We humans have populated the earth in sizeable numbers for about the last 200 thousand years only. While our universe is about 13.6 billion years old and the earth itself was formed about 4.5 billion years ago, we humans have entered the scene just very, very recently. The oldest humanoids, found in Africa date about 4 million years ago, but the Neanderthals are known as one of the earliest civilizations. The Neanderthal-tribe numbered about 20 thousand in total and populated a large area all across South-Western Europe between 200 thousand and 50 thousand years ago.

Since then the population of the earth has increased substantially. This increase of the population of the earth occurred in steps enabled by technological and societal innovations in the widest sense. Among the early innovations was tool making and the fire, which enabled preservation of food, warmth and better health in a harsh climate, and the building of defensive barriers against wild animals. The Neanderthals had already mastered these. Metal working and mining, pottery, as well as agriculture and animal husbandry were later major accomplishments. Language, writing, algebra, and also religion were important cultural achievements which enabled larger groups to live together, to communicate, and to form a society with a given set of rules.
2 Designing the Energy System of the Future

The population of the earth has grown at a slow pace reaching about 300 million 2000 years ago at the time of the Roman empire and 1 billion only around 1820. Then one of the latest big societal changes came about with industrialization. This started in Europe around 1800 and established a transition from an agriculture dominated society to manufacturing and increased urbanization. Industrialization is based upon employing the strength of machines, stronger than humans or domesticated animals, for work, production and transport. Since hydro-power and wind-power was, and is, limited, this was largely enabled by using fossil fuels as an energy source to drive the newly invented and developed machines. Without this supply of “cheap and ample” energy, which had accumulated on the earth over millions of years, the industrial age would not have been possible. Together with the industrialization the population of the earth started to grow very rapidly. Before the industrial age there were only about 1 billion humans living on the earth and by now we have reached a population of more than 7 billion and these numbers are still growing strongly. The invention and industrial-scale production of fertilizers was another important step in the 19th century. The growth of the human population of the earth over the last 320 years is shown in Fig. 1.1. It can be seen that this growth has been accelerating and over

![Figure 1.1](image_url)
the years from 1960 to 2000 the population of the earth has more than doubled. Later in this century we will reach a population of 10 billion people on the earth.

The growth of the population is largely driven by two factors: the increase in technology and general prosperity after the devastating period of the two world wars and the increase in lifespan due to vast improvements in medicine. The decline in the growth rate since 1980 is largely due to the fact that the population growth in the well-developed countries is slowing down considerably or even has come to a stagnation or declined. Even in China—due to the one child policy—the growth has slowed considerably by now. On the other hand, in Africa and Southeast Asia (India, Indonesia) there is still a large growth as shown in Fig. 1.2. These are the regions and countries that will largely determine the fate of the population of the earth in the next 50 years.

In view of this rapid growth, the question raised by many is how many humans can our “space ship earth” really accommodate. This was brought to the attention of a large worldwide audience by Dennis Meadows and the “Club of Rome” in their study published as a book with the title “The limits to Growth” in 1972 [3].

Today we are facing a more positive outlook on the world than described in this book. However, the study of the Club of Rome nevertheless had a very important impact: to raise the consciousness that the growth enjoyed by many countries following the period of the first and second world war cannot continue forever and without encountering serious limitations. Using irrigation and desalination of seawater as well as fertilization—all of which require energy—we will be able to produce enough food and water to support 10 billion people on earth, a number which will be reached by approximately 2050. By then the growth of the population is predicted to slow down, especially if we manage to raise the standard of living in the as yet underdeveloped countries, foremost in Africa and parts of Asia.

This brings in other parameters into the equation: since the beginning of the Industrial Age, not only the population has grown, we also enjoy a higher comfort in our living accommodations, a much better health care system, a large variety of cultural events, and an ample supply of food—at least in the developed countries. Our horizon has spread through rail, car, ship, and air-travel, enabling many to move over large distances at an
affordable cost and within a short time. The distance covered in a day by a stagecoach, a car or an airplane increases by about a factor of 10 between each of these means of transportation. In a stagecoach people could travel about 50 miles, in a car about 500 miles and in an airplane about 5000 miles in 10 hours each. Lately also our means of communication have expanded drastically through the use of electronic media and the internet. All of this is included in the “standard of living” and it is associated with a large increase in the demand for energy.

As a consequence, with the growth of the earth’s population and the increase in the standard of living our energy demand also is increasing steadily. The growth of the primary energy consumption is shown in Fig. 1.3. (See the text box discussing the use of the term energy demand and consumption and the difference in a scientific discussion vs. the societal use of these terms.) Looking at the growth of the population shown in Fig. 1.2 we realize that the population has about doubled since 1971, when the book about the limits to growth was published and in the same time span the demand for energy has even more than doubled (Fig. 1.3). Looking at the absolute scale, this is a huge increase. How could such an increase get accomplished? This is illustrated in Fig. 1.3, where not only the total energy but also the use of the various primary sources of energy are shown over the years. These graphs paint a quite sobering picture. Despite of all the development of nuclear energy and renewable energy sources such as solar power and wind generators the vast majority of the energy (about 80% worldwide) still comes from fossil fuels (oil, gas, and coal), and even the increase from the 1970s to today was almost exclusively accomplished by a proportional increase in the use of fossil fuels.

FIGURE 1.3 Growth in the consumption of energy over the past 55 years. The increase in demand is largely accommodated by using additional fossil fuels. Traditional biomass is used for cooking and heating in Africa and some areas of Asia. On this scale only nuclear and hydropower resources make a noticeable contribution, while wind and solar energy are too small [4,5].
“Energy” in physics and society
The language and concepts used in association with the term “energy” are significantly different in physics and in our general society.

In society, we talk about a demand for energy and energy consumption. We do have a very well defined demand for electrical energy in our society and if that demand is not fulfilled, because of an interruption of the generation or the distribution system, then literally the lights go out in our cities and the machines in the factories are standing still. Many of us are aware of incidents of large electrical power outages, for example in 2003 when the lights in New York City went out. Similarly in California in the summer, “brownouts” –severe limitations for the use of electricity—used to occur, when the electrical power generation was not sufficient to supply enough power for air conditioning the buildings, running factories and computers, and pumping the water to the fields in the Central Valley to irrigate all the crops.

We talk about electricity generation, but correctly this does not mean the generation of electricity but rather the conversion of other forms of energy into electricity. This could be chemical energy in the form of coal, which is turned into heat by burning it. The heat is used to generate steam from water and then finally electricity is produced by a steam-powered generator. Natural gas can be used directly to drive a gas turbine, which is something like a large jet engine coupled to an electric generator. Alternatively, electric power generation could also consist of the conversion of potential energy of water falling from a reservoir through pipes to a lower level and driving a water turbine. These are all energy conversion processes and they are characterized by a certain efficiency of conversion of energy from one form to the desired other form. For example, the hydroelectric power conversion has about an 85% efficiency while in a coal fired power plant only about 40% of the chemical energy available in the form of coal is converted into electrical power. More than half (60%) is ‘lost’ in the form of (unwanted) heat. We also can use the heat directly to drive processes in a chemical plant or to heat our buildings. In modern fossil fuel fired electrical power plants, located in an urban area, this is often used to heat (or cool) the buildings in the vicinity. The heat in the form of hot steam is transferred to the buildings by a network of well insulated pipelines. In technical terms this is referred to as “cogeneration.” In a centralized or district heating plant, the operation of the plant is driven by the demand for heat, while electricity is generated as a by-product.

In physics, on the other hand, one important basic law is the conservation of energy. This means in any closed system the total energy is constant. Energy is a quantity that describes the amount of work that may be performed. For example, water in a lake high up in the mountains has a certain potential energy given by its mass and the altitude it is at. We can funnel the water down the mountain in pipes and, rushing through the pipes the water has gained kinetic energy in form of its speed of motion. This kinetic energy can be used to drive an electric turbine and part of the kinetic energy of the water is thus converted into electricity. This process is a so called reversible process—we can use electricity to pump water up the mountain and store it there until we need additional electric power. This is a very efficient energy storage process.

