Chapter 2
The Nexus of Energy, Carbon and Water

All living species including the human body consist mainly of carbon and water, or—to be more precise—they consist of hydrocarbons and other chemical compounds that are dominated by the elements carbon, oxygen and hydrogen. So, it is not surprising that the carbon and water cycles are of special importance for mankind. Carbon and water in the form of food and beverage have two very different functions: they supply humans with energy and in addition they are the basic building blocks of the body. Stable, closed loops of water and carbon on our planet guaranteed our survival since the beginning of mankind.

In the modern world, industrial processes, and especially the conventional methods of energy production, require a large amount of carbon and water and destroy the natural cycles. To restore the stable cycles, we need a different energy system.

This chapter will introduce you to the extraordinary magnitude of the world energy problem and explain its link to the anthropogenic climate change, which turns out to be a game changer for the future of our human society. The restoration of the carbon and water cycles will be essential for our survival. New concepts and methods to preserve and provide freshwater and to reverse desertification and climate change are essential to fight drought and hunger of future generations. Seawater desalination and pyrolysis may be key technologies to achieve that.

2.1 The Challenge of the World Energy Supply

Many people discuss solutions to the energy problem, but often they completely underestimate the order of magnitude of the problem and solutions are offered that nicely work at small scale but not at global scale. The average global energy usage

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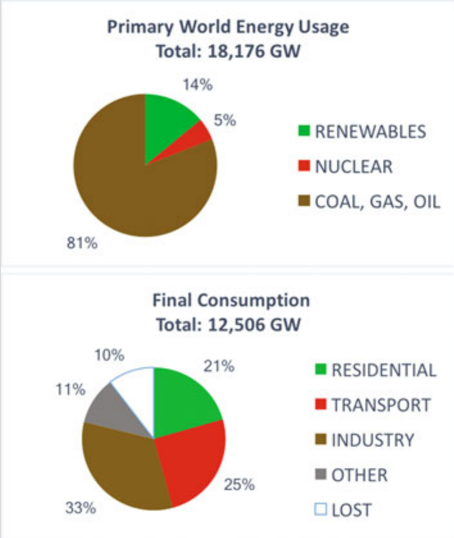
per second is about 18,000 GW, which corresponds to the electrical output of about 18,000 nuclear power plants (see Box 2.1) [1, 2].

The energy consumption per capita is very different for different countries, e.g. it is 9.9 kW/person in the US, 5.5 kW/person in Germany, and 0.9 kW/person in Africa. The world average is $18,000\,\text{GW}/7.3\,\text{billion people} = 2.5\,\text{kW}$ for each human being today. As population increases and in addition also energy consumption per capita increases, energy needs will increase rapidly in future, especially in developing countries where the consumption per capita is very low today. Neglecting this rising energy need per person, and just taking the population rise into account, an increase to 25,000 GW until 2050 is estimated. The claim, that the energy consumption of the western world stays basically constant since decades is partially misleading, as a large fraction of the industrial production of goods for Western countries has been moved to eastern countries, especially to China. To account for the total energy footprint of a society, the energy footprint of imported goods must be assigned to the consumer and not to the producer to get the picture right.

There are three basic types of energy production: nuclear, fossil and renewable. An energy transition must consider not only the additional 7000 GW that must be installed in the next 35 years to cope with the energy increase of the rising world population, but also a large fraction of the existing world infrastructure of 18,000 GW must be replaced in view of the decarbonisation of the power plants. Together, this leads to an enormous rate of more than 1 GW of newly constructed power generation facilities for every day in the next 35 years and beyond. **This is an unprecedented challenge not only in volume but also in speed**. The fundamental limitations—beyond any monetary aspects—will be shortage in basic materials and—especially for nuclear energy—limits in qualified manpower and safety aspects, especially in developing and unstable countries. This leads to the following general conclusion:

The bulk of future power plants must be technically simple and inherently safe!

Box 2.1: The World Energy Usage in Numbers [3]



The average primary world energy usage per second in 2014 was approximately 18,000 GW. 1 GW corresponds approximately to the electrical power of 1 nuclear power station. The renewable contribution of 14% is dominated by the burning of biofuel. The large majority (81%) of the world energy consumption is powered by fossil fuels.

The about 440 existing nuclear power stations count with about 5% to the primary energy in this diagram. However, the total electrical output from these thermo-nuclear reactors is only about 280 GW, which is a fraction of 1.5% of the total 18,000 GW. The 5% number that is usually quoted includes the waste heat production of the nuclear power plants.

The comparison of different energy sources has large ambiguities, as the total energy efficiencies depend strongly on the type of energy carrier and of the application. If nuclear energy or coal is used to produce electric power, the efficiency is 30–50%. If electrical power is used to produce synthetic fuel for a combustion vehicle, the overall efficiency is very low. However, if electricity from a wind power station is used to charge the battery of an electric vehicle, the overall efficiency is about 80% and much higher than in the examples above [4].

The lower panel shows that the main consumers of energy are industry, transport, and residential. The rest is agriculture, public services, etc. About 10% is lost during transport or conversion.

2.2 Nuclear Energy

Nuclear power plants have been preached to be the prime future option of the industrialized countries since the 1950s, but after 65 years of extensive governmental support, nuclear power still covers only about 11% of the global electricity consumption, which is as little as 5% of the total global energy demand [5]. There is a long-lasting debate about the pros and cons of nuclear energy, and most individuals in the field have a strong and fixed opinion with well-defined arguments and counter-arguments that cover the usual spectrum of the debates [6]. In this sense, the reader is invited to skip the following three paragraphs that present the arguments of the author and that are not generally accepted by the nuclear scientific community. Nevertheless, the arguments are scientifically correct.

Even if all technical issues would be solved in future, the nuclear fuel cycle and nuclear power plants will always be subject to terrorism and proliferation [7, 8]. A significant contribution to the global energy problem requires on the order of ten thousand nuclear power plants in all regions of the world, which will be difficult or impossible to control, especially in times of rebellion or war. Recently, an old idea was brought up again by nuclear industry and is discussed by the European Parliament and elsewhere: To build small nuclear reactors in assembly line production in large numbers to make them cheaper. Trucks could ship them to the final user as one piece. The radioactive inventory would be closed in a hermetic containment (except for the unavoidable emission of radioactive gases) and the whole reactor would be recycled when the fuel is used up. This attracting idea is a nightmare for people concerned about terrorism and proliferation, as **any nuclear reactor can be converted into a machine that breeds plutonium** and other fuels for nuclear weapons, and its inventory can also always be used to produce dirty nuclear bombs. Some years ago, another old idea was promoted again, to move from uranium to thorium as primary fuel for nuclear reactors. It was claimed that a thorium reactor has several advantages, one of them is that there is no breeding of plutonium in the regular operation mode of these reactors. Unfortunately, today we know that the breeding of nuclear material for atomic weapons is even easier in certain thorium fuelled reactors than in uranium reactors [9]. From the author's perspective, the following sentence is valid:

Nuclear power has always produced more problems than it has solved.

Many people believe that nuclear **fusion** reactors are the future of energy production, as in principle, a nuclear fusion reactor is a compact device that delivers a huge amount of power from nearly unlimited fuel, which is—depending on the technology—usually deuterium and lithium [10]. There are two technologies feasible. The first technology uses magnetic confinement. It requires cold superconducting magnets in the vicinity of the hot fusion plasma where the energy production takes place. With the advances of modern technology, it is likely that a fusion reactor will be made operational in the coming decades. However, the technological overhead of this type of reactor is so immense, that it is very unlikely that such a reactor will ever become economically competitive, especially as the special materials and expertise will not be available for the fast implementation of these devices in numerous (i.e. several thousand) copies. Due to basic physics limitation, such fusion reactors with magnetic confinement cannot be miniaturised in future.

The second fusion technology uses inertial fusion, and today a promising technology uses a combination of inertial and magnetic confinement. This technology is based on modern laser technology. If it works, it is not unlikely that it can be miniaturized in future due to the immense technical progress of lasers in the pico and femto second regime. The concept of inertial fusion can be compared with the way you make fire with a match: To light the head of a match, there has to be a small hot spot that is generated when the head is struck. Once the temperature at this spot is larger than the ignition temperature of chemical compound (e.g. sulphur), the whole head burns. A priori from the technological point of view a commercial application of inertial fusion appears much more simple compared to the magnetic devices. The danger of this technological development is that the step from inertial fusion towards a new H-bomb technology is small. Once realized, no proliferation treaty will be able to stop the technology from spreading, as it requires no fissionable nuclides to produce such a bomb. Therefore, it is not surprising that today inertial fusion is a domain of military research and mankind will be better off without it: **do not foster a technology that creates more problems than it solves**.

2.2.1 The Sun, Our Nuclear Reactor

Fortunately, there is a nuclear reactor in the vicinity of our planet that produces more than enough energy to keep our human business running as depicted in Fig. 2.1. The sun obtains its energy from a nuclear fusion reaction in its core where hydrogen is fused into helium [11]. As in every nuclear reactor, the nuclear reactions produce a large amount of lethal, ionizing radiation. At a distance of 150,000,000 km we are safe, fortunately. Most of the solar nuclear radiation is re-absorbed in the sun. The only carcinogenic radiation that arrives at the surface of the earth is a low level of cosmic radiation that is part of the cause for genetic mutations in life on earth and keeps Darwinian evolution running. In addition, especially at places where the ozone layer of the earth's atmosphere is destroyed, UV radiation arrives at toxic levels and produces skin cancer.

Fortunately, the earth is still close enough to the sun, so that its radiation can be received by simple technical means like mirrors and solar panels. Solar radiation arrives with a power density of 1.36 GW/km^2 at our atmosphere [12]. Part of it is reflected, but most of it is absorbed by the earth and re-emitted from gases in our warm atmosphere into the cold universe. The energy need of our human society of 16,000 GW is modest compared to the total solar irradiation that arrives on earth,

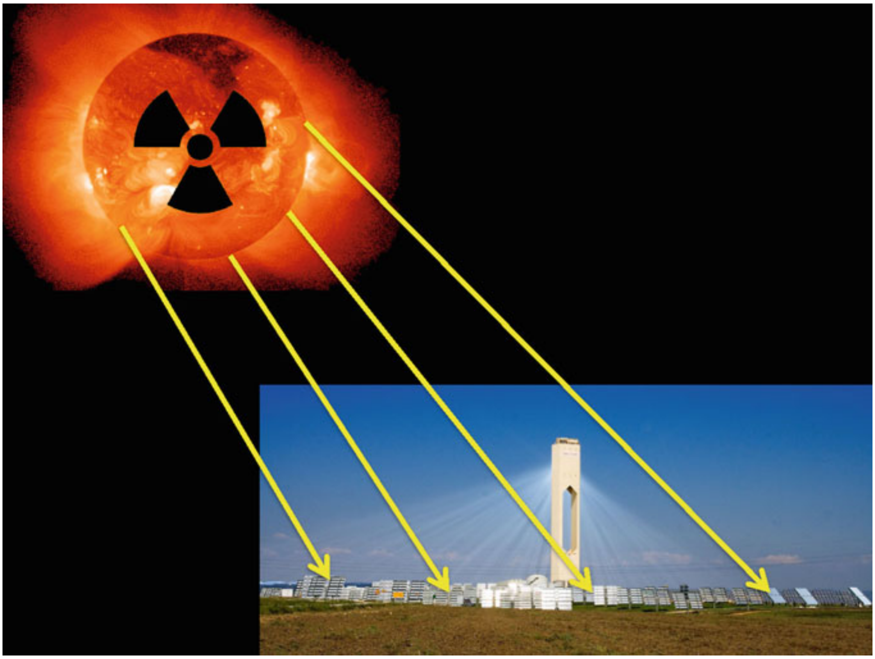


Fig. 2.1 The highly radioactive sun is the fusion reactor of our choice. At a safety distance of 150,000,000 km its radiation is still so intense that this single reactor is enough to satisfy all energy needs of human civilization. Solar devices, like the solar power tower shown in the photo, can easily collect its output energy and convert it into electrical power [13]

which is 170 million GW. This irradiation is the basic source of almost all kinds of renewable energy. Not only energy from solar panels, but also energy from wind, water and biomass originates from the sun.

