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Michael Düren

Understanding the Bigger Energy Picture

DESERTEC and Beyond

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ISSN 2191-5520 ISSN 2191-5539 (electronic)
SpringerBriefs in Energy
ISBN 978-3-319-57965-8 ISBN 978-3-319-57966-5 (eBook)
DOI 10.1007/978-3-319-57966-5

Library of Congress Control Number: 2017938138

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To my family and the whole family of life on earth

Preface

This book gives an overview of today's energy problem in the context of a rising world population, climate change and the shortage of resources. It figures out systemic connections between energy, water and the carbon cycle of today's economy and sketches a "natural" future energy scenario that is sustainable. Due to the complexity of the matter, this short book cannot be a complete compendium. The proposed solutions and no-goes are meant as a stimulus for further discussion.

Giessen, Germany Michael Düren

Acknowledgements

I want to thank my doctoral adviser Prof. Dr. Klaus Schultze who introduced me to the *Working Group Energy* in the German Physics Society. He died while he was moderating a discussion about future energy concepts in 1999. The biannual meetings of this working group formed the scientific basis of my knowledge of energy technology. The lecture series *Verantwortung für den Frieden (Responsibility for Peace)*[1] (1983–1987) that I organized as a young student in a working group together with Ranga Yogeshwar opened my eyes to the complexity of social, economic, psychological and political issues, on the one hand, and the impact of science and technology on the other hand. My activity in the *SEPA (Solar Energy Partnership with Africa)*[2] group based at *ZEU* (*Center for international Development and Environmental Research)* at University of Giessen gave me new insights into the energy and water problems in Africa. Last but not least, my activities in the *DESERTEC foundation* and the *DESERTEC University Network* allowed me to think about global solutions to the energy problem and my contacts with *Dii (DESERTEC industrial initiative)* helped me to understand the economic point of view.

It is impossible for me to mention all the people and sources that were the basis of this work. This interdisciplinary book project was for me like solving a jigsaw puzzle. A nearly infinite number of pieces of information from various conferences and discussions had to be translated into a physicist's language, put together to a common picture, and after a few missing pieces have been reconstructed, the whole picture had to be translated back into an understandable language. An indispensable tool of today's research is *Google* and *Wikipedia*, which are rapidly growing to the most complete database and compendium of human knowledge. One should be aware that the information in Wikipedia is not necessarily correct and sometimes

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[1] M. Düren, R. Yogeshwar (Ed.), *Vorlesungsreihe Verantwortung für den Frieden. Mit Hochschullehrern an der RWTH Aachen*, 1984, ISBN-13: 9783924007072 ISBN-10: 3924007071.

[2] M. Düren et al., *Solar Energy Partnership with Africa: An Interdisciplinary Research Project,* Spiegel der Forschung 25 (2008) Nr. 2 p. 4—English version; JLU Giessen; http://geb.uni-giessen.de/geb/volltexte/2009/7192/.

biased, but this applies to a certain degree also to scientific books and to governmental reports.

Finally, I must mention Dr. Gerhard Knies, with whom I worked on a common European-North African workshop together long before he invented the name DESERTEC. He is an uncompromising thinker with visions that he follows with great enthusiasm.

The main ideas in this book were presented already in conferences in 2014,[3] 2015[4] and 2016.[5] I want to thank my colleagues Prof. Dr. Gerhard Luther, Prof. Dr. Volker Metag, Prof. Dr. Christian-Dietrich Schönwiese and Prof. Dr. Hartwig Spitzer for their help, support and contributions during the preparation of this book.

Giessen, Germany
February 2017

Michael Düren

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[3] M. Düren, *Energie, Wasser und Ernährung—untrennbare Kreisläufe einer nachhaltigen Gesellschaft*, Fachtreffen “Jobs für Afrika”, Berlin-Institut für Bevölkerung und Entwicklung, Darmstadt, Germany, Oct. 10, 2014.

[4] M. Düren, *DESERTEC and beyond—“Energiewende” world-wide?* EST 2015—Energy, Science, Technology, International Conference and Exhibition; Karlsruhe, Germany, May 20–22, 2015.

[5] M. Düren, *DESERTEC and beyond—Options of a global energy transition*, ECM6—The 6th International Symposium on Energy Challenges and Mechanics—towards a big picture, Inverness, Scotland, Aug 14–18, 2016.

Contents

Abbreviations

AC	Alternating current, electrical current that changes direction periodically (typically 50 or 60 times per second)
AD	Anno Domini/year of the lord, label for years > 0 in the calendar
BMW i3	A German electric passenger car
CCS	Carbon capture and storage, storage of the CO_2 exhaust of fossil power plants
CEA	Controlled environment agriculture, grow plants in greenhouses with controlled light, temperature, humidity, soil, etc.
CERN	Conseil Européen pour la Recherche Nucléaire/European Organization for Particle and Nuclear Physics, Research centre in Geneva/Switzerland
CHP	Combined heat and power: cogeneration of electrical and thermal energy
CH_4	Chemical formula for methane gas, a main component of natural gas
CO_2	Chemical formula for carbon dioxide, a greenhouse gas
CPV	Concentrated photovoltaics, application of photovoltaic cells where the sunlight is concentrated before it hits the cell. Usually, the concentration is realized by matrices of lenses
CSP	Concentrated solar power, solar radiation is concentrated by large mirrors or large mirror systems onto an absorber where the solar radiation is converted to heat and electricity in a two-step process
DC	Direct current, electrical current that has fixed polarity and a well-defined direction of charge flow in contrast to AC
DESERTEC	DESERTEC denotes a concept of making use of deserts for large-scale renewable energy technology, mainly solar and wind. It is promoted by the non-profit DESERTEC Foundation, the Dii GmbH and the DESERTEC University Network D.U.N. e.V.

Dii	Dii GmbH, a company formed in 2009 to study options for a power generation in MENA for export to the European power market. Today, it focusses on the implementation of renewables for local use in MENA
DPG	DPG—Deutsche Physikalische Gesellschaft/German Physical Society
EEG	EEG Energieeinspeisegesetz/Renewable Energy Act to promote the decentralized production of renewable power in Germany
EV	Electric vehicle
GDP	Gross domestic product, monetary measure of all goods and services produced in a year
GEMA	Gesellschaft für musikalische Aufführungs- und mechanische Vervielfältigungsrechte/German state-authorized collecting society and performance rights organization
GW	1 GigaWatt = 1000 megawatt = 1 million kilowatt = 1 billion watt, power unit with the order of magnitude of 1 nuclear power station
HVDC	High-voltage DC, technology to transfer electric power using DC current and high voltage of up to about 1000 MV
IPCC	Intergovernmental Panel on Climate Change, United Nations endorsed scientific body to find scientific answers to the questions about climate change and its political and economic impacts
IQ	Intelligence quotient (IQ) is a measure to assess the intelligence of individual humans
kW	1 kW = kilowatt = 1000 watt, physical unit to measure power, i.e. energy usage per second. 1 kW is about the power consumption of a hair dryer or a microwave
kWh	1 kWh = kilowatt hour, physical unit to measure energy. 1 kWh is the energy that corresponds to a power consumption of 1 kW over one hour. About the energy consumption of a microwave that runs continuously for one hour
MENA	Middle East and North Africa
MW	1 megawatt = 1000 kilowatt, power unit
MW_P	1 megawatt peak denotes the peak power. For PV, it denotes the installed power capacity that would be delivered by the PV farm under standard solar radiation conditions
NGO	A non-governmental organization is a non-profit organization independent from governments and their organizations
ppm	Fraction of 1 part-per-million $=10^{-6}$
pH	Logarithmic measure of basicity (positive pH value) or acidity (negative pH value) of a solution
PV	Photovoltaics, device to convert light directly into electrical power, using the photoelectric effect

SNG	Synthetic natural gas denotes technically produced hydrocarbons like methane
SROCC	Special report on "climate change and the oceans and the cryosphere" by IPCC
UV	Ultraviolet light with wavelengths shorter than visible light (10–400 nm)

Chapter 1
Introduction

Since thousands of years, the human race has been developing cultural skills and technological capabilities that support its struggle for survival and lead to dominance over all other species. Since about a century, the exponential growth of knowledge, technology, industry and population (see Fig. 1.1) has reached a scale where man modifies biosphere to an extent, that living conditions on the whole planet earth start to change significantly. Resources that had been abundant are becoming scarce within decades. We have arrived in the Anthropocene [1] where man has a significant impact on the basic living conditions of the biosphere of the whole planet. A continuation of this growth rate will unavoidably reach its natural limits where resources vanish; the biosphere will change more rapidly than the ability of organisms and ecosystems to accommodate, and contaminations will endanger living. When such a condition is reached, it is likely that our human civilization will collapse and human population will diminish rapidly. Historic examples demonstrated that drought, hunger, wars and epidemics were typical endpoints of drastic environmental changes and overpopulation. While historic examples mostly affected only individual towns, islands, countries or indigenous nations, the limits of growth this time affect the whole planet and there is no "new world" to which our civilization can migrate. Recent research has proven that the era of a new biological mass extinction has already started [2] and it can be assumed that finally also our species will be affected.

The challenge of this century is the deceleration of growth in general, especially the limitation of the world population to a stable number (e.g. 10 billion people), and the conversion of industrial processes to renewable and sustainable cycles, which will have to be able to supply food and a reasonable standard of living to this large number of people. This paper will focus on the subject of "energy" as one of the essentials of our society, but it will also point out the importance of the nexus of climate, energy, food, water and the carbon cycle.

M. Düren, *Understanding the Bigger Energy Picture*,
SpringerBriefs in Energy, DOI 10.1007/978-3-319-57966-5_1

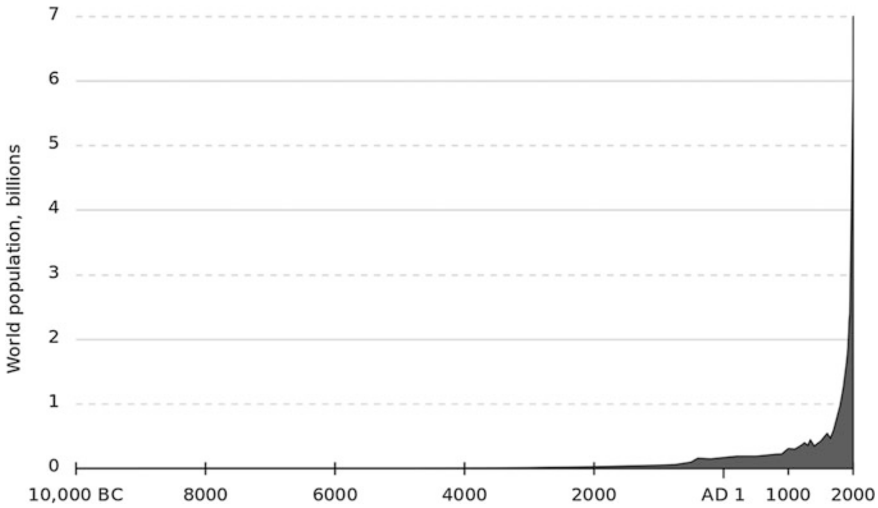

Fig. 1.1 The estimated human population of the last 12,000 years. It has been small and growing moderately for thousands of years. In the last 50 years, population increased by 1 billion every 13 years [3]

How can a stabilization of the population be achieved before millions of people die from starvation, epidemics, environmental catastrophes or wars? Birth control is essential and not the subject of this paper, but it is important to know that since the begin of industrialization, there has been a strong anti-correlation between the economic wealth and the birth rate, termed the demographic-economic paradox [4] : As soon as a country reaches a high level of education, low unemployment and safe living conditions, birth rates stabilize at low levels instead of using the wealth to nourish more children. The self-determination of women is a prerequisite for this process, as there are examples of countries where a high standard of living for men is realized, but to the cost of the repression of women and of high birth rates. For example, Saudi Arabia has a GDP per capita at the level of Europe, but a fertility rate comparable to India or Egypt. Also, religion plays a role here. All major religions have their roots from a time where birth control was counterproductive for the survival of a cultural cohort and not all religions adjusted the interpretation of their basic articles of faith to the current situation where overpopulation is counterproductive for development. In this sense, solving the energy problem is only one out of several aspects, but still it is an important prerequisite for a peaceful future of the global community.

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2. Ceballos et al. (2015) Accelerated modern human–induced species losses: entering the sixth mass extinction. Sci Adv. 1:e1400253 19 June
3. Figure: by El T [Public domain], via Wikimedia Commons https://commons.wikimedia.org/wiki/File%3APopulation_curve.svg; The data is from the "lower" estimates at census.gov (archive.org mirror)
4. Wiki: *Income and fertility;* https://en.wikipedia.org/wiki/Income_and_fertility#Paradox

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

M. Düren, *Understanding the Bigger Energy Picture*,
SpringerBriefs in Energy, DOI 10.1007/978-3-319-57966-5_2

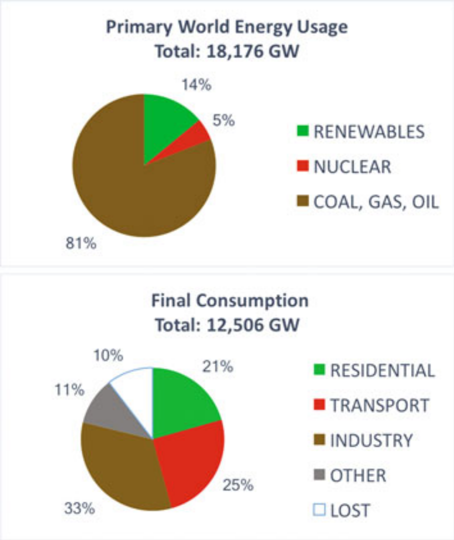
per second is about 18,000 GW, which corresponds to the electrical output of about 18,000 nuclear power plants (see Box 2.1) [1, 2].

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 $18,000\,\mathrm{GW}/7.3\,\text{billion people} = 2.5\,\mathrm{kW}$ 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 $\mathrm{GW/km^2}$ 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,

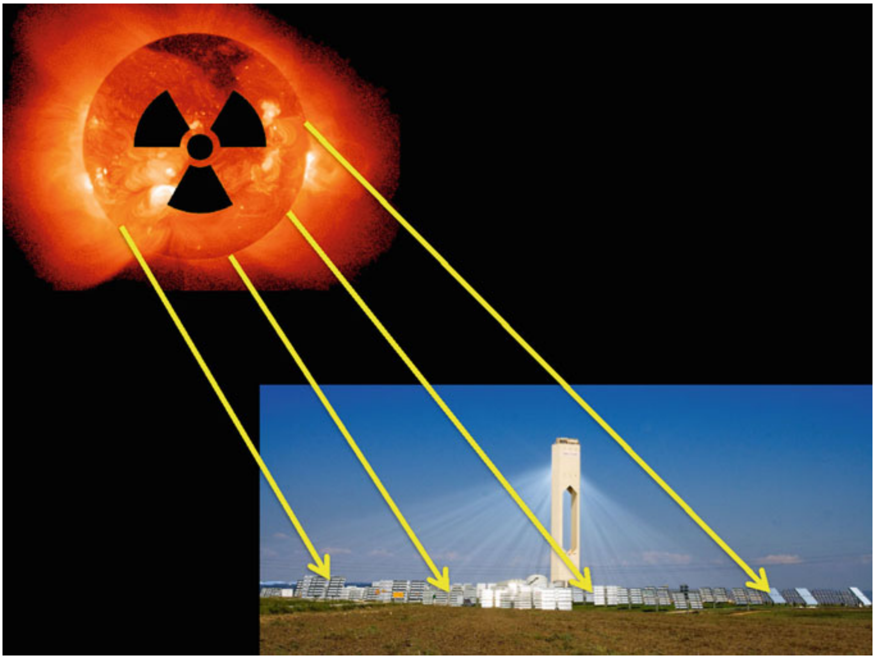


Fig. 2.1 The highly radioactive sun is the fusion reactor of our choice. At a safety distance of 150,000,000 km its radiation is still so intense that this single reactor is enough to satisfy all energy needs of human civilization. Solar devices, like the solar power tower shown in the photo, can easily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

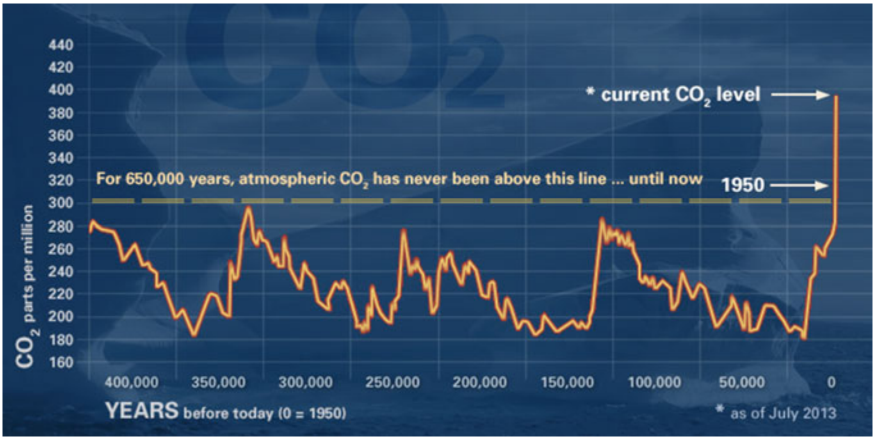


Fig. 2.2 In the last 650,000 years—until 1950—the CO_2 concentration has always been below 300 ppm. Only in the last century, due to the burning of fossil fuels, the CO_2 concentration has risen above its prehistoric values. The periodic structure nicely shows how the CO_2 concentration slowly decreases 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].

