and multiple step conversion

As Fig. 3-1 shows, energy conversion can be in a single step or in multiple steps when several conversion processes are connected in series. Conversion in a single step is common in materials and many components, while conversion in multiple steps is typical for devices, machines and power plants.

The different energy forms allow a large number of options for conversion. Some of the energy forms in addition have internal conversion options, like for mechanical energy there is a conversion option between gravitational and kinetic energy or vice versa; some of them have also no conversion option, for example, there is no energy conversion process with nuclear energy as output.

It is not possible and not necessary regarding the scope of this book to discuss all possible conversion options. The following sections discuss selected examples that are important and common in the energy system.

3.2 Technology – single step: materials and components

The discussion starts with single steps of energy conversion as they naturally have the lowest level of complexity. They are common in materials and components; only in rare cases, engines are based on a single step. In addition, single steps of conversion are naturally directly connected to the physical and chemical basis of the energy forms, as discussed in section 2.1.2.; in fact, this is where it becomes clear how energy is converted on the microscopic level. For this reason, the discussion includes the basic physical and chemical effects leading to the conversion between energy forms.

Some options of single step conversion between different energy forms, which are important and common in the energy system, are listed in Tab. 3-1. The energy form of E_{in} is varied from the right to the left covering all energy forms as discussed in section 2.1.2 (Tab. 2-1); the energy form of E_{out} is varied from top down. The diagonal positions show options with $E_{in} = E_{out}$ and thus of conversion within an energy form; the conversion then refers to another aspect, for example force, distance, or temperature.

The text is structured starting with the basic possibilities to convert mechanical energy, following what is necessary to build all types of thermal / heat engines. After this, the processes to convert between electrical energy and other energy forms are discussed. They are followed by processes involving light.

Tab. 3-1 Options for energy conversion from E_{in} to E_{out}: single steps, common in materials and components (brackets: options not used)

E_{in}								
nuclear	**chemical**	**electro-magnetical (incl. light)**	**magnetical**	**electrical**	**mechanical**	**thermal**		
nuclear decay	combustion	solar thermal abs.	-	resistance heater, (Peltier effect)	friction	heat exchanger	**thermal**	E_{out}
-	-	-	-	(piezoelectric effect)	piston, turbine gear, …	thermal expansion	**mechanical**	
-	el.-chem. react., fuel cell, battery	photovoltaic effect / cell	induction coil	el. transformer	(piezoelectric effect)	(Seebeck effect)	**electrical**	
-	-	-	-	el. magnet	-	-	**magnetical**	
-	-	-	-	LED	-	thermal emission	**electro-magnetical (incl. light)**	
-	-	(photosynthesis)	-	electrolysis	-	thermo-chem. process	**chemical**	
-	-	-	-	-	-	-	**nuclear**	

3.2.11 Chemical energy ↔ electrical energy

Changes in chemical energy are due to chemical processes, and electrical energy is connected to electrical charges. Redox reactions (section 2.1.2.2) involve a transfer of electrons, and are thus basically suitable for the conversion between chemical and electrical energy. In ordinary redox reactions, oxidation and reduction occur together such that the transfer of electrons is directly between the reacting atoms and molecules; when the substances react with each other directly, the electrical energy cannot be used. In **electrochemistry**, redox reactions are separated. To achieve this, the different charges are forced to use different paths (Fig. 3-9): an ion conductor, also called **electrolyte**, is used for the transport of ions and an electron conductor, in the form of **electrodes** and wires, for the transfer of the electrons. The electrochemical reaction occurs at the interface between the electrodes and the electrolyte, exchanging ions with the electrolyte and electrons with the electrodes. For the electrochemical reaction to proceed, a source or a sink for electrical energy must complete the electrical circuit.

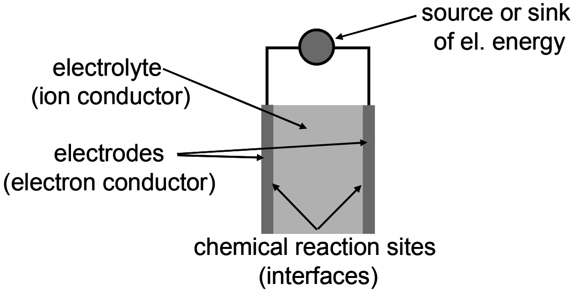


Fig. 3-9 General approach for electrochemistry

If the electrical current is the cause for the electrochemical reaction, the circuit must be closed by a source for electrical energy. The result is a conversion from electrical energy to chemical energy. This is realized in electrolysis. If the electrochemical reaction is the source of the electrical current, the circuit is closed by a sink. The result is a conversion from chemical energy to electrical energy. This is realized in a fuel cell or battery. A fuel cell is thus doing the reverse process of electrolysis, in a continuous process. In a battery the process is not continuous, as it is limited by the amount of reactants; it is thus a storage technology (section 4.3.3.3).

Electrolysis and electrolytic cell

In **electrolysis**, a continuous electric current drives a non-spontaneous chemical reaction, thereby converting electrical energy to chemical energy. Depending on the kind of reaction a minimum voltage, called the decomposition potential, is needed for electrolysis to occur. Fig. 3-10 shows an **electrolytic cell**, the device used for electrolysis, with the electrolysis of water as example. The water also acts as the electrolyte.