As a second example, if two cars crash, then their kinetic energy of motion is used to do the work to deform the metal of the car bodies in the impact. This is an irreversible process, since a specific amount of work is performed in bending the metal. Unfortunately bending the metal back involves work again and consumes energy. As a third example, if we burn a piece of coal, then this contains a certain chemical energy, which is released into the environment as heat and light and the carbon is transformed into CO₂. The photosynthesis in plants manages to reverse that process, to take CO₂ and energy (sunlight) and to produce carbon and oxygen.
The conservation of energy also implies that perpetual motion machines are not possible, since even in the most efficient machines some energy is lost to friction or the environment slowing down the motion. This is even applicable to a large body such as the earth itself. The earth’s rotation is slowed down by the friction encountered from the tides and our days get longer and longer. This effect is so small that it is only measurable using the most precise clocks, but it does exist.

Primary energy versus use energy

The energy demand of the world or a country is most commonly listed as primary energy demand—this means the amount of energy used up in the form of coal, gas or oil, but also as renewables in the energy system. The conversion processes in the energy system have huge losses. Far more than half of the primary energy is lost during conversion. For example, the best coal fired power plants have an electricity output of about 40% of the primary energy that was used in the form of coal. If we want to replace this by wind or PV electricity we do not have to replace the primary coal energy but only the electricity generated.

That means in order to replace 2.5 TWh of coal or oil used to generate electricity we only need 1 TWh of wind or solar energy. This is a huge savings and gain in efficiency. Very often when PV or wind generated energy is compared to the primary energy these conversion losses are not properly taken into account. In fact, it is often used as an argument of how small a share renewables contribute to the system. Fig. 1.3 is an example of this. If we are plotting the electricity generated rather than the primary energy used to generate electricity, renewables do show up in the graphics—please see later chapters.

The same holds also for the transport sector. If we replace a combustion engine driven vehicle by an electric vehicle then immediately we save about 75% of the primary energy presently required. An electric passenger vehicle needs about 15 kWh to drive 100 km, whereas a gasoline powered vehicle needs 6 L of gasoline—which has an energy content of about 60 kWh—to drive the same distance.

The demand for energy increases as the population increases. Additionally, as Fig. 1.4 demonstrates, the demand for energy correlates with the standard of living in the different countries. The per capita energy consumption in the OECD countries across the board is much larger than in China or India and countries in Africa, even though China and India are rapidly catching up. We simply cannot deny China, India, and the African countries the economic development and standard of living that we are enjoying in the developed world. On the other hand, we also see that even among the developed countries there are large differences, which are reflected by the various societies. Furthermore, in the countries on the Arabian Peninsula or in the United States there has not been much concern about using the world’s fossil resources. In the United States some progress in terms of reducing CO₂ as initiated by the Obama administration was rapidly eradicated by his successor. There is also a clear correlation that the CO₂ emissions are especially high in countries where the economy is based entirely or predominantly on supplying the rest of the world with fossil energy.

The lesson we have learned from the past 60 years is that the population has doubled and that the energy consumption is increasing even more rapidly than the population.
This is clearly not developing on a sustainable trajectory. Some hope is in technological development helping to increase the efficiencies all throughout the energy conversion and use processes. This is important, but cannot be the only solution. The energy efficiency of our economies has improved over the past decades as shown in Fig. 1.5, however this is so far only able to offset some of the additional demands.

In the developed world the slope of improving the energy efficiency corresponds to about a 30% reduction over the 25 year period shown. This is in principle good news, because there is a need to decouple the increase in GDP, which is an indicator of the standard of living, from being directly proportional to the energy use. Unless this decoupling happens, there is little hope that the standard of living in India, Africa, Latin America or Southeast Asia can be raised to the OECD standard without a large increase in energy demand. China is improving more rapidly, but altogether has not reached the same level of efficiency as the countries of the European Union or Japan. The energy efficiency of the GDP is not an absolute measure, since it is affected by the geographical and climate parameters of the countries. For example, Russia has a distinct disadvantage concerning this indicator. Russia is a very large country with long transport routes and it has a quite harsh climate, which requires a lot of energy for heating. Other factors influencing these data are the fraction of GDP generated by heavy, energy intensive industry (see chapter 5). On the other hand, it is also interesting to note that the energy efficiency in the United States is about 50% worse than in the European Union, even though the climate

**FIGURE 1.4** CO\(_2\) emissions per capita vs. GDP. The CO\(_2\) emissions are taken as a measure of the energy use and the standard of living is reflected by the GDP. Note that the GDP/capita is plotted on a logarithmic scale. The size of the symbols reflects the relative size of the population. There is a very clear correlation between the energy use and the standard of living around the world. The plot is taken from [6] while the data is based upon the “Global Carbon Project” [7].
parameters and geographical extension are similar and quite favorable. This might be associated with the costs of energy. As prices for electricity or gasoline are much lower in the United States compared to Europe, consumers, commerce, as well as industry do not engage in energy saving measures as much as in other countries. Especially if this involves capital investment for replacing older, less efficient technology. The important message of this graph however is that improving the efficiency is important, wherever possible. Nevertheless, this can only reduce but not compensate for the increase in the energy demand to be expected over the next decades.

What can we project for the future? In the ExxonMobil Outlook for Energy (2018) [9], the total energy demand is projected to increase by 25% from 2016 to 2040. The same report states that without improvements in efficiency the energy demand would about double over this period. The BP Energy Outlook 2018 estimates even a 33% increase in energy demand by 2040 [10] and the Energy Information Agency (EIA) of the US Department of Energy (DOE) projects a 35% increase for the same period until 2040 [11]. The data of this report are graphically represented in Fig. 1.6. We have chosen to plot the projections from this report, since it reflects the views of a government agency rather than a major company active in this area. Both latter estimates do not rate the gains in efficiency as favorably as in the ExxonMobil report.

In view of the fact that these are projections more than 20 years into the future these are small differences. All these reports project still a substantial increase in the use of fossil fuels over this period, mostly from gas and oil. Coal demand is projected approximately constant.
over this period. A strong rise of coal consumption in India and China is offset by a decline in the western world. If the Clean Power Program, which was initiated in 2016 in the United States and abandoned in 2018 is reinstated in the future, then coal will actually decline. This is an excellent example how political decisions have an influence on these projections.

The EIA report [11] reflects all government policies enacted so far (2017) as a reaction following the Paris climate accord. The very sobering observation is that fossil fuel consumption will still continue to rise over the next decades, even though the projections report a considerable increase in the contributions from renewable energies and even nuclear energy. The worldwide government policies that have been put in place so far are simply not sufficient to combat climate change.

Geographically, the major growth of the energy consumption is originating from (Southeast) Asia. China is turning from fossil energy to nuclear and renewables, but the other less developed countries such as India and Indonesia are heavily expanding in conventional energy. The technology associated with the use of fossil fuels in electric power generation, transportation, and in the industrial, commercial, and domestic use is developed, readily available, and affordable under the current economic parameters. More important, it also is at par with the scale of the overall amount as well as the anticipated increase in demand. Taking electricity generation as example, it is much easier to build a coal fired power plant capable of delivering 1 GW of electricity than to build a wind park that has the same generation capacity. Furthermore, a coal fired power plant delivers electricity at its rated power for about 8000 hours yearly, whereas the wind farm delivers only about 2000 to 2500 hours at the fully rated capacity averaged over the year. The windmills run much longer than these 2000 hours, but often at reduced capacity. (For a more detailed discussion see later in chapter 2 and 6). The economics however will change if for example a carbon tax is levied worldwide. Once a realistic price tag for CO\textsubscript{2} emissions is implemented, then fossil fuels will become much less affordable and renewable energies will win the race.