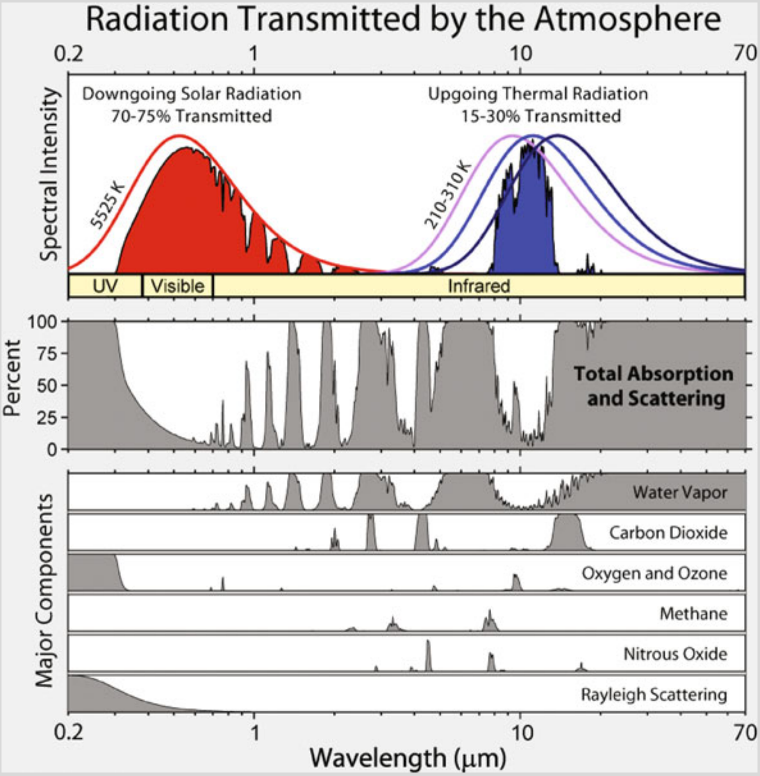
2.4 The Greenhouse Effect and Global Warming

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].

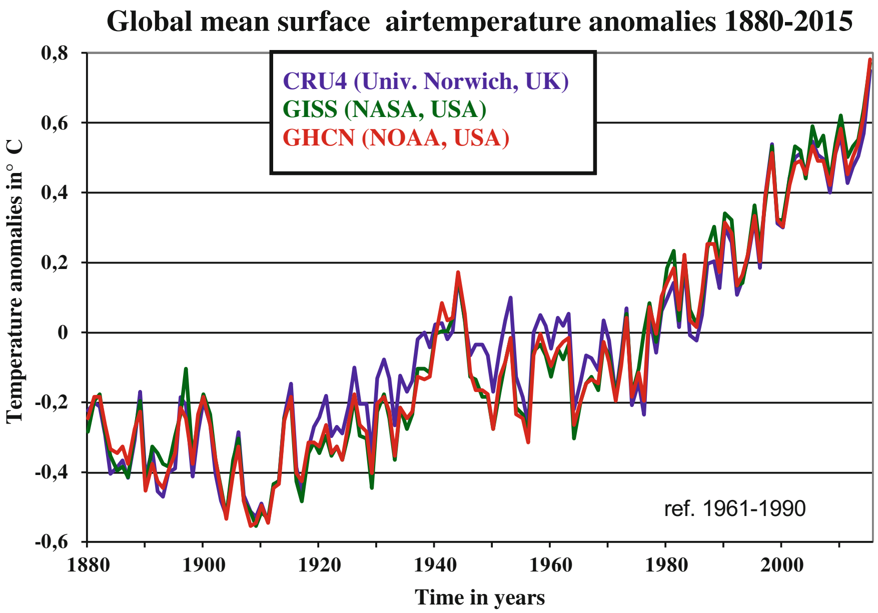


Fig. 2.3 The observed global mean temperatures (land and ocean surface combined) from 1880 to 2015 compared to the average of the years 1961–1990. A significant rise is observed. The 10-year's average went up steadily in the last 40 years and also in the time between the two world wars. The different 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

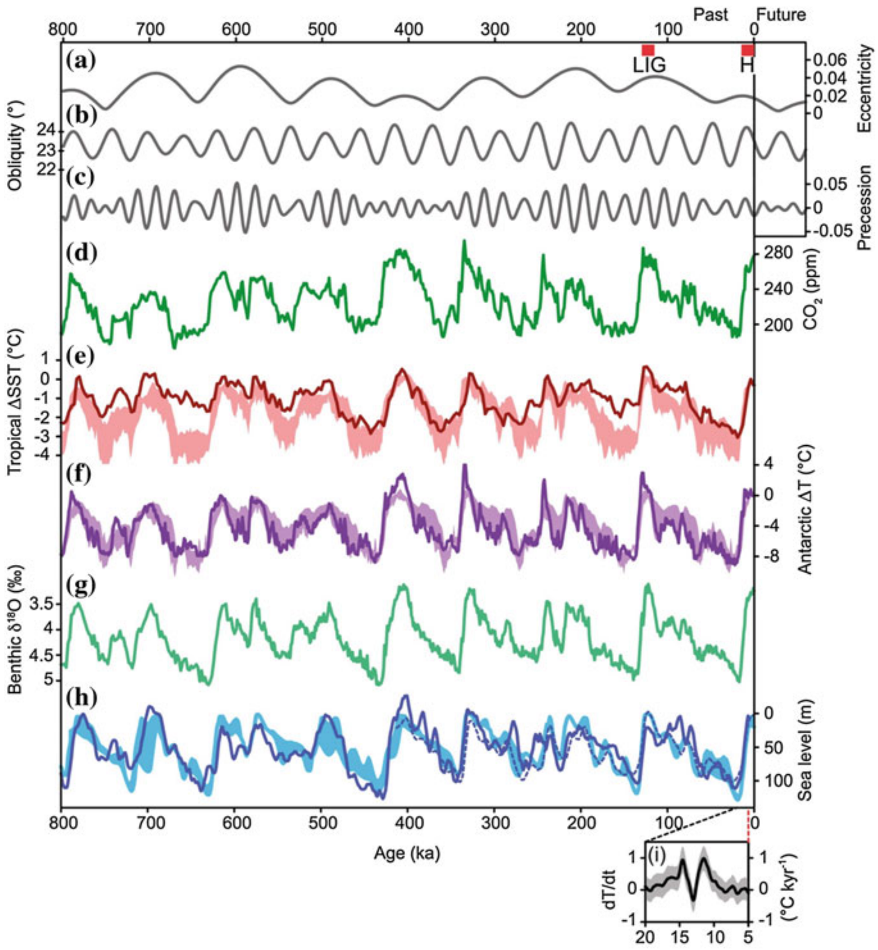


Fig. 2.4 The global climate parameters of the last 800,000 years. Driving force of the earth's climate system is the solar irradiation. The curves **a**–**c** show the orbital parameters of the planet earth that define the intensity and orientation of the sunlight for the past 800,000 and the future 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:

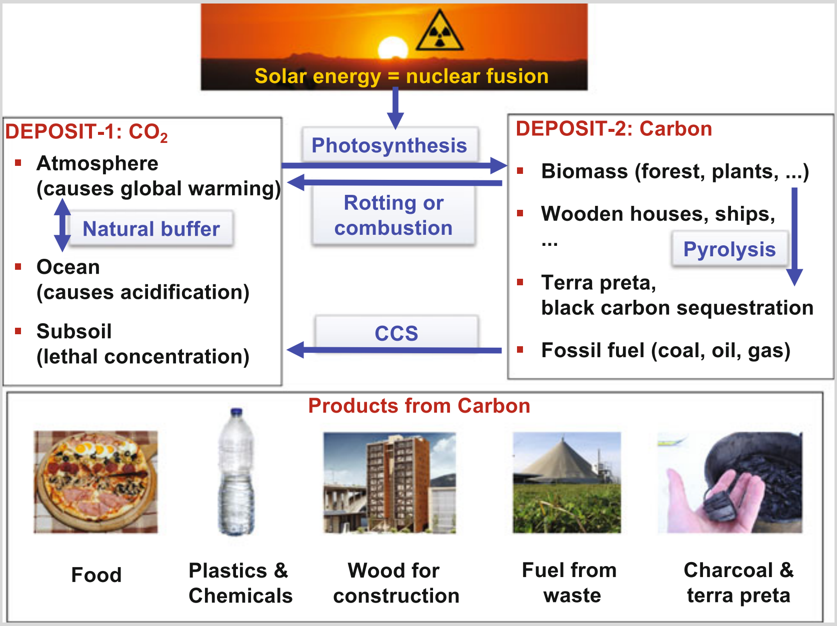
Deposit-1: The chemically very stable and quite inert state of carbon that is bound in CO_2 or HCO_3^- molecules. It contains very little chemical energy and is naturally deposited in our atmosphere as gas or solved in the oceans as carbonic acid.

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

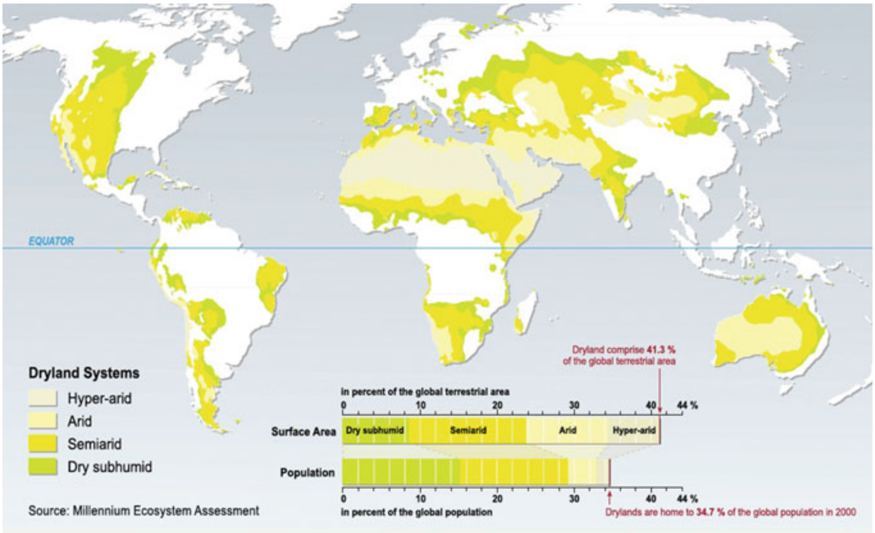
In our industrialized world, water became a traded good. In many regions, natural freshwater is not potable due to pollution by faeces, fertilizers, road-salt, mining, industrial waste or environmental disasters. The main consumer of water is agriculture. Especially in dry regions, the extensive exploitation 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.



Source: Millennium Ecosystem Assessment

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.

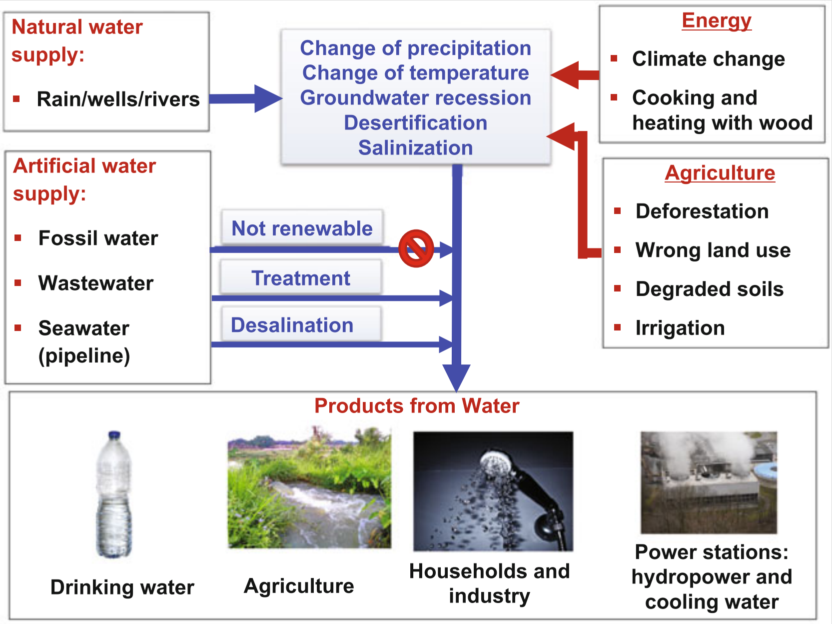
2.10.4 Water from Humidity

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.

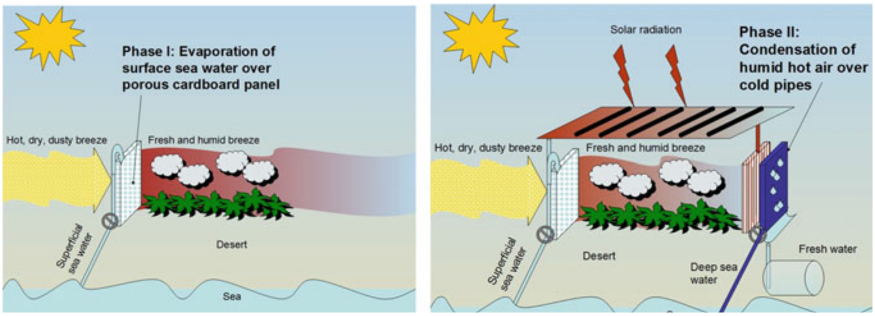


Fig. 2.9 The seawater greenhouse uses seawater for agriculture in drylands. The seawater evaporates in a porous wall where air is blown through by natural wind (Phase I). The cooled and humidified air is ideal for growing crops. In phase II a housing is added with a roof which is transparent for light 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.

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Chapter 3
Energy in Times After the Energy Transition

The global energy transition is a complex and difficult process and neither its pathways nor its target points are well defined. Typically, in political debates the aim and the technologies of the transition are subject to belief, prejudice or a hidden agenda. Governments in a democratic system may be forced by public pressure to take action, however, in order not to lose majorities, only small steps are taken to have a minimum of collateral damage to existing power structures and interest groups and to minimize opposition. The government tries to give these small steps approximately the right direction with respect to the aim and the external pressure. In the best case, this approach will improve the current energy situation but it will not necessarily lead to a solution of the energy problem. From the mathematical point of view, the solution follows incrementally a promising gradient in a multi-dimensional parameter space, but it may still be useless in view of the best path to the optimum position.

In this chapter the opposite approach is taken. It is attempted to find the optimum and consistent energy model for the future (e.g. in 80 years from today), guided by general scientific and technological considerations, without taking the detailed status quo into account. The pathway to achieve this future goal by an energy transition process is regarded as an independent, second step that will be determined largely by economic and political considerations.

This chapter will describe the basic technologies that are available to produce renewable energies. It will point out the necessities and options of energy transport and energy storage and set up a concept for an integrated global energy system that includes trade of electricity and gas and combines the sectors of electricity, heat and mobility.

M. Düren, *Understanding the Bigger Energy Picture*,
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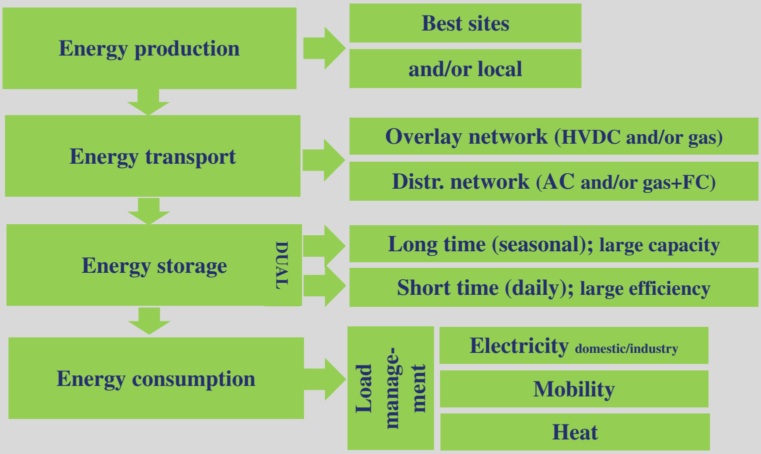
3.1 Overview of the Future Energy System

The energy system can be divided into four categories: energy production, transport, storage and consumption. The proposed future configuration of these four categories is subject of this chapter and depicted in Box 3.1.

Box 3.1 Energy in Times after the Energiewende [1]



The envisaged future energy system is structured as follows: Energy production will be done at the most cost-efficient places but also locally at the consumer side.