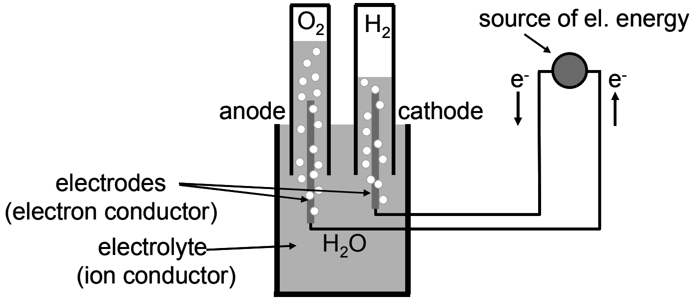


Fig. 3-10 Electrolysis in an electrolytic cell - example H_2O

The reactions occurring on the electrodes are

anode (oxidation): $H_2O \rightarrow ½O_2(g) + 2H^+ + 2e^-$

cathode (reduction): $2H_2O + 2e^- \rightarrow H_2(g) + 2OH^-$

After cancelling out H_2O and e^- on each side results

overall (redox reaction): $H_2O \rightarrow ½O_2(g) + H_2(g)$

Overall, the electric current leads to the decomposition of water to hydrogen and oxygen, which means electrical energy is converted to chemical energy. The gaseous O_2 and H_2 can be collected at the surface.

Applications of electrolysis are for getting pure materials for example copper (non-energetic use), fuels like H_2 (energy carriers) …

Fuel cell

A **fuel cell** is a device that converts chemical energy to electrical energy in a continuous process, thus doing the reverse process of electrolysis. There are many types of fuel cells, usually classified by the type of electrolyte; examples are the solid oxide fuel cell (SOFC) and the polymer electrolyte membrane (PEM) fuel cell.

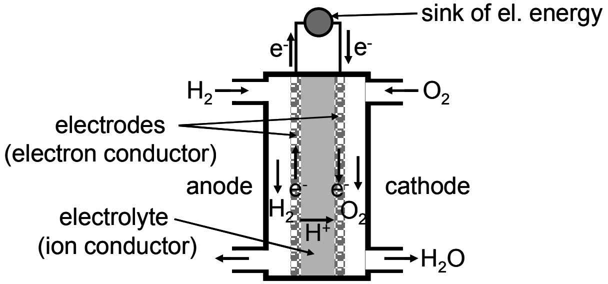


Fig. 3-11 Fuel cell – example of a fuel cell oxidizing hydrogen with a proton conducting electrolyte

Fig. 3-11 shows a fuel cell with the oxidation of hydrogen as example and a proton-conducting electrolyte. The reactions occurring on the electrodes are

anode (oxidation): $H_2 \rightarrow 2H^+ + 2e^-$

cathode (reduction): $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

After cancelling out H^+ and e^- on each side results

overall (redox reaction): $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Overall, the oxidation of hydrogen by oxygen to water leads to an electric current, which means chemical energy is converted to electrical energy. The reaction discussed as example is the reverse of the reaction used as example in electrolysis.

The efficiency of fuel cells is defined as the ratio of the output energy, which is electrical energy, to the input energy, which is the chemical energy in the fuel. The maximum theoretical energy efficiency of fuel cells is above 80%; however, what is typically achieved is between 40% and 60%.

Applications of fuel cells are increasing, mainly because they deliver electric energy while their fuel stores energy as chemical energy with high storage density. In addition, they do not produce any unwanted gases, fumes, noise etc. They were applied by the NASA in its space program, and more recently in submarines, cars, and power generation for the electrical grid.

4 Energy storage

This chapter is the second of three chapters that describe the three basic types of processes: energy conversion, energy storage, and energy transport; it discusses energy storage as a technology applied in the energy system.

Energy storage shifts energy in time, such that energy available at one time can be used at a later time. In the energy system, energy storage is used to balance between variable energy supplies and / or variable demands. Without energy storage, the supply of useful energy would have to meet the demand at any time, or the demand would have to be adjusted to the availability of useful energy.

The chapter begins with some necessary basics, followed by the description of the different technologies. The description of the technologies of energy storage starts with options for direct storage of the different energy forms, followed by options for indirect storage.

4.1 Basics

Storage in general means keeping something for some time for using it later. The device used for storage is called the **storage**.

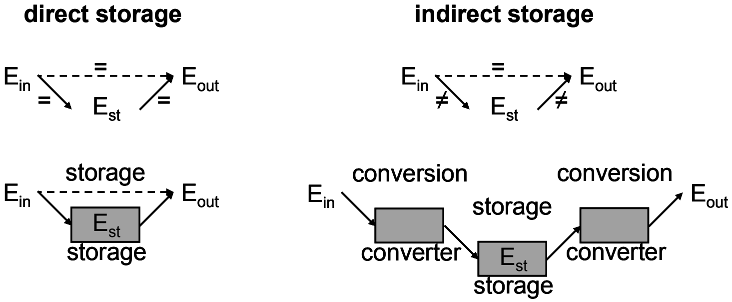


Fig. 4-1 Energy storage schematic – direct and indirect

Energy storage, **ES**, means keeping energy for some time to use it later. In the simplest case, this is without any change in the energy form, quantity, and quality; changes during storage are however common. Changes of the energy form are referred to by the terms direct / indirect storage (Fig. 4-1).