In summary: The demand for energy is driven largely by two factors, the increase in both the population and the average standard of living. Both of these clearly are growing. The total population of our planet will reach about 10 billion people by 2050, unless
some real catastrophic incidence occurs. Furthermore, countries in Asia and Africa still have a lot of catching up to do in terms of their standard of living—we have to raise the standard of living in these countries substantially over the next decades in order to prevent mass migration and/or civil unrest. In planning the future energy system, we not only have to replace existing technology with more efficient and sustainable technology, but also accommodate the expected growth in the overall demand. This will be a gigantic effort that requires a timescale of 20 to 30 years and substantial investments.

Can we accommodate the future growth of the energy demand and what are the consequences?

The use and exploitation of the fossil energy reserves has enabled the Industrial Age and it also has accommodated the growth in the earth’s population and the increase in standard of living for most of the population on earth. Without this stored energy, which has been accumulated over millions of years, this could not have been accomplished. Realizing this, three questions immediately come to mind:

1. How long will these reserves last and can they accommodate even further growth?
2. What are the side effects and drawbacks associated with the use of these sources?
3. What are our alternatives once these deposits run out or become too costly to use?
   (This last question is discussed in Chapter 2.)

The first of these questions is answered by the graphs in Fig. 1.7. We immediately see that the proven reserves for all fossil fuels, even for oil, are still plentiful and available for decades if not more than a century, despite of the ever-rising demand. Actually, we also see that the new discoveries of oil and gas have been able to more than compensate for the increase in demand over the 30-year period. The plot shows that the proven reserves of oil and gas will last for 50 years, at the current production level. It is safe to assume that even more reserves will become available once new recovery methods have been

![Proven Reserves in Years (R/P)](image)

**FIGURE 1.7** Proven reserves of fossil fuels listed as ratio R/P (reserves/production) in years for the past 30 years. The R/P value denotes the reserves in years at the rate of production in the current year. As the production has been rising considerably over the past 30 years this means that the actual proven reserves right now are much larger than 30 years ago. Data taken from the “BP Statistical Review of World Energy (2019)” [12].
established and new regions of the earth will be explored. One of the dramatic changes in these estimates originated from fracking as a new recovery method. This resulted in the United States to become a net exporter of hydrocarbons rather than having to depend on imported oil. It is also interesting to note here that for all fossil fuels, including oil, the proven reserves are larger or at least match the amount that has been taken out of the ground and used so far since the beginning of the Industrial Age. Coal reserves are especially plentiful and it is safe to assume that coal will remain fairly inexpensive and plentiful for at least another century. For coal, the R/P rate has been declining, however the proven reserves are so large that there is much less incentive for exploring new coal deposits than for the other fossil fuels. Beyond the proven reserves there is an estimate that the actual exploitable reserves for all three types of fossil fuels are at least double that amount. Thirty years ago there was a lot of discussion of “peak oil”—meaning the production of oil has “peaked” and will actually decline in future years. So far this has not occurred. Even today OPEC (the Organization of the Petroleum Exporting Countries) is working hard to keep the production levels low such that there is a stable level of pricing and income from oil resources for the participating countries.

The second question about the side effects and drawbacks is more difficult to answer. One obvious answer is that the use of fossil fuels has resulted in an increase in the CO₂ in the atmosphere. This increase is shown graphically in Fig. 1.8.

**FIGURE 1.8** Global annually measured CO₂ concentration in the atmosphere in ppm (parts per million) during the last 2000 years. Since the pre-industrial age (1800), this concentration has risen by more than 45%. Please take note of the offset of the vertical scale. The data are from [13], the graph is from [6].
While from the year 0 to about 1800 the level of CO$_2$ remained relatively unchanged, since
the onset of the Industrial Age the CO$_2$ level kept rising constantly and by now (2020) has
reached a level of about 410 ppm. The overall CO$_2$ content in the atmosphere by now is about
45% above the level of the pre-industrial age. Furthermore, the level of CO$_2$ (and other green-
house gases such as CH$_4$ and N$_2$O) during the last 800 thousand years has never reached
such a high level. Remember, the Neanderthals populated the earth about 100 thousand
years ago. That means during the entire history of a substantial human population living on
earth we never encountered such conditions.

Presently (2020) the total carbon emissions into the atmosphere amount to about 10
Gt (Giga-tons) of Carbon or 37 Gt of CO$_2$ annually. Only about 44% of this remains in the
atmosphere resulting in an increase of about 2 ppm annually, whereas 26% are absorbed
by the ocean waters and 30% are taken up by plants in photosynthesis. For more details,
see “The carbon cycle,” below.

The detailed curve in Fig. 1.9 shows clear annual oscillations with a maximum reached
in the months of April-May and a minimum in September-October [15]. This is explained
by the plant growth cycle. Since the landmass on earth is largely concentrated in the
Northern Hemisphere, the CO$_2$ uptake by plant growth is largest from spring to fall and
lowest in winter in this region of our planet. Interestingly, during this growth season the
total CO$_2$ concentration in the atmosphere is actually declining. The plants and oceans
are taking out more CO$_2$ than we are emitting during this period. Also, taking a closer look
at the data in Fig. 1.9, the amplitude of these seasonal variations has increased steadily
over the past 50+ years, i.e., when comparing 1960 and 2015. This is an indication that the
uptake of CO$_2$ by vegetation on land and the oceans has increased in line with the overall
increase of the CO$_2$ content of the atmosphere. These observations are very important
in developing strategies to mitigate climate change and will be discussed in more detail
below.

![Figure 1.9](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAABqAAAABCACAAAAAb1hJAAAABGdBTUEAALGPC/xhBQAAAAFz</html>
The carbon cycle

Chemical reactions do not change the number of atoms involved. This means when we take coal and burn it, the number of carbon atoms remains exactly the same. This also implies that the total amount of Carbon atoms on earth remains the same, independent whether they are in the form of limestone (CaCO$_3$), methane (CH$_4$), coal (C), or carbon dioxide (CO$_2$). The total inventory of Carbon on earth thus remains essentially constant.

We have to point out that the chemical state of carbon obviously is related with the mass that is referred to. Accordingly, there is a relationship that 1 Gt of Carbon corresponds to 3.664 Gt of CO$_2$ and both of these numbers are used when discussing CO$_2$ emissions. Only physical processes (nuclear reactions) change the actual atoms involved. The nuclear fusion cycle in the sun produces carbon from hydrogen in a longer reaction pathway. Additionally, radioactive $^{14}$C is created in the upper atmosphere. There cosmic radiation produces neutrons interacting with $^{14}$N, changing this to $^{14}$C plus a proton. $^{14}$C spontaneously decays, with a lifetime of 5730 years, into $^{14}$N by $\beta$-decay (emission of an electron and a neutrino). This process is the basis for Carbon dating, since in living materials (plants, animals) fresh $^{14}$C is incorporated and once the material is dead the incorporated $^{14}$C decays. Natural gas, or fossil fuels which were formed millions of years ago do not contain any $^{14}$C anymore. This physical process, however, is such that the carbon inventory on earth essentially remains unchanged. The production of radioactive $^{14}$C starts from $^{14}$N and the decay again results in a $^{14}$N atom.

Let’s come back to the various reservoirs of Carbon on the earth—this might be quite surprising to some extent. By far the largest reservoir with an estimated 100,000,000 Gt is the limestone (inorganic CaCO$_3$) in the earth’s crust. Organic carbon bound in rock amounts to about 15,000,000 Gt, whereas the fossil fuel deposits (coal, oil, gas) amount to “only” 1000-2000 Gt. This is even smaller than the estimated amount of carbon in the form of hydrates on the ocean floor and similar the permafrost of the tundra (1700 Gt). The living biomass (plants, animals) on the earth contains about 680 Gt, whereas the soil contains about 1700 Gt of carbon. Incidentally, the 7 billion humans living on earth contain only about 0.1 Gt of carbon.