A distribution network will connect all consumers and all small producers using an AC high voltage grid. In addition, a HVDC overlay network will connect distant centres of electricity consumption and/or production. A gas network will exist in parallel to allow for international trading and for special applications, e.g. for chemical industry and for fuel cell applications in mobility.

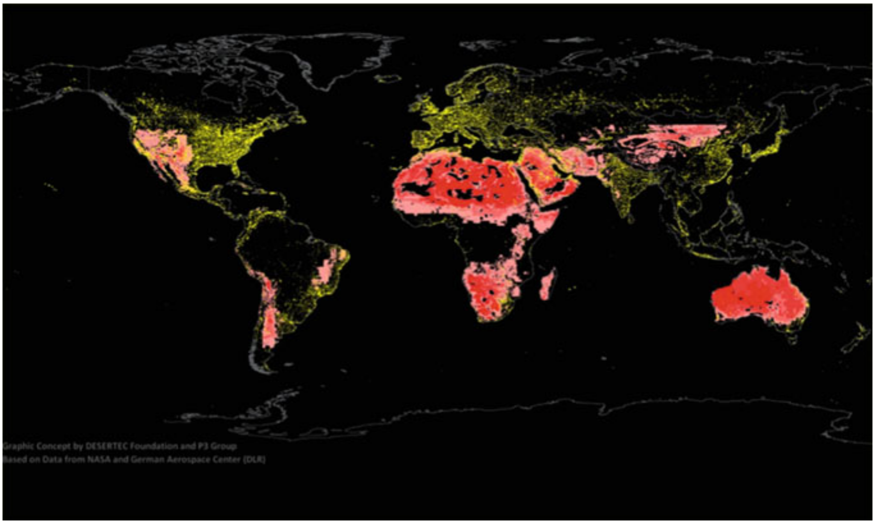
A dual energy-storage system is needed: one system that has large (but cheap) capacity and one that has high efficiency. The highly efficient storage with limited capacity is needed to absorb daily fluctuations. A second, large-capacity storage is needed for seasonal storage. It may have low efficiency, as its cycle time is long, and it will be based on gas or other chemical fuels.

The energy consumption is divided into the electricity, the mobility and the thermal sector. A load management system will allow for a central regulation of the electricity consumption, especially in the mobility and the heat sector.

3.2 Energy Production: Locally or at Best Sites?

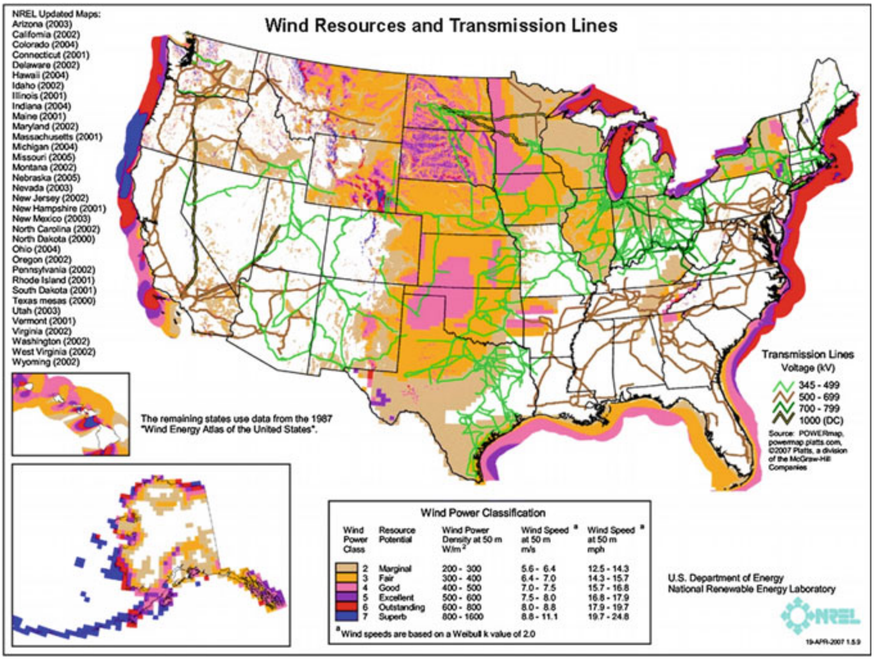
More than ten years ago, when people thought about the options of renewable energy production at large scale, the technologies for solar and wind energy were still in their infancy and quite expensive. At that time physicists and engineers from Germany and North Africa developed the DESERTEC idea [2–4]. It was based on the insight that it is cheaper to produce solar energy at large scale in Africa and transport it to Europe instead of producing it in Europe and save the investment of the long cables. It has been calculated that the technical solar energy potential of the deserts is about 340,000 $\mathrm{GW_{el}}$ on day/night, all year average, using current technology and a land use factor of 4.5%. That means that there is potentially about 20 times more energy available in deserts than needed to solve all energy problems of the world.

DESERTEC has generalized this concept and proposes to use a mixture of all suitable renewable energies, but to focus the energy production in those areas, where the production is most cost effective. This means, that preferentially the relatively stable and strong winds offshore and the stable and strong solar radiation in deserts should be harvested (see Figs. 3.1 and 3.2). DESERTEC had its highlight in 2009, when Dii, the DESERTEC Industrial Initiative [6], was formed as a consortium of a number of major German players from power industry, banking and insurance companies in cooperation with a few other European and North



raphic Concept by DESERTEC Foundation and P3 Group
ased on Data from NASA and German Aerospace Center (DLR)

Fig. 3.1 The solar radiation in deserts (*red*) is sufficient to supply the energy for the whole mankind. The technical potential of solar energy in deserts is about 20 times larger than the current global energy demand. The *yellow* points show the electrical lights at night, pointing to today's centres of electricity demand. 90% of the world population lives in a distance of less than 3000 km from the next desert and can easily be supplied with solar power from deserts [5]



Source: POWERmap, powermap.platts.com, ©2007 Platts, a division of the McGraw-Hill Companies

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed^a at 50 m m/s	Wind Speed^a at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

^{a}Wind speeds are based on a Weibull k value of 2.0

Fig. 3.2 Wind power can be harvested anywhere, but the most suited areas are regions with strong average wind, especially in coastal areas. The map shows a compilation of wind resources of the US, taking environmental and land use issues into account [9]

African companies. One of the shareholders of Dii was the DESERTEC Foundation [7], a non-profit NGO, that had been founded a year before to foster the realization of the DESERTEC concept between Europe and MENA (Middle East and North Africa). Investments on the order of 400,000,000,000 € were discussed to supply 15% of the (electrical) power of Europe. For comparison: According to the European Environment Agency, this number equals the economic losses in their member countries due to climate-related extreme events since 1980 [8].

The DESERTEC concept was very convincing to many people, because it was the most cost-effective Ansatz for a European energy transition. It was attractive for the companies because it was at the same time forward-looking, sustainable and it preserved the predominance of big companies, as only big players could handle the technology and the scale of the investments.

The alternative draft to this concept is the production of energy locally as proposed by e.g. Hermann Scheer, Eurosolar and many others [10]. The idea behind this concept is to promote energy autonomy and to disempower big power companies, using the—at that time—very expensive photovoltaics in combination with local on-shore wind power and biogas production. This idea became very popular in the solar community in Germany and was picked up by the (green) government by releasing the "Stromeinspeisungsgesetz" (Act on the Sale of Electricity to the Grid) and the “Erneuerbare-Energien-Gesetz” (Renewable Energy Law, EEG) in 1991 and 2000 respectively [11]. In combination with a high feed-in-tariff, the installation of PV became a money-spinner. While originally, after the German unification in 1990, the newly created East-German PV industry and many German house owners profited from this political decision, very soon the dominant PV producers came from China, and also the owners of the PV fields were—to an increasing extend—foreign investors. As a collateral damage of this boom, the German PV industry collapsed and private German electricity consumers will have to payback a high EEG feed-in compensation payment for the coming 20 years.

With the Arab Spring in 2010 and major conflicts in the Arab World, the realization of the DESERTEC concept, i.e. to set up a strong power trading between Europe and MENA, became more and more difficult. The political situation made any long-term planning and investments difficult for occidental investors. At the same time, the power market in Europe was saturated, the oil prices fell and the political atmosphere in Europe was not in favour of creating additional dependencies with Arabian energy markets. As a consequence, most of the big players left Dii, and its headquarter moved from Germany to Dubai. Dii started to focus on the fast-growing domestic market in MENA. The new players of Dii are mainly Arabian and Chinese companies with only one German company left from the original Dii. It can be expected that these companies try to dominate the renewable energy market in MENA in future, and once the domestic market is saturated and the prices are down, MENA will have the potential to flood the European market with low priced renewable energy. In case this scenario is realized, Germany would have missed the opportunity to profit from its pioneering position in renewables.

One of the geopolitical aims of DESERTEC was to increase prosperity and stability in MENA by a closer economic interdependence with Europe through energy trade and an increased employment rate in MENA. Also this objective failed for political reasons and the states in both regions were unable to build these new bridges between Africa and Europe, at least for the time being. Instead, unemployment, destabilisation of political structures and wars lead to migration of Arabic people to Europe, which caused new political problems there. All that emphasizes the importance to reconsider the political approach of DESERTEC.

3.3 Technologies for Renewable Energy Production

Which renewable energy technologies will we use in future? Even if forecasts of the future usually fail, valid predictions, based on certain preconditions, can still be made when they are based on scientific facts. Various renewable energy sources are distributed very unequally in time and in space around the globe. Therefore, there is not one technology that will take over the future renewable energy production, but a locally adjusted mixture of several technologies.

Renewable energies fluctuate at all relevant time scales: minutes (the timescale of passing clouds), hours (the timescale of the day/night rhythm), weeks (weather conditions), months (seasons, monsoon, …) and years (e.g. good and bad years for biomass production, or phenomena like El Niño). Figures 3.1 and 3.2 show examples of the geographical potential of solar and wind power around the globe. The by far strongest source is solar energy. Its technical potential exceeds the energy demand of humans by large factors. The most suitable areas for solar energy production are the deserts of the world in Africa, Asia, America and Australia (e.g. the Deserts Sahara, Gobi, Atacama, Kalahari etc.). The wind potential is especially large offshore, in coastal areas, on mountains, and in the areas of trade winds (e.g. Morocco) and anti-trades (Westerlies) north of the Horse latitudes. Biomass production is best in areas that have sufficient water and sun and good soil. Hydro energy is best in rain-laden, mountainous areas like Norway. Marine hydro energy can be easily harvested in areas with large tidal amplitudes. Geothermal energy is best suited for areas with recent volcanic history (New Zealand, Iceland). It cannot be predicted which energy technology political and economic leaders will foster in their region of interest. Nevertheless, it can be expected that sooner or later the most suitable technology will establish in the most suited areas, provided that a global energy exchange and a global free market for renewables will be established.

Photovoltaics

Today, photovoltaic modules are highly efficient and less and less expensive devices to convert solar power to electricity [12]. They have the advantage to be scalable, i.e. to use the same technology for small and for large devices (from mW to GW), to be easy to use, to have low maintenance costs, to need hardly any infrastructure, and especially no cooling water. PV panels sometimes are installed on devices that track the sun in order to maximize output. Today, due to the decreased prices of PV modules, the tracking mechanism usually does not pay off any more, especially in cloudy regions with a large contribution of stray radiation where tracking has a limited effect. The prices dropped dramatically as shown in Fig. 3.3. Energy generation costs for PV were as low as 3 $ct/kWh in a recent bid in Dubai for an 800 MW power station and 2.91 $ct/kWh in a bid for a 120 MW station in Chile [13].

Concentrated Solar Power

Concentrated solar power (CSP) uses direct radiation by tracking the sun and focusing the solar radiation [15]. This makes the technology suitable only for regions that usually have clear sky without clouds, mist, dust or sand storms. Four different technologies are available: Sterling Dishes, Concentrated Photovoltaics (CPV), Solar Troughs and Power Towers.

Stirling Dishes use parabolic mirrors in combination with a Stirling engine. This technology is not economically viable any more due to the cost decline of PV.

CPV uses arrays of mirrors or lenses that focus the solar radiation on an array of small PV cells [16]. The advantage of CPV is the largely reduced size of the PV cells, that allow for the use of more expensive but highly efficient cells. The disadvantage of CPV compared to PV is that it requires movable parts, that it cannot make use of diffuse radiation, and that it—due to the concentration of the

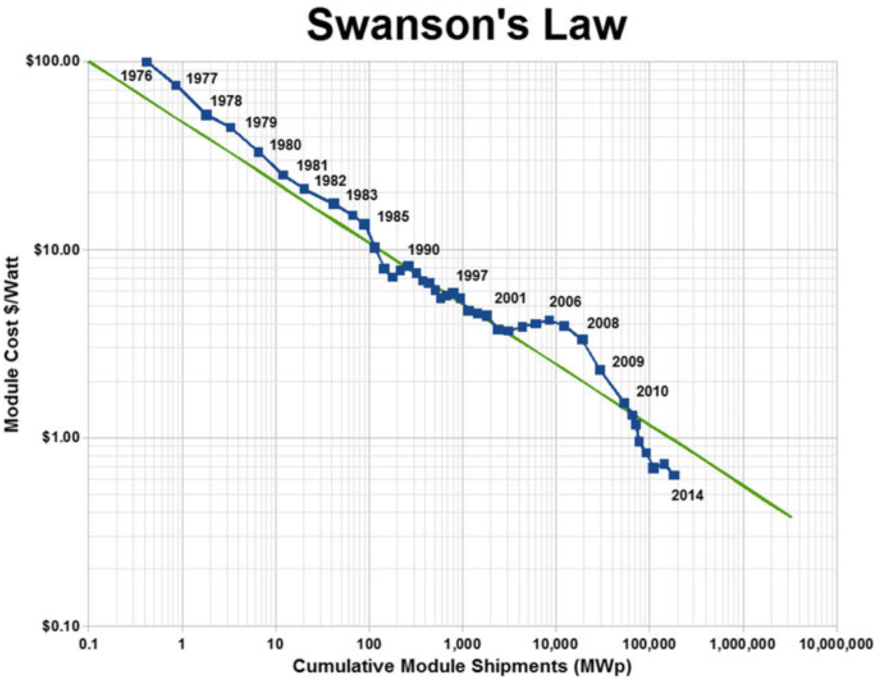


Fig. 3.3 In agreement with the economies of scales, the prices for PV modules dropped by about 20% for every doubling of cumulative shipped volume, which corresponded to about halve costs every 10 years. The module production is given in the unit MW_P which is defined as the (peak) power of the modules at nominal solar irradiation in megawatts [14]

radiation—may need cooling in hot environment. The cost advantage of CPV compared to PV is currently diminishing due to the cost decline of standard PV.

Solar Troughs and Power Towers convert solar radiation into heat and heat into electrical power. The advantage of the solar thermal technology is that it converts the whole radiation spectrum of the sunlight into heat and not only parts of the visible light. Further, it does not require semiconductor technology, and the conversion of heat to power uses mature, conventional technology as developed for fossil power stations. The most important advantage of solar thermal power plants is their ability to produce electrical power on demand by storing thermal energy. In addition to electricity production, the CSP plants can also deliver thermal energy for industrial applications that need process heat, e.g. for desalination plants. During periods of insufficient solar irradiation (e.g. bad weather periods), thermal power plants can be fired with fossil or renewable fuel to guarantee 100% operation without having to invest in a separate backup power station.

Today, most CSP installations use parabolic troughs as 1-dimensional focus elements. The whole system is turned and follows the position of the sun. Light is focused on a central moving absorber pipe that receives the energy and transports it to the generator. In an advanced design, a Fresnel reflector with small movable mirrors and a fixed absorber pipe replaces the large movable parabolic mirror system.

The **Power Tower** technology uses a 2-dimensional tracking system of numerous heliostats, which are realized as more or less flat mirror systems (Fig. 3.4). This technology is still in its infancy, but first commercial systems are operating successfully. The 2-dimensional focusing allows for very high temperature (∼1000 °C), which leads to a higher Carnot efficiency compared to solar troughs. There has been much progress to reduce the price for the heliostats and the tracking system.