Changes of the energy quantity are due to losses and gains, which means a decrease / increase of the amount of energy from E_{in} to E_{out}, described by the storage efficiency.

Energy storage shifts energy in time, such that energy available at one time can be used later. In the description of a storage process, different times are distinguished for **charge**, **storage**, and **discharge** (Fig. 4-2).

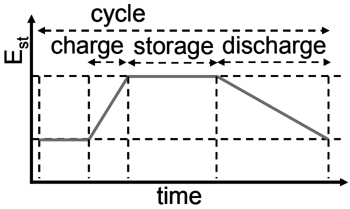


Fig. 4-2 Charge, storage, and discharge time - schematically

The term capacity (section 2.2.2) in the field of storage means the ability to hold or contain something for storage. It is used in different areas. In general, the **storage capacity** refers to the amount that can be stored in a storage. Often a specific storage capacity is used, giving the storage capacity per volume, weight, cost etc.

When energy is stored, losses and gains can occur during storage, as well as during charge and discharge.

For giving an overview or when making a comparison of different storage technologies, it is convenient to neglect losses and assume constant power at charging / discharging. Then, from energy conservation follows that

$$\text{storage capacity} = \text{ch./disch. power} \cdot \text{ch./disch. time} \;. \qquad \textbf{Eq. 4-1}$$

Eq. 4-1 is the basis for different diagrams. It can be used directly for diagrams showing the storage capacity versus ch. / disch. power (Fig. 4-3, left), and the same way versus time. For diagrams showing ch. / disch. time versus ch. / disch. power a logarithmic scale on both axis leads to lines of constant storage capacity (Fig. 4-3, right); diagrams showing ch. / disch. time versus ch. / disch. power are useful to understand the effect of an energy storage or in general a technology in an energy grid with respect to buffering supply or demand fluctuations; an example shows Fig. 6-6.

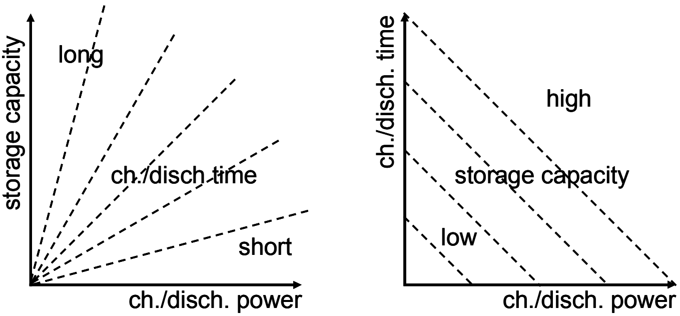


Fig. 4-3 Diagrams used for an overview or a comparison of different storage technologies

The nomenclature used in energy storage is often confusing and therefore explained here briefly. From the point of view of the energy system, E_{in} and E_{out} are the most important as they are what comes from the energy supply and what goes towards a demand. In addition, the energy form in the storage E_{st} is important, and can be the same or different.

- If the energy is stored in the same form as it comes in and goes out without any conversion, $E_{st} = E_{in} = E_{out}$ (Fig. 4-1, left); the energy is stored directly and the storage is called a **direct energy storage**. A special and important case of direct storage is when an energy carrier, like uranium, oil, coal, gas, or gasoline is stored directly in a storage, such that the energy transfer in and out of the storage is by transferring a certain mass of the energy carrier. The storage is then just a container.
- If the energy is stored in a different form as it comes in and goes out due to conversion, $E_{st} \neq E_{in} = E_{out}$ (Fig. 4-1, right); the energy is stored indirectly and the storage is called an **indirect energy storage**. Choosing an energy form for E_{st} that is different from the energy form of E_{in} and E_{out} allows having additional options. First, it allows storing energy forms that cannot be stored themselves, for example light. Second, it allows choosing a more suitable energy form, for example to increase the storage density, increase the availability of storage capacity, increase charge and discharge power respectively decrease the necessary times, and decrease the storage cost.

Tab. 4-1 Options for energy storage with $E_{in} = E_{out}$ by storing energy as E_{st} (diagonal elements = direct storage)

		E_{st}						
		thermal	**mechanical**	**electrical**	**magnetical**	**electro-magnetical (incl. light)**	**chemical**	**nuclear**
$E_{in} = E_{out}$	**thermal**	heating of solids or liquids, melting	-	-	-	-	thermo.-chem. processes	-
	mechanical	-	flywheel, weight, spring	-	-	-	-	-
	electrical	ETES, DESC	flywheel, pumped hydro, CAES	capacitor	induction coil	-	el.-chem. reaction, battery	-
	magnetical	-	-	-	-	-	-	-
	electro-magnetical (incl. light)	-	-	-	-	-	fluorescence	-
	chemical	-	-	-	-	-	chem. fuels rev. chem. reactions	-
	nuclear	-	-	-	-	-	-	nuclear fuel

4.3.3.1 Storage of electrical energy as mechanical energy

Kinetic energy in a flywheel

A way to store electrical energy indirectly is by storing it in form of mechanical energy as kinetic energy. The corresponding device is the **flywheel electrical energy storage (flywheel EES)**; often, the "electrical" is omitted.