The present knowledge of the reservoirs and fluxes of Carbon is graphically shown in Fig. 1.10. The values are approximate and rounded to full Gt’s of Carbon. (1 Gt of Carbon corresponds to 3.66 Gt of CO$_2$) Small fluxes and reservoirs are omitted. All major annual changes in the reservoir values are shown in green. Emissions are shown in red. Industrial emissions include cement production. Agricultural emissions include CH$_4$ and NO$_x$ measured in CO$_2$ equivalents. The increase in land biomass is offset by the land use change from burning forests. Data are compiled from various sources mostly [16,19]. There are large uncertainties as far as some of the reservoirs are concerned. Interestingly, the CO$_2$ content in the atmosphere is one of the most precisely known values.

The oceans also constitute a reservoir which contains large amounts of Carbon. The living animals in the ocean only amount to 3 Gt—despite of the fact that whales are the largest living animals. About 40 000 Gt of carbon are in the form of CO$_2$ dissolved in the ocean water, especially in the deeper, colder regions. Additionally, there are sediments amounting to about 1750 Gt and dissolved organic carbon in the amount of 700 Gt. The most important message in all these numbers is that there is about 50 times as much CO$_2$ stored in the oceans as there is in the atmosphere (860 Gt). This is also a major concern: as the temperature of the ocean water is rising the solubility of CO$_2$ is decreasing, the oceans can take up less CO$_2$. Fortunately,
the warming of the oceans only concerns the surface regions. The deeper regions of the oceans are and remain at a fairly stable temperature, which is around 2°C, since the oceans consist of saltwater. As a negative influence, CO₂ in the ocean water changes the pH value, the water becomes more acidic and this destroys the coral and it disturbs the processes that lead to the formation of Ca(CO₃) sediments.

There is an ongoing dynamic exchange between the various sources and sinks for Carbon (CO₂) on earth. The flux between these various reservoirs, especially between the atmosphere and the biomass on land or the ocean is huge, it is estimated at more than 200 Gt of carbon annually. The increase of the level of CO₂ in the atmosphere is only a very small fraction of it, which reflects a relatively small imbalance (5 Gt C) between the sources and sinks participating in this Carbon Circle on earth. This is kind of scary, since this small imbalance could potentially get disturbed by as yet unknown or undetermined factors.

The sources for Carbon released into the atmosphere are:

1. The burning (use) of fossil fuels
2. Decomposition of organic materials
3. Deforestation or change in land use
4. Withering processes of rocks and soils
5. Breathing of living organisms
The sinks for CO₂ are:

1. Uptake by the ocean water and the organisms living in it
2. Forest, plant, and animal growth
3. Deposition into the atmosphere

It is quite difficult to obtain accurate estimates for the total amount of carbon exchanged between the various reservoirs. The most precise values are the atmospheric concentration and the amount released from burning fossil fuels. Burning of fossil fuels results in CO₂, which annually releases about 10 Gt of Carbon (37 Gt of CO₂) into the atmosphere. However, it does not remain there. The annual increase of the CO₂ level in the atmosphere amounts to only about 5 Gt of Carbon (18 Gt of CO₂). More than half of the CO₂ released into the atmosphere is taken up by oceans and plants. In the ocean in a first step the CO₂ is dissolved in gaseous form. Plants on land or algae in water take CO₂ and, using sunlight, convert this CO₂ into hydrocarbons and O₂. Without this process, called photosynthesis, there would be no life on earth as we know it and the oxygen content of the earth's atmosphere would be so low that humans could not live here. In the early periods of the earth's evolution, more than 3 billion years ago, this actually has been the case. Our planet became habitable for higher oxygen demanding living species only after algae and plants had converted sufficient CO₂ into O₂ such that the atmosphere content of O₂ had risen from an initial value of less than 5% to the 20% we have now.

What we learn from this immediately is that a high concentration of CO₂ in the atmosphere will not destroy our planet. The real and immediate danger, however, is that it will destroy our societal habitat, which we have created to accommodate our needs as humans on earth. When ‘climate skeptics’ point out that the CO₂ level on the earth has been much higher than now, then this is true. However our society, where and how we live, how we produce our food, is directly depending on the CO₂ level not rising too far. Whatever that means will be discussed in the box about the Greenhouse Effect.

Fig. 1.11 shows the current best estimates for the annual emissions and the sinks of CO₂ from 1960 to the present. The values themselves have different accuracies associated. The use of fossil fuels and cement production as well as the increase in the atmospheric CO₂ concentration...
can be determined with much higher accuracy than the total uptake by land and ocean or the CO$_2$ emission associated with the change in land use. During all these 6 decades, the emissions and sinks do not balance accurately. This may be taken as a representation of the current limitations of the monitoring and understanding of these processes. What is also interesting to note is that the ocean sink, as well as the growth on land, exhibit large fluctuations. Despite the 10 year data averaging used in Fig. 1.11, part of the oceanic fluctuations may be attributed to the El-Nino phenomenon, where in the Pacific Ocean a large surface current is periodically established. The most important information from this collection of data however is that as the emissions from burning fossil fuels are increasing, not only the uptake by the atmosphere increases but also the uptake by growth of the vegetation on land and by the oceans is increasing—and this roughly in proportion. Over this period of 60 years of observations it has been established that oceans and plants remove more than half the carbon released from the burning of fossil fuels. Obviously, this does not happen at the source, but as the concentration in the atmosphere is rising, oceans and land increase their uptake. In a simple view this suggests that if we manage to reduce the manmade emissions by 50%, the CO$_2$ in the atmosphere will remain approximately stable at today’s level, unless the processes responsible for land and ocean uptake are disturbed. If we manage to reduce the emissions even further, the CO$_2$ level in the atmosphere will actually start to decline—and we have reached a “turning point” with respect to climate change. The temperature however will still rise, since we have not yet reached the equilibrium temperature corresponding to 410 ppm CO$_2$ in the atmosphere. Because of the uncertainties in some of these values and our limit of understanding of the underlying processes, we should definitely proceed further than 50% in the reductions of the CO$_2$ emissions. The positive message however is that the earth can tolerate a certain substantial level of CO$_2$ emissions—we do not have to eliminate all carbon emissions to zero to stop climate change.

CO$_2$ and climate change

The increase in the atmospheric content of CO$_2$ are causing a change in our climate—this is one of the very serious consequences of using (burning) all the fossil fuels. CO$_2$ is a colorless gas, not visible to our eyes, but nevertheless it substantially contributes to the greenhouse effect on our planet (see enclosure greenhouse effect). Even though there are some uncertainties, the increased CO$_2$ content in our atmosphere is causing global warming and the consequence of this is a change in the climate of our planet. The first observation, this rise of CO$_2$ content in the atmosphere, is generally accepted as a fact, whereas already the second one—that the global temperature is rising—is debated by some so-called climate skeptics. This leads to even more debate about the third point: what are the effects of a rising temperature on our climate? Incidentally, this is not a recent discussion. The first scientific article that associated climate change with the level of CO$_2$ in the atmosphere was published by Svante Arrhenius about 135 years ago [17].

Let’s first concentrate on the global temperature. This mean derived global temperature, measured relative to the temperature averaged over a reference period of 30 years
from 1961 to 1990, is shown in the graph of Fig. 1.12. This clearly establishes a consistently rising temperature. In the periods before 1960 the average temperatures are lower, and past 1990 the averages are higher than the mean of the reference period. We can measure with reasonable precision the temperature at any point on the earth and its variation over time. The difficulty arises from the fact that the local, daily, and seasonal variations of these temperature measurements are so much larger than the rise in the mean value, which is about 1 degree so far. This does not sound like much, but the total change between a warm period in the climate history of the earth and an ice age is about 5°C in the average temperature value, and this usually occurred over 1000 years.