The Power Tower has the advantage, that except for the central installation of the heat exchanger and the turbine, the rest of the solar field is low technology that can be fabricated locally in developing countries. Therefore, this technology will have large cost saving potential in mass production and a large part of the investment will have local value added. One example is the new Solar Tower station *Khi Solar One* in South Africa. In contrast to a trough system, the power tower field does not require a horizontal surface and can be installed in hilly areas. The size of a power tower field is limited by light diffusion to an output of about 100 MW. Larger power stations require multiple towers, which makes the technology scalable. The high temperatures of around 1000 °C are a challenge to material scientists, but their

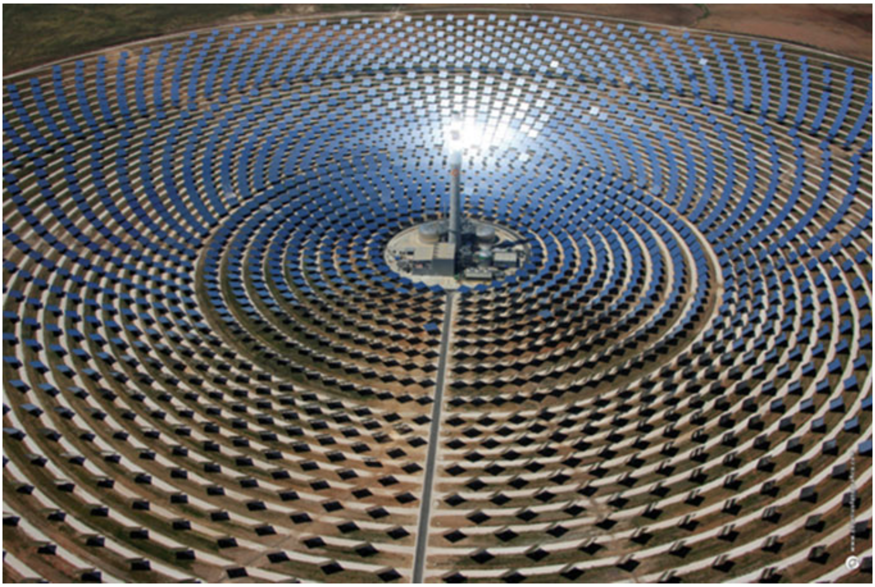


Fig. 3.4 The Power Tower technology focuses solar radiation onto a central tower where the high temperatures of the focus are used to generate electricity with high efficiency. Tanks with molten salt store the solar thermal energy to allow for a continuation of electricity production after sunset. The storage tanks are visible as small cylinders at the bottom of the tower. This photo shows a plant in Spain [17]

effort will pay back, as high temperatures increase not only the Carnot efficiency of the generator but also reduce the costs and conversion losses of the heat storage.

Wind Power

Since decades, wind turbines are well established as a very profitable technology of producing renewable power, especially in coastal regions and on top of mountain ridges [18]. Wind turbines have problems with public acceptance, especially in the well-populated Germany, where the fight of residents against the landscape disfiguring pylons reminds us of Don Quixote's tilting at windmills. Possibly, the eye-catching continuous movement of the propellers in a steady landscape and the unconscious perception of subsonic noise might disturb sensitive people, however, one can expect that future generations will get used to the view of wind farms like our generation got used to the view of busy and noisy roads everywhere in our originally peaceful landscapes.

It can be expected that wind turbines will be—together with solar energy—the prime choice for large-scale renewable power production. Wind power has the drawback of being volatile, but it is a means to produce power at night and at least in the northern hemisphere it is complementary to solar energy in the cycle of the year as solar power has its maximum in summer and while wind has its maximum in winter.

The question if onshore or offshore wind farms are more economical is not decided yet and depends on the architecture of the total energy system. The German offshore wind farms are far away from the coast, which makes the technology very expensive, as long high voltage DC (HVDC) cable connections are needed and the maintenance costs increase with the distance from the coast. On the other hand, the offshore winds are stronger and less volatile, and the potential for a future expansion is much larger offshore than onshore. Generally speaking, the ocean is for wind energy what the desert is for solar energy (see Fig. 3.5).

Hydropower

Mankind has used waterpower since more than 5000 years and modern hydroelectric power is certainly the most mature technology in the renewable energy

Fig. 3.5 Offshore wind farms, here in the vicinity of Copenhagen, have a large future potential due to the strong and less volatile winds and the almost unlimited space for wind farms [19]

market. The power of a hydroelectric installation is approximately proportional of the product of the amount of water running through it per second and the difference in height of the upper and lower water surface upstream and downstream of the turbine. This leads to two extreme constructions: the run-of-the-river hydroelectricity with only a small difference in height but a large flux and the hydroelectric stations with a huge dam and a moderate flux. The biggest installations combine large fluxes and large differences in altitude. There are hydroelectric power stations available from some kW to a range above 10 GW [20].

Most hydroelectric power stations have an upper barrier lake that is used as a water reservoir to provide a controlled water flow to the downstream river for agriculture and for a continuous power production throughout the year. Constraints from agriculture and landscape preservation limit the applicability of hydropower installations.

In the context of a 100% renewable energy system, the most important feature of hydropower stations is not the generation of power but the storage and regulation of power to compensate the volatility of solar and wind power.

A large physical potential can be assigned to marine hydropower stations that make use of waves, tides and ocean currents. Technology is still in its infancy and only a few stations have been realized so far. Figure 3.6 shows a tidal stream generator that could be upgraded to a whole "fence" of turbines to multiply the output [21]. Alternatively, other damless technologies may be used [22]. A major advantage of marine hydropower is the predictability of the power production and the apparently infinite magnitude.

Fig. 3.6 *Left* Example of a tidal stream generator that converts the kinetic energy from marine currents (e.g. Gulf stream or tidal currents) into electricity. The technical concept is similar to that of a wind power station, but due to the high density of water compared to air, also the energy density is higher and the "propeller" can be much smaller. In the photo, the rotor is moved above sea level for maintenance. A "fence" of these current turbines can convert tidal power at large scale using existing technology. *Right* A chain of horizontal helical turbines is another option for hydropower generation [23]

Biomass

Energy production by biomass is—besides the human's own metabolic process—as old as the first usage of fire by our prehistoric ancestors. It is a vast field that can be structured according to the origin of the biomass, its treatment and its application [24]. The origin of the biomass is versatile: wood from forests, bushes from scrubland, energy plants from agriculture, algae and plants from lakes, ocean, or hydro culture, waste from agriculture or households, faeces from livestock or communities. To make use of biomass, it can be treated in several ways. Besides direct burning, the main two methods are pyrolysis and fermentation. Pyrolysis can be applied to produce gas (mainly methane and hydrogen), oil, tar and/or to produce charcoal. Fermentation is used to produce biogas or alcohol (Fig. 3.7). Certain energy plants are used to directly produce biodiesel, e.g. seeds from Jatropha Curcas that contain up to 40% oil. The big advantage of biomass as energy carrier is that it is easily storable e.g. as pellets, liquids or gas and can be used as "energy on demand". In a sustainable future, biomass will have an increasing importance as raw material for construction (as in the old days) and for chemical industry. These applications diminish the fraction of biomass that can be used as energy source.

Geothermal Energy

High temperature geothermal energy can be harvested directly by injecting water into boreholes and running turbines with the ejected steam [26]. The amount of geological energy is seemingly infinite, but due to the very limited heat conduction

Fig. 3.7 Biogas production will replace natural gas as storable energy carrier and as base material for chemical industry [25]

in the underground, the harvesting of geothermal energy at large scale is difficult. It requires large collection areas or aquifers and pays off mainly in areas with an active volcanic underground like on the islands of New Zealand and Iceland.

However, there is also low temperature thermal energy in the ambient air, in rivers, in groundwater and the underground in general [27]. These low temperature energy sources are not very suitable for electricity production because of their low exergy, however they can play an important role in the future energy system for air conditioning and heating systems of buildings. Using heat pumps, the low temperature energy can be boosted to higher temperature for heating, to lower temperature for cooling and it can be stored thermally in tanks or subsoil over days and months to average out temperature changes in buildings due to external weather conditions (Fig. 3.8). The combination of solar thermal rooftop panels with heat pumps and subsoil storage allows for very efficient and simple methods of air-conditioning. More about thermal energy will be discussed in the chapters below.

Further renewable energy sources

There is a long list of further energy sources, which are not considered in this overview, either because the potential is small or because there is no mature technology available to harvest them, like for example wind power from kites or osmotic energy from river mouths [29].

Fig. 3.8 A ground heat exchanger can be used for heating in winter and cooling in summer. Depending on its shape and depth, it is used for subsoil heat storage, and also for the extraction of geothermal energy. The thermal conductance depends on the ground water flow and many other site-specific conditions [28]

3.4 Entropy, Exergy, and Why Energy Cannot Be Produced

The first thing a physicist learns in his studies is that energy is conserved. Energy can never be produced or destroyed; it can only be converted from one form of energy to another one [30]. In this paper the colloquial phrase "energy production" is used in the sense of "production of a useful form of energy". The physical quantity that comes close to this expression is the term "exergy" that describes the maximum possible work that a system can deliver before it reaches (thermal) equilibrium [31]. The distinction between useful and useless energy has to do with a quantity called entropy that governs the connections between energy and exergy. A full discussion of these quantities is beyond the scope of this paper, but in order to understand energy issues related to heating and cooling, air conditioning and heat storage, one does not have to have the full knowledge of thermodynamics [32], but one should know four basic effects as described below that follow from the laws of thermodynamics:

i. To keep a building warm or cold does not require energy (in the ideal case). Most important is the insulation of the building to prevent heat exchange with the outside. Exhausted air can be replaced by fresh air using a heat exchanger to minimize energy losses.

ii. The optimum way of heating and cooling a building (i.e. to compensate for insulation losses and other heat flows) is the use of heat pumps. A heat pump produces typically three to four times more thermal energy compared to the energy that is needed to operate the device. Apparently, it violates the conservation law of energy, but in reality it makes use of ambient thermal energy. For the heating of a room it "pumps" thermal energy from outside into the building and delivers the energy at a higher temperature level (see Box 3.2).

iii. A temperature difference of a hot and a cold thermal reservoir can be used to generate electrical energy. This is the working principle of all fossil-fuel, nuclear and solar thermal power stations. The larger the temperature difference is, the better is the efficiency of the energy conversion, as described by Carnot's law:

$$\eta = \frac{T_H - T_C}{T_H - T_0}$$

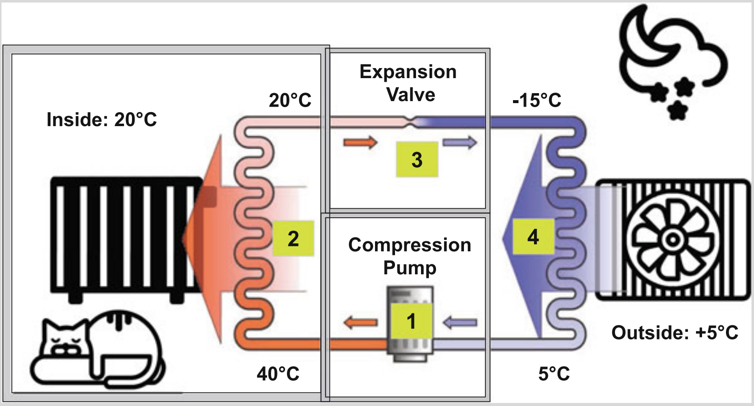
Here, η is the Carnot efficiency, i.e. the maximum efficiency that a cyclically operating technical device can have when it uses heat energy at high and low temperatures T_H and T_C to produce electrical energy. $T_0 = -273.15$ °C is the absolute zero, the lowest possible temperature. The efficiency of every thermal power station is limited by this law. It shows that a hot side alone is not enough to produce electricity. It also requires a cold side, i.e. a cooling. In a concentrated solar thermal power station, the hot side is powered by the sunlight. The efficiency of a solar thermal power station is optimized by increasing the temperature in the solar focus up to 1000 °C. The “cold” side of power stations is typically cooled by rivers, seawater or cooling towers that evaporate water. In deserts the cooling is achieved by ventilation of ambient air. The maximum efficiency for a concentrated solar power station is limited according to Carnot’s law to:

$$\eta = \frac{1000\,^{\circ}\mathrm{C} - 30\,^{\circ}\mathrm{C}}{1000\,^{\circ}\mathrm{C} + 273{,}15\,^{\circ}\mathrm{C}} = 76\%$$

The overall efficiency of real power towers achieved today is about 17%, which competes well with the efficiencies of PV panels and has a large potential for future improvement.

iv. Thermal energy can be easily stored for later conversion into electrical power. The higher the temperature difference compared to the ambient air, the higher is the capacity of the heat storage for a given volume. The larger a storage tank is, the smaller are the relative heat losses at the surfaces. In CSP plants, big tanks of liquid salts from fertilizer production are used as low-cost thermal storage medium. They are typically operated at temperature ranges of about 290–390 °C. The most efficient way of thermal storage uses phase transitions of materials e.g. from solid to liquid. There are e.g. ice tanks on the market that use the freezing of water in tanks in combination with heat pumps as energy source for domestic heating in the winter. The same device is used in summer for cooling by letting the ice melt.

Box 3.2 How a Heat Pump Works [33]



It is possible to understand the functionality of a heat pump on a basic level of physical chemistry without using any mathematical formalism or abstract terms like entropy and exergy.

1: The heat pump compresses the cold vapour of a special cooling agent. On the atomic scale, the compression brings the molecules of the vapour closer together, and attractive cohesive forces induce the phase transition of the vapour to the liquid state. The attractive energy of the intermolecular forces is released and heats up the liquid.

2: The hot liquid flows through a radiator and heats up the room. This way the liquid loses some of its thermal energy and leaves the radiator at approximately room temperature.

3: The pressurized liquid is pressed through a throttle. Due to the compression pump, there is a large pressure difference before and behind the expansion valve. Due to the low pressure behind the valve, the liquid evaporates. While the molecules separate during evaporation, the intermolecular potential slows the relative motion of the molecules down, which means that the vapour becomes very cold. This is because on a molecular level low temperature equals small relative motion of molecules. The thermal energy is now converted to potential energy between the detached molecules.

4: When the cold vapour passes the chiller, it is warmed up by the outside air and becomes a bit warmer. In the ideal case, it will have the same temperature as the outside air when it leaves the chiller.

Then the cycle begins again. This way, thermal energy of the outside air is "absorbed" by the cooling agent, pumped to a higher temperature level, is "released" by the radiator, and used to heat the room. The electrical power that runs the pump keeps the cycle running, but it is not the main source of energy that heats the room. The energy conservation law tells us that the total energy that is delivered to the room is the sum of the energy that is absorbed in the chiller plus the electrical energy that runs the pump.

By reversing the pumping direction, the heat pump can be used for cooling the room.

3.5 Electrification of Mobility and Heat

One of the common, big mistakes in energy discussions is mixing up the electricity sector with the total energy consumption and vice versa. Electricity is only about 17% of the total energy consumption [34]. The main, and the most difficult part of the energy transition is not the electricity sector but the rest. A second common mistake is to predict that due to energy saving and efficiency increase the electricity demand will decrease in future. Instead, a dominant part of the heat and mobility sector, which is currently predominantly energized by fossil sources, will have to be converted to electrical supply for the following reasons: First, the future primary energy source will be solar and wind, which can be directly harvested as electricity. Other energy carriers (like biogas) will not be available in the required amount.

Secondly, electrical engines and heat pumps are more efficient than fuel or gas driven devices. Therefore, the electricity sector will experience an increase in volume by a factor of somewhere between 2 and 6, depending on the efficiency increase and saving potential of the future heating and mobility sector.

Mobility

The most efficient engines for the mobility sector are electric engines. They have efficiencies of 80–90% compared to about 30–40% of combustion engines. In the part-load operational range the supremacy of electrical versus combustion engines is even better. Public transportation, especially electrical trains and subways, will be the most efficient way of transportation in populous regions and for long distances.

The individual motorcar traffic will never be replaced completely by public transportation due to its attractiveness, and also due to its advantages in regions with low traffic and population density outside of cities. Due to the rapid development in lifetime and energy density of batteries, it can be expected that a majority of cars will run as zero emission electrical vehicles in future.

The reach, weight and charging of batteries is the main issue of electric vehicles today. This problem has been avoided for the electrification of trains, subways, and trolleybuses by overhead lines or conductor rails. First examples of overhead lines on highways that supply trucks are currently tested in several countries. In future, the charging of batteries can possibly be achieved by contactless inductive charging stations at parking lots, bus stops or even as subsurface rails along certain roads and highways. If the charging of batteries has to be done in short time during a stopover, one has to take into account that the required peak power of the charging station has to be quite high. Take e.g. a Tesla Model S car with an 85 kWh battery and a consumption of 24 kWh/100 km [35]. The range of the car is nominally 85/24*100 km = 350 km. If one wants to charge it at a standard home connector with a 16 A fuse, it requires nominally 85000 Wh/230 V/16 A = 23 h to recharge it. To charge it within about one hour, a connection with 85 kW is required. This numerical example illustrates, that the electrification of mobility requires not only an overall increase of electricity supply, but also dedicated connectors with high power wherever people want to charge their cars in short time.

While private vehicles normally can be charged over night or during working hours, commercially used vehicles and especially long distance trucks cannot operate with limited range and long recharging times for batteries. A much more useful concept for long-distance routes is a business model where the battery is semi-automatically exchanged at charging stations and replaced by a charged battery. Another option is to use a redox flow battery instead of a standard battery (see Fig. 3.9) [36]. In this case the truck driver just has to exchange the “discharged” electrolytes by “charged” electrolytes. In both cases the stopover time of the truck or motor coach is short. Another advantage of such a model is that the charging of the battery or electrolyte is completely decoupled from the time of travel and can be done in the charging station at a time of the day where electrical energy is abundant and cheap.