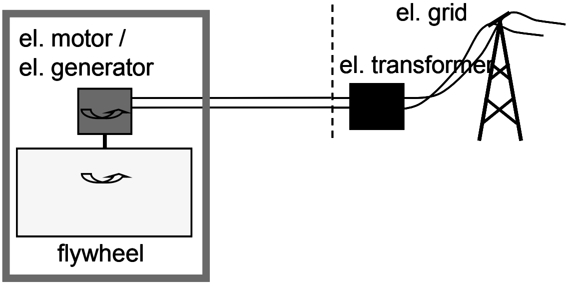


Fig. 4-6 Flywheel EES - schematic

The basic concept shows Fig. 4-6. The whole process involves three steps (Fig. 4-1, right):

1. Conversion: E_{in} = electrical energy is converted to mechanical energy of rotation by an electric motor (see section 3.3.2) to increase the speed of the flywheel
2. Storage: E_{st} = mechanical energy of rotation is stored by the flywheel
3. Conversion: E_{out} = electrical energy is regained by conversion of the stored mechanical energy by an electric generator (see section 3.3.2)

Electric motor and generator can be a single device. For transport, the electric energy is transformed to the appropriate voltage (section 3.3.3) and supplied to the electrical grid (section 6.3.5, Fig. 6-5).

Storage of electrical energy with flywheels is limited by the centrifugal forces (up to 50000 rpm) to small systems. According to IEC 2011, flywheels have an energy density of 5 - 30 Wh/kg or of 20 – 80 Wh/l, and a power density of 5000 W/l. They have a response time of less than a second, and discharge also in seconds. Their energy efficiency is 80 – 90 %

(drawback is the high level of self-discharge due to friction losses). Typical lifetime is 15 – 20 years, with a cycle lifetime of more than 20000 cycles.

Application of flywheel EES is for power quality (Fig. 6-6) in industry.

Potential energy in pumped hydro

Another option to store electrical energy indirectly by storing it in form of mechanical energy is as gravitational energy. The most common way in the electricity grid is by pumping water from a low-lying to a high lying reservoir, giving it the name pumped hydro (PH) ES. This shows Fig. 4-7.

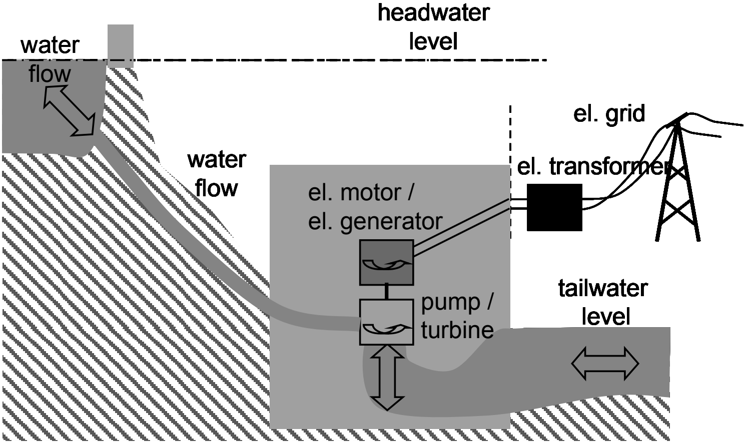


Fig. 4-7 Pumped hydro ES - schematic

The whole process involves three steps (Fig. 4-1, right):

1. Conversion: E_{in} = electrical energy is converted to gravitational energy by pumping water from a low lying to a high lying reservoir. This is done by an el. motor (section 3.3.2) driving a pump (section 3.2.1).

2. Storage: E_{st} = gravitational energy is stored as water in the high lying reservoir

3. Conversion: E_{out} = electrical energy is regained by conversion of the stored gravitational energy; for this, the water from the high lying reservoir runs down through a turbine (section 3.2.1) driving an el. generator (section 3.3.2)

Electric motor and generator as well as pump and turbine are usually a single device that can be operated both ways. The last step is like on a river power plant (Fig. 3-28). For transport, the electric energy is transformed to the appropriate voltage (section 3.3.3) and supplied to the electrical grid (section 6.3.5, Fig. 6-5).

As an example, 1 kg of water, equivalent to about 1 l, lifted by 100 m has a gravitational energy (Eq. 2-8) of 1 kg · 10 N/kg · 100 m = 1000 Nm = 1 kJ. This is, according to section 2.1.1.1, equal to 0.272 Wh or about 0.234 kcal. This amount of energy is sufficient to run a hair dryer for about 0.01 min, or to raise the temperature of the same 1 kg of water by 0.234 °C.

According to IEC 2011, pumped hydro ES has an energy density of 0.2 – 2 Wh/kg or of 0.2 – 2 Wh/l, and a power density of 0.1 - 0.2 W/l. The response time is in the order of minutes and a typical discharge time in the order of hours to days. The energy efficiency is 70 – 80 %. Typical lifetime is larger than 50 years, with a cycle lifetime larger than 15000 cycles. The approach of storing electrical energy this way depends on a suitable geographic location with large reservoirs and / or large height differences, but is of comparatively low cost. Reservoirs can be natural (stream, lake …) or artificial.

