

Figure 1.4: The different energy carriers and how we utilise them (Adapted from L. Freris and D. Infield, *Renewable Energy in Power Systems* (copyright John Wiley & Sons Inc, Chichester, United Kingdom, 2008))[12].

1.3 Methods of energy conversion

Figure 1.4 shows different energy sources and the ways we utilise them. We see that usually the chemical energy stored in fossil fuels is converted to usable forms of energy via heat by burning, with an efficiency of about 90%. Using heat engines, thermal energy can be converted into mechanical energy. Heat engines have a conversion efficiency of up to 60%. Their efficiency is ultimately limited by the Carnot efficiency limit that we will discuss in Chapter 10. The vast majority of the current cars and trucks works on this principle. Mechanical energy can be converted into electricity using electric generators with an efficiency of 90% or even higher. Most of the World's electricity is generated with *turbogenerators* that are connected to a steam turbine, where coal is the major energy source. This process is explained in more detail in our discussion on solar thermal electric power in Chapter 22. Along all the process steps of making electricity out of fossil fuels, at least 50% of the initial available chemical energy is lost in the various conversion steps.

Chemical energy can be directly converted into electricity using a fuel cell. The most common fuel used in fuel cell technology is hydrogen. Typical conversion efficiencies of fuel cells are 60%. A regenerative fuel cell can operate in both directions and also convert electrical energy into chemical energy. Such an operation is called *electrolysis*; typical conversion efficiencies for hydrogen electrolysis of 50-80% have been reported. We will discuss electrolysis in more detail in Chapter 23.

In *nuclear power plants*, energy is released as heat during *nuclear fission* reactions. With the heat steam is generated that drives a steam turbine and subsequently an electric generator just as in most fossil fuel power plants.

1.3.1 Renewable energy carriers

All the energy carriers discussed above are either fossil or nuclear fuels. They are not renewable because they are not "refilled" by nature, at least not in a useful amount of time. In contrast, *renewable energy carriers* are energy carriers that are replenished by natural processes at a rate comparable or faster than their rate of consumption by humans. Consequently, hydro-, wind- and solar energy are renewable energy sources.

Hydroelectricity is an example of an energy conversion technology that is not based on heat generated by fossil or nuclear fuels. The potential energy of rain falling in mountainous areas or elevated plateaus is converted into electrical energy via a *water turbine*. With *tidal pools* the potential energy stored in the tides can also be converted to mechanical energy and subsequently electricity. The kinetic energy of *wind* can be converted into mechanical energy using windmills.

Finally, the energy contained in sunlight, called *solar energy*, can be converted into electricity as well. If this energy is converted into electricity directly using devices based on semiconductor materials, we call it *photovoltaics* (PV). The term *photovoltaic* is derived from the greek word $\phi\omega\varsigma$ (phos), which means light, and -volt, which refers to electricity and is a reverence to the Italian physicist Alessandro Volta (1745-1827) who invented the battery. As we will see in this book, typical efficiencies of the most commercial *solar modules* are in the range of 15-20%.

The energy carried with sunlight can also be converted into heat. This application is called *solar thermal energy* and is discussed in detail in Chapter 22. Examples are the heating of water flowing through a black absorber material that is heated in the sunlight. This heat can be used for water heating, heating of buildings or even cooling. If concentrated solar power systems are used, temperatures of several hundreds of degrees are achieved; this is sufficient to generate steam and hence drive a steam turbine and a generator to produce electricity.

Next to generating heat and electricity, solar energy can be converted into chemical energy as well. This is what we refer to as *solar fuels*. For producing solar fuels, photovoltaics and regenerative fuel cells can be combined. In addition, sunlight can also be directly converted into fuels using photoelectrochemical devices. We will discuss solar fuels in Chapter 23.

We just have seen that solar energy can be converted into electricity, heat and chemical energy. The sun is the energy source for almost all the processes happening on the surface of our planet: wind is a result of temperature difference in the atmosphere induced by solar irradiation; waves are generated by the wind; clouds and rain are initially formed by the evaporation of water due to sun light. As the sun is the only real energy source we have, we need to move to an era in which we start to utilise the energy provided by the sun directly for satisfying our energy needs. The aim of this book is to teach the reader how solar energy can be utilised directly.

1.3.2 Electricity

As we see in Fig. 1.5 (a), 17% of all the World's final energy is used as electricity, which is a form of energy that can be easily and cheaply transported with relative small losses through an electric grid. It is important to realise that without electricity modern society as we know it would not be possible. Electricity has been practically used for more than 100 years now. It provides us the energy to cook food, wash, do the laundry, illuminate buildings and streets, and countless other applications. The access to electricity strongly determines our living standard. Despite this importance of electricity, in 2009 still about 1.3 billion people had no access to electricity.

As we see in 1.5 (b), about 67% of the electricity is generated using fossil fuels, where coal is the dominant contributor. As coal emits about twice as much CO₂ per generated

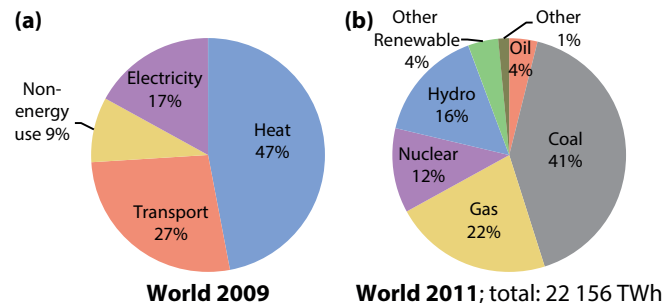


Figure 1.5: (a) The final energy consumption by energy service [13] and (b) the energy carriers used for electricity generation [14] (©OECD/IEA 2012, Insights Series 2012: Policies for renewable heat, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions).

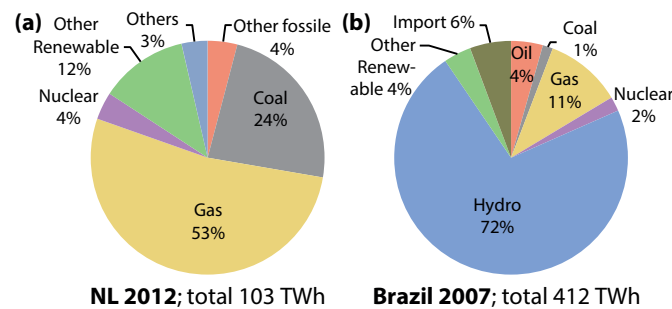


Figure 1.6: The energy mix used for electricity production in (a) the Netherlands [15] and (b) Brazil [16] (Data from Centraal Bureau voor de Statistiek (CBS; Statistics Netherlands) and used according to Creative Commons license: <https://creativecommons.org/licenses/by/3.0/nl>).

kWh as natural gas, coal power plants are a major contributor to global warming. Nuclear is responsible for 12% of the World's electricity generation. With 16%, hydroelectricity is by far the largest contributor among the renewable energy sources.

Of all the generated electricity, about 40% of the electric energy is used for residential purposes and 47% is used by industry. 13% is lost in transmission. In 2007, transport did not play a significant role in the electricity consumption. However, this is expected to change as electric cars are becoming more and more important.

Figure 1.6 shows which energy carriers are mainly used for electricity generation in the Netherlands and Brazil. We see that in the Netherlands, electricity generation heavily depends on the local gas resources, whereas in Brazil hydroelectricity is the most important resource.

1.4 Exercises

1.1 How many million joules (MJ) are equivalent to 2.5 kWh?

1.2 To get a feeling of the concepts of power and energy, let us look at the power and energy