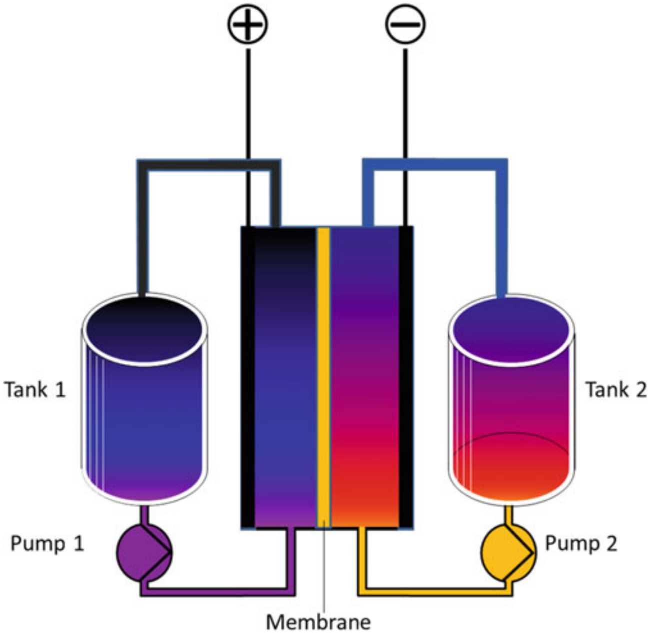


Fig. 3.9 Flow batteries are batteries where the electrolytes (which contain the energy) are stored in tanks separately from the device that converts the chemical energy into electrical power. The capacity of a flow battery can be enlarged unboundedly by larger electrolyte tanks. While maximum power of the device depends on the size of the converter, the maximum capacity depends on the size of the tanks. A flow battery has similar functionality as the combined system of a hydrogen storage, a fuel cell, and an electrolyser. However, the total efficiency is larger for a flow battery than for a fuel cell plus electrolyser. In mobile applications, the flow battery can be "loaded" by exchanging the tank fillings with regenerated electrolyte [39]

Alternatively, especially for heavy traffic in remote areas, for aviation and for vessels, biologically or electrically produced fuels like biogas, biofuels, and hydrogen are alternatives to standard batteries. Recently, it was found that there is an efficient way to produce alcohol from CO_2 using copper nanoparticles on a carbon nanospike film [37]. Another attractive alternative for a mobile energy carrier is liquid ammonia produced from electrolysis of water and nitrogen. A transition from petrol to ammonia has the advantage that it can make use of the existing infrastructure of filling stations and there are fuel cells available that convert the energy directly into electric power in the car.

The ideal energy carrier is the so-called super-super-capacitor, a capacitor with very high energy density, ultra-fast loading capacity and almost infinite life cycles. First promising results to build such a device have been made using graphene, claiming that cars with such energy storage could be charged within one minute [38].

Heating and Cooling

A large fraction of the world energy consumption is used for heating and cooling. From the physical point of view, in most applications it is not the thermal energy that is needed, but it is a certain temperature that is needed. The amount of energy that is needed to obtain the temperature depends mainly on the quality of thermal insulation and on the options for heat recovery. Therefore, the starting point for a renewable transformation of the thermal sector is energy saving by insulation and heat recovery. This applies to all scales: from industrial process-heat, to heating and air-conditioning of houses up to a bakery and methods for individual cooking in the households.

What is the best way to air-condition a building? In the best case, a building becomes a zero-energy house by good thermal insulation, with centralized air conditioning and heat exchangers [40]. In most cases, the most efficient device to add or to extract thermal energy to or from a room is the heat pump. A heat pump uses the energy of the outside ambient air or other external thermal energy sources (e.g. geothermal) and pumps it to the temperature level that is required for the air conditioning. Such a heat pump can have efficiencies up to 300–500%, i.e. the ratio of produced (or removed) thermal energy is much larger than the electrical power that is used to run the heat pump (see Sect. 3.4 and Box 3.2).

In a transition period of the Energiewende, when anyway part of the electricity is still produced by fossil fuels, heating by combined-heat-and-power (CHP) [41] systems makes sense, however CHP systems have the disadvantage that power and heat production is coupled and most likely does not meet the needs at all seasons, especially in well insulated buildings. Also, the electrical efficiency of small CHP systems is much lower than that of large combined cycle power plants with a district-heating network. Therefore, combined-heat-and-power systems are not a prime choice for the future.

To conclude, the electrification of the mobility sector and of the thermal energy sector is of prime importance to reduce the world energy consumption. In the next section we will discuss that the electrification of these two sectors will have an additional benefit for the global energy transition as it allows for an efficient time shifting of electrical load.

3.6 Energy Sharing: The Smart Grid

A conventional power grid is operated in a way as described below in a simplified picture: The grid contains several large-scale power generators, which are synchronized among each other and which provide AC voltage with a constant frequency of 50 Hz (in some countries 60 Hz). This power is distributed to the consumers in a common grid. The power consumption has more or less known variations over the day. It can be split into a large base load and an additional varying contribution [42].

The regulation of the power stations with respect to the load changes is described in a simplified way as follows: If the load on rotating generators increases, the rotation becomes slightly slower, and the frequency and the voltage decrease slightly. When a frequency shift is observed, the operators of the power station will increase the power production of the power station, e.g. by additional firing in case of a fossil power station or by additional water flow in a water power station. This way the frequency rises again to its original value and is kept constant over the day.

In a large, international power grid the frequencies and phases of the power grid need an overall synchronization. If two sub-nets start to be out of phase, there will be voltage differences at the two ends of the power line that connects the subnets. These out-of-phase voltages can generate huge electric currents in the connecting lines. This effect has to be strictly avoided as otherwise the wires will overheat. If a sudden load or production change happens in the grid, this transient has to be compensated within a short moment. If this is not done, the subnet where the transient happened will start to be out of phase and it will be (automatically) disconnected in order not to destroy the power lines. In some cases, switching off a subnet causes load problems in the neighbouring subnet. In a chain reaction, a large-scale blackout can be produced. These large-scale blackouts are a direct consequence of the archaic design of the AC power grids.

In future, large-scale grids should get rid of the frequency synchronization by using DC instead of AC grids as described in Sect. 3.8. In principle, power transients can be compensated not only by controlling generators but also by fast load and storage control. The brute force method of load control is to switch off electricity in whole subnets in case the demand is higher than the production. In some African cities it is common to switch off electricity in several districts of big towns every evening. In this case, not only air conditioning and washing machines, but also light, computers, TV's and lifts get stuck. A more sophisticated system, called "smart grid" is needed to regulate the consumption in a more intelligent way.

In a renewable energy system, the few large-scale power stations are replaced by a large number of power generators at all scales, from small PV panels to large solar power stations, wind farms and hydroelectric dams. In this system, not only the power consumption but also the power generation is volatile. Therefore, it is of increasing importance to control the power generation and also the power consumption in a large-scale coordinated but still decentralized manner in order to keep the grid stable. In the past, the power generation followed the power demand. In a smart grid, both, production and consumption should be matched in the most economic and safe manner. The smart grid has three ingredients:

Monitoring: Online metering and monitoring allows for a better forecast of power consumption and production.

Accounting: Time-dependent accounting allows for tariffs that encourage power consumption at times where power is abundant and that discourages power consumption at times where renewable power is scarce.

Remote control and time shifting: Switching on and off producers and consumers as well as loading and discharging power storage are means to guarantee a safe power supply, to avoid power failures, and to maximize the economic output.

The typical example is the washing machine that is running at night when there is little power consumption or at lunchtime when there is too much solar power. Studies have shown that today the impact of smart metering in households is small, because the average consumer does not care about small additional costs for electricity. Today, the number of devices that can be delayed in power consumption without comfort loss of the consumer is small and not really relevant compared to the overall electricity production. In contrast to the average person's feeling that electrical power is very expensive, even in a German household with large additional EEG charges the electricity costs are usually small compared to the monthly costs for heating and mobility.

In a 100% renewable energy system, this will be completely different. The main consumers of power will not be the electric lighting, the hover, hairdryer and the TV set in the households, but heat pumps, air conditioning and batteries of cars. Power consumption peaks can be avoided by time shifts in the operation of these devices. This is uncritical most of the time and can be done in an intelligent way without notice by the consumer. It will require that the remote operator software has access to private data, e.g. that it knows at what times and for which distances the car is used on a normal working day and it should know when the client arrives at home and expects a cosy flat.

Power production peaks can be avoided by either switching off wind and solar stations remotely, or by dumping the power somewhere, e.g. into simple boilers for domestic warm water storage. If a consumer owns a home-battery, the situation will be even more flexible. The private home-battery can be a device to earn money by allowing the grid operators to charge and discharge it in a remote-controlled mode to minimize fluctuations and loads on the grid. The same is true for electric vehicles in charging mode as described in Sect. 3.11.

3.7 Energy Transport: Reducing Local Volatility

As discussed above, renewable energies have a large volatility as well in their spatial as in their temporal distribution. There are basically two ways to handle the volatility: storage capacities level out the temporal fluctuations and power grids average out spatial fluctuations. An intelligent combination of the two methods will yield the most economical way to provide everybody with the power that is needed. According to the laws of statistics, the relative amount of fluctuations of uncorrelated sources and consumers becomes smaller and smaller the more sources and consumers are connected to the network. In the simplest example of uncorrelated fluctuations, the relative amount of fluctuations is proportional to the root of the inverse number of participants. In reality, the sources and the consumptions are both correlated statistically. For example, the production of a single PV module fluctuates according to the clouds that are passing by, so that two modules at a distance of e.g. 1 km are statistically independent at a first glance, but on an over clouded day all PV modules in a certain region produce low output at the same time, which means they are correlated. Weather phenomena that define the output of PV and wind energy are typically correlated on scales of a few hundred kilometres.

One needs to interconnect solar and wind power on scales of $1000 \times 1000\ \text{km}^2$ or more (depending on the geographical region) to average out a large fraction of the spatial fluctuations of renewables that are induced by weather phenomena. This is in line with the proposal of DESERTEC. It proposed to have an overlay network in Europe and to connect it with North Africa. This way Europe can take advantage not only of the averaging of the European energy consumptions (e.g. different times of rush hour) and of different weather conditions from the Mediterranean to the Scandinavian countries, but it can also take advantage of the stable conditions of the trade winds in North Africa and the stable solar irradiation in the Maghreb region (see Fig. 3.10).

Some plans go beyond the DESERTEC ideas and propose to construct a global power grid that crosses all continents and includes the arctic regions with their strong everlasting winds. Such a global grid could produce solar power 24 h a day, and the dark side of our planet could be powered by solar energy from the illuminated side of the planet. This sounds like science fiction, but nevertheless connections between Europe, and various regions in Asia and Africa make a lot of sense, regardless if the circle around the globe will be closed or not (see Fig. 3.11).

Fig. 3.10 The original DESERTEC concept suggests a HVDC transmission network to trade electricity between Europe and Middle East and North Africa (MENA). The dominating sources were Concentrated Solar Power stations in the deserts and wind power in the coastal areas, on- and offshore. In addition, all other renewable energy sources like hydro, PV, biogas, and geothermal energy were included [43]

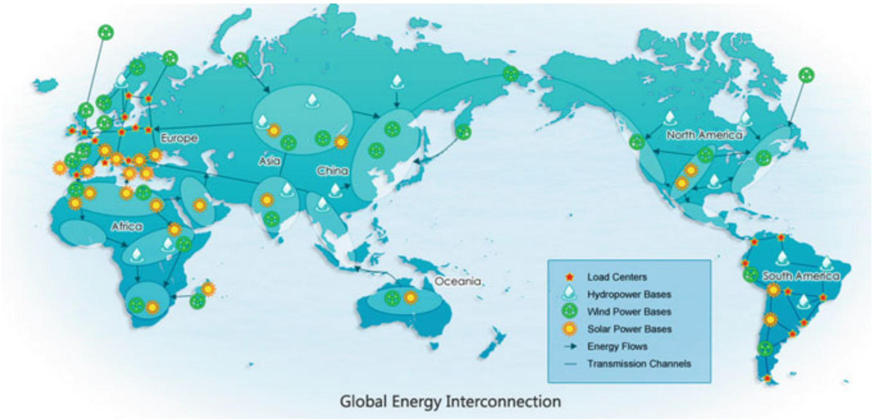


Fig. 3.11 The global power grid. In future, overlay grids will connect more and more countries and allow for efficient international trading of power. At that point it starts to make sense to interconnect all these grids to a single global net and to make use of sun from deserts, wind from polar regions, and to shift power in west-east direction to compensate at least part of the day/night periodicity and the morning/evening peaks [44]

3.8 The Overlay Network: AC or DC?

Today, the majority of primary energy is transported by pipelines (gas, oil), ships, trucks and trains (coal, oil, gas, nuclear fuels). Electricity is usually transported by AC overhead transmission lines [45]. In the future, fossil sources will lose their pre-eminence and electricity will become a prime energy carrier. Energy transport by electrical lines will have to be enforced and extended.

One has to distinguish between a distribution network and a so-called overlay network. In future, the task of the distribution network is to connect every small producer (e.g. PV module) and every small consumer (e.g. household) with a general network. The range of the distribution network covers typically a town or a rural area up to a diameter of a few hundred kilometres.

The task of the overlay network is to interconnect distribution grids and major consumers and producers of electrical energy on a scale of up to several 1000 km. To a large extend, the existing electricity networks in many countries (e.g. Germany) were designed 50 years ago, centred on the main conventional and nuclear power stations. They connect to almost every household and are interconnected and synchronized throughout most of Europe. However, even if today most of the European countries are interconnected, this does not mean that there is an efficient way to trade electricity from one country to another one over long distances. The AC power lines have large losses at large distances. This is due to the emission of electromagnetic radiation at 50 Hz (also called electro-smog), due to the heat loss in dielectrics that surround the cables, and also due to the skin-effect [46]. The skin effect is caused by electro-magnetic induction. It produces circular currents inside the conductor that heat it up and expel the transmission current to the outer surface of the cable. The transport of AC electricity over more than a few hundred km is not very economic.

This problem can be overcome by using high voltage DC currents. Today, this technology is well established for point-to-point connections, using voltages of almost 1 GV with losses of less than 3% every 1000 km. Only very recent technologies allow for a designs of HVDC networks [47] that are multiply interconnected, and where the direction and amount of the power flow can be well controlled. They will likely be the basis for future overlay networks. Inverter stations are needed to connect the AC distribution networks with the HVDC overlay network. The problem of large-scale blackouts should be solvable in DC networks, as the various AC distribution networks can run asynchronously, so that a power failure in one network does not necessarily screw up the other ones. The converter stations will adjust the frequency of the AC networks electronically.

What is the reason why AC has been established as the prime choice in the old days, if DC is the better choice for transmission lines? There are two main reasons: The generation of electricity was mainly done by rotating generators and the main users were rotating engines. Rotating devices use naturally AC, or, more precise, three-phase alternating current. More important is the next reason: The transmission of power in cables requires voltages that are as high as possible to minimize ohmic losses. On the other hand, the voltage in households has to be sufficiently low for safety reasons. Therefore, the transformation of voltages is an essential part of any grid. Until recently, there was no technology available to transform DC voltages on the MW or GW level, whereas the transformation of AC voltages can easily be done using transformers. This is the reason why AC was the only choice for high voltage lines in the old days. Today, more and more producers (e.g. PV modules) and consumers (LEDs, electronic devices) use direct currents (DC), so that in principle the whole grid could be DC. However, DC-DC transformation requires still expensive power electronics. Therefore, the AC technology will probably remain the best choice in future for distribution networks, while DC will be the choice for efficient long distance lines.

3.9 Gas or Electricity?

In addition to the electricity network, Germany and many other countries have a widely ramified distribution network for natural gas to supply gas for heating. In addition, there is an overlay network of gas pipelines as interconnection for international trading and to connect to gas fields in Russia, the Netherlands and Arabic countries.

In principle, the future energy distribution system can be based either on (renewable) gas or electricity or both. Also other renewable energy carriers (liquid or solid) are conceivable in a future renewable system. Examples are liquid ammonia or solid burnable metal like magnesium, both (re-)generated by renewable energies.

Today's double infrastructure of gas and power is historic in the sense that gas was required for affordable heating energy and power was needed for electrical equipment.

In principle one can imagine that in future a pure gas distribution system without a power grid is sufficient. Today there are efficient ways available to convert gas to power on demand in individual households or blocks of houses, e.g. by using fuel cells [48].

However, it seems more likely, that a pure electricity distribution system will be the future of the typical household for the following reason: An electrical connection is simple, cheap, efficient, and has low maintenance costs. It allows for an immediate feed-in of self-produced power from PV into the grid, and it allows for easy load management (smart grid). Due to improved insulation of houses, the future energy consumption for heating will be reduced significantly, so that a gas supply system in addition to the electrical supply will probably not be economical any more. Instead, electrically driven heat pumps will be the most economical way of heating and cooling, possibly in combination with rooftop solar heaters or geothermal heat collection. Also cooking is more ecological by using modern induction cooktops or microwaves compared to gas cookers.