Application of pumped hydro ES is for time shifting (Fig. 6-6), power quality, and emergency supply reserve. For load balancing of the electrical grid (Fig. 6-6), low-cost electric energy available in times where supply exceeds the demand is used to run the pumps and thereby store energy; when the demand exceeds the supply, especially during high-peak demand, the electrical energy is regained and sold as high-price electrical energy. The difference in price between charging and discharging offsets the energy losses due to the charging and discharging process. According to IEC 2011, the worldwide power of pumped hydro ES is about 120 GW, which is 99 % of the power of electrical energy storage, and about 2 to 3 % of the power of electricity generation.

Compression energy in compressed air storage

Another way to store electrical energy indirectly by storing it in form of mechanical energy is as compression energy. It is realized by compressing air, giving it the name **Compressed Air Energy Storage**, **CAES**. A possible design for CAES shows Fig. 4-8.

5 Energy transport

This chapter is the third of three chapters that describe the three basic types of processes: energy conversion, energy storage, and energy transport; it discusses energy transport as a technology applied in the energy system.

Energy transport moves energy in space, such that energy generated at one location can be used at another location. In the energy system, energy transport is used to balance between supply and demand of energy at different locations. Without energy transport, the supply of energy would have to meet the demand at any place, everywhere in the energy system.

The chapter begins with an introduction into basics of energy transport, followed by the description of the technologies. The description of the technologies of energy transport starts with options for direct transport of different energy forms, followed by options for indirect transport.

5.1 Basics

Transport in general means moving something in space, from one location to another location. It is complementary to conversion and storage, as discussed in section 2.2, Fig. 2-7.

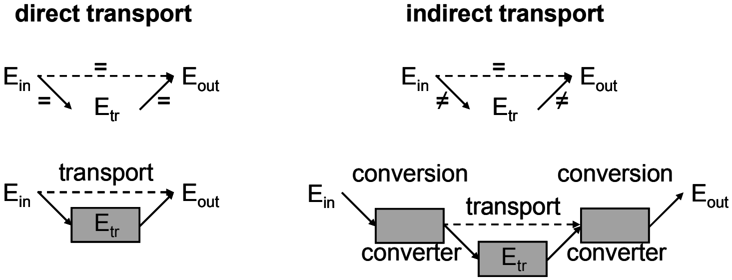


Fig. 5-1 Energy transport schematic – direct and indirect

Regarding energy, a process of transport refers to the transport of an amount of energy of an energy form. Thus, **energy transport** moves energy in space, such that energy of an energy form generated at one location can be used at another location. In the energy system, energy transport is used to balance between supply and demand of energy at different locations.

While energy storage allows a balance in time, including the storage in fuels, energy transport does the same in space, also including transport of fuels. Fuels like coal, oil, and gas contain chemical energy, and nuclear fuels nuclear energy. Fuel transport inevitably is connected to mass transport, the mass of the fuels. Mass transport is also the basis of energy transport when thermal energy is transported by pumping hot or cold water. The efficiency of energy transport is then also affected by losses through mass loss, and by the energetic effort to transport the connected mass.

Like in energy storage, which can be direct or indirect, there is also **direct energy transport** and indirect energy transport (Fig. 5-1). In **indirect energy transport**, the energy to be transported E_{in} is converted to another energy form E_{tr}, which is transported, and after transport it is converted back to the initial energy form $E_{out} = E_{in}$. Choosing a different energy form allows having additional options. Regarding the characteristics of transport processes (section 2.2.2, Tab. 2-3), indirect transport often allows choosing a more suitable energy form, for example to increase the transport distance, the transport capacity, or decrease the cost. By indirect energy transport it is for example possible to avoid mass transport, like when thermal energy is not transported in hot water but indirectly as electrical energy.

The description of processes of energy transport is mainly by the energy form of $E_{in} = E_{out}$, and the energy form E_{tr} in case of indirect transport. The following discussion is therefore structured this way, like before the discussion on energy storage. Technical information given includes the transport distance, the efficiency, and the transport capacity meaning the power.

5.2 Technology – direct energy transport

Tab. 5-1 shows options for energy transport with $E_{in} = E_{out}$ by transport of energy as E_{tr}. The diagonal elements have $E_{tr} = E_{in} = E_{out}$ and thus are options of direct transport.

Again, as was the case in the discussion of energy storage, only for direct transport the physical and chemical details are discussed; for indirect transport the transport basics are then known, and the additional conversion steps have already been discussed before.

