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Energy

As this book is on *Solar Energy*, it is good to start the discussion with some general thoughts on *Energy*. We begin with a quote from *The Feynman Lectures on Physics* [1].

> There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.
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> Energy has a large number of *different forms*, and there is a formula for each one. These are: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy. If we total up the formulas for each of these contributions, it will not change except for energy going in and out.
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> It is important to realise that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, and when we add it all together it gives . . . always the same number. It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas.

1.1 Some definitions

We will now state some basic physical connections between the three very important physical quantities of *energy, force, and power*. These connections are taken from classical mechanics but are generally valid. We start with the *force* F, which is any influence on an object that changes its motion. According to Newton's *second law*, the force is related to the acceleration a of a body via

$$\mathbf{F} = m\mathbf{a}, \tag{1.1}$$

where m is the mass of the body. The bold characters denote that $\mathbf{F}$ and $\mathbf{a}$ are vectors. The unit of force is *newton* (N), named after Sir Isaac Newton (1642-1727). It is defined as the force required to accelerate the mass of 1 kg at an acceleration rate of 1 $\mathrm{m\,s^{-2}}$, hence 1 N = 1 $\mathrm{kg\,m\,s^{-2}}$.

Energy E, *the* central quantity of this book, is given as the product of F times the distance s,

$$E = \int F(s)\,\mathrm{d}s, \tag{1.2}$$

Energy is usually measured in the unit of *joule* (J), named after the English physicist James Prescott Joule (1818-1889). It is defined as the amount of energy required to apply the force of 1 Newton through the distance of 1 m, 1 J = 1 Nm.

Another important physical quantity is *power* P, which tells us the rate of doing work, or, which is equivalent, the amount of energy consumed per time unit. It is related to energy via

$$E = \int P(t)\,\mathrm{d}t, \tag{1.3}$$

where t denotes the time. P is usually measured in the unit of *watt* (W), after the Scottish engineer James Watt (1736-1819). 1 W is defined as one Joule per second, 1 W = 1 J/s and 1 J = 1 Ws.

As we will see later on, 1 J is a very small amount of energy compared to human energy consumption. Therefore, in the energy markets, such as the electricity market, often the unit *kilowatt hour* (kWh) is used. It is given as

$$1\,\mathrm{kWh} = 1000\,\mathrm{Wh} \times 3600\,\frac{\mathrm{s}}{\mathrm{h}} = 3\,600\,000\,\mathrm{Ws}. \tag{1.4}$$

On the other hand, the amounts of energy in solid state physics, the branch of physics that we will use to explain how solar cells work, are very small. Therefore, we will use the unit of *electron volt*, which is the energy a body with a charge of one elementary charge ($q = 1.602 \times 10^{-19}$ C)[1] gains or loses when it is moved across an electric potential difference of 1 volt (V),

$$1\,\mathrm{eV} = q \times 1\,\mathrm{V} = 1.602 \times 10^{-19}\,\mathrm{J}. \tag{1.5}$$

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[1] Often, the symbol e is used for the elementary charge. However, in order to not confuse the elementary charge with the Euler number, we use q, just as many others in the solar cell and semiconductor device communities.

1.2 Human energy consumption

After these somewhat abstract definitions we will look at the *human energy consumption*. The human body is at a constant temperature of about 37°C. It therefore contains *thermal energy*. As the body is continuously cooled by its surroundings, thermal energy is lost to the outside. Further, blood is pumped through the blood vessels. As it travels through the vessels, its *kinetic energy* is reduced because of internal friction and friction at the walls of the blood vessels, *i.e.* the kinetic energy is converted into heat. To keep the blood moving, the heart consumes energy. Also, if we want our body to move this consumes energy. Further, the human brain consumes a lot of energy. All of this energy has to be supplied to the body from the outside, in the form of food. An average body of a human adult male requires about 10 000 kJ every day.[2] We can easily show that this consumption corresponds to an average power of the human body of 115.7 W. We will come back to this value later.

In modern society, humans not only require energy to keep their body running but in fact consume energy for many different purposes. We use energy for heating the water in our houses and for heating our houses. If water is heated, its thermal energy increases, and this energy must be supplied from the outside. Further, we use a lot of energy for transportation of people and products by cars, trains, trucks and planes. We use energy to produce our goods and also to produce food. At the moment, you are consuming energy when you are reading this book on a computer or tablet. But also if you are reading it in a printed version, you implicitly consume the energy that was required to print it and to transport it to your place.