Also the moon contributes to our spectrum of renewable energies [14]. It is responsible for part of the geothermal heat and part of the maritime energies as tidal forces in the interior of the earth heat up our planet and tidal forces in the oceans keep the oceans moving. Part of the geothermal heat comes from natural nuclear fission and radioactive decays in the interior of our planet [15].

2.2.2 The Future of Our Planet Earth

The earth, being 4.5 billion years old, just arrived in its "mid-life crisis", as the sun will swallow it in about 5 billion years. At that time our nuclear fusion reactor will "blow up" and will expand our sun by a factor of 100 [16]. In this respect, our energy supply is save for the next 4.5 billion years, but after that we should think about moving to another planet.

2.3 The Era of Fossil Fuels

Since the beginning of the industrial age, fossil carbon has been used extensively as energy source for industrial processes, for mobility and for heating purposes. Already in the early days of industrialization, the availability of wood and other biomass was insufficient to cover the rising energy needs. Therefore, an industry has been developed to mine coal and lignite and later also oil and natural gas. Today about 80% of the total primary energy is generated by the combustion of fossil carbon.

But carbon is not only an energy carrier in our modern world; it is also a basic building block in a majority of synthetic industrial products. Almost all gadgets of modern technology contain plastics; all organic chemistry is based on carbon, including drug and certain food production. Huge amounts of hydrocarbons are used to cover our roads with asphalt. After usage, a large fraction of these carbon products will appear as pollution in the environment and in the oceans, and sooner or later they will rot or be combusted and thus reappear as CO_2 in the atmosphere.

Basically all our carbon products (food, fuel, plastics, asphalt, …) originate from photosynthesis in plants. The green parts of plants make use of solar energy to crack CO_2 and H_2O and to construct various new products from carbon, oxygen and hydrogen. Prehistoric photosynthesis has generated large deposits of fossil carbon. These biological processes reduced the concentration of CO_2 in the atmosphere and generated an atmosphere with a large content of oxygen (21%), which was not available in the early days of our planet [17]. It is assumed that formation of coal at large scale stopped after the biological appearance of certain lignicolous fungi [18], which were able to decompose wood by cracking carbohydrates and lignin at the end of the Carboniferous, 300 million years ago. However, recent studies claim that this is not the main reason for the peak of coal production in the Carboniferous, but that instead a unique combination of climate and tectonics during Pangea formation was the reason [19].

The large concentration of O_2 together with the low concentration of CO_2 and CO in the ambient air were prerequisites for the genesis of animals, as they make use of the combustion of organic material (called cell respiration) as energy source for living. It is not surprising that CO_2 and CO are lethal gases, as respiration requires a large gradient of partial pressures between O_2 and CO_2. A CO_2 concentration of 8% leads to unconsciousness and death within less than an hour, and the limits for CO are even much smaller [20]. Due to the production of fossil deposits over hundreds of millions of years, CO_2 has been reduced in our atmosphere to be below 0.03% long before the anatomically modern man, the homo sapiens developed about 200,000 years ago in Africa. Oxygen in combination with a low CO_2 concentration is the chemical prerequisite for a concentrated basal energy rate in biology. One of the organs with large energy expenditure is the brain of mammals. In this sense, the low CO_2 concentration in our atmosphere was a prerequisite for the high-performance brain that gifted humankind with unique

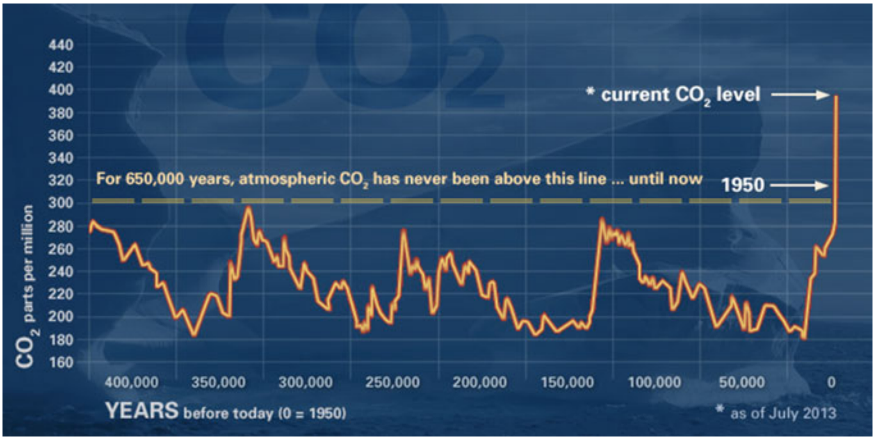


Fig. 2.2 In the last 650,000 years—until 1950—the CO_2 concentration has always been below 300 ppm. Only in the last century, due to the burning of fossil fuels, the CO_2 concentration has risen above its prehistoric values. The periodic structure nicely shows how the CO_2 concentration slowly decreases over typically 50,000–100,000 years, while the earth's climate system transforms into an ice age. The ice age ends abruptly (on geological time scales) due to positive feedback loops of the greenhouse effect [24]

intelligence, and with the abilities of fast learning and the usage of tools, language and fire.

Humans used a 100% renewable energy system for 200,000 years [21], including heating (biomass), mobility (sailing boats, horse-drawn carriage, camels, carrier pigeons, …), machines driven by humans or animals (e.g. oxen in a flour mill) and machines driven by water or wind (wind and water mills) until about 1850 AD during the industrial revolution: At that time man started the usage of coal for running steam engines at large scale [22]. Since then, the balance of the extraction of CO_2 from the atmosphere by photosynthesis and allocation of CO_2 by the decomposition of biomass is disturbed by a steady rising combustion rate of fossil fuels, which brings carbon that has been accumulated in the earth's crust millions of years ago, back to the atmosphere at a rate of currently 17 ppm per decade (see Fig. 2.2) [23].

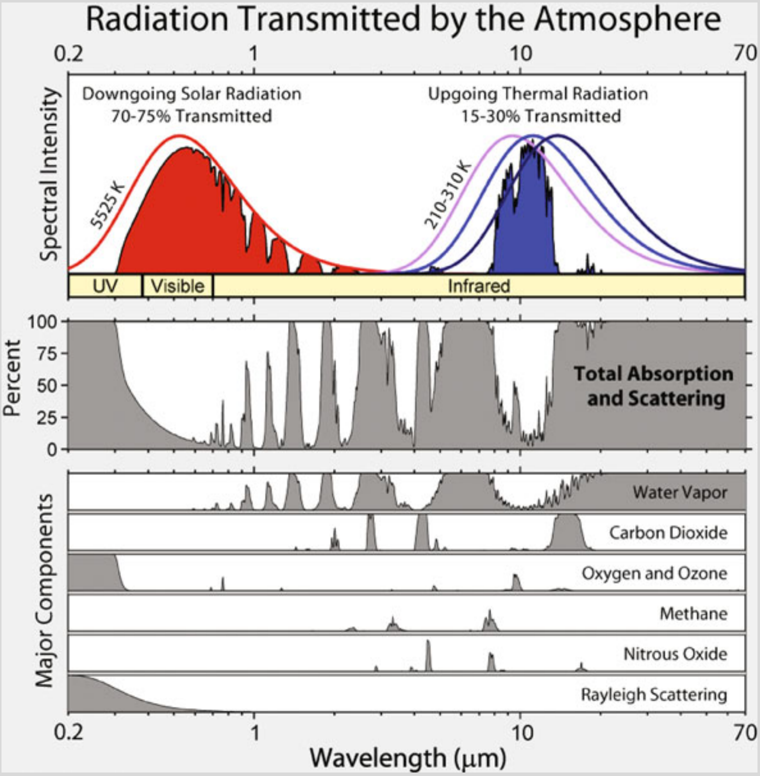
2.4 The Greenhouse Effect and Global Warming

The increased level of CO_2 in today's atmosphere is still far away from a toxic level for all breathing living, but it acts as so-called greenhouse gas. Greenhouse gases are gases that are transparent for visible light, but absorb infrared radiation, just like the glass roof of a greenhouse does. The greenhouse effect is easy to understand (see Box 2.2) [25]: The atmosphere is transparent for visible sunlight; otherwise we would not see the sun during the day. The energy of the sunlight heats up the surface of the earth. If the atmosphere would be transparent for infrared radiation, the earth surface would emit the radiation back to the cold outer space and cool down drastically, just like the first men on the moon experienced it: The temperature during day/night changes by about ±150 °C with an average surface temperature as cold as about −55 °C (depending on the position), even though the moon has the same average distance to the sun as the earth [26]. Because there is a certain percentage of greenhouse gases in our atmosphere, the infrared heat radiation cannot easily escape to the outer space as it is reabsorbed by the greenhouse gas. This absorbed radiation energy heats up the molecules of the greenhouse gas and according to the laws of thermodynamics the heat is transferred to the neighbouring molecules (nitrogen, oxygen,…) of the surrounding air in a second step. Heat radiation is re-emitted isotropically with longer wavelength to either the outer space or back to the earth surface. The fraction of backscattered radiation leads to a significant temperature increase of the lower atmosphere and of our planet's surface.

A major greenhouse gas in the atmosphere is water vapour. Anybody who likes to sleep outside in nature knows that usually a cloudy night is much warmer than a night with a clear sky. But why is CO_2 relevant, even though there is much more H_2O than CO_2 in the air? The reason is that infrared radiation has a broad spectral distribution, and CO_2 is able to block some of those wavelengths which H_2O cannot absorb. The absorption spectrum can be compared with a water dam which is disrupted at a certain position: The water level in the dam does not depend on how high the dam is, but how well the hole is closed where the water can escape. In this sense, the CO_2 concentration is the lever to control the leakage of infrared radiation from our planet.

Even though the greenhouse effect is basic physics and any student who denies it will fail his or her examination, the detailed predictions of the effects of anthropogenic CO_2 emissions required hard and careful work of thousands of scientists. An Intergovernmental Panel on Climate Change (IPCC) [27] was set up to study details and consequences of climate change. Today we know that the anthropogenic CO_2 emissions will cause significant global warming, climate change, extreme weather conditions, and rising sea levels.

Box 2.2: The Greenhouse Effect [28]



Solar Spectrum:

The sun has a temperature of about 5800 °C and radiates electromagnetic waves according to Planck's law (red line in the upper panel). The red area below is the fraction of the light that passes the earth's atmosphere on a clear day and arrives at the ground. It peaks at the visible light and has additional components in the near infrared (heat radiation) and the near ultraviolet. The panel below shows the fraction of light that is absorbed or scattered by the atmosphere. The lowest panels show the contributions from different gases. The absorption of the UV light is mainly due to the ozone layer in the upper atmosphere. The Raleigh Scattering process in air affects the UV and the visible light and is responsible for the blue colour of the sky and the red/orange colour of the sun during sunset. The absorption of infrared radiation mainly comes from water vapour.

Greenhouse Effect:

The sunlight warms up the earth surface. According to Planck's law, every warm body or gas emits thermal radiation. The hotter it is, the more radiation is emitted. An ideal black body emits a spectrum as shown in the upper panel for temperatures between +37 and −63 °C (violet, blue, black lines). Most of the thermal radiation is reabsorbed by the different layers of the atmosphere and reemitted isotropically with a red-shifted spectrum. This way, effectively only a small fraction of the thermal radiation makes it through the whole atmosphere and is emitted to the cold universe (blue area in the upper panel). The gases that reabsorb the thermal radiation are called greenhouse gases, as they act like the glass roof of a greenhouse that lets the sunshine in but blocks the thermal losses. The most important greenhouse gas is water vapour. Carbon dioxide is the second important greenhouse gas as it blocks part of the spectrum where water vapour is transparent and where the thermal spectrum is close to its maximum.