Tab. 5-1 Options for energy transport with $E_{in} = E_{out}$ by transport of energy as E_{tr} (diagonal elements = direct transport)

		E_{tr}						
		thermal	**mechanical**	**electrical**	**magnetical**	**electro-magnetical (incl. light)**	**chemical**	**nuclear**
$E_{in} = E_{out}$	**thermal**	hot/cold water, air, steam …	-	in el. grid	-	-	-	-
	mechanical	-	rod, belt, chain …	in el. grid	-	-	-	-
	electrical	-	-	el. power lines	-	-	power to gas/liquid to power	-
	magnetical	-	-	-	-	-	-	-
	electro-magnetical (incl. light)	-	-	in el. grid	-	light guides	-	-
	chemical	-	-	in el. grid	-	-	transport of chem. fuels in pipes …	-
	nuclear	-	-	-	-	-	-	transport of nuc. fuels by trucks …

Application of pipelines, tanks, and open vessels, depend on the type of energy carrier and the connection between supply and demand. When transport is not between fixed points, tanks and vessels on trucks for road transport must be used. Medium distance transport can also be by train or on ships for transport on rivers. When transport of liquids and gases is between fixed points, medium distance transport can be by pipelines, and long distance transport is preferably by pipelines (often having own names due to their importance, like Alaska pipeline …). Across large bodies of water like the oceans, large parts of long-distance transport are today by ship; this holds for all types of energy carriers: coal, oil, and gas. Gas is often liquefied in the harbor of origin for transport and must be gasified again in the harbor of destination; in that case, the efficiency is considerable reduced by the effort for liquefication.

5.2.7 Nuclear energy

The only means of transport of nuclear energy is by transport of the nuclear fuels, and therefore in many ways comparable to the transport of solid chemical energy carriers. The masses that have to be transported are however much smaller, due to the much higher storage density (section 4.2.7). Another difference is the necessary safety measures.

The transport of nuclear fuels is world wide, from few sources of raw materials to the facilities for refinery, and finally to the nuclear power plants.

5.3 Technology – indirect energy transport

Options for energy transport with $E_{in} = E_{out}$ as indirect transport, meaning that the form of the energy being transported E_{tr} is a different one $E_{tr} \neq E_{in} = E_{out}$, are shown as non-diagonal elements in Tab. 5-1.

5.3.1 Thermal energy

The direct transport of thermal energy (section 5.2.1) in the energy system is based on the direct storage of thermal energy in a medium and the transport of that medium. This is accompanied by heat losses, energetic effort for moving the respective mass, and the cost for the infrastructure for pipes or similar. As a result, the maximum distance for transport of thermal energy in district heating and cooling networks is about 40 km. Options for indirect transport try to avoid these negative aspects.

5.3.1.1 Transport of thermal energy as chemical energy

A promising approach for the indirect transport of thermal energy is as chemical energy. The respective section 4.3.1.2 on indirect storage of thermal energy already gives an idea how this can be done: by thermochemical reactions. Thermochemical reactions are used for conversion $E_{in} \rightarrow E_{tr}$, result in a form E_{tr} that is suitable for transport, and finally for back conversion $E_{tr} \rightarrow E_{out}$. The whole process involves three steps (Fig. 5-1, right):

1. Conversion: E_{in} = thermal energy is converted to chemical energy by a thermochemical process, thereby chemically modifying a substance
2. Transport: E_{st} = chemical energy is transported in the chemically modified substance
3. Conversion: E_{out} = thermal energy is regained by a thermochemical process bringing the substance back to its original chemical state

The reaction $CH_4 + H_2O + \Delta Q \leftrightarrow CO + 3H_2$ was aready mentioned as an example of a thermochemical reaction (Fricke and Borst 2013) for storage of thermal energy (section 4.3.1.2). Because of the gas phase, it is actually more suitable for transport than for storage. The reaction proceeds at several 100°C, and was investigated as an option to convert high temperature waste heat from nuclear reactors to chemical energy, which can later be used to generate heat again, but also for other purposes. Another option is the thermo-chemical reaction $H_2O + \Delta Q \leftrightarrow H_2 + ½O_2$; the thermal splitting (decomposition) of water for storage or transport of energy as H_2 (while O_2 is in the air), and finally use in combustion. There are also thermochemical processes that are not reactions: sorption processes based on a liquid salt-water solution or porous solids like zeolite can store chemical energy when water is desorbed, and release it when it is absorbed. The water poor solution can be transported in pipes, the water poor solid in tanks.

Application of this option for indirect transport of thermal energy in the energy system is still in the state of research. Only the transport of thermal energy by trucks carrying dried zeolite is tested on a prototype scale.

5.3.1.2 Transport of thermal energy as electrical energy

Thermal energy is still the main energy form that is used to get electrical energy, using different conversion processes based on thermal engines combined with electric generators. They are used in coal, oil, gas, biomass, geothermal, and solar thermal power plants (section 3.4). Also, quite a fraction of the electrical energy is converted to thermal energy for use. This can be by electrical resistance heating, often used in the industry, or more efficient using an electrically driven heat pump (section 3.3.1, an electric engine combined with a mechanical heat pump) in residential buildings. The process of transport can then be described by three main steps (Fig. 5-1, right):

1. Conversion: E_{in} = thermal energy is converted to mechanical, and then to electrical energy. This is done by a thermal engine combined with an electric generator.
2. Transport: E_{st} = electrical energy is transported. This includes transformation of current and voltage by a transformer
3. Conversion: E_{out} = thermal energy is regained. This is done by an electric engine running a heat pump, electric resistance heater …

Fig. 5-6 shows the process schematically with a heat pump. Passing through an intermediate step of mechanical energy, thermal energy is thus transported by the electricity grid as electrical energy on a large scale.