As mentioned above, energy is never produced but always converted from one form to another. The form of energy may change in time, but the total amount does not change. If we want to utilise energy to work for us, we usually convert it from one form to another more useable form. An example is the electric motor, in which we convert electrical energy to mechanical energy.

To measure the amount of energy humankind consumes, we refer to two concepts: first, *primary energy*, which 'is the energy embodied in natural resources prior to undergoing any human-made conversions or transformations. Examples of primary energy resources include coal, crude oil, sunlight, wind, running rivers, vegetation[3], and uranium' [2]. Humans do not directly use carriers of primary energy, but converted forms of energy, which are called *secondary energy* or *final energy*. Examples for secondary energy carriers are electricity, refined fuels such as gasoline or diesel, or also heat which is transported to the consumers via district heating.

Modern society is very much based on the capability of humankind to convert energy from one form to another form. The most prosperous and technologically developed nations are also the ones which have access to and are consuming the most energy per inhabitant. Table 1.1 shows the primary energy consumption per capita and the average power consumed per capita for several countries. We see that the average U.S. citizen uses an average power of 9 319 W, which is about 80 times what his body needs. In contrast, an average citizen from India only uses about 800 W, which is less then a tenth of the U.S. consumption.

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[2] The energy content of food usually is given in the old-fashioned unit of kilocalories (kcal). The conversion factor is 1 kcal = 4.184 kJ. An average adult male human requires about 2500 kcal a day.

[3] Or biomass *authors note*.

Table 1.1: Total primary energy consumption per capita and average power used per capita of some countries in 2011 [3].

Country	**Energy consumption** (kWh/capita)	**Average power use** (W/capita)
U.S.A.	81 642	9 319
Netherlands	53 963	6 160
China	23 608	2 695
Colombia	7 792	890
India	6 987	797
Kenya	5 582	637

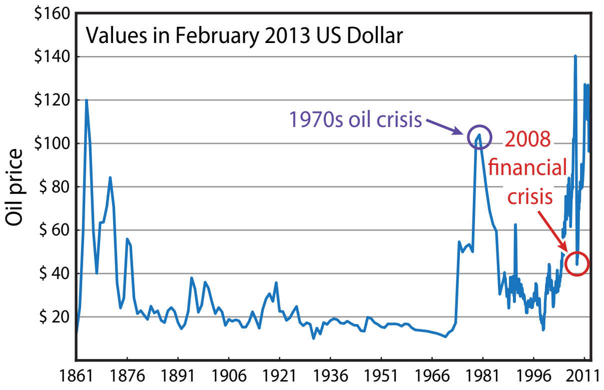

Figure 1.1: The history of the oil price per barrel normalised to the February 2013 value of the U.S. Dollar [4].

Many people believe that tackling the *energy problem* is amongst the biggest challenges for humankind in the 21st century. This challenge consists of several problems: First, humankind is facing is a supply-demand problem. The demand is continuously growing as the world population is rapidly growing – some studies predict a world population of 9 billion around 2040, in contrast to the 7 billion people living on the planet in 2014. All these people will need energy, which increases the global energy demand. Further, in many countries the living standard is rapidly increasing; like China and India, where approximately 2.5 billion people are living, which represents more than a third of the World's population. Also the increasing living standards lead to an increased energy demand.

According to the IEA World Energy Outlook 2013, the global energy demand will grow about one third from 2011 to 2013 [5]. The increasing demand in energy has economic impact, as well. If there is more demand for a product, while supply does not change that much, the product will get more expensive. This basic market mechanism is also true for Energy. As an example we show a plot of the annual averaged price for a barrel of oil in Fig. 1.1. We see that prices went up during the oil crisis in the 1970s, when some countries stopped producing and trading oil for a while. The second era of higher oil prices started at the beginning of this millennium. Due to the increasing demand from new growing

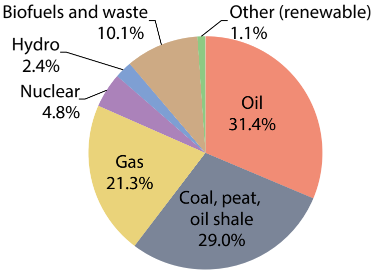

Figure 1.2: The primary energy consumption of the world by source in 2012. The total supply was 155 505 TWh (Data from Ref. [6]).

economies, the oil prices increased significantly.