While the question of gas or electricity is probably decided for the distribution network in favour of a pure electrical system, the situation may be different for the overlay network where a combined system of HVDC and gas may be the most economical choice:

The necessity of a HVDC overlay network has been described above. It is needed to average out power fluctuations at large distances, and it can save costs by reducing the need for large local storage capacities and local power stations. Nevertheless, there is one major problem for the expansion of the overlay network: There is a strong public opposition against new overhead lines, especially in Germany. The arguments can be mitigated by using underground cables, by repowering existing AC lines by stronger HVDC lines, or by locating new lines along train and highway structures or rivers. A successful approach is also to share planning and profit with local stakeholders, as studied for example by the Renewables Grid Initiative [49].

In addition to the electrical overlay grid, a gas pipeline infrastructure may be useful and necessary for the following reasons: In the next chapter, a gas-based storage system for uninterrupted electricity supply is introduced. This storage system will profit strongly from (renewable) gas trading within a transnational, long-distance pipeline system. A gas infrastructure is also useful for mobile applications, e.g. for hybrid vehicles with fuel cells.

Gas pipelines have several advantages compared to HVDC lines: Typically, they have 10 times the capacity, a fifth of the costs, they have basically no environmental impact, are accepted by the public and there is an existing infrastructure of long distance exchange pipelines in many countries. The disadvantages are the large loss in the conversion processes of renewable power to gas and back to power and larger energy costs for transmission (pumps and leaks).

3.10 The Dual Storage Concept

In order to provide power to the consumer at all times, energy storage is required to average out the volatile nature of renewable energies. To some extent, a large power grid can take over this task without using storage, as it averages out not only spatial but also temporal fluctuations at a given spot. For example, individual PV modules show fast transients if clouds pass by, but these transients are flattened if many spatially distributed PV modules are interconnected in one distribution grid, especially at timescales in a range of minutes. The flattening of the output could also be done using a local storage at each PV module, but a large-area power interconnection is usually much cheaper than any storage.

On the other hand, by far not all of the volatility averages out spatially, even if the grid covers a whole continent. The dominant time scales that remain are the day/night rhythm and the cycle of the year (Fig. 3.12). Not only the production, also the consumption has the same two dominant timescales: the day/night rhythm (electric lighting in the morning and evening, rush hour, industrial production at day, air conditioning during midday heat, etc.) and the cycle of the year (heating in winter, air conditioning in summer, reduced industrial consumption at vacation times, etc.).

The "Dual Storage Concept" incorporates these two dominant timescales in the design of a storage system in order to minimize as well the investments as also the running costs of the storage system. Electrical storage in general is expensive and different storage technologies have very different costs and are optimized for different purposes. The Dual Storage System consists of a first system denoted **Short-Term Storage** that is optimized for the day/night rhythm and a second system, denoted **Long-Term Storage** that is optimized for the cycle of the year (see Table 3.1). Of course, a future system can take many more timescales into account, but the main effect comes from the two dominating timescales.

A storage system is characterized by several important physical parameters: Its capacity C denotes the total output energy W_{out} that the storage can provide and the efficiency η defines the fraction of the electrical output energy W_{out} compared to the

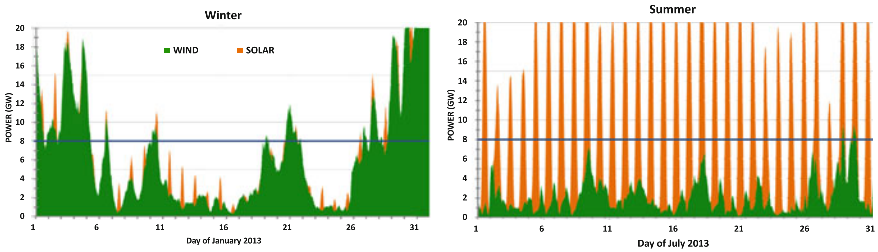


Fig. 3.12 The renewable energy production by wind (*green*) and PV (*red*) in January (*left panel*) and July (*right panel*) in Germany 2013 show the typical mix of periodic and random fluctuations. The blue line indicates the average annual renewable power production [50]

Table 3.1 Main parameters of the proposed Dual Storage System. It accounts for the two dominating time-scales of energy production and consumption: the day/night rhythm and the summer/winter cycle

Storage type	Short-term	Long-term
Technology	Batteries, pump storage, demand controlled hydro, CSP-heat storage, …	Gas storage
Capacity C	Large: Cover electricity consumption of 1–2 days	Huge: Cover electricity consumption of a few months or more
Max. power input (Charging)	Very large: Cover surplus peak power of solar and wind	Medium: Charging (power-to-gas) is done at times of low power consumption or high renewable surplus or from short-term storage
		In addition: Direct charging by biogas, whenever available
Max. power output (Discharging)	Very large: Cover peak power consumption, stabilize grid	Large: Cover average daily power consumption (but not peak power)
		Discharge by combined cycle power stations (base load), fuel cells and/or gas turbines (peaks)
Efficiency η	High: ~80–100%	Medium: ~30–45%
Cycle time T_C	Short: several days (2–10)	Long: one or several years (1–5)
Energy loss/year $(1 - \eta)/\eta * C/T_c$	Moderate: ~0…50 C/y	Moderate: ~0.2…2.3 C/y

electrical input energy W_{in} during loading: $\eta = W_{out}/W_{in}$. Important for the ability to compensate rapid fluctuations in the grid is—among other quantities—the maximum power output $P_{out,max}$ during discharge and the maximum power input $P_{\mathrm{in,max}}$ for loading. The total capacity C divided by the average output power $P_{\mathrm{out,ave}}$ is the average cycle time $T_C = C/P_{out,ave}$. T_C can be interpreted as the time that would be needed in an average operation until a full storage is emptied if it were not refilled in between. The inverse of this number defines the number of storage cycles per year.

The **Short-Term Storage** is optimized to handle power fluctuations on a typical scale of hours, especially the day/night difference of solar (and wind) energy and of the power consumption with peaks—depending on the country and climate—in the morning, at midday or in the evening. In the extreme, the short-term storage has to be able to cover timescales somewhere between 15 min and 1–2 days, as it should be able to handle power transients in rush hours but also the storage of surplus energy at weekends. The storage system must have high power input capacity $P_{in,max}$ to cover the solar peak power production in summer at midday and it must have high power output $P_{out,max}$ to cover the peak power consumption in winter in the evening hours. The capacity C of the short-term storage has to be on the order of the daily energy consumption to cover the total energy requirement of one or two dark days in winter without wind. An exact capacity of the storage system cannot be calculated from first principles. It has to be tuned using system simulations and can be adjusted to an economic optimum that depends on an trade-off between the long-term and the short-term storage system costs and the load management capabilities of the consumers. The turnaround of the short-term storage is on the timescale of several days. The efficiency η of the storage has to be as high as possible, as the power loss from storage inefficiencies accumulates day by day. Typical realizations of efficient short-term storage are batteries (including redox-flow batteries and future super-super-capacitors), pump-storage power stations (including intermittently operated hydro power stations), thermal storage in connection with CSP, and others.

The **Long-Term Storage** is optimized to handle power deficits and power excess on the scale of several days, weeks, months, and from one year to the next one. It does not have to handle daily power peaks, as those are covered by the short-term storage. The maximum power output capacity $P_{out,max}$ of the long-term storage is adjusted to the maximum of the power consumption averaged over about 1–2 days. This means that the power output is significantly smaller than the one of the short-term storage as peaks are handled only by the short-term storage and not by the long-term storage. In contrast, the capacity of the long-term storage has to be much larger than the capacity of the short-term storage. It has to cover the maximum expected deficit of renewable power production in the timescale of several months up to a few years. Therefore, the storage medium has to be inexpensive. The cycle time of the long-term storage is about one year or longer. Therefore, the integrated energy loss during the charging (i.e. power-to-gas conversion) occurs only once per year. In other words, the long-term storage has to have a large, inexpensive capacity but it does not have to have high storage efficiency. The most cost-effective realization of huge long-term storage is gas storage.

The important economical parameters for the design of a storage system are the investment costs, the required overcapacities, the power costs, and the overall efficiencies. As described above, the Short-Term Storage requires high efficiencies, high maximum power. The Long-Term Storage requires large, cheap storage capacities and only moderate power output. An important ecological and economical quantity is the average loss of power $P_{loss,ave}$ by the operation of the storage system. It can be calculated from the storage efficiency η and the average cycle time T_c of the storage as follows:

$$P_{loss,ave} = \frac{1-\eta}{\eta} P_{out,ave} = \frac{1-\eta}{\eta} \frac{C}{T_c}$$

This means that a storage of a given capacity C and efficiency η with the operation modus as Short-Term Storage with an average cycle time T_c of two days has power losses which are 365 times as high as for a storage operated with a two year cycle time. This confirms that the Short-Term Storage needs very high efficiencies, whereas for Long-Term Storage high efficiencies are not as important. Their loss is suppressed by a factor of ~ 365, i.e. a 50% inefficiency of a Long-Term Storage corresponds to a 0.14% inefficiency of a Short-Term Storage.

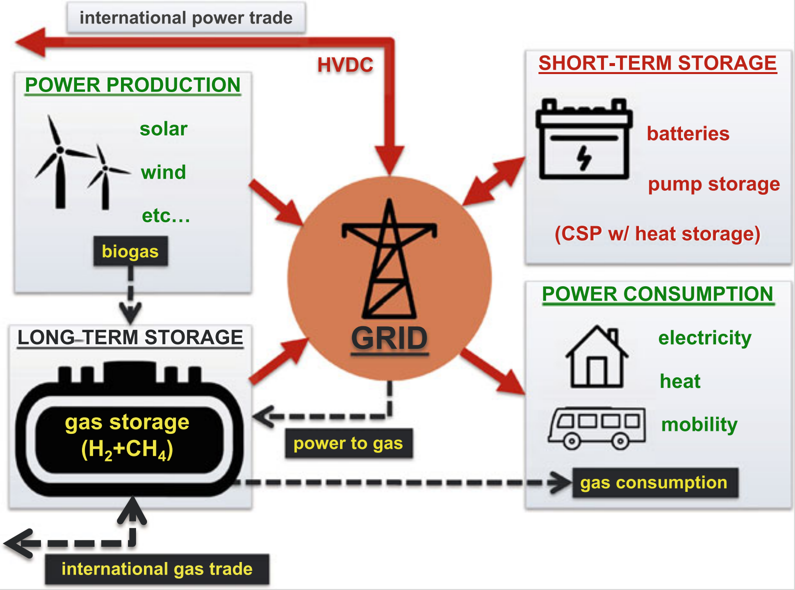
New business models are needed in the future energy system. The new business models have to account for the different tasks of the storage systems, because otherwise there is no way for a Long-Term Storage to compete with a Short-Term Storage, because that one is used all day while the Long-Term Storage is used basically only once per year.

Models of a future German Energy System have been calculated at very different levels of sophistication, for example in Luther [51] and acatech [52].

Box 3.3 shows the energy flow of the whole system: energy production, storage and consumption of energy. The renewable energy systems couple their power directly into the electricity grid, except for the biogas production that is piped into a distributed gas storage system.

The Short-Term Storage System is charged from the grid when the power production is higher than the consumption. It is used to stabilize the grid and to provide power whenever there is a deficit in power production.

Box 3.3 Structure of the Energy System in a Sustainable Future [53]



Central part of the future energy system is a large scale HVDC overlay grid in combination with local AC distribution grids that connect producers, consumers, and storage devices and allows for an efficient international electricity trade. The power grid has to be smart to allow for communication and remote control of producers and consumers. A separated gas network allows for efficient gas management, for the supply of gas for mobile applications, and for the import of renewable gas from deserts.

Power production will be mainly based on solar and wind, but also all other renewable energies will be included. Biogas will not be converted to power directly, but it will be stored in the long-term gas storage for later usage.

For efficiency reasons, energy consumers will have to use electrical devices to a large extend, using heat pumps in the heat sector and EVs and electric trains in the mobility sector. The gas from the long-term storage will be available to the gas-consumer for special applications where gas is superior compared to electricity.

The Dual Storage System has the important function to provide power at any time and to prevent overloads and black outs of the grid. It consists of a Short-Term Storage with high efficiency and a Long-Term Storage system with large capacity. The Short-Term Storage can be realized by batteries, pump storage, hydro power by demand control and heat storage in connection with concentrated solar power stations. The Long-Term Storage is a gas storage system using power-to-gas for loading and gas power stations or fuel cells for discharge.

During the years of the energy transition, natural fossil gas will be used until sufficient renewable resources are available.

The Long-Term Storage System uses hydrogen, methane or heavier gases. In an initial time during the energy transition, it is charged by imported natural gas. After the energy transition in a 100% renewable world it will only be charged by biogas or by surplus power from the grid that will be converted to hydrogen or other gases (power-to-gas) [54]. This will happen whenever the short-term storage is fully loaded and additional power is available.

Of course, in reality it will not be as simple. More sophisticated software will be used to optimize the loading of the various storage systems according to forecasts of production and load. It may be necessary to charge the Short-Term Storage System from the Long-Term Storage System to be prepared for peak loads in situations where there is a renewable power shortage over a longer period. The gas-to-power conversion will be done by combined-cycle-plants [55] with high efficiency, or possibly by fuel cells. Cheap surplus gas turbines might be used for times of high demand and as backup power for power failures. Gas can also be provided for the end-user directly (e.g. mobile users or chemical industry), wherever necessary.

The location of the storage devices can be at the point of production, at the point of consumption, or anywhere else in the grid. A distributed storage system is favoured, as it allows minimizing the capacity of transmission lines. Most of the storage devices can be situated locally at the level of the AC distribution networks. Only larger systems (e.g. large pump storage plants) have to be directly connected to the HVDC overlay network.

3.11 Overview of Energy Storage Technologies

The grid operator has to make sure that the power grid runs stable at all times. The control includes the required voltage, the required power, and in case of alternating current the stability of frequency, phase, and the correct impedance. To achieve that, there is a multitude of storage technologies available at all required timescales.

Millisecond Storage

For very short timescales of milliseconds to minutes, the predominant stabilizer of the electric power has always been realized by the rotational energy of the generators that is able to average out power spikes in demand. In times of PV and HVDC [56] converters, fluctuations in these timescales have to be regulated by electric field energies of capacitors in the inverter station and by the magnetic energy in the power lines. Further technological options for very short time storage are super-capacitors, superconducting magnets, and, as replacement of the old rotating generators, flywheel energy storage. The efficiency of these devices is typically close to 100%.

Overcapacities and Time-Shift of Consumers

For timescales, longer than seconds or minutes, the required capacities exceed the possibilities of the above technologies. Instead of building dedicated storage capacities, there is another way to balance the equilibrium of power production and consumption: In many cases, the cheapest way to provide regulating power at these timescales is to provide overcapacities of wind, solar and hydropower stations. These overcapacities are fed into the grid for stabilization purpose whenever needed. Otherwise they are either switched off or dumped to low-priority applications (e.g. heating of hot water tanks in households or the production of power-to-gas). In addition, a “smart grid” as described above will be used to cut spikes of consumption and to apply time shifting of certain consumers to times where there is less power demand. Only for times where these measures are not sufficient, a dedicated storage is needed.

Hydropower by Demand Control

An especially elegant way to use hydroelectricity is to operate the station as regulating power device instead of as base load device, i.e. to run the station in an interrupted mode where the output power is adjusted to the power consumption (Fig. 3.13). The “storage”-efficiency of this device is about 100%, as the average regulated power is basically equal to the base load that it would provide in continuous operation. The investment costs for a hydropower station that runs on demand are a bit higher than for a station for base load due to stronger or additional turbines that are needed for peak power production. The impact of the interrupted operation has to be made compatible with needs from agriculture, ecology, shipping and other requirements, which may mean to construct a second, downstream dam to average out the downstream water flow.

Fig. 3.13 A hydropower storage dam collects water continuously but produces hydropower only at times where there is specific demand, e.g. when wind and solar energy are insufficient. In contrast to a pumped-storage hydroelectric power station there are no pumps installed to pump up water in times of overcapacities and low demand [57]

Pumped-Storage Hydropower

Today's most economic large-scale storage systems with high efficiency are pump-storage devices [58]. They consist of an upper and a lower reservoir where power is used to pump up water at times when abundant power is available, and they produce hydropower when there is a power demand. Pump-storage devices have an efficiency of typically 80%. The maximum charging and discharging power depends on the size of the pumps and can be very large. The capacity of the pump-storage plant depends on the height difference of the upper and the lower basin, and on the effective volume of the lake. To have large capacities, pump storage is often built in mountains with large height differences. Alternatively, it requires large area storage lakes or large rivers. One option is to use an ocean as the lower basin at the edge of a steep coast. Other unusual options are to use a large basin that is sub-sea-level as lower basin (as available e.g. in the south of Morocco) or to disconnect a "Fjord" (e.g. in Norway) by a dam from the sea and use seawater that is pumped in or out. These kinds of seawater pump-storage plants could have huge capacity, but their environmental impact may be large.