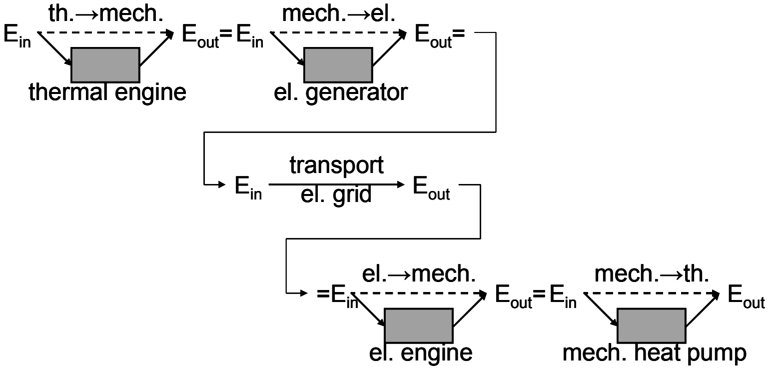


Fig. 5-6 Indirect transport of thermal energy by electrical energy

Of course there is no strict connection; thermal energy entering the process series is not necessarily exiting as thermal energy, because in the electric grid everything is mixed (section 6.3.5, Fig. 6-5). Nevertheless, it happens and shows up as a significant part in the energy balance of the electric grid.

6 The energy system as a network of technologies

This chapter concludes the discussion of the different technologies in previous chapters by showing how they form the energy system as a network of technologies.

In the previous chapters, the technologies of energy conversion, energy storage, and energy transport were discussed separately and in their pure form. In the energy system, they are combined to supply energy to the user in the desired energy form, and at the desired time and location. For this, suitable technologies must be selected such that they work together, installed correspondingly, and must be coordinated in operation.

The chapter begins with basic considerations on energy networks. It then discusses the networks for thermal, electrical, chemical, and nuclear energy individually and also their connections. After a review of current problems, the chapter closes with options and trends for the future development.

6.1 Introduction

At the beginning (section 1.2), the energy “system” was so simple that it was actually not a real system. Mechanical work was performed and used by humans themselves (using up food), and light came from the sun and wooden fires, which also supplied heat. Conversion was only by combustion of wood, storage only in wood (not counting the food), and transport of wood not yet significant.

With the use of animals and simple machines, like the water wheel and the windmill, several additional sources for mechanical energy became available. At this stage, energy was still locally produced and used, such that the energy “system” consisted of many small systems. The focus was on energy conversion, with little storage (for example food for animals) and transport.

The invention of the steam engine allowed a much higher output of mechanical energy, with significant consequences. The generated mechanical energy was distributed on the scale of several meters by belts and rods to different user sites. In addition, local fuel supplies were insufficient and the supply of fuels from a far distance by transport became necessary. Further on, with the storage of the fuels like coal and later oil the storage of energy became common. With these changes, the energy system started to become a network of technologies, in other words a real “system”.

With the invention of the electric generator and electric engine, the transport of energy by electricity for long distances became possible. Initially, single plants to supply electricity were connected with different user sites. Later, more plants were successfully integrated, forming the electricity network. Today, the electricity network dominates the public and political discussion, even though the networks for thermal energy as heat and cold, and the networks for chemical and nuclear energy (fuels) are also of vital importance.

6.2 Basics

Today, the **energy system** is a network of technologies of energy conversion, energy storage, and energy transport, connecting primary energy sources with users using useful energy (Fig. 1-1).

As discussed in section 2.2.1, each process of energy conversion, storage, and transport, has an input and an output. Processes are connected by the output of one process being the input of another process. The technical terms for a point where something comes out / goes in are **source / sink**. The terms **supply / demand** (side) refer to the location where something useful, here energy, originates / where it is needed, as well as to the amounts and amounts per time (for example a supply / demand of 10 kWh/day). The terms **generation / consumption** describe the act of producing (making) / using (consuming). Corresponding to them are the terms **generator / consumer**, or more common **producer / user**, which are the entities (persons, companies …) of generation / consumption.

In connecting primary energy supplies with the users demand for useful energy, there are three general requirements in the energy system (Fig. 1-1). They refer to the balance between supply and demand

- regarding the energy form
- regarding the time
- regarding the location

The technologies for energy conversion, storage and transport (Fig. 2-7) are used in a way to meet these requirements for balance.

The balance in the energy system between supply and demand regarding the energy form, the time, and the location, is done the following way:

- The main purpose of a network is transport of an energy form;
- Between networks for different energy forms is where conversion between the energy forms happens
- Storage is within a network, as well as at its sources (primary energy, conversion output) and its sinks (conversion input and useful energy).

6.3.3 Networks - the energy system as a whole

Fig. 6-4 shows the energy system comprising several networks.

