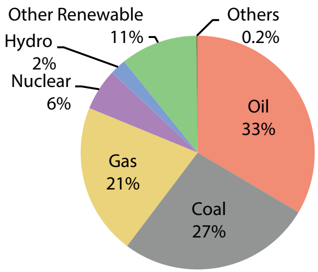

Figure 1.2: The primary energy consumption of the world by source in 2008. The total supply was 143 851 TWh [5].

global energy demand will grow about one third from 2011 to 2013 [4]. The increasing demand in energy has economic impact, as well. If there is more demand for a product, while supply does not change 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 an oil barrel, normalised to the value of the 2008 US Dollar 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 economies, the oil prices have been significantly increased.

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. 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 available 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 fracturing such as in large parts of the United States. This new methods use much more energy to get the fossil fuels out of the ground. Further, off-shore drilling is put 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 like 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 2000. 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. Car-

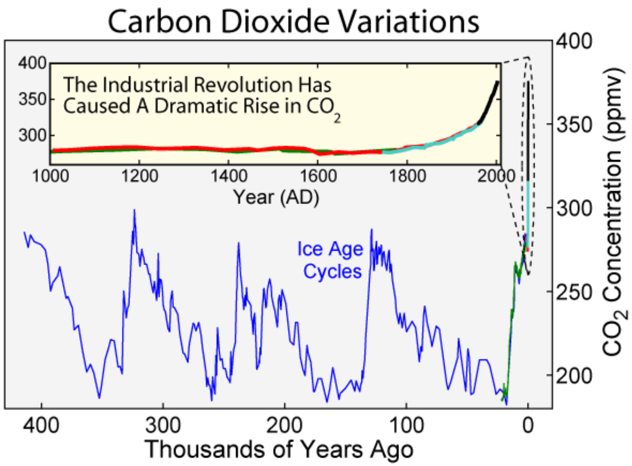

Figure 1.3: The atmospheric CO_2 content in the last 400 000 years [6].

> bon 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 [7].

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 [7].

and

> 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 [7].

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

Since the beginning of the industrial revolution, mankind is heavily dependent on fossil fuels. Within a few centuries, we are using solar energy that was incident on Earth for hundreds of millions of years, converted in to chemical energy by the photosynthetic process and stored in the form of gas, coal and oil.

Before the industrial revolution, the main source of energy was wood and 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, mankind 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.

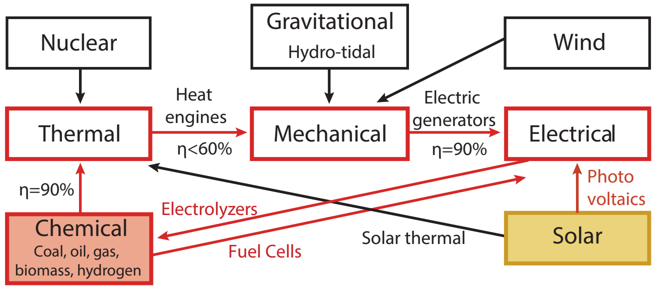

Figure 1.4: The different energy carriers and how we utilise them [8].

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 far majority of the current cars and trucks works on this principle. Mechanical energy can be converted in to electricity using electric generators with an efficiency of up to 99%. Most of the World's electricity is generated with an *turbo generator* that is connected to a steam turbine, where the coal is the major energy source. This process is explained in more detail in our discussion on solar thermal electric power in Chapter 20. 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 of hydrogen electrolysers of 50-80% have been reported. We will discuss electrolysis in more detail in Chapter 21.

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 its 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 wind mills.

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* consists of 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 discuss in great detail in this book, typical efficiencies of the most commercial *solar modules* are in the range of 15-20%.

Solar light can also be converted into heat. This application is called *solar thermal energy* and is discussed in detail in Chapter 20. 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 temperatures of several hundreds of degrees are achieved, which 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