Detailed assessment reports of this panel are available for free and can be regarded as the most detailed and precise summary of human research in this complex field [29]. It is beyond the scope of this book to cover the complex field of climate change, but one plot on climate change should not be missing here: Fig. 2.3 shows the measured global mean temperature in the time since the start of industrialization until today [30]. A significant rise of global temperatures well beyond the short-term fluctuations is indisputable. Model calculations have been used to estimate the effect of global warming on our future living conditions. Usually it is concluded that we need to limit the global mean temperature increase to 2 °C compared to the pre-industrial value because larger values have more disastrous effects on our civilization and the probability will be larger, that the climate system will run out of control into a regime where life on earth might be completely distorted.

2.4.1 *Evil Twins: Global Warming and Ocean Acidification*

A large fraction of the anthropogenic CO_2 is buffered in the oceans as carbonic acid. This acidification will lead to pH-values that are inacceptable for shellfishes and other species of the marine diversity. Many people believe that the acidification of the ocean is a problem that is even more severe than the climate change of the atmosphere, as the ocean is the cradle of life on earth and an essential component in the nutrition cycle of the biosphere [33, 34]. The IPCC is currently discussing to write a special report on "climate change and the oceans and the cryosphere" (SROCC) [35].

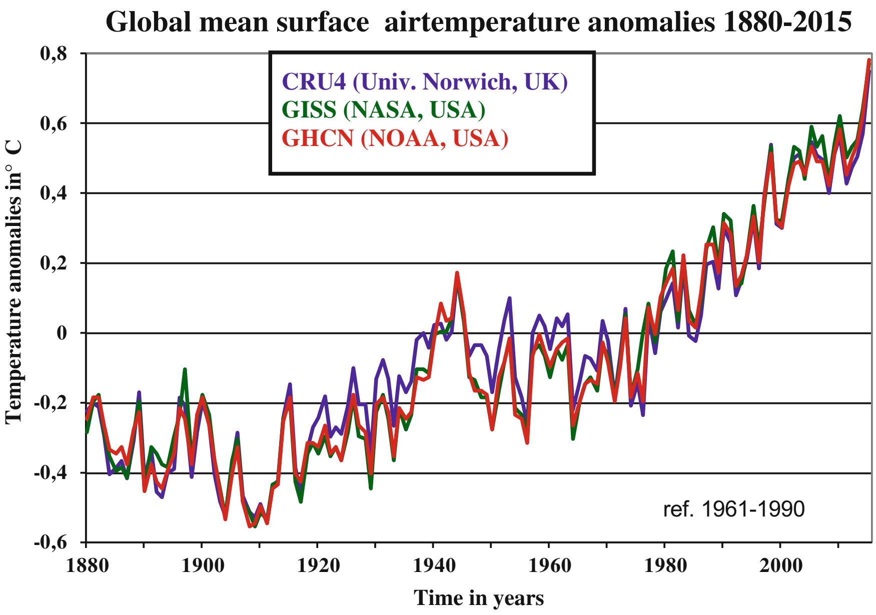


Fig. 2.3 The observed global mean temperatures (land and ocean surface combined) from 1880 to 2015 compared to the average of the years 1961–1990. A significant rise is observed. The 10-year's average went up steadily in the last 40 years and also in the time between the two world wars. The different curves correspond to independent estimates and data sets. The detailed characteristics of these curves are well reproduced by climate simulations [31, 32]

Typically, the biosphere is able to adapt to climate change. You find plants and animals everywhere in the world that have shown amazing abilities to adapt to any extreme condition. However, the problem of the anthropogenic climate change is its speed, as we are observing significant climate changes within decades and not only within thousands of years. We can assume that most of the species will not be able to adapt within a few generations. Secondly, today's nutrition of mankind depends on very few species of highly cultivated plants that are not necessarily resistant against changing external conditions.

If the worst comes to the worst, temperature might even reach tipping points where climate change enters a positive feed-back loop, as it might be the case when for example large amounts of methane are released from permafrost regions or when the oceans become so warm that large amounts of CO_2 are released instead of being buffered. In the history of earth, five events of mass extinction have been identified, the best-known event happened 66 million years ago where about three quarters of all plant and animal species, including the dinosaurs were wiped out because of an abrupt climate change due to an asteroid impact and an associated increase of volcanism [36]. Today we have just started the sixth period of mass extinction. This time it is caused by the expansion of human civilization including deforestation, environmental impacts and climate change [37].

Many scientists doubt that the political 2 °C aim can still be fulfilled. According to simulations, the amount of CO_2 emissions that are already in the atmosphere today will likely lead to a 2.5 °C temperature increase in future, even if combustion of fossil fuels is stopped today completely [38]. In addition, there is room in the climate system of our planet for scenarios, which are much worse than predicted by the mainstream of the climate models [39]. There are several positive feedback mechanisms that create tipping points beyond which global warming rises rapidly.

2.4.2 Evidence for a Self-amplified Global Climate System

Climate research is a complex science and most people cannot comprehend it. To me there is one plot (Fig. 2.4), which I can understand as a physicist, and which tells me that the anthropogenic CO_2 must have a big impact on our future climate. If you are a climate change denier [40], you have four choices: either you say the data are wrong, or you do not agree with the interpretation, or you do not understand it, or you just deny it for reasons of your own choice. In the following, I will try to explain the main conclusions that a person with scientific background can discover in these curves:

(i) The global temperatures show some “rhythmic” changes over the last 800,000 years. These changes correspond to the well-known ice ages with warm periods in between. The temperature changes are global (curves e, f, g) and correlate with the sea level that shows changes of up to 100 m.

(ii) The concentration of CO_2 in the atmosphere (curve d) is strongly correlated with the global mean temperature. This alone does not say if CO_2 is the cause of the high temperature, or if the high temperature is the cause for the CO_2 concentration.

(iii) Where does the “rhythm” come from? Is this an internal “clock” of our planet or is the rhythm coming from outside? Looking at the planetary motion (curves a, b, c), it is obvious that there is a correlation between the planetary parameters and the global temperature. Whenever the precession (c) starts to oscillate with increasing amplitude, the ice ages come to an end and temperatures (e, f, g) increase. The so-called Milankovitch cycles [41] cause a change of the intensity and direction of the solar irradiation, due to the change of the distance between sun and earth and due to precession of the rotating planet earth. Obviously, the change of solar irradiation triggers the rhythm of the global temperature.

(iv) The most important observation is the following: The planetary motions are rather smooth and time-symmetric: There is no systematic difference in the curve if you read it forward or backward in time. However, all the climate curves are not symmetric in time: All the curves have a tendency for a steep rise and a smooth fall. This is true for the main peaks and for most of the intermediate peaks. If the sun is really the driving force of the climate, you

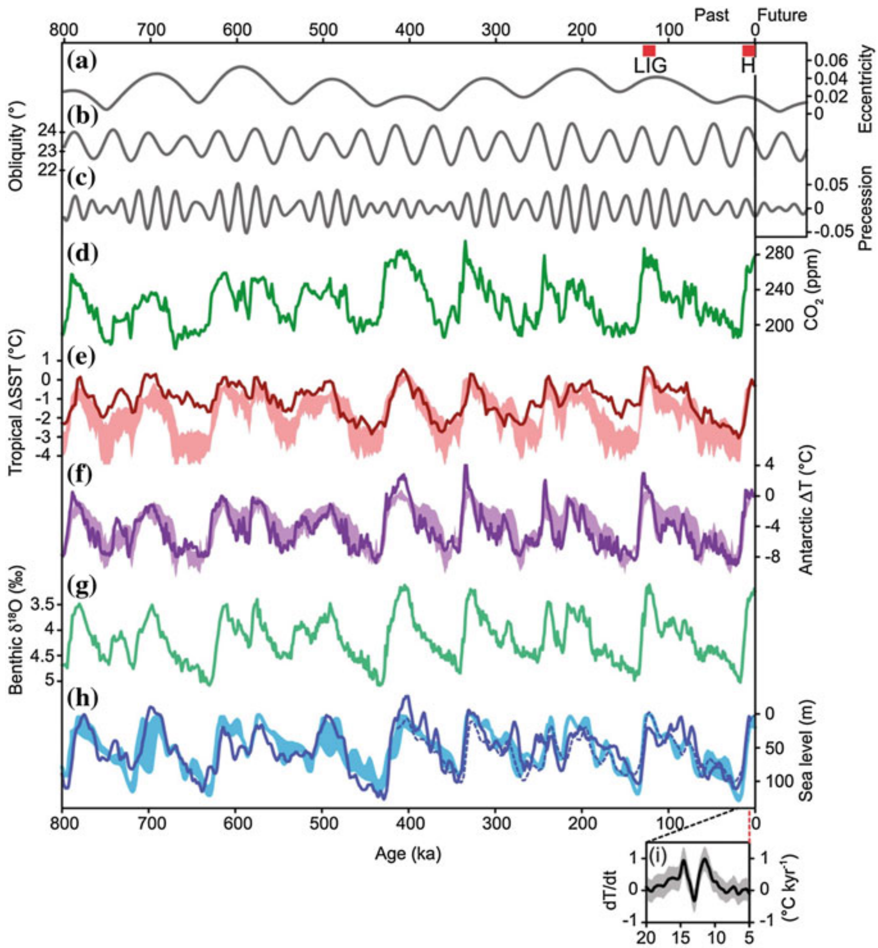


Fig. 2.4 The global climate parameters of the last 800,000 years. Driving force of the earth's climate system is the solar irradiation. The curves **a**–**c** show the orbital parameters of the planet earth that define the intensity and orientation of the sunlight for the past 800,000 and the future 50,000 years. The coloured lines show following experimental data: **d** The atmospheric concentration of CO_2 from ice cores; **e** The tropical sea surface temperature; **f** The Antarctic temperature based on ice cores; (g): The ^{18}O concentration of benthic deposits that are a measure for the deep-ocean temperature and the size of the polar ice-shields. **h** The reconstructed sea level. The lines are reconstructed measurements and the shaded areas are results of climate simulations that use the orbit parameters (**a**–**c**) as input [42]

normally would expect to have some kind of proportionality between the cause and the effect. What is happening here? The answer will be given below this list.

(v) The shaded lines show results of the climate simulations. It is amazing how well the simulation can reproduce the complex reality of the last 800,000 years.

How can we explain the sharp rise of temperature at the end of the ice-ages and the slow fall back to the next ice-age? The synchronicity with the solar forcing of the Milankovitch cycles leaves only one explanation: The global temperature rise is triggered by increased solar radiation, but it is not proportional to the solar forcing. Instead, temperature rises very fast due to internal mechanisms of our planet, according to the plot with a speed of about 1 °C in less than 1000 years. Once it reaches its maximum it falls slowly over 50,000 years back to the next ice age. The earth behaves like a sleeping tiger that you hit with a cudgel: it jumps up immediately and takes a long time to fall asleep again.

This kind of behaviour is well known in physics from all kind of non-linear feedback systems [43]. It means that the climate system on the earth must have a large self-amplification. In this picture, the ice-age is the ground level. A small external signal is over amplified and produces a large temperature rise. Due to saturation of the feed-back system, the temperature falls slowly back to the ground level.

From our physical knowledge, we know that the greenhouse gases and their deposits in the oceans and the permafrost regions exactly produce the kind of non-linear behaviour that we see in the historic data. One of the dominating feedback mechanisms is that the ocean releases CO_2 when the temperature rises and that the temperature rises when the CO_2 concentration of the atmosphere increases. In such a coupled system, it does not make sense to ask the question if CO_2-increase is the cause or the result of climate change. It can be both.

It is nice to see that modern climate simulations confirm this and many other feedback mechanisms, but for a scientist it is always convincing to see the basic behaviour also directly in the experimental data without the involvement of complex calculations.