The variety and complexity of this data collection which results in one final value—designated as global mean temperature—has to be appreciated. Even in medical diagnostics procedures had to be established where and when to measure the temperature of a patient in order to be able to diagnose whether the patient has a fever or not. In view of that, the determination of the temperature of our patient “earth” seems an almost impossible task. Satellite-based observations and monitoring, which started in about 1980, helped to improve this situation considerably.

While there are differences in the average temperature values when various regional data sets of the world are considered—the temperature rise in South America and
Australia is clearly below the rise on the Northern Hemisphere—the overall fact cannot be negated.

As far as the cause of this increasing average temperature is concerned, one has to resort to climate model calculations. These are very complex models which require a lot of computer power. These models are not perfect and there are a lot of discussions emphasizing various shortcomings. While most of the time these models are used to predict the future development of the earth's climate, the confidence in these models can be derived from the fact that they more or less accurately model the climate variations that we have encountered over the past 60 years where reasonably reliable data are available. In these model calculations, the effect of the increase in the concentration of greenhouse gases in the atmosphere can be arbitrarily switched off. When that is done, the calculated curves actually do not agree anymore with the observations over the past 60 years. This is the scientifically derived evidence that man-made CO$_2$ and greenhouse gas emissions are the main cause of the overall mean temperature increase of our planet. This is discussed in much more detail in the IPCC reports [18].

There are other effects, such as the melting of glaciers all around the world or the dramatic reduction in the arctic sea ice shown in Fig. 1.13, which has been observed over the past 50 years. The rise of the sea level, which results from both melting of land-based snow
and ice and warming (heat expansion) of the surface ocean water, is also often mentioned as example of the effects of global warming.

The melting of the glaciers and sea ice illustrates two more important ingredients of climate change. First of all, there are positive-feedback mechanisms which we should be aware of. The reduction of the ice and snow coverage reduces the albedo, the reflectivity of the earth for sunlight, since the ocean and rocks are dark and they absorb rather than reflect the incoming radiation. This constitutes a positive feedback, since when the ice has melted the absorption of sunlight by bare rocks will in turn generate even more global warming.

Secondly, the famous Northwest Passage around the northern shore of Canada opens fairly regularly in the fall every year, when the minimum of the ice coverage is reached and it also seems possible to open up shipping routes between Europe and far east Asia along the northern Russian shore, which substantially reduces the distance and time for such a transport. This will most certainly generate economic benefits and as such this part of the climate change has a positive effect.

This illustrates the major dilemma of climate change in general—not all people and nations see the effects of climate change as negative. While the cause is in the global CO$_2$—and generally greenhouse gas-emissions, the local outcome and effects vary greatly for each nation. This is also reflected by the climate models. Some nations even hope for an improvement, which could mean more rain water, a longer growing season for crops or more moderate temperatures. Even events such as the slowing down or stopping of the gulf stream, which is viewed as a major catastrophe for Northern and Western Europe, is of little concern in South America, Africa, or Asia.

On the other hand, there are many more components and dangers associated with climate change. A rising sea level is one of them. Various groups of islands, most of them in the Pacific, are threatened to be drowned or submerged. Even in Southern Florida huge pumping stations have already been installed to keep the water levels in certain luxury real estate development areas under control. Any major rainstorm causes roadways to be flooded and renders them impassable, because the water takes a long time to drain. Increasing the numbers and capacities of these pumping stations will increase the energy consumption and the greenhouse gas emissions even further—to the detriment of the people and countries that cannot afford such luxury.

The increase in the strength of hurricanes or tropical storms is another effect associated with climate change. While the total number of tropical storms has not increased beyond statistical uncertainties, their strength has. Hurricanes derive their energy from water that is evaporated from the ocean and condensed in the clouds. As the ocean surface temperature rises, more water is evaporated and thus the storm gains more energy and becomes more violent. This seems to be the case already now—the number of really dangerous class 5 hurricanes has increased in the last years, despite of the fact that there are large statistical uncertainties in this.

The last phenomenon I want to mention here is the change in the climate zones. In the Eastern Mediterranean for example the average annual precipitation has declined
by about 20%. The climate of the Sahara Desert is actually expanding northward into the Mediterranean. This is what climate models predict and it has already now a drastic effect on the agriculture and people in this region.

Climate change is nothing new for our planet Earth. During its evolution much more drastic changes in climate have taken place. Ice ages have come and gone, which have resulted in large changes of the climate. The major cause for the ice ages is attributed to small variations in the earth’s orbit around the sun, which have different cycle periods. These so-called Milankovitch cycles are a superposition of several orbit variations of the earth with different periods, but they match quite well the periodic pattern of ice age cycles. The Milankovitch cycles as cause for ice ages are not undebated, but nevertheless this offers the best explanation for the periodically recurring ice age phenomenon available so far. The average temperature of the earth during an ice age is about 5 K lower than during the present warm period. Even though this temperature change seems small the climate change on the northern hemisphere during the ice age made a large part of this living space uninhabitable, since the land was covered by glaciers. People could only find food outside of this ice-covered area. Our planet can easily survive these changes. The real challenge of climate change is whether the habitat that we humans have created for ourselves on earth will suffer major damages and we as humans and our civilization can survive on this planet.

For the last few thousand years we have been near the peak of a warm cycle and the climate is going to change towards the next ice age. So why should we be concerned about a little bit of warming in the earth’s temperature right now? The present man-made climate change occurs on a much more rapid time scale than any of the natural geophysical cycles and changes, where the typical timescale is thousands of years. Furthermore, even if we stop all CO₂ emissions now and do not add any more CO₂ to the atmosphere by burning fossil fuels, the temperature will still be rising for several decades, because we have not reached the equilibrium temperature that corresponds to the present CO₂ concentration in the atmosphere. The current models predict that only within the (totally unrealistic) scenario of immediately stopping all emissions would it be possible to keep the global warming below 2°C, compared to the reference period of 1960–90.

Furthermore, we can predict the future changes of the climate only through quite sophisticated and complex models. These models are not perfect, since the climate system is very complex and we also do not understand completely all the various components and their interplay. While climate skeptics and the major oil and energy producers have gladly used this to point out the uncertainties of the predictions, reality could also turn out to be much worse than predicted.

Anyone who feels a responsibility for our kids and future generations on earth has to come to the conclusion that we have to try to stop this potentially dangerous development as soon as possible. This is why I am glad that the responsible politicians around the world have signed the Paris climate accord and almost all countries in the world are working toward limiting the CO₂ output they are responsible for. One goal of writing this book is that the general public gets educated in these matters and the hope is that based on this knowledge they will hold those politicians accountable who think and especially act otherwise.
The greenhouse effect
As a planet in space, the earth is a well isolated object and the temperature is determined by the balance between the amount of energy taken in and the amount of energy emitted from it into space. The incoming energy comes from the sun and it is transmitted in the form of electromagnetic radiation, which for the sun happens to have a maximum in the visible (green) photon energy range (sunlight). The spectrum of light emitted by the sun actually in physics terms is described by a black body radiation, whereby the temperature of the body is about 5600 K. This black body radiation also describes the emission of a filament in an electric light bulb, invented by T. Edison. Passing a current through a filament it heats up and the hotter it gets, the more light is emitted, i.e., the spectral distribution shifts more and more into the visible range. The emission spectrum of the sun, a black body at a surface temperature of 5600 K, is described by Planck’s law and shown graphically in Fig. 1.14. Also shown there in the second panel is the spectral distribution of the radiation emitted by a black body at 290 K, which corresponds to an average temperature of the surface of the earth of 17°C.

How do we now balance the incoming (absorbed) energy and the energy emitted from the earth?