A second challenge that we are facing is related to the fact that our energy infrastructure heavily depends on fossil fuels like oil, coal and gas, as shown in Fig. 1.2. Fossil fuels are nothing but millions and millions of years of solar energy stored in the form of chemical energy. The problem is that humans deplete these fossil fuels much faster than they are generated through the photosynthetic process in nature. Therefore fossil fuels are not a sustainable energy source. The more fossil fuels we consume, the less easily extractable gas and oil resources will be available. Already now we see that more and more oil and gas is produced with *unconventional* methods, such as extracting oil from tar sands in Alberta, Canada and producing gas with hydraulic fracturing [7], such as in large parts of the United States. These new methods use much more energy to get the fossil fuels out of the ground. Further, off-shore drilling is put in regions with ever larger water depths, which leads to new technological risks as we have seen in the Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

A third challenge is that by burning fossil fuels we produce the so-called greenhouse gases such carbon dioxide (CO_2). The additional carbon dioxide created by human activities is stored in our oceans and atmosphere. Figure 1.3 shows the increase in carbon dioxide concentration in the Earth's atmosphere up to 2015. According to the International Panel on Climate Change (IPCC) Fifth Assessment Report (AR5),

> The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification [11].

Further, in the AR5 it is stated that

> Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system [11].

and

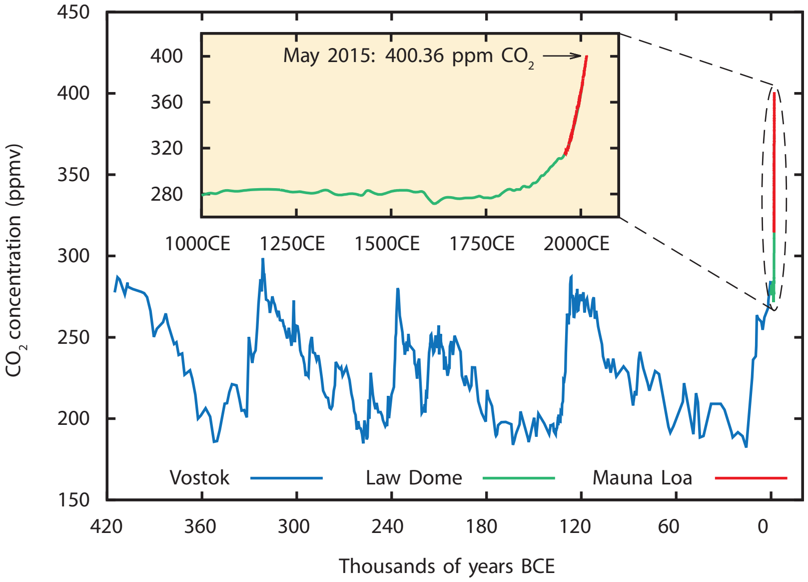

Figure 1.3: Atmospheric CO_2 concentration in the last 420 000 years (detailed view since the year 1000 shown in the inset). The drastic rise of the CO_2 concentration since the onset of the industrial revolution (ca. 1750) is clearly visible. The figure combines data from the antarctic Vostok [8] and Law Dome [9] ice cores and updated data from the Mauna Loa Observatory in Hawaii [10].

> Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century [11].

Hence, it seems very clear that the increase in carbon dioxide is responsible for global warming and climate change, which can have drastic consequences on the habitats of many people.

Since the beginning of the industrial revolution, humankind has been heavily dependent on fossil fuels. Within a few centuries, we are exhausting solar energy that was incident on Earth for hundreds of millions of years, converted into chemical energy by photosynthetic processes and stored in the form of gas, coal and oil.

Before the industrial revolution, the main source of energy was wood and other biomass, which is a secondary form of solar energy. The energy source was replenished in the same characteristic time as the energy being consumed. In the pre-industrial era, humankind was basically living on a secondary form of solar energy. However, also back then the way we consumed energy was not fully sustainable. For example, deforestation due to increasing population density was already playing a role at the end of the first millennium.

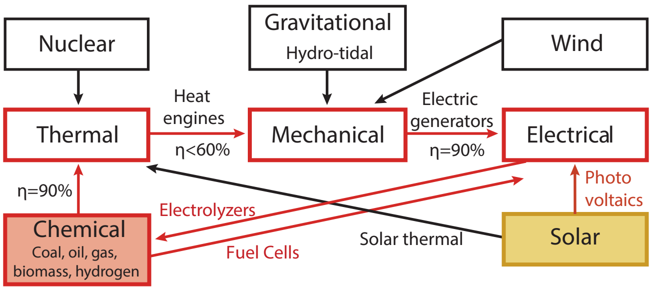

Figure 1.4: The different energy carriers and how we utilise them (Adapted from L. Freris and D. Infield, Renewable Energy in Power Systems (copyright John Wiley & Sons Inc, Chichester, United Kingdom, 2008))[12].

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 in to 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 in to 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 CO_2 per generated