2.4.3 Tipping Points that May Screw up Our Future on This Planet

Figure 2.4 shows that the CO_2 concentration and the global temperature followed each other during the last 800,000 years where the total amount of CO_2 of ocean, biosphere and atmosphere in sum must have been basically constant as the majority of fossil carbon was deposited more than 300 million years ago. Today, this "sum rule" is broken, as large deposits of fossil fuels are released to the atmosphere. The slow change of insolation on the scale of thousand years and the arrival of the next ice age become secondary for our today's life. Instead the increase of atmospheric CO_2 concentration can be the trigger for a temperature increase within decades, followed by whatever feedback mechanisms are available to reinforce the effect [44].

In the picture of the sleeping tiger that I introduced above, it would mean that the tiger was hit by the cudgel 12,000 years ago at the end of the last ice age. It jumped up, and today, while it is still excited, we continue to hit him with the fossil cudgel that was hidden in the ground 300 million years ago. When we recall that at those times the global mean temperature fluctuated by more than 15 °C [45, 46], we should not be so confident that we will manage to keep our global warming problem within the anticipated 2 °C with the fossil cudgel in our hands.

Here a few examples of climate tipping points that might surprise us in future:

(i) If a glacier (e.g. in Greenland) starts to melt, it melts at the surface, meaning that all the dust that is included in the snow will show up as a dark sandy layer on top of the surface. This decreases the albedo of the surface, more sunlight will be absorbed, the ice will melt faster and the temperature increases until all the ice is melted. A globe without ice will have a small albedo and will persist in the state of high temperature.

(ii) When a permafrost region melts, a lot of methane from ancient biological disintegration processes is released. This methane acts as additional greenhouse gas that will increase the global temperature rise until all the methane is evaporated.

(iii) The oceans on earth have distinct flow patterns that are driven by gradients of salt and temperature, and by evaporation. They are hard to calculate and are a result of the asymmetric distribution of the continents and of centrifugal and Coriolis forces due to the spin of our planet. These flow patterns strongly influence the climate on our earth, especially also the yearly patterns of rain. One of them is the Atlantic Gulf Stream that is responsible for the mild climate of Western Europe. There are estimates that changes of the Arctic ice pack can modify or stop it.

(iv) The most dangerous example: the cold and deep ocean water has stored a large amount of CO_2 as carbonic acid. Once the water starts to warm up, it will release an amount of CO_2 at rates that are rising with the temperature. This leads to a positive feedback of the greenhouse effect until equilibrium at a much higher global temperature level is reached.

To conclude: it will be hard to keep the climate in the 2 °C limit, and feedback mechanisms and tipping points might accelerate the warming in a way that is hard to predict. The later we start, the higher is the risk to reach tipping points which are irreversible in timescales of hundreds or thousands of years. Therefore, we have to try as hard and as fast as possible to bring the massive emission of greenhouse gases to an end now, and to reverse it in distant future.

2.5 How to Stop Climate Change?

The combustion of fossil fuels at large scale is causing climate change due to the atmospheric greenhouse effect. This has been pointed out already in 1987 by the energy working group in the German Physical Society (DPG) as follows [47]:

> The climate change caused by trace gases (i.e. CO_2) will not give notice in a spectacular way, but it will come to appearance gradually in the course of decades. Once it becomes clearly visible, no mitigation will be possible any more. … Climate change is - apart from a war with nuclear weapons - one of the greatest threats to humanity.

Despite this clear message, it took about 20 years and thousands of scientists working on the confirmation of these statements against the agenda of powerful multinational companies and governments. According to the IPCC we are now 95% certain that human activity is the cause of the current global warming. The longer we wait with reducing greenhouse gas emissions, the more severe will be the impact for people and ecosystems. IPCC concludes that the climate system is likely to remain stable when we limit global warming to 1.5 or 2 °C above the temperature of the preindustrial value. Above these limits, key risks like drought related water and food shortage, damage from river and coastal floods, heat-related human mortality, vector-borne diseases, economic instability, and many others will be very high and hard to adapt [48].

After many years of ups and downs in the United Nations Climate Change Conferences, the 21st Conference of Parties (COP-21) in 2015 in Paris found consensus of all 195 participating countries and agreed to a global pact, the Paris Agreement, to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2 °C" [49]. The statement is certainly vague, but it seems to represent an official turning point of the political world leaders. Already a few months later, on October 4, 2016, the threshold for adoption was reached with over 55 countries ratifying the agreement. These countries represent more than 55% of the world's greenhouse gas emissions.

2.5.1 Fossil Options

The consequence is that a major fraction of fossil fuels has to stay under ground. This message is a threat to all the rich and powerful owners of coalmines and oil and gas fields. Many people believe that a ban of fossils equals an expropriation and is therefore illegal, or at least compensation money would have to be paid to the owners. To the opinion of the author this judicial argument is wrong. Instead, the owners of fossil fuels have to realize that fossil resources are harmful and have no value in the human community anymore. Today, fossils are recognized as toxic and dangerous substances. The fact that a significant fraction of the known and easy to haul fuels has to stay in ground means indirectly that globally it does not make sense and it is even counterproductive to look for additional (and expensive) fossil resources (e.g. in arctic regions) or to impose novel methods (like fracking) to increase the amount of disposable fossil fuels. The devaluation is not restricted to the fossil fuels themselves, but also to the infrastructure that is related to it. It can be expected that there will be a sudden stock market crash of the conventional energy market one day, including certain pipelines, distribution systems, refineries, and conventional power plants. Also the end user will have to say goodbye to his fossil heating system and his beloved gasoline operated car one day.

Often it is claimed that carbon capture and storage (CCS) [50] is a way out of the dilemma. This argument, which has been used by fossil industries to acquire large amounts of renewable energy research money, has two counter arguments: A significant fraction of fossil fuels is burned in small and/or mobile burners and there is no technology available to collect CO_2 from these devices. Secondly, also here the scale argument is the show stopper: Today's emissions are about 100 Megatons of the toxic CO_2 gas every day. The mass and volume of liquid CO_2 is 3–4 times larger than the corresponding coal that has been burned. To be relevant on the global scale, a large fraction of that would have to be transported to subsoil caverns and stored in a safe and everlasting manner.

Keeping in mind that 1 litre of liquid CO_2 is enough to kill all breathing life in a closed room without ventilation, one can imagine that safety aspects will boost the costs of this technology. There have been many accidents in the past when people handle CO_2 e.g. in the form of dry ice, or when they get in contact with CO_2 in combustion or fermentation processes. CO_2 has the nasty properties that, due to its high molecular mass, it accumulates in depressions, cellars, caves or subsoil, it is odourless, and it makes unconsciousness without that the affected persons realize it.

To conclude, there is no indication that CCS at large scale will be feasible and economic one day, and fossils cannot be regarded as a future option of a sustainable energy system.

2.5.2 Transition to Renewable Energies

A global renewable energy system is the only remaining, sustainable option for our planet to solve the energy problem and to stop the anthropogenic climate change. Designing such a system is the main subject of this paper. A simple free economy will not be able to account for the energy challenge, as e.g. the risks of terrorism on nuclear facilities or the long-term destruction by climate change are not priced and therefore cannot be handled by a free market [51]. As a first step towards a successful energy transition, politics must take actions to internalize at least all the external and long-term costs of the energy systems that can be quantified today [52]. However, due to the complexity of the global system and the time pressure due to the growth of the global population and its energy demand, market mechanisms will not be sufficient. At least that is the conclusion of the author and there is no prove of the opposite of this statement. A global policy has to be established to direct economy into certain preferred, sustainable roads, under the guidance of scientific scenarios that reproduce and quantify the complex global requirements.

These scientific models will have to include the availability of raw materials, as there is not only a global energy problem, but also a global limitation of raw materials. For example, a global energy system design has to account for the limited availability of certain rare earths for PV technology or for the extended use of copper for transmission lines. It also has to involve socio-economic factors that are beyond technical considerations. It was a hard lecture for me as a scientist to realize, that a colleague from the history department was right when he predicted the "failure" of the anticipated realization of the DESERTEC concept already at a time when I still was enthusiastic about it [53–57]. History tells us that the complex human societies follow rules that are normally not in the repertoire of a natural scientist. Another major complication is that the timescale of the energy transition has to be decades rather than centuries. If we continue now with business as usual, many regions of the world will be affected already in the coming decades. Taking all that into account, we conclude as follows:

The global energy transition is a non-trivial challenge to the intelligence and ethics of the human species.

2.6 The Carbon Cycle in a Sustainable Future

As mentioned above, the carbon atom is a basic building block of the human body, of our food and of all organic chemistry. As fossil fuel consumption changed the natural carbon cycle, it is important to understand the cycle in detail and to have a plan to control it in future [58]. Box 2.3 shows a possible conceptual design for a carbon cycle in a sustainable future. The cycle contains two kinds of deposits for carbon:

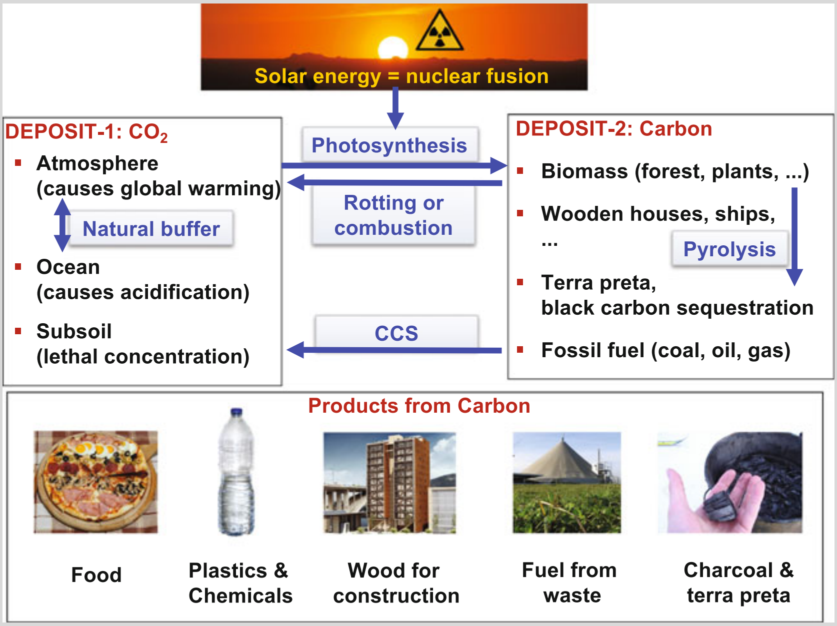
Deposit-1: The chemically very stable and quite inert state of carbon that is bound in CO_2 or HCO_3^- molecules. It contains very little chemical energy and is naturally deposited in our atmosphere as gas or solved in the oceans as carbonic acid.

Deposit-2: The states of pure carbon, hydrocarbons, or other organic molecules that are chemically reactive (coal, oil, natural gas, and also wood and biomass). They contain a lot of chemical energy that is released when they are oxidized in chemical reactions, for example in living cells, in fuel cells, or simply burned in combustion engines or bush fires.

Deposit-1 existed on earth since its creation, whereas Deposit-2 is of biological origin. It contains all the fossil fuels, most of which were formed in the Carboniferous 300 million years ago [59]. A significant fraction of the fossil Deposit-2 has been burned within the last 150 years and brought back to the original state. In a sustainable world, the remaining rest has to stay untouched in the ground in order not to accelerate climate change.

Photosynthesis takes carbon from Deposit-1 and produces biomass from it. In the history of our planet, Deposit-1 has been reduced in our atmosphere by photosynthesis down to a level below 300 ppm and stayed there over hundreds of thousands of years. Only within the last 150 years the concentration increased by about 30% to a value of 400 ppm (see Fig. 2.2). Carbon is the raw material for all organic compounds, and it is also an energy carrier. Today, newly created carbon from biomass will almost always return to Deposit-1 after months or years either by rotting or by combustion.

Box 2.3: The Carbon Cycle in a Sustainable Future [60]



Photosynthesis uses nuclear fusion energy of the sun to produce biomass from CO_2. Sooner or later the generated biomass is rotting or combusted and the carbon is brought back to the atmosphere as CO_2.