Since the temperature is stable, the amount of these energies has to be equal. This is again graphically shown in Fig. 1.15.

The incoming radiation energy has been quite well characterized and is monitored by satellite observatories. It is described by the so called solar constant and its power corresponds to 1370 W/m². This is measured in the cross sectional area perpendicular to the beam of solar radiation. Even though it is called solar constant, it exhibits slow variations in time, since the activity of the sun varies (sunspot activities) and in the long term it has risen on the time scale of millions of years and will keep doing that because of the evolution of our sun as a star that derives its energy from nuclear fusion processes.

The cross section of the earth catching this energy is given by \( Q = \pi R^2 \), whereas the surface of the earth is given by \( O = 4\pi R^2 \). The receiving and the emitting surfaces of our planet just differ by a factor of 4, which makes calculations quite easy. Not all the sunlight hitting our planet is

![Figure 1.14](image_url)

FIGURE 1.14 Spectral distribution of the radiation emitted by the sun (left panel) and the earth (right panel). This is just the so called ‘black-body’ radiation spectrum. As the temperature of the emitting surface is higher the spectrum is shifted to shorter and shorter wavelengths and the total power emitted increases. The color bar at the bottom of the left panel indicates the visible photon energy range. Please note that this is the spectral distribution of the radiation. The total power emitted of the sun is about \( 10^5 \) times larger than the total power of the earth’s emission.
absorbed—it is partially reflected. This is the difference between the day and night side of the planet and we also see this very well on our moon. The bright area of our moon is actually coming from reflected sunlight, whereas the dark area shows the intrinsic thermal emission from the moon, which has its maximum in the infrared range (see Fig. 1.14 above) and thus not visible to our eyes.

Before we now can come up with a temperature estimate for the earth based on the radiation balance, we have to estimate how much sunlight is reflected directly into space. This reflectivity of the earth, which is called albedo, is estimated to be about 30%. Obviously, this is not easy to estimate since it varies a lot. The oceans are dark and reflect less light than the landmass. Clouds, as well as snow and ice have quite a high reflectivity but vary a lot in time and clouds have a larger effect when they are over water than over land. This is also the reason why clouds pose a major challenge in climate modeling.

So let’s forget about clouds and first look at our moon, which by astronomical distance is just as far away from the sun as the earth is and thus also receives the same radiation input. It happens that the albedo of the moon is also about 30%, but it is fairly constant in both time and across the surface area of the moon.

Any object that is at a certain temperature emits energy in the form of electromagnetic radiation (light) as described by the so-called Stefan-Boltzmann law with an intensity I given by

\[ I = \varepsilon \sigma T^4 \]

This has to be balanced with the incoming energy. For simplicity, we assume that the incoming energy is distributed evenly all across the surface (of the moon). Looking at Fig. 1.16 this means the average input corresponds to 1370/4 or 343 W/m². Taking the reflected radiation into account 70% are absorbed of 343 W/m², which corresponds to 240 W/m². We assume 1 for the emissivity \( \varepsilon \) and the radiation constant \( \sigma \) is known (\( \sigma = 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \)). Taking these values, we come up with an average surface temperature of the moon being 255 K or –18°C. This also would be the average temperature of the earth, if the earth would be a bare planet without an atmosphere (and would still have the same albedo).

From this, maybe surprising, estimate, we have to first of all conclude that the “Greenhouse effect” is actually very positive for us. Without it, life as we know it, would not exist on earth. Our atmosphere not only has sufficient oxygen for us to breathe but also raises the temperature of our planet’s surface to a level where water is liquid, plants can grow, and we feel reasonably comfortable.
Let’s now build a “perfect” greenhouse around our planet earth, as graphically illustrated in Fig. 1.16. This would mean, we build a glass sphere, which encloses the atmosphere. So let’s assume it has a radius 20 km larger than the earth itself and it has the property that it is totally transparent for the incoming sunlight, whereas it totally absorbs the emitted (IR) radiation from the earth. This is the definition of a perfect greenhouse. We also can take the albedo into account by directly reflecting 30% of the incoming radiation and only transmitting the remaining 70%. At an altitude of 20 km, it is essentially above our atmosphere, and taking the above considerations for a bare planet into account, we know that this glass sphere will be at a temperature equilibrium of 255K. (The slight increase in diameter or surface area relative to the earth does not make a significant difference on the scale of these calculations.) The glass sphere is assumed to not absorb any sunlight. Accordingly it is only heated by the radiation coming from the earth, which it totally absorbs in our model. To the outside space this glass sphere will radiate the surplus energy of 240 W/m² into space to keep the temperature equilibrium, but it also radiates the same amount of energy to the inside. Thus our planet’s surface is actually hit by an additional energy flow of 240 W/m² originating from the glass enclosure. For a perfect greenhouse the energy input to the surface of the earth actually has doubled. As a consequence of this additional energy input, the temperature will rise to bring the emission of the earth to a value of 480 W/m², which corresponds to the new equilibrium. According to the radiation equation discussed above, the new equilibrium temperature will be 255 K*2^{1/4}, which is 255 K*1.189 = 303 K. The temperature of the earth’s surface thus is actually raised by 48 K to a temperature of 30°C. This estimate is obviously higher than the actual mean temperature value of 17°C, but this is due to the crude model we are using. On the other hand, this is the limit of warming that a “perfect” greenhouse can achieve (Fig. 1.17).
How far is the actual situation different from this assumption of a glass sphere which is totally transparent for sunlight and totally absorbing for the IR emissions of the earth? This is illustrated in Fig. 1.17. Here the actual absorption of the atmosphere is shown for the relevant wavelength ranges. The incoming solar radiation is largely distributed across spectral area shaded in light green, whereas the outgoing thermal radiation of the earth is within the red shaded region. The maximum of the incoming radiation is around 0.5 μm and the peak of the outgoing spectrum is around 10 μm wavelength as shown in Fig. 1.14 above and indicated by the arrows.

For the incoming radiation the atmosphere is largely transparent, whereas the outgoing radiation is seriously inhibited by the absorption of mostly water, CO₂, and ozone. Especially CO₂ closes some gaps around 4 μm and 15 μm wavelength near the maximum of the thermal emission, which are left open by water vapor. From this graph it is also apparent that water vapor is actually the major contributor to the greenhouse effect. Since 70% of our planet is covered by oceans, the water concentration in the atmosphere is largely determined by the surface temperature of the oceans. Incidentally, as this temperature rises, the water concentration in the atmosphere will also rise. Influencing or modifying the water vapor content of the atmosphere on a scale that matters is not possible. CO₂, on the other hand is an atmospheric component which can be actively influenced by the amount of fossil fuels we are burning to satisfy our demand for energy. Other gases, such as methane (CH₄) and N₂O are contributing also to the greenhouse...
effect, but at present concentrations to a lesser extent. For methane this could change in the future, if the permafrost in the arctic regions thaws and large amounts of methane are released into the atmosphere in this process.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Concentration</th>
<th>Present Effect on Temperature</th>
<th>Relative Greenhouse Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>2,6%</td>
<td>20°C</td>
<td>60%</td>
</tr>
<tr>
<td>CO₂</td>
<td>387 ppm</td>
<td>8,6°C</td>
<td>26%</td>
</tr>
<tr>
<td>O₃</td>
<td>0,04 ppm</td>
<td>2,3°C</td>
<td>7%</td>
</tr>
<tr>
<td>N₂O</td>
<td>0,32 ppm</td>
<td>1,3°C</td>
<td>4%</td>
</tr>
<tr>
<td>CH₄</td>
<td>1,8 ppm</td>
<td>1°C</td>
<td>3%</td>
</tr>
</tbody>
</table>

The above table lists the relative greenhouse contribution of various gases in the atmosphere quantitatively at the present level of concentration. As these concentrations change, the relative contributions and the importance of these different greenhouse gases for global warming changes. Presently the major sources of CH₄ and N₂O are from agriculture, while CO₂ originates from the burning of fossil fuels.