Plans for the construction of new pump-storage plants often affect recreation areas or nature protection areas. This may be disliked by the population and/or excluded by law. Some experiments have been made to use abandoned mines for underground pump-storage plants. When the mines are deep enough, they can act at the same time as geothermal energy supply. The problem with abandoned mines is that they often are not suitable because they have solvable wall materials or are not tight and too ramified. The more economic approach is to build new, dedicated, deep (e.g. 2000 m) shafts in suited rocks for underground pumped-storage hydropower stations [59].

Another option is to go under water instead of under ground: In this approach, large concrete sub-marine bowls are anchored in deep sea (e.g. at −2000 m, see Fig. 3.14) [60]. Electric pumps evacuate the seawater. The energy stored in the evacuated bowls depends on the volume and the water pressure. At a depth of 2000 m the energy density of such a bowl equals the energy density of a natural gas storage tank at normal pressure and of the same volume. The energy can be recovered by using the pumps as generators during the refill of the bowls. The advantage of the bowls compared to gas storage is the good turn-around efficiency of the order of 85%.

Artificial Energy Atoll

Building an Artificial Energy Atoll in a shallow sea (see Fig. 3.15) can solve several problems at a time. It can be the base for offshore wind power plants to ease construction and maintenance, including hotels for maintenance workers and a platform for helicopter landing. In addition, it can host HVDC converter stations that connect to undersea cables. The most important feature is that the inner lagoon can be used as energy storage: It can be stabilized by a round inner concrete wall and pumped out. The ring island itself can be formed from the excavated interior.

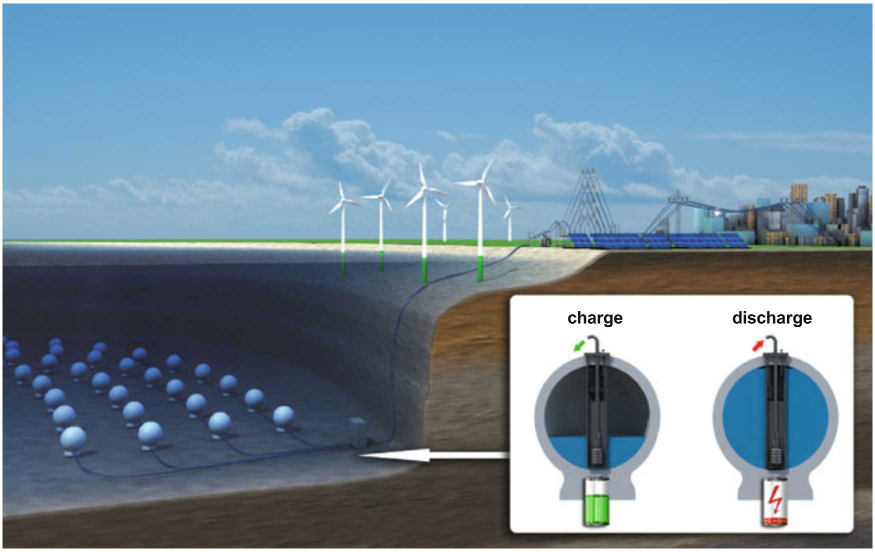


Fig. 3.14 A new idea for pump-storage are large sub-marine bowls that are anchored in deep-sea and which act as efficient pumped-storage hydropower station [61]

Fig. 3.15 An Artificial Energy Atoll can be used as base for off-shore wind power plants and as location for HVDC converter stations for undersea cables. The lagoon can be pumped out and used as pumped storage hydropower and as tidal power plant. The photo shows an example of an artificial atoll. This one is not used for energy but as depository to store polluted silt [63]

The inner water basin serves as pumped-storage hydropower station to stabilize the power on the HVDC cables or to provide power on demand from the stored wind power. In addition, depending on the phase and amount of the tidal range, tidal power can be harvested by this device. An atoll with a radius and depth of for example 200 m can store an energy of 1.7 GWh. An ideal European site for such an Artificial Energy Atoll is the area close to the Dogger Bank [62] in the centre of the North Sea, where it could be a point of intersection for North-European power exchange between England, Scotland, Norway, Denmark, Germany, and The Netherlands.

Concentrated Solar Power by Demand Control

Another efficient method to produce power on demand is to use CSP devices with thermal storage (Fig. 3.16) [64]. The integrated power of a CSP station is not much different if it runs directly on solar heat or if it runs on stored heat. This means that also in this case the storage efficiency is close to 100%, except for losses from heat exchangers. The actual number depends on the size of the storage, the storage medium, and the mode of operation. If the power of the CSP station is exported (e.g. from Africa to Europe), the interconnecting power line has to be dimensioned

Fig. 3.16 A solar thermal power plant can deliver electricity on demand 24 h a day. Instead of expensive batteries for electricity storage, it stores thermal energy in tanks filled with liquid salt. One of the two storage tanks is filled with "cold" liquid salt at 290 °C. During the day, the salt is pumped through a solar powered heat exchanger and stored in the second, "hot" tank at 390 °C. During the night, the hot salt is pumped in the other direction to produce electricity on demand. The cooled salt is stored back in the first tank [65]

to the peak power transmission. As long as the power line is the limiting bottleneck, it does not make sense to run the CSP station on demand control. Instead, the CSP storage will be used to produce a 24 h stable base load on the cable.

Batteries

Batteries are ideal short-term storage devices, as they have high efficiencies, however the costs and the cycle times limit large-scale applications today [66]. While the price/performance ratio becomes better, batteries are currently becoming economic for mobile applications (EVs), for off-grid home applications and as backup devices (Uninterruptable Power Supply/UPS) devices.

There are plans to make use of batteries in EVs as short-term storage in a smart grid. In this concept, it is assumed that a large number of vehicles is connected to the grid during parking. The charging of the vehicles can be time-shifted (e.g. over night) and even a certain percentage (e.g. the upper 20%) of the battery can always be disposable for the grid operator. In the industrialized countries, basically everybody has his private car. If we project today's mobility concept to the future, indeed a huge number of vehicles are parking most of the time, and can be connected to the grid and are available for charging and discharging. As an example, we take a BMW i3 vehicle [67] with a battery of 33 kWh and a 3 kW grid connection. Germany has currently 45 million passenger cars. If in future this number of cars would have batteries equivalent to the i3 and all cars would be available and connected to the grid, this yields a total power of 135 GW and a total energy of 1.5 TWh. Today's total power consumption in Germany is about 600 TWh/y, which means that the integrated power in car batteries would be able to back up the total German electricity grid for 1.6 days, and already a small fraction of the car pool would be sufficient to supply electricity demands during peak hours.

If in a sustainable future most of the people will use public transportation or self-driving cars from a car-sharing-pool, the concept will not work, as the number of unused cars that fill up our parking lots will diminish, and cars that are used all day in a sharing mode cannot be used as free storage devices for the grid.

However, it may well be that another concept makes more sense: Batteries in cars are typically exchanged when their capacity drops below 80% because otherwise the range of the vehicle becomes too small. These second-hand batteries are still fine for home storage. They will probably be cheap and can have a second, long life as short-term storage connected to the distribution grid.

Battery research made a lot of progress in the last decades and will provide further economical options in future. As described in chapter 3.4, flow batteries are an interesting option as they may offer cheap solutions for large-scale storage at high efficiencies. Also the super-super-capacitors as mentioned in the same chapter will have a game changing impact if they can be produced with sufficient capacity at reasonable costs.

Gas Storage

The primary Long-Term Storage in our Dual Storage Model will be gas storage. In the initial years of the energy transition, the storage can be filled with natural gas, as natural gas will still be used anyway. A next step is to load the gas storage with biogas. If biogas is anyway used for electricity production, the storage of the biogas has (almost) no additional efficiency loss; therefore, the efficiency η of the storage is approximately 100%.

With power-to-gas we denote the production of hydrogen, methane or other gases from electricity. Hydrogen is produced by electrolysis of water. Carbon in the form of CO_2 or from certain biological material can be used to produce methane or other hydrocarbons, using chemical reformers plus water and electrical energy. There is a long list of alternative synthetic gases and fuels that can be produced using all kind of chemical reactions. A discussion of those options is beyond the scope of this paper and subject of current research.

Hydrogen can be mixed with natural gas and transported in the same pipe system, as long as the H_2 fraction is below about 10–20%. In many countries, there exist large storage tanks for natural gas, exploiting e.g. old caverns of salt mining. In Germany, there exit underground gas storage capacities of $25*10^9$ m^3

(Equivalent normal pressure) natural gas [68]. If this gas would be used for electricity production, it would cover about 3 months of today's total German (electrical) power consumption.

The efficiency of the power to gas and back to power is only about 30–45%, which is not very good, however, taking into account that the Long-Term Storage system can have an inefficiency which is 365 times larger than the inefficiency of the Short-Term Storage, the yearly energy loss is still less expensive than the energy loss of the Short-Term Storage systems with the same capacity.

Liquid and Solid Energy Storage

Power-to-gas is not the only option for a renewable energy storage system. There is a whole variety of chemical technologies available. One interesting option of a solid and liquid energy carrier should be mentioned here: Pure lithium can be regarded as energy carrier, as it reacts for example with nitrogen forming lithium nitride. Lithium nitride can be used to form ammonia. Ammonia is a liquid fuel that can be used in fuel cells in vehicles. The lithium can be regenerated using solar energy, for example in solar thermal power plants in the desert. This example leads us to the next chapter.

3.12 A New Chance for DESERTEC

As described in the DESERTEC papers, the solar energy in deserts is abundant and cheap. Energy can be exported in the form of gas or electricity, or even as liquid or solid energy carrier. In the original DESERTEC concept, it was discussed whether solar power should be converted to hydrogen to be transported to Europe or if it should be transported directly as electricity. It turned out that HVDC power lines were the most economic choice, as a gas transport would require the conversion of power to gas and back to power, which includes large conversion losses.

From the point of view of the dual storage concept, the situation is different. Gas is needed for the long-term storage anyway, therefore one can consider filling the gas storage with imported renewable gas using the existing pipeline system from Arabic countries to Europe. Solar energy can be used to produce hydrogen at quite low costs in future. The higher solar radiation in the deserts compensates the efficiency losses of electrolysis. The gas could be synthesized either using the electricity of CSP or PV devices, or directly using thermal energy in catalytic reactions at high temperature in CSP devices. Also, photochemical reactions or biological reactions of solar light are studied to produce gas from water and possibly from CO_2.

For certain applications, the production of other energy carriers might be useful, e.g. the production of ammonia for the fertilizer industry or the production of burnable metals.

Part of the reason for the failure of the DESERTEC idea in the 2010s was that European's did not want to create immediate dependencies by power lines from Africa that could be cut at any time and were regarded by some people as a potential instrument for the abuse of power by the desert countries. This (psychological) problem will probably not be present when gas is imported, as gas import from Arabian countries is nothing new for the public and it has no immediate effect on the stability of the electricity supply in Europe. Figure 3.17 shows the existing gas pipelines from Africa to Europe [69]. Without large investments, the transfer of "DESERTEC GAS" to Europe could be established as soon as the production of renewable gas becomes economically viable. This may happen as soon as climate protection actions restrict the use of natural gas and carbon certificate trading becomes efficient.

Fig. 3.17 The existing gas pipeline network between Europe and North Africa can be used to transport renewable gas from desert energy to Europe. The coloured and the grey lines indicate existing gas pipelines. The thin black lines are country borders [70]

3.13 Conclusions

The amount of renewable energy resources, especially wind and solar, exceed by far the demand of our human society. Prices of renewable power are decreasing, and in preferred regions power prices beat those of conventional power production already today.

There is a large **variety of technologies** available to harvest renewable energies. The most mature ones are hydro power stations, wind power plants and photovoltaics. In desert regions, concentrated solar power with thermal storage is of special importance due to its ability to deliver solar power at night. Offshore wind power is expected to have an increased importance in future due to its large capacity and reduced volatility. Marine hydropower is still in its infancy and has a huge potential. Tidal power is very predictable and reliable and wave power has a certain time-shift with the corresponding wind power, which makes it a complementary source of power especially for the use on islands. Biomass, especially biogas, is of prime importance as storable energy carrier. Geothermal energy has its niche for power production in volcanic regions.

In a renewable energy future, it is of prime importance to **electrify the mobility and heat sectors** to abolish fossil energy carriers and to increase the energy efficiencies. This will multiply the demand of electrical power by a factor of 2–6.

The first choice for heating and air conditioning of buildings are **electric heat pumps** in combination with heat recovery and, most importantly, a good **insulation** of the buildings. The cogeneration of power and heat is useful in (renewable) gas power stations for district heating, however small, combined heat and power generators have low efficiencies in power production and are also less efficient than heat pumps for heat production. Therefore, small combined heat and power generators are only useful for certain niche applications.

As batteries are improving drastically, it can be expected that **electric vehicles** will be a good option for efficient passenger mobility. However, today’s business model where everybody has his/her own car has a lot of disadvantages with respect to the consumption of resources, fatal accidents, traffic jam, parking problems, limited space in cities, noise, roadkill etc. A mixture of efficient public transportation, self-driving cars on demand and car sharing, in combination with (electric) bikes and scooters will allow future communities to be much more resource conserving and more worth living in.

The main challenge of a 100% energy supply with renewables is their volatility. It has been argued many times that “base load” cannot be provided by renewables in an economic way due to the immense costs of energy storage. Here we show that a clever combination of different devices and methods allows for a cost-effective handling of the volatility of power. A main feature of this proposal is the **Dual-Storage System**, where the required storage capacities are split into expensive powerful and efficient Short-Term Storage with limited capacity and into Long-Term Storage with large inexpensive gas storage capacity with limited turn-around efficiency. In addition, the electrification of the thermal and mobility

Table 3.2 Measures to control the volatility of a renewable energy system

Method	Measure	Function
Regional power shift	AC distribution grid	Provide grid access for all producers and consumers
		Average out power peaks in load and in generation on the community level
	HVDC overlay grid	Average out fluctuations in load and production between communities
		Average out renewable energy production due to weather and climate conditions
		Allow for power production at the most viable geographic regions
		Allow for efficient international power trading
	Gas pipelines	Allow to produce renewable gases (biogas, power-to-gas and solar gas) at the most viable geographic regions
		Allow for international gas trading
		In the energy transition phase, natural (fossil) gas can be added to the renewable gas
System design	Fine-tuning of combinations of renewables	A clever mix of renewables can reduce the integrated volatility. For example, wind power dominates in the European winter and solar in the summer. The right quota of both reduces the annual change and the need for compensation
Over-production	Build more renewable power stations	Build a certain percentage more power stations than needed in average. This reduces the time with a lack of power and thus it reduces the required power storage. Additional power production is cheaper than storage in many cases
Power cuts	Remote control of power generation	Switch off peaks of power production if useful (e.g. PV at noon during week-ends when the load is small). This helps to limit the required capacities of the grid and of storage devices
	Remote control of consumers and special tariffs	Switch off or limit certain consumers in times of power scarcity according to certain rules and tariffs. Contrary to a total switch off, a limitation of power consumption at certain times of a day are easily acceptable by the consumer. Households and industry can be attracted by cheaper tariffs to allow for that
	Adjusted industrial production	In some countries, it could be economic to limit certain industrial productions to the daytime when cheap solar energy is available instead of running factories 24/7
Shift of power in time	Smart grid	Demand site management in the heat sector is very efficient due to the inertness of thermal energy. In most applications, it is no problem to

(continued)

Table 3.2 (continued)

Method	Measure	Function
		time-shift heat and coldness production by hours. Local thermal storage can increase this capability
		Demand site management in the mobility sector is possible for all devices with batteries or synthetic fuels. Car batteries can be used as efficient Short-Term Storage
		Demand site management for electric equipment in households has limited flexibility and the demand is relatively low so that not too many measures make sense. Home batteries can be used as efficient Short-Term Storage
		Demand site management in certain industries can be very efficient, especially if the energy intensive part of the daily production can be adjusted according to energy prices
	Short-term storage	Demand controlled hydro, pump storage, batteries, CSP-heat storage, etc. are used to stabilize generation and consumption on the timescale of hours and days
		Short-Term Storage is used for grid stabilization and as local backup and emergency power
	Long-term storage	Demand controlled biogas turbines, combined cycle turbines, fuel cells, power-to-gas, etc. are used to balance average power generation and consumption on timescales of weeks and months
		Long-Term Storage is used as backup for severe power failures and emergencies

sectors allows for a much more efficient demand site management compared to today's situation. Overcapacity in generation and flexible ways of "soft" power cuts complete the concept, as presented in Table 3.2.

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Chapter 4
Political Implications

The global energy problem is the result of our modern economy and of our basic style of living. We have to consider fundamental changes of our socio-economic systems to find a sustainable solution. A technical solution alone will not be sufficient. This book, written by a physicist, does not raise the claim to solve the socio-economic problems of our modern world. Nevertheless, the view of a scientist might be useful to emphasize a few things that go wrong in our society.