The burning of fossil fuels at large scale in the last 100 years brought more and more CO_2 into the atmosphere. This additional CO_2 causes global warming. The oceans act as chemical buffer for CO_2. If the concentration of CO_2 increases in the atmosphere, part of it is absorbed as carbonic acid and leads to a decrease of the pH value of the ocean and endangers marine life. The saturation of CO_2 in the ocean depends on temperature: if the ocean gets warmer, it releases a surplus of CO_2 back to the atmosphere. This way a positive feedback mechanism starts to work that may lead to an unstoppable cycle of 1: release of CO_2 from the ocean, 2: increase of the greenhouse effect of the atmosphere, 3: heating of the ocean due to global warming and again 1: …, and so on.

Carbon is of immense importance for our human life as our food consists chemically mainly of carbon and water (C, O, and H). Food is needed to generate the building blocks of our bodies and it gives us energy for living. Therefore, priority 1 for the usage of biomass must be food production. Priority 2 should be the usage of carbon as building block in industry as organic chemistry will have to replace fossil resources by biomass in a sustainable future. In addition, biomass can be used for construction. Especially wood is a universal natural material for the construction of houses, furniture, bridges etc.

Pyrolysis is a way to produce charcoal from organic material. It allows to re-use of all kind of organic waste including plastics and faeces. Charcoal can be used as ingredient for agriculture to improve the soil. In addition, it can be brought out on fields or in deserts as a safe way of carbon sequestration to make amends for the burning of fossil fuels in the past. The use of the CCS technology, where the exhaust gas from burning fossil fuels is stored subsoil is not an option to circumvent the energy transition as it creates new long-term risks when it is applied at large scale.

Only as a last option, biomass should be used as fuel. There are many alternative energy carriers available that are not in competition with nutrition.

There are many options for mankind to make use of biomass. The most important one is food production. There is no humanistic alternative to feeding the future world of 10 billion people by an extended production of food, i.e. biomass. The "food or fuel" discussion clearly showed that food must have priority [61]. The second most important option is to use biomass as building block for industry, because for many applications carbon is needed as raw material (e.g. for all plastic products). A lot of industrial products can be recycled, but there will always be inefficiencies in the industrial recycling processes that lead to large losses of the material budget [62]. Carbon from biomass will have to fill the gap of the carbon recycling losses in future. Only as a last option, biomass should be used as energy carrier because there are plenty of alternative energy sources and carriers available.

2.7 Reversing Climate Change

Due to the sins of the fossil era, there is too much CO_2 in Deposit-1 and it would be desirable to bring the carbon back to Deposit-2, in other words, we should bring the CO_2 concentration in the atmosphere back to pre-industrial values in the far future. There are basically three natural ways to do it:

1. Reforestation and recultivation
2. Use of organic construction material
3. Black carbon sequestration.

First of all, deforestation has to be reversed to increase the total amount of living biomass back to the old values. Of special importance is to stop the fire clearance of the rain forests and to start to rebuild them wherever possible. The expansion of deserts and drylands has to be stopped and reversed and the size of the humus layer has to be increased wherever possible.

Secondly, we should use wood and other natural organic materials as construction material for houses, furniture, ships, bridges etc., because this way we preserve the biomass from rotting which means that we obtain a negative carbon footprint as long as these objects remain intact. Nowadays it is possible to construct high-rise buildings in hybrid technology that contain a large fraction of wood, that are fire safe, and that can last for 100 years [63, 64]. As a curiosity, it should be mentioned that even windows can be made of wood nowadays [65]. These wooden windows are made transparent by extracting the lignin by chemical treatment. Their thermal insulation is even better than that of glass.

2.7.1 Black Carbon Sequestration

The third and very interesting option is black carbon sequestration. Usually we talk about carbon sequestration in the context of Carbon Capture and Storage (CCS) when CO_2 is captured at the exhaust of a fossil power plant and stored subsoil or in deep sea. As mentioned above, CCS stores a substance that brings death to all animals and people when a concentration close to 5% or higher is reached and we do not expect that CCS technology will work in a safe way on the scale of many Giga-tons every year.

Black carbon sequestration stores solid carbon instead of CO_2. It effectively brings the coal that we burned in the last decades back into the ground [66]. Black carbon is a completely safe material that can be brought out anywhere. Due to the mass differences of the stored molecules, the amount of storage material of black carbon compared to CCS is reduced by up to 73%. But how do we make solid carbon?

Pyrolysis [67] is the key technology for black carbon sequestration. It denotes the thermo-chemical decomposition of organic material at high temperatures under the absence of oxygen. It is a process that produces charcoal and burnable syngas. The syngas can be used to produce hydrogen, synthetic natural gas (SNG), other synthetic fuels, or it is used in situ to keep the pyrolysis process running.

Pyrolysis is one of the oldest human crafts. Historically, and still today, charcoal is used as energy carrier for cooking, especially for barbecues, but also for industrial production. The charcoal can be brought out on fields or deserts to act as carbon storage in unlimited quanta. Depending on the type of soil and charcoal, the lifetime of charcoal can extend hundreds of years before it decays due to microorganisms.

Agriculture will have to be re-thought to become sustainable at large scale again. Good soil is a valuable good and the most important prerequisite of food and biomass production. In many regions, today's industrialized agriculture depletes the humus layer instead of building it up. Charcoal with its large internal surface, its capability to sponge up water, and its broad range of minerals is known as an excellent habitat for microorganisms and as an additive in agriculture to improve the fertility of soil [68]. Pre-historically, charcoal appeared naturally in every forest and bush fire. More than 2000 years ago, the advanced civilization of the Indians in the Amazon basin recognized the value of charcoal. They produced terra preta, a fertile soil generated by mixing the poor soil of the jungle with charcoal and excrements [69].

Today, many regions have problems with over-fertilisation or harmful substances (e.g. heavy metal legacies) in farmland. If charcoal is brought out on fields and deserts in an industrial scale, special attention is required as charcoal may reduce or increase this problem.

In summary, pyrolysis of biomass has four important application areas: The usage of charcoal in agriculture, the option of safe black carbon sequestration, the production of base material for organic chemistry and the production of synthetic fuels including hydrogen.

2.8 Water, the Elixir of Life

Water is the elixir No. 1 of life. Water inside a living body is used for the transportation of molecules and as electrolyte, i.e. for the transportation of electrical charges. Trees are amazing examples as they transport minerals and water from the roots to the top, in some cases more than 100 m upwards, using vapour pressure of water at ambient temperature in leaves as driving force. Life started in the oceans and was adapted to the limited salt concentration there. So why is it, that we need freshwater to survive and to do agriculture?

The architecture of life uses cell membranes, filled with pressurized water, as basic building blocks [70, 71]. Where does the pressure come from? The pressure is an osmotic phenomenon of the ion-rich cell content compared to an environment of water with lower salt concentration [72]. When plants and animals started to populate the land, the osmotic pressure had to be large enough to carry the much larger weight of the beings on land. This might be the reason why their organisms adjusted to the supply of freshwater with low salt content. Pressures up to 4 MPa are present in plant cells, which is 20 times the pressure of a car tire. Without regular drinking of freshwater, humans start to suffer of dehydration. A loss of 10% of the body water will have serious effects on the body, and after typically three days without drinking, a person will die.

Life on land has always been supplied with freshwater from the global water cycle [73]: The solar radiation evaporates surface water, especially from the ocean, and it evaporates humidity from plants, especially in rain forests. A complex system of winds carries the vapour around the planet, and, depending as well on the weather conditions as also on the amount of condensation nuclei from dust, spores, chemical radicals and ionizing cosmic rays, the vapour condensates and clouds are formed. Finally, rain, snow or hail are produced. Precipitation, melting snow and glaciers, water-sucking soil, wells, rivers and lakes are the natural freshwater suppliers for all living beings. Plants and animals in dry areas have accustomed to low fresh water supply and many species of plants and animals are able to store water in their bodies to be prepared for dry seasons. One of these astonishing species is the camel [74] that is able to drink a large amount of water in short time (kind of 200 litres in 3 min) and store it in the blood circulation system with specially adapted red blood cells. It is also able to resorb water through breathing of humid air. The broad cutaneous pads at their feed are ideal for walking in the sand, however they were originally developed as “show shoes”. Camels originate from ancestors living in the hostile and cold arctic snow deserts [75].

There are complex relations between water and climate. Here a few examples.

(i) Water vapour is an important greenhouse gas that blocks certain wavelengths in the infrared region. As mentioned above, only the combination of H_2O and CO_2 is able to block the earth’s emission of heat radiation through the atmosphere in almost the entire relevant infrared region and is thus responsible for the moderate temperatures on planet earth due to the induced greenhouse effect. Without greenhouse effect, the average global temperature of the earth would be about −15 °C.

(ii) Clouds, glaciers and snow affect the global temperature by increasing the albedo of the planet earth while surface water and vegetation reduces it.

(iii) The water in the oceans is a huge thermal energy buffer and the circulations in the oceans affect significantly the global temperature distribution. A well-known example is the mild Western European winter temperature, which is a result of the Atlantic Gulf stream.

For a better understanding of the water and climate cycles, all these effects have been simulated in detail in climate models, which have been and still are a major, non-trivial task.

2.9 Fossil Water and Desertification

In our industrialized world, water became a traded good. In many regions, natural freshwater is not potable due to pollution by faeces, fertilizers, road-salt, mining, industrial waste or environmental disasters. The main consumer of water is agriculture. Especially in dry regions, the extensive exploitation of water leads to a depression of the ground water level and to an ebbing of natural sources. Irrigation with mineral-rich water leads to salinization of the soil in drylands.

Modern technology allows to access fossil water reservoirs, which have been formed thousands or millions of years ago and are basically disconnected from the global water cycle since then. The largest single project in this respect is the “Great

Man-Made River Project” [76] in Libya where 2820 km underground pipes with cross sections of up to 4 meters have been installed to supply the coastal regions and the large cities of Libya with 6.5 million m^3/day of fossil water from the last ice age. While the government had claimed that this source would last for up to 5000 years, international experts predict a lifetime somewhere between 30 and 200 years, showing clearly that this is not a sustainable source of water.

The progressive desertification that is observed in many continents is anthropogenic. Causes are deforestation followed by soil erosion due to wind or water, salinization by irrigation, and last not least climate change. Overgrazing is claimed to be another reason for desertification. This statement must be taken with caution, as prehistoric lands used to support large herds of wildlife, like buffalos, gnus, elephants, and—in prehistoric times—herds of dinosaurs. Despite the fact that the land is devastated if large herds pass by, these roving herds had important functions in fertilizing and stabilizing the soil and renewing the vegetation. It has been shown in field studies that a controlled nomadic grazing by large herds is a mean to reverse desertification [77].

Today, drylands cover as much as about 40% of the earth’s land surface (see Fig. 2.5). This shows the importance of integrating deserts and drylands into a global energy and nutrition system.