**CO₂ is not the only reason why we have to eliminate fossil fuels from our energy system**

The emissions from CO₂ have a worldwide effect and impact. Fig. 1.18 illustrates that it is actually only a few countries whose efforts really matter in this respect. The four countries that are the largest CO₂ emitters—China, the United States, India, and Russia—actually account for about 65% of the worldwide emissions. Adding the emissions of all the countries shown in Fig. 1.18 this accounts for more than 80% of the emissions worldwide. Also shown are the per capita emissions of these countries.

**FIGURE 1.18** CO₂ emissions (blue data points and line) of the 14 countries that cause the largest emissions amounting to more than 80% of the worldwide emissions (2018) [6]. Shown in green are the per capita emissions of these countries. Please note that the data is listed as Gt of CO₂, which is 3.7 times larger than the value listed as Gt of C.
capita emissions which exhibit a very large spread and disparity. The per capita emissions can be taken as a rough indicator of the standard of living (see earlier discussions above). By now also the attitude toward saving energy and reducing emissions enters into these numbers.

The efforts of mitigating climate change thus rests upon the shoulders of just a few countries. The United States and China are the worst offenders, but of course also India, having the largest population, belongs to these. Furthermore, industrialized countries with large populations such as Russia, Japan, Germany and Korea also matter. If these countries do not seriously cooperate in the mitigation of climate change or if the upcoming nations with large populations in Southeast Asia and Latin America do not pay attention to climate change when upscaling their energy system, then the climate accord of Paris will fail.

While CO\textsubscript{2} emissions spread rapidly and have a global consequence, there are other reasons and benefits to eliminate fossil fuels, which have a direct local benefit. The reason is that apart from CO\textsubscript{2}, fossil fuels are also responsible for other pollutions such as heavy metal emissions, carbon soot and poisonous gases or carcinogenic substances. The effect of eliminating these pollutants results in immediate local health benefits. Accordingly, every single country should have an incentive to eliminate fossil fuels and in return derive immediate health benefits for its own local population.

**Pollution from coal fired power plants**

CO\textsubscript{2} is a colorless and transparent gas, which is not visible to the human eye, but it is not the only contaminant that is emitted into the atmosphere when burning coal. The emissions from factories, power plants, and car exhaust also are responsible for the accumulation of smog that clouds the air and causes difficulties in breathing or respiratory problems. This is especially evident in the megacities in Asia, as the photo taken in Shanghai (Fig. 1.19) showing the author on a “clear” summer day demonstrates.

![Figure 1.19](image)
Massive air pollution was also very much a problem in Los Angeles in the 1970s and 1980s before more stringent environmental rules were enforced. Many European cities are also violating the clean air standards as set by the European union, if not continuously then at least for a substantial fraction of days during the year.

During the Beijing Olympics in 2008 the Chinese government simply decided to shut down factories, power plants and limited traffic a few weeks prior and during the Olympics in order to improve the air quality for the athletes and visitors. These were drastic measures and not sustainable long term solutions, but its temporary success clearly points to the source of the problem: coal fired power plants, factories, car and truck traffic. In this way, China has demonstrated to the world that if we manage to eliminate these sources of pollution the air quality will certainly improve everywhere in a very short time.

In California there was a substantial move for cleaner air and that has shown a positive effect already. The standards for fuel were raised to contain less nitrogen and sulfur and cities like Los Angeles have drastically changed their utility vehicle fleet to run on cleaner fuels, such as LNG (liquefied natural gas) or to use electric or fuel cell based busses. The city of Los Angeles also shut down coal fired power plants and invested in wind farms. It is very important that cities and public bodies take a leading role in this and do not only put the burden on private citizens and businesses.

Coal fired power plants, especially when running on cheap, surface mined soft coal do not only contribute a lot to the CO\textsubscript{2} emissions but add additional even more dangerous pollutants. Despite all the filters installed into the exhaust gas system, they emit a substantial amount of heavy metals and radioactivity. The radioactivity comes not only from radioactive carbon naturally contained in any carbon material but from radioactive elements, mostly heavy metals. The radioactivity measured at the perimeter of a coal fired power plant is typically a factor of 100 higher than the one measured at the perimeter of a nuclear plant of the same generation capacity. This is often discussed but is nevertheless not a major concern. Radioactivity is all around us in rocks, in Radon emissions from the ground and also in the cosmic radiation from the sun. Actually, in a city such as Denver which is at an altitude of 1650 m above sea level, the radioactivity is about twice as high as in a city located at sea level, because the natural shielding provided by the atmosphere is much smaller. This effect is much more pronounced for airplanes flying at high altitude and on polar routes. While there is a clearly measurable exposure to radiation, it is nevertheless currently not thought of as posing a measurable increased health risk for airline crews or the general population living around power plants.

Returning to coal fired power plants: what really poses a substantial health risk is emissions of heavy metals and mercury. Coal-fired power plants in the United States emitted about 50 tons of mercury into the atmosphere (in 2011). In Germany 10 coal fired power plants emitted more than 3.5 tons of mercury into the atmosphere in 2015 [21,22] (Fig. 1.20). This has to be put into perspective regarding the regulations that energy saving light bulbs, containing a few milligrams of mercury each, have to be processed as toxic waste by the general public. The legally permitted emissions of the power plants in Germany amount to more than 100 million energy saving light bulbs annually. These are
definitely double standards. The effect of mercury is much more local than the CO$_2$ emissions. Mercury emissions make it into the soil and the water system. While plants fortunately do not take up much mercury, the mercury in the water ends up in the fish and seafood, where it accumulates. Consuming fish and seafood it gets into other animals and the human body, where it is also stored.

The other heavy metal emissions of power plants also pose substantial health risks. Arsenic is well known to be toxic, whereas chromium forms some highly carcinogenic substances. This was the subject of the blockbuster movie “Erin Brocovich.” This is why in 2011 the EPA (Environmental Protection Agency) in the United States introduced the MATS (Mercury and Toxics Air Standards) regulations. In 1990, the EPA had already introduced major air quality standards, which resulted in substantial improvements of the mercury and heavy metal emissions from municipal and medical waste incinerators. As documented by the EPA, these new standards resulted in the reduction of emissions by values exceeding 95%. Even though the technology for cleaning the exhaust gases is at hand, the power companies in the United States, through an intense lobbying effort, managed to avoid this regulation until Dec 2011. Then, finally, also the power companies were required to reduce their mercury and toxic pollutant emission by 90% within the next four years. In the course of implementing these new standards from 2012 until 2016 the power companies in the United States shut down coal-generating capacity amounting to about 40 GW, whereas the total remaining capacity amounts to about 260 GW. These were mostly older and smaller units, where the upgrade to the new environmental standards was not cost effective. Unfortunately, the current administration of the United States (2017) obliterated most of the environmental standards established in 2011 by presidential decree in favor of creating more jobs in the coal industry. They clearly were putting some potential economic gains ahead of protecting the health of the people.
While toxic heavy metal emissions are largely associated with burning coal, gas and oil based power plants are not burdened by these emissions on a comparable scale. Nevertheless, in addition to the CO$_2$ emission, there are other pollutants from burning fossil fuels which are also of concern. Foremost among these are small carbon particles, which may be carcinogenic, NO$_x$, and SO$_2$. The source of these emissions are not only the fossil fuel based electric power plants but also residential heating and cooking, agricultural burning, and factories. The transportation sector also contributes a major part to these carbon particle emissions. The residence times of the so called black carbon is substantially shorter than of CO$_2$ and it has a more local effect. More important is the direct effect on human health. Black carbon is one of the major environmental causes of premature deaths and serious health effects globally. In 2010 small carbon particle (PM$_{2.5}$) emissions are estimated to have been the cause of 3.5 million premature deaths worldwide.