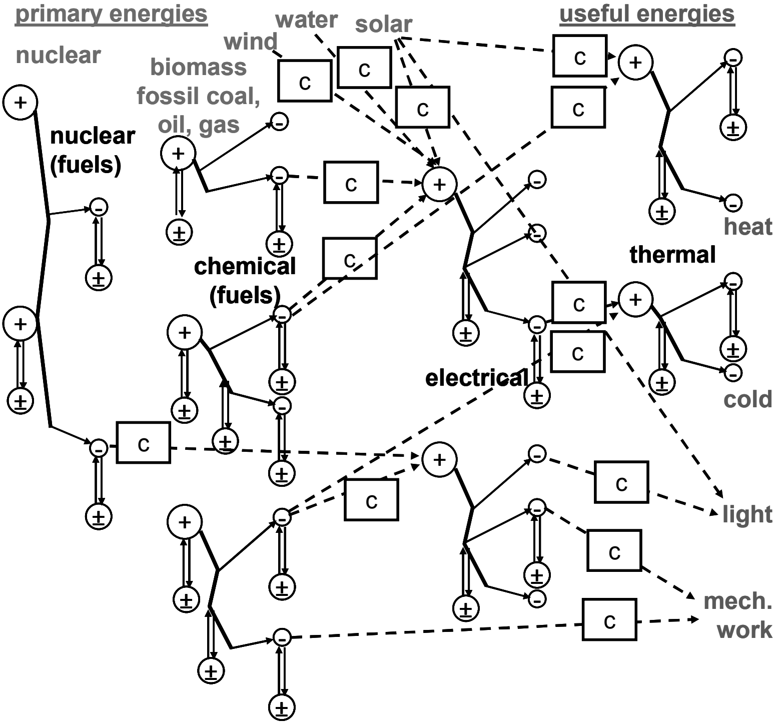


Fig. 6-4 Energy system, comprising several networks

The energy system, as a network of technologies of energy conversion, energy storage, and energy transport, connects primary energy sources with users using useful energy. Fig. 1-1 shows this qualitatively, Fig. 6-4 now with more detail, including the technologies in a schematic way.

The main networks used for energy transport are the networks for nuclear energy and chemical energy, which are as fuels connected to primary energy, and the networks for electrical energy and thermal energy, which are close to the user. Due to the advantages and disadvantages of the different technologies in energy conversion, storage, and especially transport (section 5.2 and 5.3), the networks for chemical and nuclear fuels cover the world, the networks for electrical energy cover regions up to nations (connected with neighbor networks from other regions …) and the networks for thermal energy cover buildings, districts, and towns individually. For mechanical energy, the networks are small, covering only machines and plants, such that they are not discussed here.

Conversion takes place between the transport networks for different energy forms. The biggest converters in the energy system are the different power plants, using nuclear, chemical, wind, water and solar energy to generate electrical energy. Somewhat smaller are the converters to generate thermal energy, like from solar energy by solar thermal absorbers, from chemical energy by combustion, and from electrical by electrical resistance heating or heat pumps.

Storage in the energy system is needed for for time shift to deal with common energy or power fluctuations (short term, called regulation, or long term regarding off-peak and on peak supply or demand), for reserve (reliability) to deal with unusual cases (like excess demand or plant failure), and in addition for power quality (stability) in the case of electricity (frequency and voltage). The need for storage thus comprises short to long-term storage, high to low power, and small to large storage capacity. Storage is within a network, as well as at its sources (primary energy, conversion input) and its sinks (conversion output and useful energy). Storage capacity close to a source includes fuel storage. Storage close to a sink is for example a storage for useful energy like domestic hot water storage. Storage in the transport network integrated is for example pumped hydro, and in addition, there is also storage in the facilities for transport, for example the gas and the hot water in the distribution pipes.

Electrical resistance heating (section 3.2.8) is widespread because of its simplicity. The efficiency of the device “electrical resistance heater”, which converts electrical energy to thermal energy, is 100 %. But to optimize the energy system it is of course necessary to look at the energy system as a whole and not just at an individual device. If the electricity is generated by a thermal power plant, converting thermal energy to get electrical energy, its conversion efficiency must be taken into account. The value depends on the type of technology used; for the discussion here it is assumed to be 40 %. The efficiency in the energy system from the thermal energy input to the power plant to the thermal energy output of the electrical resistance heater is then 40 % · 100 % = 40 %. This is not only a different result. Even more important is that by delivering the heat directly at the user site, for example by combustion of oil or gas, without the thermal power plant and the electrical resistance heater, 100 % is possible and thus much more. But there is also another option for heating: a heat pump. As discussed in section 3.3.1, for an electrical driven heat pump, the COP (efficiency) is the heat delivered divided by the input of electrical energy. Due to the use of a non-ideal process in common machines and losses, typically attained in reality is about 3 to 7. This is much better as the value of 1 (100%) for electrical resistance heating, however, it does not include the conversion efficiency to get the electrical energy (section 3.4). If this is also included, the range is about 1.2 (= 40% ·3) to 2.8 (= 40% ·7), much better than the other options. According to Dubbel 1997 the range is about 1.03 to 2.25, probably due to using a lower value for the efficiency of the thermal power plant. The results, summarized in Tab. 6-2, show how the efficiency of the conversion from heat to heat depends on which part of the energy system is analyzed and which technology is used.

Tab. 6-2 Device and system efficiency – comparison of different cases for a heating application, assuming a plant efficiency of 40 %

device	device efficiency	system (heat to heat)	system efficiency
el. resistance heater	100 %	thermal power plant + el. resistance heater	40 %
heat pump	300 % to 700 %	thermal power plant + el. heat pump	120 % to 280 %
direct heating	100 %	direct heating	100 %