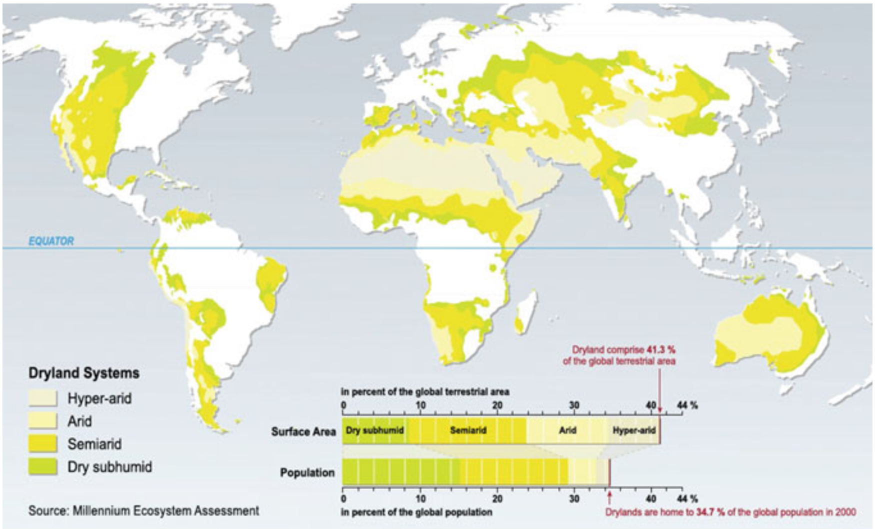


Fig. 2.5 Drylands cover about 40% of the earth’s land surface today. The expansion of deserts and drylands has to be stopped and reversed. Means must be found to use the area for agriculture and/or energy production [78]

2.10 Technical Options of Fresh Water Supply

The nexus of water security, agriculture and energy supply has a long tradition. Starting with terrace cultivation, small barrier lakes, aqueducts and watermills, technology is very advanced today and uses massive concrete dams, long water pipelines and modern hydroelectric turbines. It combines a solution for the supply and the regulation of freshwater and the generation of hydroelectric energy. The most recent large-scale project is the *Three Gorges Dam* [79] in China with an installed power of currently 18 GW. Box 2.4 illustrates the most important interconnections of water management. There are basically five options available to handle water scarcity:

2.10.1 Water Collection and Storage

Today, in many regions artificial barrier lakes regulate water for agriculture. In areas where not enough fresh water is available over the whole year, this option is not sufficient.

2.10.2 Water Saving

The potential of water saving is large. Water consumption in agriculture can be reduced by special irrigation methods and by using foil tunnels or greenhouses. Water usage also depends strongly on the kind of crops that are grown.

2.10.3 Water Recycling

The reuse of waste water by all kinds of water treatment is already done at large scale, especially in big cities along rivers, where freshwater is obtained from river filtrate [80]. This way, the wastewater of one city is used as freshwater in the downstream city, over and over again. Using modern filtration methods, wastewater can be recycled almost 100%, which is shown in astronautics where the people effectively drink their own urine. However, due to evaporation and percolation, water recycling is limited in agriculture.

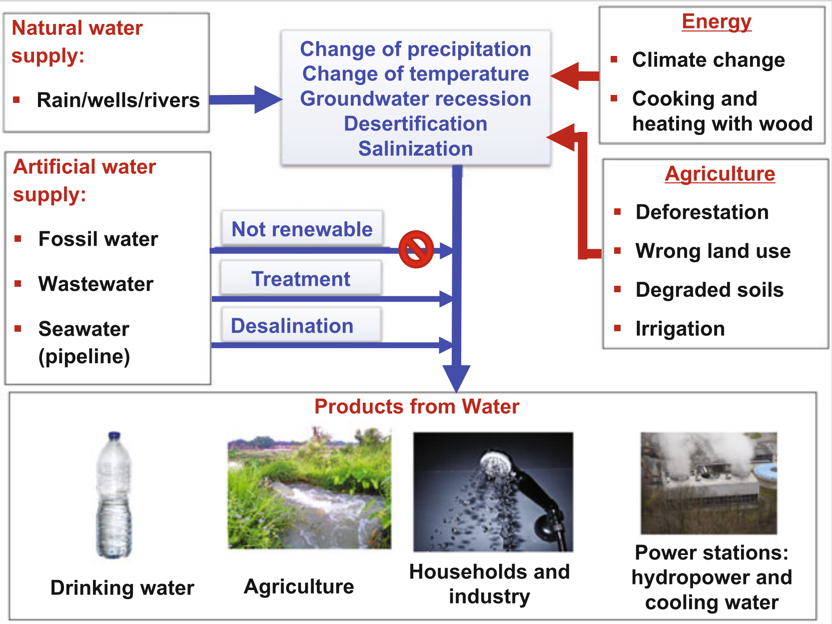
2.10.4 Water from Humidity

Theoretically, a technical way-out of water scarcity is to extract freshwater from humid air as some plants and animals do. Due to the small amount of water in the air, the extraction of water from air is only an option for drinking water in special regions, but not applicable for agriculture at larger scale in arid regions.

2.10.5 Seawater Desalination

The last technical option, seawater desalination, is an expanding field of growing importance and will be described in more detail below.

Box 2.4: The Water Cycle in a Sustainable Future [81]



Water became a traded good in our civilization. Water is essential for our survival as drinking water and for agriculture. In addition, modern society needs a lot of water in households and industry.

The original supply by rain, wells and rivers is degraded in many regions of the world due to groundwater recession, desertification, salinization, contamination, and in general due to climate changes that affect the yearly patterns of precipitation, humidity and temperature.

Energy industry has a complex role in the water business. Hydropower stations often serve a dual purpose as energy supply and to regulate the yearly supply of water for agriculture. In contrast, fossil and nuclear power stations have a negative impact, as they require a lot of cooling water and are in competition with agriculture in arid regions of the world. In addition, the fossil energy industry is the main cause of the anthropogenic climate change.

Cooking and heating with wood as energy source and the expansion of industrial scale agriculture lead to deforestation, degraded soils and groundwater recession. Wrong land use and irrigation leads to salinization of the soil and the ground water.

There are a number of technologies available to extract fresh water from salty seawater [82]. All of them require a significant amount of energy that depends on the degree of salt before and after the desalination process and the percentage of freshwater that is extracted from a given volume of seawater. The theoretical minimum has a value of about 0.8 kWh/m^3 for typical seawater with 3.5% salt.

The most common method of desalination is distillation. The easiest concept for distillation uses a transparent condensation trap where humidity in the ground or seawater in a black vessel evaporates by solar heating and condensates on a surface at ambient temperature. The device as shown in Fig. 2.6 is inefficient, but it works and is simple, cheap, and useful to produce clean drinking water for individuals in rural areas.

For large-scale applications, more efficient technologies are available that use heat and/or reduced pressure for evaporation. The recycling of the latent heat of condensation in one or several evaporation stages increases the efficiency significantly. Plants using "Multi Stage Flash Evaporation" operate at typically 25 kWh/m^3 and can produce drinking water at large scale. The *Jebel Ali Power and Desalination Plant* in the United Arab Emirates produces 500,000 m^3/day for instance. This technology is well suited for stations with cogeneration of power and heat and especially also for concentrated solar power (CSP) stations. As CSP needs clear air for operation, locations at the seashore with regular mist are suboptimal for CSP, while areas inland often lack cooling water for the power generation. Here, seawater pipelines might be an option, to allow for water-cooling of the power generator and for desalination at the same time.

The most energy efficient desalination method that is established at large scale is reverse osmosis, where a membrane is used that is permeable for water but not for salt ions and where external pressure is applied to the seawater to overcome the osmotic pressure. The energy demand is typically about 2–4 kWh/m^3, which is already relatively close to the theoretical limit.

Fig. 2.6 A simple transparent funnel put on top of a wet area or a pan of sea water or sewage is sufficient to produce drinkable fresh water: Solar energy during the day (and even warm ground during the night) will evaporate water that condenses as droplets on the inner surface of the funnel. The droplets will be collected in the rim of the funnel. By turning the funnel upside down, the collected water is filled into a vessel [83]

Another promising future technology uses membranes that are selective for certain ions like Na^+ and Cl^-. The required energy for extracting the ions from the water can be obtained indirectly from solar evaporation of seawater in this case. The concentrated brine is used to extract the ions from the seawater [84].

2.11 The Water Cycle in a Sustainable Future

It is clear that in a sustainable future the exploitation of fossil water has to be stopped, as well as the pollution of soil, rivers and oceans. Measures should be taken to reverse desertification and climate change, but these aims are too ambitious to be reached in the coming decades. Let's start with the personal need of water. As a first step, sufficient and safe drinking water has to be provided for mankind.

2.11.1 Potable Water

In Germany, about 2000 years ago, the roman invaders constructed 130 km of aqueducts to connect the roman town Cologne with nearby mountain regions (close to the author's birthplace) [85]. This way, instead of having to use the water from the Rhine River, they were able to have running, high quality freshwater from mountain sources. The fact that they undertook these large infrastructure enterprises (using "Germans" as slaves) emphasizes the importance of water already in the ancient days. Today, everybody in Germany is used to have unlimited freshwater "on demand" [86]. The required amount of water for drinking and cooking is about 3 l per day and person, but the actual usage of drinking water today is more than 122 l, including personal hygiene, washing, cleaning and toilet water. If industry and agriculture are added, the daily usage per person is as high as 4000 l per person in Germany. This example illustrates the waste of water and the potential for savings.

A large fraction of the world's poor population has no access to clean drinking water. Especially in many regions in Africa children and women spend several hours a day for fetching and carrying water (Fig. 2.7). It is clear that this situation could be changed easily. Solar driven water pumps and a water distribution system with plastic pipes could free human resources for education and productive work. It is a shame that in the 21st century, where millions of people live in abundance, there is a lack of basic living conditions for a large fraction of the global population. Despite and partially also because of development aid over decades and despite or in many cases due to the exploitation of local resources, an efficient self-organization of these nations did not take place.

The sterilization of drinking water can be achieved by irradiation with sunlight in transparent plastic vessels, as the UV component of the solar spectrum kills most bacteria within 1–2 days (see Fig. 2.8) [88]. This way, neither sterilizing chemicals nor energy for boiling are required to produce drinkable water in many regions.

Fig. 2.7 Many women and children have to spend several hours a day to fetch water for the survival of the family. Their work could easily be taken over by a small pump and a plastic pipe [87]

Fig. 2.8 Solar water disinfection in PET plastic beverage bottles kills most pathogenic germs (e.g. bacteria, viruses, protozoa and worms) by a combination of UV light irradiation and solar thermal temperature increase [91]

One key water problem is the usage of water closets, which require typically 40 l per person per day. Due to the technology of water flushing, a small amount of excrements contaminates large amounts of fresh water and distributes pathogenic germs to canalization systems, which are than redistributed by rats and other animals. In new approaches toilets are designed that use little or no water. The separation of liquid and solid parts allows for a simple biological processing and recycling. One approach uses pyrolysis to produce energy, aseptic charcoal and fertilizer from faeces [89, 90].

2.11.2 Rural Exodus

We say that our world is overpopulated. This is certainly true when we look at the usage of resources and the damage to the biosphere that happens today. Nevertheless, the average population density is still moderate. If population were distributed homogeneously on the earth's land surface, your nearest family members and neighbours would live at a distance of 140 m away from you. However, for many reasons humans have the tendency to live in large clusters, similar to ants and termites. There has always been a fast population rise in cities and megacities, as long as the supply with clean water and food from outside was guaranteed and infectious diseases could be mitigated. Today, in several regions of the world megacities are growing to urban agglomerations with up to 50 million people each [92].

To the author's opinion, it would be a big step forward towards a beneficial and sustainable life if today's trend of rural depopulation and migration into mega-cities were inverted in future. In former times, there were many advantages to live in a big city. Big cities were important centres for manufacture and trading and also centres of cultural and intellectual exchange. Today, in many cases they are polluted areas that act as magnets for jobless and homeless people. Big cities have lost their unique benefits due to the internet, home offices, the distributed production of goods, modern logistics and future options of enhanced production by robots and remote 3D-printing.

Rural areas in the vicinity of cities are becoming more and more attractive in view of quality of life. Some people developed concepts for a future life in medium sized communities. Here, a more or less significant part of the agricultural products can be produced locally. People in this model society have mixed jobs, combining intellectual and manual work, so that the people's job is less monotonous and has a direct relevance to the local community [93].

2.11.3 Water for Agriculture

A sustainable water usage in agriculture and livestock breeding is the main challenge of water economy. The subject is too complex to be discussed in depth, but a few aspects will be picked out here [94].