There are large regional variations as far as the major sources of these particles are concerned. In Africa and parts of Asia a large source is from cooking fires and oil lamps, whereas in the United States and Europe transportation is contributing to a major extent. The smog that engulfs major cities in Asia is a definite warning sign to take these pollutions seriously. As the actions of the Chinese during the Olympics in Beijing show, local remedies are at hand to eliminate this. While shutting down factories and power plants and banning traffic can only be temporary measures, for stationary installations efficient filter systems can be installed. The emissions from the transportation sector can be cleaned up by changing to a different fuel (LNG, electric drive vehicles) or installing better filters. The incentive to introduce these changes are large and the benefits are fairly immediate and local, even though transport patterns of particle plumes across the Pacific Ocean or from the Sahara to Europe have been observed.

As far as the transport sector is concerned, land-based transport (trucks, buses, passenger vehicles) is responsible for more than 70% of the pollution associated with the transportation sector. Shipping and air traffic make up the smaller part. Unfortunately, all of these sectors are expected to grow and will almost double in energy demand between now and 2050 (see Chapter 4). What can be seen from these future projections is that the demand will be rising and the largest growth is driven by road transportation, with the increase about evenly divided between light duty passenger vehicles and freight trucks. The transportation sector is also mostly dependent on liquid fuels. As we have discussed above, the supply of liquid fuels will last at least for another 50 years and more. The world reserves are still larger than what has been consumed until now. The concern here is essentially the climate change by CO$_2$ emissions and the pollution created from burning fossil fuels. While airplanes and ships, especially on long haul routes, will also in the future depend on liquid fuels, for land based transportation alternative means should be established in order to mitigate climate change and air pollution. Electric rail transport is technologically well established and it certainly could play a much more prominent role in the future for both passenger and even more so for freight transport.
Accumulated health risks of burning fossil fuels

Recently several independent studies were published, which related the emissions from coal-fired power plants with health risks and premature deaths. One was published under the auspices of the World Bank and summarized in the NY Times [22] and another one from the organization HEAL [23]. The European HEAL study cumulated in relating more than 18000 premature deaths/year and health costs ranging between 15 and 43 billion annually to the coal-fired power plants in the 27 countries of the EU. The results of this study are graphically represented in Fig. 1.21. The deaths associated with coal-fired power plants in this study is staggering—it is far more than the number of traffic-related deaths in the same countries. The World Bank study also came up with comparable numbers in “hidden” costs associated with lost productivity or increased health care expenses that the general public has to cover because of the burning of coal for electricity generation. A newer study also clearly relates the incidents of lung cancer across several countries in the world with the total coal power generation in these countries [24].

The economic reality also is very much in tune with these developments. Between April 2011 and March 2016, the stock of the group of the 13 major US coal producers has lost more than 92% of its value, with the companies’ combined market capitalization falling from $62.5 billion to $4.6 billion. The parliament of Norway, controlling the state-owned pension fund with a total investment of about 900 billion US$, has in 2015 publicly voted that they will sell off their investments into companies whose business is more than 30% based on coal. Other worldwide operating financial institutions and insurance companies

![Health Problems from Coal-fired Power Plants in the EU](image)

**FIGURE 1.21** Health problems (annual numbers) associated with electricity generation by coal-fired power plants in Europe. From [24].
have also publicly announced a similar strategy. This raises the question: If the business sector has clearly acknowledged this risk, what are governments doing to protect the health of their citizens?

In Europe and especially Germany there is a lot of lip service by the politicians to a clean environment, but fact is that the large power companies are still not required to refurbish their coal fired plants to reduce mercury and toxic metal emissions. The various governments seem to be more worried about losing jobs in this industry than about protecting the health of their citizens and the environment. As already mentioned above, in the United States, the Trump administration has even obliterated some of the standards imposed by his predecessor.

China has built up huge amounts of coal based electric generating capacity in order to accommodate the economic growth and the increase in the standard of living. But also China has learned its lesson concerning air pollution. The large buildup of coal fired power plants has been capped to limit the total coal based generating capacity to 1100 GW. By the beginning of 2017 this has resulted in cancelling more than 100 projects for power plants with a total generating capacity of 120 GW, about half of these (54 GW) were already under construction.

The trend to divest electric power generation from coal is clearly there, even in countries such as India, which weigh heavily in this development because of their population which exceeds 1.3 billion people. On the other hand, India and several countries in Southeast Asia have established long term contracts with coal mines in Australia, a move very much welcomed and celebrated by the Australian government. In view of these competing business interests there is unfortunately no clear consensus to abandon coal fired power generation and to do what is necessary in accord with the Paris climate agreement.

Electricity as the main power source should also be expanded whenever heating, cooling, and lighting of residential and business infrastructure is concerned. Again, the technology is at hand here but it requires infrastructure developments, mostly into renewable electricity generation and the development of the electrical grid. There is also a major cost driver at present—it is more economical to heat a building using oil or natural gas than using electricity. As long as that persists, there will be little or no incentive to change to another energy source. Raising a carbon tax on this is an appropriate measure, provided it is at a realistic price.

There is hope, though. In 2015 the total installed new power generation capacity of wind and solar power exceeded the installation of new coal fired power plants. Indications are that this trend continues. China alone has installed 34 GW (50GW) of photovoltaics and 18 GW if wind power in 2016 (2017). The 2016 value is almost equal to the total PV generating capacity in Germany, which takes pride in being one of the pioneering countries for renewable energy. The recent actions executed by the German government however have slowed down this process substantially. One important fact to keep in mind however is that the duty factor of these plants differs, a coal fired plant delivers about 8000 full capacity hours/year, whereas for wind and PV this number is substantially lower. In favorable locations this can reach 2000 to 2500 full load hours/year.
Summary: there are many compelling reasons to change our energy supply to a more sustainable and environmentally benign system

Both the increase in the population paired with an increase in the standard of living demand for more energy. So far we have used the abundant deposits of fossil energy to accommodate the vast majority (about 80%) of this demand. These resources are not yet depleted and are projected to be available for the next 50 to 100 years (oil) and for several 100 years as far as gas and coal are concerned. The by-products of this use of fossil energy however are pollution and global climate change. This poses a substantial threat to the health of the people and the health of our planet. Our planet will survive climate change, but the question is what price our society has to pay for the consequences of global climate change. Additionally, the use of oil and gas results in a transfer of huge sums of money into countries that in some cases support terrorism.

All of these are very compelling reasons to change our energy supply away from the use of fossil fuels. This is a huge project, and it has to be undertaken in a way not to disrupt our society and economy. The general guidelines for this change have been formulated in a fairly clear and simple fashion in a report published by the US-Department of Energy (DOE) [25].

**We have to produce electricity without generating of CO$_2$.**

**We have to produce hydrocarbon-based fuels or substitutes in a CO$_2$-neutral way.**

**It certainly will help to improve efficiencies and eliminate losses all along the way.**

In this transition we have to balance the environmental benefits, the security of our energy supply and the economical consequences. This change has to be based upon economically affordable and technologically attractive solutions such that many nations will be stimulated to follow along this path. It is also obvious that the solutions will not be identical for all countries but have to take the geographical and societal circumstances into account.

The appropriate summary for this introductory chapter can also be found by the following quote from the 2020 BP world energy outlook [26]:

“The world is on an unsustainable path. A rapid and sustained fall in carbon emissions is likely to require a series of policy measures, led by a significant increase in carbon prices. These policies may need to be reinforced by shifts in societal behaviors and preferences. Delaying these policy measures and societal shifts may lead to significant economic costs and disruption.”

It is very encouraging to read this statement by the CEO of one of the major oil companies.
Chapter 1 • Population, standard of living, pollution, and climate change

References


Designing the Energy System of the Future