There are regions on our planet, which are well suited for intensive agriculture and others, where a productive agriculture is difficult and expensive in terms of water supply, energy usage and manpower. A high-quality soil and the availability of water and sun in a moderate climate will easily multiply the crop yields compared to regions where these external conditions are poor. On the other hand, there exist eatable plants in all climatic regions. Many "exotic" plants that were used in the ancient cultures are hardly known and not used anymore today. A revival of a diversity of plant species and cultivation techniques could enrich agriculture in all climate zones.

There are basically two political roads to secure nutrition: One road is to enhance cheap mass production of food in well-suited regions. By an enhanced global trading a fair distribution of food could be achieved in all world regions. The other road is to enhance local food production to a level that secures the local needs, even though it may be costly with respect to manpower and efforts. The benefit of the second option may be an enhanced regional autonomy and an employment of the local population. Real life should probably develop an economically and ecologically worthwhile combination of the above two complementary approaches, while also the respect of old traditions has to be taken into account as an important asset to increase the quality of life of the population.

As mentioned above, drylands and deserts cover a large fraction of the planet and it is worthwhile to think about the best usage of these regions. Two examples will be mentioned here, which might have their niche in feeding the world of the future.

2.11.4 Controlled Environment Agriculture

The most extreme example is the Controlled Environment Agriculture (CEA) where crops are grown in containers or even high-raised "farmscrapers" with artificial light and air conditioning and controlled irrigation in closed loops [95]. This technology, originally developed for space stations, uses 99% less water than open field agriculture. The energy for the operation of the CEA has to come from outside, e.g. from solar collectors. Currently, this technology is rather expensive, but there seems to be a large cost saving potential for the future, once the strict requirements for space stations are released and economical aspects are included in the design. One big advantage of this approach is the almost complete recycling of water and soil, and the fact that fertilizers can be applied very efficiently without losses, and—due to protective barriers—there is no need of pesticides.

2.11.5 Seawater Greenhouse

A technology that pays off in certain regions already today is the seawater greenhouse, which exploits the power of wind and sun to desalinate seawater and to generate fresh and humid air in a greenhouse [96]. This concept seems to be well suited for agriculture, as the technology is simple in installation and maintenance. It provides food, and, in addition, freshwater, salt and minerals from the sea.

The working principle is as follows (see Fig. 2.9): Seawater is evaporated at the permeable front wall of the greenhouse and generates cooled humidified air inside the greenhouse. Fans at the rear side of the house draw the air through when there is insufficient wind. The roof is transparent for visible light to allow plants to grow, but it is absorptive for infrared and heats up a stream of seawater, which is evaporated and generates saturated vapour. This vapour precipitates at a condenser that is cooled by seawater and thus produces freshwater for irrigation. A stream of humid air leaves the greenhouse and enables the growth of less demanding plants in the downstream outside area of the greenhouse.

The Sahara Forest Project takes up this idea and proposes to apply it at large scale in North Africa [97]. Solar power towers are proposed to provide the power for running the greenhouses and the waste heat of the steam turbines can be used to support the evaporation of the seawater.

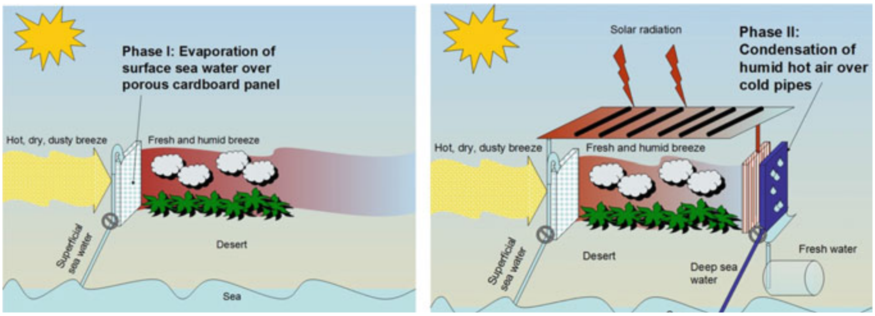


Fig. 2.9 The seawater greenhouse uses seawater for agriculture in drylands. The seawater evaporates in a porous wall where air is blown through by natural wind (Phase I). The cooled and humidified air is ideal for growing crops. In phase II a housing is added with a roof which is transparent for light but may contain additional seawater pipes where water is evaporated to increase humidity and to cool the roof. A condenser wall on the opposite side of the air inlet is cooled by seawater and produces fresh water for irrigation by condensing the humid air. Fans can be added that blow the air through the greenhouse to support or replace the natural wind [98]

2.12 Reversing Desertification and Soil Degeneration

Not all drylands can be covered with greenhouses and not all of them are in the vicinity of the sea. But seawater pipelines can be used to bring water to remote areas and CSP desalination plants at large scale can be used to produce freshwater for open field agriculture. Keys to a high yield are: the correct method of irrigation, the selection of a suitable crop, and the improvement of the soil.

A suited plant for dry and hot areas is for example Jatropha Curcas, a plant that is drought resistant, that grows fast if there is water and sunlight available, and that produces nuts with a high level of oil that can easily be converted to biodiesel. The remaining biomass of the plant can be converted to charcoal by pyrolysis. As mentioned above, the Indians in the Amazon basin used charcoal to produce terra preta, a soil that made the otherwise poor ground fertile. As the plant is poisonous, it is not eaten by wildlife and can be used as fence. One can imagine, that after a few generations of Jatropha Curcas and the usage of the corresponding charcoal, the soil is fertile enough to carry other, more demanding types of crops. This way the controlled farming of Jatropha Curcas could be a profitable way of moving the zone of desertification backwards step by step. How well this works at large scale has to be studied. Most important is to involve of the local population and to carefully study the effect that the new vegetation has on the native ecosystems [99]. There are more than enough examples, where overdrawn financial expectations and the exploitation of the local farmers produce more damage than output.

The combination of irrigation, soil regeneration and the above mentioned controlled nomadic grazing by large herds are examples of ideas how to reverse the expansion of drylands on our planet: The soil would gain an increased ability to soak and store water from rain periods, the enhanced vegetation increases the humidity of the local climate and the dung of the herds in combination with the absorptive capacity of charcoal will revive the microorganisms and the flora of the area.

Unfortunately, the progressive climate change will counteract these and other efforts, due to the increasing probability of extreme weather conditions like heavy rainfalls, floods, heat waves and droughts. This last statement should not discourage us, but it emphasises the time pressure for the transformation of our society.

2.13 Conclusions

According to the best knowledge of science, mankind is currently entering an era of **climate change** which is triggered by the extensive use of fossil fuels and which will be hard to stop. In accordance with the Paris Agreement, the immediate and earnest reduction of the usage of fossil fuels has to be pursued with high priority and most of the still existing fossil inventory has to stay in ground, losing its economic value.

Due to the nexus of population rise, energy usage, climate change and water scarcity, an uncontrolled development of the human societies might end up in drought, starvation, epidemics, migration and wars, unless mankind finds a way to solve its global problems, above all the energy problem.

While there are many technologies available to attack the energy problem, the author concludes that only renewables will be able to solve the global energy crisis at large scale:

Renewable energies are simple and safe, while other energy technologies produce more problems than they solve if they are implemented at global scales.

Carbon is one of the main building blocks of all living on earth and also of modern industry. The natural global cycle of carbon in the form of organic matter in the biosphere, of CO_2 in the atmosphere, and of carbonic acid in the oceans has been disturbed by the extensive usage of fossil fuels in the last century. This disturbance has to be stopped not only by stopping the usage of fossil fuel, but also by developing a sustainable chemical industry based on renewables, by using wood and other biological materials in the building sector and by reforestation and a more sustainable agriculture. **Pyrolysis** is a way to produce biogas, charcoal and chemical resources from faeces, bio-waste and plastics scrap. Charcoal products can be used as organic fertilizer and additive for a future agriculture. When charcoal is brought out on fields and drylands on a global scale, this so-called “**black carbon sequestration**” will reduce the atmospheric CO_2 concentration and will be a safe and inexpensive way to reverse climate change on the long term.

The **natural cycle of water**, the second main building block of all living on earth, is also heavily disturbed today by extensive water usage in modern industry and modern intensive agriculture on the one hand, and by the anthropogenic climate change, deforestation and desertification on the other hand. The usage of water has to be rethought, especially in agriculture, in order to be able to feed a future world of 10 billion people. Several ideas are listed to attack the water problem. One of them is the energy-costly **desalination of seawater** at large scale, which emphasises the nexus of energy, water and nutrition.

References

1. Wiki: World energy consumption; https://en.wikipedia.org/wiki/World_energy_consumption
2. World Energy Balances—2016 edition—excerpt—Key World Energy Trends; http://www.iea.org/publications/freepublications/publication/world-energy-balances—2016-edition—excerpt—key-world-energy-trends.html
3. Box: Own work; Data from World Energy Balances—2016 edition—excerpt—Key World Energy Trends; http://www.iea.org/publications/freepublications/publication/world-energy-balances—2016-edition—excerpt—key-world-energy-trends.html
4. Wiki: Energy conversion efficiency; https://en.wikipedia.org/wiki/Energy_conversion_efficiency
5. Wiki: Nuclear power; https://en.wikipedia.org/wiki/Nuclear_power
6. Wiki: Nuclear power debate; https://en.wikipedia.org/wiki/Nuclear_power_debate
7. Wiki: Nuclear terrorism; https://en.wikipedia.org/wiki/Nuclear_terrorism
8. Wiki: Nuclear proliferation; https://en.wikipedia.org/wiki/Nuclear_proliferation
9. Ashley SF, Parks GT, Nuttall WJ, Boxall C, Grimes RW (2012) Nuclear energy: thorium fuel has risks. Nature 492:31. http://dx.doi.org/10.1038/492031a
10. Wiki: Fusion power; https://en.wikipedia.org/wiki/Fusion_power
11. Wiki: Solar core; https://en.wikipedia.org/wiki/Solar_core
12. Wiki: Solar constant; https://en.wikipedia.org/wiki/Solar_constant
13. Figure: Own work; Figure contains 3 pictures: (a). By NASA Goddard Laboratory for Atmospheres and Yohkoh Legacy data Archive [Public domain], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3ASun_in_X-Ray.png; (b) By Maxxl2 [Public domain], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3AISO_7010_W003.svg; (c) By afloresm (SOLUCAR PS10 (2)) [CC BY 2.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3APS10_solar_power_tower_2.jpg
14. Wiki: Earth tide; https://en.wikipedia.org/wiki/Earth_tide
15. Wiki: Geothermal energy; https://en.wikipedia.org/wiki/Geothermal_energy
16. Wiki: Sun; https://en.wikipedia.org/wiki/Sun#Life_phases
17. Wiki: Photosynthesis; https://en.wikipedia.org/wiki/Photosynthesis
18. Wiki: Wood-decay fungus; https://en.wikipedia.org/wiki/Wood-decay_fungus
19. Nelsen MP, DiMichele WA, Peters SE, Kevin Boyce C, Delayed fungal evolution did not cause the Paleozoic peak in coal production. PNAS 113(9):2442–2447. doi:10.1073/pnas.1517943113
20. Wiki: Hypercapnia; https://en.wikipedia.org/wiki/Hypercapnia
21. Wiki: Anatomically modern human; https://en.wikipedia.org/wiki/Anatomically_modern_human
22. Wiki: Industrial Revolution; https://en.wikipedia.org/wiki/Industrial_Revolution
23. Wiki: Carbon dioxide in Earth's atmosphere; https://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere

24. Figure: By Global Climate Change—Earth Science Communications Team at NASA's Jet Propulsion Laboratory/California Institute of Technology (data from NOAA) (http://climate.nasa.gov/evidence/) [Public domain], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3AEvidence_CO2.jpg
25. Wiki: Greenhouse gas; https://en.wikipedia.org/wiki/Greenhouse_gas
26. Wiki: Moon; https://en.wikipedia.org/wiki/Moon
27. Intergovernmental Panel on Climate Change (IPCC) www.ipcc.ch
28. Box: This figure was prepared by Robert A. Rohde for the Global Warming Art project. (Creative Commons Attribution-Share Alike 3.0 Unported) https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.png
29. IPCC reports; https://www.ipcc.ch/report/ar5/
30. Working Group I contribution to the IPCC Fifth Assessment Report AR5 WG1 https://www.ipcc.ch/report/ar5/wg1/
31. Figure: Schönwiese Ch-D (2016) Globale Klimavariabilität im Industriezeitalter – Phänomene und Ursachen. In: Bruhns H, AKE der DPG (eds) Energie, Forschung und Perspektiven; http://dpg-physik.de/veroeffentlichung/ake-tagungsband.html
32. IPCC Fifth Assessment Report AR5-WG1-SPM-01; https://www.ipcc.ch/report/graphics/images/Assessment%20Reports/AR5%20-%20WG1/SPM/FigSPM-01.jpg
33. Wiki: Ocean acidification; https://en.wikipedia.org/wiki/Ocean_acidification
34. Global warming's evil twin: ocean acidification http://theconversation.com/global-warmings-evil-twin-ocean-acidification-19017
35. Special report on "climate change and the oceans and the cryosphere" by IPCC; https://www.ipcc.ch/report/srocc/
36. Wiki: Extinction event; https://en.wikipedia.org/wiki/Extinction_event
37. Ceballos et al. (2015) Sci Adv 1:e1400253 19 June 2015
38. Schönwiese Ch-D, Globale Klimavariabilität im Industriezeitalter – Phänomene und Ursachen in "Energie, Forschung und Perspektiven", 2016, Ed.: H. Bruhns, AKE der DPG, p. 32 and references therein; http://dpg-physik.de/veroeffentlichung/ake-tagungsband.html
39. IPCC. "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. p 53" http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf
40. Wiki: Climate change denial; https://en.wikipedia.org/wiki/Climate_change_denial
41. Wiki: Milankovich cycles; https://en.wikipedia.org/wiki/Milankovitch_cycles
42. Figure: from Masson-Delmotte V, Schulz M, Abe-Ouchi A, Beer J, Ganopolski A, González Rouco JF, Jansen E, Lambeck K, Luterbacher J, Naish T, Osborn T, Otto-Bliesner B, Quinn T, Ramesh R, Rojas M, Shao X, Timmermann A (2013) Information from paleoclimate archives. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: thephysical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar5/wg1/ Chapter 5: https://www.ipcc.ch/report/graphics/images/Assessment%20Reports/AR5%20-%20WG1/Chapter%2005/Fig5-03.jpg
43. Wiki: Positive feedback; https://en.wikipedia.org/wiki/Positive_feedback
44. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Inaugural article: tipping elements in the earth's climate system. Proc Natl Acad Sci 105(6): 1786. doi:10.1073/pnas.0705414105, https://dx.doi.org/10.1073%2Fpnas.0705414105
45. Wiki: Geologic temperature record; https://en.wikipedia.org/wiki/Geologic_temperature_record
46. Royer DL (2014) Reference module in earth systems and environmental sciences treatise on geochemistry, 2nd edn, vol 6, pp 251–267. Atmospheric CO_2 and O_2 during the phanerozoic: tools, patterns, and impacts http://dx.doi.org/10.1016/B978-0-08-095975-7.01311-5
47. Phys. Bl. 43 (1987) Nr. 8, p 347. http://www.dpg-physik.de/dpg/gliederung/ak/ake/publikationen/dpgaufruf1987.pdf
48. IPCC Climate Change 2014: Synthesis Report https://www.ipcc.ch/report/ar5/syr/

49. Wiki: 2015 United Nations Climate Change Conference; https://en.wikipedia.org/wiki/2015_United_Nations_Climate_Change_Conference
50. Wiki: Carbon capture and storage; https://en.wikipedia.org/wiki/Carbon_capture_and_storage
51. The Stern Review on the Economics Of Climate Change says "Climate change presents a unique challenge for economics: it is the greatest example of market failure we have ever seen."; Stern, Nicholas (2006). "Introduction". The Economics of Climate Change The Stern Review (PDF). Cambridge University Press. ISBN 978-0-521-70080-1. http://webarchive.nationalarchives.gov.uk/20130129110402/; http://www.hm-treasury.gov.uk/d/Part_I_Introduction_group.pdf
52. Wiki: Externality; https://en.wikipedia.org/wiki/Externality
53. Wiki: Desertec; https://en.wikipedia.org/wiki/Desertec
54. "DESERTEC—Clean Power from Deserts", Desertec Foundation, 4th edn. ISBN: 978-3-929118-67-4, Protext Verlag, Bonn, February 2009; http://www.dun-eumena.com/sites/default/files/files/doc/trec_white_paper.pdf
55. Speitkamp W, Stange D, History—The politics of energy in Africa: Energy partnership with Africa burdens of history and current perspectives; Spiegel der Forschung 25 (2008) Nr. 2—English version; JLU Giessen; http://geb.uni-giessen.de/geb/volltexte/2009/7201/
56. Düren M (2008) Physics—the future of our energy supply: a scientific overview. Spiegel der Forschung 25. Nr. 2—English version; JLU Giessen; http://geb.uni-giessen.de/geb/volltexte/2009/7195/
57. D van Laak (2008) History—towers of modernism: the tendency towards technological mega-projects in the 20th century. Spiegel der Forschung 25. Nr. 2—English version; JLU Giessen; http://geb.uni-giessen.de/geb/volltexte/2009/7192/
58. Wiki: Carbon cycle; https://en.wikipedia.org/wiki/Carbon_cycle
59. Wiki: Carboniferous; https://en.wikipedia.org/wiki/Carboniferous
60. Box: Own work; Figure contains 7 pictures: (a) Jessie Eastland [CC BY-SA 3.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3AAnatomy_of_a_Sunset-2.jpg; (b) By Maxxl2 [Public domain], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3AISO_7010_W003.svg; (c) By Pizza Masetti Craiova from Craiova, Romania (Flickr) [CC BY 2.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3APizza_with_various_toppings.jpg; (d) By Jesusalconada [GFDL or CC BY-SA 4.0-3.0-2.5-2.0-1.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3ABotella_agua.JPG; (e) http://www.woodskyscrapers.com/building-systems.html http://www.woodskyscrapers.com/uploads/1/1/6/0/11600959/2876464_orig.jpg; (e) By No machine-readable author provided. Gerfriedc assumed (based on copyright claims). [GFDL, CC-BY-SA-3.0 or CC BY 2.5], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3ABiogasspeicher.jpg; (g) By K.salo.85 [CC BY-SA 3.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3ABiochar.jpg
61. Wiki: Food vs. fuel; https://en.wikipedia.org/wiki/Food_vs._fuel
62. Wiki: Plastic recycling; https://en.wikipedia.org/wiki/Plastic_recycling
63. Green M (2013) "Why we should build wooden skyscrapers"; TED2013 · 12:22 · Filmed Feb; http://www.ted.com/talks/michael_green_why_we_should_build_wooden_skyscrapers
64. E.g. Cree GmbH, Färbergasse 17b, A-6850 Dornbirn; http://www.creebyrhomberg.com/en/
65. Li T, Zhu M, Yang Z, Song J, Dai J, Yao Y, Luo W, Pastel G, Yang B, Hu L (2016) Wood composite as an energy efficient building material: guided sunlight transmittance and effective thermal insulation. Adv Energy Mater 6:1601122. doi:10.1002/aenm.201601122; http://onlinelibrary.wiley.com/doi/10.1002/aenm.201601122/full
66. Wiki: Slash-and-char; https://en.wikipedia.org/wiki/Slash-and-char
67. Wiki: Pyrolysis; https://en.wikipedia.org/wiki/Pyrolysis
68. Wiki: Biochar; https://en.wikipedia.org/wiki/Biochar
69. Wiki: Terra preta; https://en.wikipedia.org/wiki/Terra_preta
70. Wiki: Cell (biology); https://en.wikipedia.org/wiki/Cell_(biology)
71. Wiki: Turgor pressure; https://en.wikipedia.org/wiki/Turgor_pressure
72. Wiki: Osmosis; https://en.wikipedia.org/wiki/Osmosis
73. Wiki: Water cycle; https://en.wikipedia.org/wiki/Water_cycle

74. Wiki: Camel; https://en.wikipedia.org/wiki/Camel
75. Latif N (2015) You have no idea where camels really come from Filmed November 2015 at TED Talks Live; https://www.ted.com/talks/latif_nasser_you_have_no_idea_where_camels_really_come_from
76. Wiki: Great Man-Made River; https://en.wikipedia.org/wiki/Great_Man-Made_River
77. Savory A (2013) How to fight desertification and reverse climate change TED2013, Filmed Feb 2013; https://www.ted.com/talks/allan_savory_how_to_green_the_world_s_deserts_and_reverse_climate_change
78. Figure: By Dorhodor [CC BY-SA 3.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3ADrylandmap.jpg
79. Wiki: Three Gorges Dam; https://en.wikipedia.org/wiki/Three_Gorges_Dam
80. Wiki: Water purification; https://en.wikipedia.org/wiki/Water_purification
81. Box: Own work; Figure contains 4 pictures: (a) By Jesusalconada [GFDL or CC BY-SA 4.0-3.0-2.5-2.0-1.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3ABotella_agua.JPG; (b) By Mohammed Tawsif Salam [CC BY-SA 3.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3APump-enabled_Riverside_Irrigation_in_Comilla%2C_Bangladesh%2C_25_April_2014.jpg; (c) By turydddu @ Flickr, retouched by JovanCormac ([2]) [CC BY 2.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3AHigh_speed_shower_filtered.jpg; (d) By ChNPP [CC BY-SA 3.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3AZellstoffwerk_Rosenthal_17.jpg
82. Wiki: Desalination; https://en.wikipedia.org/wiki/Desalination
83. Figure: http://watercone.com; http://watercone.com/pics/jemen.jpg
84. Cheaper desalination-Current thinking, The Economist, Oct. 31, 2009; http://www.economist.com/node/14743791
85. Wiki: Eifel Aqueduct; https://en.wikipedia.org/wiki/Eifel_Aqueduct
86. Wiki(D): Wasserverbrauch; https://de.wikipedia.org/wiki/Wasserverbrauch
87. Figure: By Juxtaposed in GIMP and uploaded by User:Jafet.vixle; [GFDL or CC-BY-SA-3.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3AHippo-vs-head.jpg
88. Wiki: Solar water disinfection; https://en.wikipedia.org/wiki/Solar_water_disinfection
89. Danso-Boatenga E, Holdich RG, Shama G, Wheatley AD, Sohail M, Martin SJ (2013) Kinetics of faecal biomass hydrothermal carbonisation for hydrochar production. Appl Energy 111:351–357
90. Sohail M, http://www.lboro.ac.uk/microsites/view/autumn-winter-2012/reinvent-the-toilet/
91. Figure: By SODIS Eawag [GFDL or CC BY 3.0], via Wikimedia Commons: https://commons.wikimedia.org/wiki/File%3AIndonesia-sodis-gross.jpg
92. Wiki: Megacity; https://en.wikipedia.org/wiki/Megacity
93. Private communication, R. Otterpohl, https://www.ruvival.de
94. Wiki: Agriculture; https://en.wikipedia.org/wiki/Agriculture
95. Wiki: Controlled-environment agriculture; https://en.wikipedia.org/wiki/Controlled-environment_agriculture
96. Wiki: Seawater greenhouse; https://en.wikipedia.org/wiki/Seawater_greenhouse
97. Wiki: Sahara Forest Project; https://en.wikipedia.org/wiki/Sahara_Forest_Project
98. Figure: By Raffa be [CC BY 3.0], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3ASG_phase_I.jpg, https://commons.wikimedia.org/wiki/File%3ASG_phase_II.jpg
99. Ribeiro D, Matavel N (2009) Jatropha! A socio—economic pitfall for Mozambique, August 2009; https://www.swissaid.ch/sites/default/files/Report_Jatropha_JA_and_UNAC.pdf