Our biosphere is a complex, fragile system which hosts an even more complex society of innumerable egos that like to divide the world into theirs and others. There are reasons to assume that—with the help of modern science and technology—it is in our hands to either destruct our living conditions within a few decades, or to use our talents and intelligence to organize the human society in a way, that it can happily live for many more future generations on a liveable and peaceful planet earth. To achieve the positive outcome, science and humanities, including philosophy and religion have to come together again in a cooperating fashion.

In general, complex systems can be stable, oscillating, or completely instable and diverging. When we look at the system design of our economic systems, we find that they are based on growing markets and on inequality, but there is nothing implemented, that would guarantee an inherent stability of the systems. In view of globalization, free capitalism, limited resources, overpopulation and powerful financial markets, it becomes unlikely that our economy remains stable. Instead, economic power will centralize, inequality will explode, and inner or outer warfare might be viewed as the only option to survive by all sides.

The energy market will be affected by the Energiewende in a particular manner, as it will decentralize the market and many consumers will become producers of energy at the same time. Storage capacities and the flexibility of production and consumption will define new business models. The whole energy market will have to be redesigned in many aspects to foster the transition to renewables.

M. Düren, *Understanding the Bigger Energy Picture*,
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4.1 One World

“Mother Earth” should not be regarded as an eternal base that was made to host the “creation’s crowning glory”. Instead, we are just a glimpse in an almost infinite and continuously evolving universe [1]. Life is not necessarily a uniqueness of our planet. From the scientific point of view it is likely that there are many other planets in our universe that host some kind of life, taking into account that there are about 10^{23} stars in the visible part of the universe and a lot of them have a planetary system. At the big bang 13.8 billion years ago, our universe exploded and it took only minutes before the first atomic nuclei were created. After that, stars and galaxies formed, and it took about 10 million years before the universe cooled down enough for the existence of molecules like water [2]. This is the earliest time at which life similar to our life on earth could have developed somewhere in the universe [3].

It took another 9 billion years before our sun and earth were formed. The standard theory says that primitive life developed on our earth half a billion years after the earth was created, which is a rather short time in the scale of the universe. However, in principle it could well be, that there was life in the universe long before there was life on earth, and there might have been conditions in the early universe where the genesis of first cells was much more favoured compared to the conditions on earth.

Some people consider the possibility that life on earth was initiated by a shower of meteors that contained protozoa from outer space. We know that it is possible that primitive forms of life, e.g. spurs of protozoa, survive long voyages in interstellar space when they are enclosed in rocks or frozen water. Recently it was found that even animals as complex as water bears (Tardigrades) can survive vacuum, frost and solar radiation in space [4].

Independent of the question if our life had its origin from outer space or from our own mother planet, we know for sure that evolution from primitive multicellular forms of life to highly intelligent primates took place on our own planet. This part of the biological evolution needed another 1.5 billion years. The findings of palaeontologists verified these basics of the Darwinian theory in great detail.

Nevertheless, the creation and/or development of the world, of life and of consciousness remain an enigma and a challenge for modern sciences, and it requires a certain level of abstraction to accept that traditional religions, philosophy and sciences are not contradicting each other in their different approaches to answer similar questions in different ways.

Since decades we are looking for signals from outer space to find signs of intelligent life somewhere else in our universe. All these attempts failed up to now, and there are two explanations for that: either there are no planets with intelligent life in reach of our scientific instruments, or intelligent life on all these planets in our reach has been extinguished already. If we imagine that we on our planet earth are able to send radio waves into space since only about 130 years, and that it is not clear that our sophisticated and technologically advanced civilization will survive the next 100 years due to anthropogenic climate change or nuclear wars, we have a time span of 230 years compared to a development time of 2.5 billion years, which makes a chance of 1:10 million to find intelligent life on a planet like ours.

Of course this example is a bit overdrawn, but it should make clear how fragile our life as highly developed human being is and how short the lapse of time is that remains to bring our civilization back on track again.

4.2 Capitalism in a Global Market

From the empirical point of view, the capitalistic, or free market approach has proven to be a very efficient and fast method to promote technical progress, to maximize productivity and to exploit natural and human resources. From the systemic point of view, this economic paradigm is comparable to the Darwinian biological system, the "survival of the fittest", where thousands of different species optimize and accommodate their interaction with the environment such that they survive better than competing species. Darwinism can be characterized as a "win-lose" system on the level of individuals and individual species. But it is a "win-win" system for life in total, as it evidently generated a great variety of ecosystems with highest forms of life.

Capitalism can be characterized as a "win-lose" system on the level of individual people and companies. But can it be regarded as a "win-win" system for the global human community?

How Evolution Avoids Centralization

There is a crucial difference between biological systems and today's economy as illustrated in the following comparison: Biological systems require very long timescales for changes compared to the lifespan of individuals. Significant changes take many generations of individuals, and the repetition rate is even slower for more complex (i.e. "strong") animals compared to more simple living beings like bacteria.

Imagine, at some time a species develops that is a "winner" of the "Darwinian Game-of-Life" in the sense that it dominates all the other species. This forces the concept of "eating others and being eaten" out of balance, and the ecosystem will either accommodate or break down. In the extreme case the winner species will eat all the loser species and will die from starvation afterwards.

How come, that evolution has been progressing over billions of years without a breakdown of the whole system? The key of stability are the slow changes and the limited spatial influence of the individuals. The impact of genetically caused changes is usually very limited in space, as certain races occupy usually only a certain niche of the global biospheres. If a certain species kills its own biosphere, life will continue somewhere else. Also mankind will not change that, as independent of global warming or nuclear wars, life on earth will continue—possibly not for most of the mammals, but certainly for cockroaches, ants and mushrooms.

Global Capitalism of Today is Instable

Today's global economy is different compared to biological evolution. Technical progress and economic changes become more and more rapid, without principle limits and without a natural regulation or damping system. The stronger a company is, the faster it can develop. It is like in any non-linear system with feedback loops: if the parameters run out of a limited stable range, if amplification increases, damping decreases, then values typically grow exponentially until they hit boundaries and the system breaks down or becomes static.

About 50 years ago, there were rich and poor countries, and many rich countries had a large, educated and wealthy middle class. To become rich, companies had to make inventions, get resources, e.g. from undeveloped countries far away, and build infrastructure and factories. In many countries companies had to pay a significant amount of taxes which was invested in infrastructure and education. A large number of educated and well-paid craftsmen were needed that produced and consumed the goods. The process to become a rich company usually took many years or even generations. Today the situation is different. The technical progress is more rapid and the global market allows for a fast exchange of huge resources. New business models sometimes have life cycles of only months between the first ideas, the realization and being outworn again.

Most children (at least in Germany) know the game *Monopoly* [5] that was invented in 1903 by Elizabeth Magie Phillips with the intention to educate people about economic systems. Anybody who has played it has experienced that the game is designed in a way that sooner or later all but one will be insolvent and the game is over. In the real world in a global market, there is no second chance once the game is over.

The Financial Capitalism

The main economic revolution of the last decades is the step from a capitalism based on the creation and organisation of production and service facilities to a capitalism based on the exchange of financial resources and the evaluation of credit ratings. The financial capitalism created a virtual world in which it is possible to create money from money without affecting any goods, manpower or resources. The value of a share or of a currency is not necessary related to "physical" values. A "rumour" (i.e. a virtual entity) is enough to change their values. In the language of a physicist, the Stock Exchange is a strongly coupled complex system, and those systems tend to show chaotic behaviour, which means that small fluctuations in one corner of the system can propagate and cause amplified reactions somewhere else in the system. In our "Modern Times" such a small initial fluctuation can be for example a simple madcap tweet on twitter. In principle, any company at any time can be claimed to be a looser, and this self-fulfilling prophecy can cause so much disturbance in the credit ratings that the competing company can take over their business before the first company is able to recover. A similar, recent example is the exchange rate of the British Pound GBP on the day when the English and Welsh people voted for Brexit. That day, the "physical capacities" of the British industries did not change, and the vote had no direct legal impact, but still people could make millions of Euro on that day using the drop in the currency exchange rate. If a few months later the Brexit would be cancelled, the same people could make money again from the opposite currency exchange.

To make money from fluctuations in the stock market, one must have a good understanding and computer modelling of the market and a kind of early-warning system, but more efficient is insider knowledge and the possibility to generate one's own fluctuations in the market by significant transactions. From the point of view of the capitalist the ideal situation is, when the financial system has direct ties to the government of a country and can influence regulations and preferences. In that case making money from a fluctuating financial market is as easy as the task of an electric rectifier to extract electrons from an alternating current.

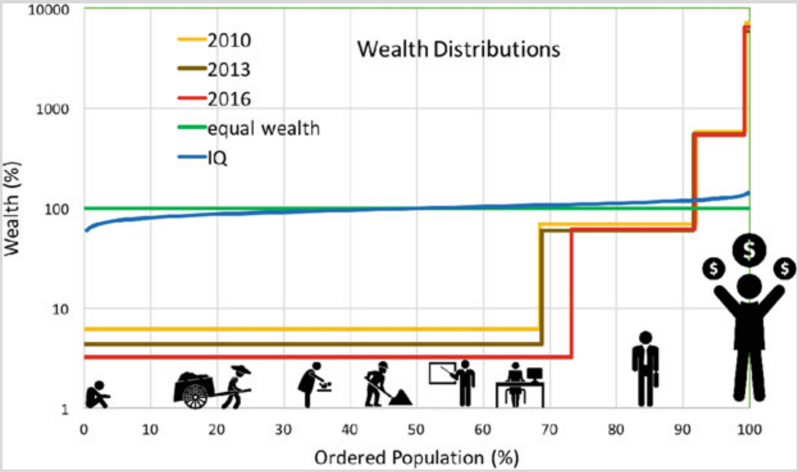
By creating financial bubbles and playing with oscillations of prices, these virtual games generate more and more money. This money must be matched with real values in order to have an impact in the real world. As the amount of values is limited, at some point the increasing amount of money cannot be matched with actual values any more, instead it is matched with debts. The debts are assigned to house owners, communities or whole states. In this game, the rich stakeholders have more opportunities than the poor ones, therefore the rich ones become richer and the power centralizes ultimately at a few people or companies. The tempo of the financial capitalism is not limited by the time it takes to build up infrastructure or to produce goods. It can be as fast as the information exchange in the stock market allows it. It can make companies, communities or even whole countries bankrupt from one day to the next.

For a mathematician, the global financial market may be a fascinating example of game theory with all the artificial feedbacks and bubbles that seem to appear from nowhere but actually are an inherent property of the system design. For a financial gambler it is the ultimate kick to satisfy his greed of gain. But for 95% of the population, this game of greed is a disaster. One example is the subprime mortgage crisis in the US in 2006 after which nearly 9 million people lost their jobs.

A look at the statistical numbers shows two aspects of today's world economy: One conclusion is that—despite the fast growth of the world population—the production of food, energy and goods grew even faster, so that the relative number of people below the poverty level decreased over the last decades [6]. A strong bonus on the world economic statistics comes from China, where the population increase was limited and the production and export has been strongly increased. In other regions of the world, especially in Sub-Saharan Africa, the situation is still desperate in many areas.

The second conclusion of the world statistics proves that, despite these achievements, the capitalism of today is a system that brought an extreme disparity into our world. The world's wealth is centralized in less than 1% of the population while the majority of the people have very little wealth. Box 4.1 shows the numbers [7–9]. If the total wealth were distributed equally (green line), everyone would have the same, i.e. everybody would have 100% of the average wealth. This would be the case of an "extreme socialism" which is of course neither realistic nor worth pursuing. In a realistic model of the world, one expects that some people have more and other people have less, but that the majority of the people have a wealth that is balanced around the 100% average line.

Box 4.1 Human Inequality Distributions [10]



The horizontal axis shows the world population ordered according to their wealth. The vertical scale shows the wealth in percent of the average wealth of the world population.

The green line corresponds to the case where everybody has the same, i.e. 100% of the average.

The three lines below show the distribution of wealth in the years 2010 (yellow), 2013 (brown) and 2016 (red). The crossing of these lines with the green line is beyond 90% of the population, which means that more than 90% of the population has less than the numerical average of the wealth.

Most the people have only a small fraction 6.1% (2010), 4.3% (2013), 3.2% (2016) of the average wealth. This means that in 2016, 73% of the people have a factor of 30 less than they would have if the wealth were distributed equally among all people. One interesting point is, that this number changes rapidly in the last 6 years, making the inequality of most people compared to the rest larger and larger.

In contrast, the upper 0.7% of the richest people have a wealth that is at a value of 6500%, of the average, i.e. far above the 100% line. Note that the vertical scale is logarithmic. The steps come from the binning of the input data, in reality the curve is a steep, but smooth curve.

The blue line is shown for comparison. It shows the distribution of the intelligence quotient (IQ). 50% of the people have an IQ lower than 100, 50% higher than 100. Few people have a very high or a very low IQ. However, the broad majority of the people has a value that would allow them to be productive when they would have the financial means for it.

The blue line shows the distribution of the intelligence quotient (IQ) as an example for such a distribution, where some have more, others have less, but the majority of the people have an IQ around the average [11].

In our modern world today the economical distribution of wealth shows a completely different trend. Not only that more than 90% of the population has less than the average, most people (68%) actually have so little (4% of the average wealth per person) that their share on the society as a whole is marginalized. On the contrary, the major part of the wealth is concentrated at a few percent of the richest people. It is the mechanism of exponential growth in the global financial system that produces these unnatural, huge differences. The comparison of the years 2010, 2013 and 2016 (yellow, brown, red line in Box 4.1) shows the trend that the gap between the poor and the superrich is growing. Within 6 years, the share of the "poor majority" decreased by a factor of 2 from 6.1 to 3.2%. If the trend continues, it is likely that the system will break down already in a few years.

It is useless to blame the superrich for the global economic situation. As long as the governments of most states accept the existence of an instable economic system, one will always find numerous more or less irresponsible and more or less intelligent people that fill the positions that the system offers them. It is the task of the politicians and their voters to decide which system is preferable for the human society and which system violates basic human rights.

> **Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control.**
>
> *Universal Declaration of Human Rights; Article 25.1, Paris, 1948* [12]

The End of Economic Creativity

What are the consequences of such a financial capitalism for the future? Education and decision-making abilities of the general public, as well as mass purchasing power and usable manpower in general will diminish when the funding of the large majority of the people is marginalized. There is no market mechanism for which the welfare of people in certain regions of the world with high population but low productivity is of any interest. Important long-term communal projects as well as long-term global changes like global warming are also not necessarily on the agenda of the super-rich companies.

It seems that our capitalistic system has been so successful and superior compared to the centrally planned economy because of the apparent collective intelligence and creativity of the free markets or rather their numerous stakeholders. This supremacy can obviously break down as soon as the market is centralized and reduced to a small number of decision makers.

It seems likely that such a capitalistic system with a free market but a centralized power of only few super-rich companies in each commercial sector will have the same deficiencies as a simple state monopoly capitalism, where also few decision makers have to control a whole complex system.

The Dilemma of the Politician and the End of Democracy

There is a global market, but there is no global government. Therefore, multinational companies are decoupled from political influence and democratic control to a large extend. Trading agreements make sure that international companies can rely on their investments and on their long-term plans and no government can interfere significantly.

If for example a political party in a country wants to fight poverty by increasing the salary for the workers, and it wants to fight pollution by sharpening the environment protection laws, any economist will explain them that this leads to a drift of industry away from this country with the consequence of unemployment and impoverishment. Most multinational companies today can move their places of production to the countries of cheapest labour, cheapest energy prices, worst/best industrial laws and smallest taxes. This way, any politician that wants to improve the situation of the people in his country is in a dilemma and realistically, the political power of local governments in a global market is basically neutralised.

Economic power today means also power in politics, research and education. Private universities are the best examples for that. In many of the 206 sovereign states on our earth one has the impression that the political leaders are the floor managers of the financial world, which have the task to care about the human capital of a specific country, but they have no control on basic economic decisions any more.

Today, some political leaders take advantage of this inequality in the population. They promise unrealistic short-term goals, where the own country will be protected and becomes rich to the cost of other countries or to the cost of minorities. This trend is well known from history and has always been a big danger for all democratic countries.

To conclude these thoughts, the global capitalism is designed in a way that most of the states strongly depend on it, but have no or only little control of it. The rate of change in our economy is much faster than the response of the global system, which makes the system unpredictable and instable. This instability is there at many timescales. There are the extremely short timescales of financial capitalism that can affect the economy of millions of people from one day to the other. Then there are the timescales of decades where the global economy is affected. The best example for an instability that acted on the timescale of hundred years is the use of fossil fuels and the response by climate change: The economic changes that lead to the extensive use of fossil fuels started 150 years ago, but the climate feed-back was delayed and starts to affect us only today.

Today's capitalism is based on growth and inequality, and it is inherently instable. We can replace it by an economic system that is sustainable and inherently stable.

We are accustomed to our economic values so much, that we accept them as God-given. But the basic economic laws are not laws of nature. They are constrained by mathematical and scientific relations, but they are designed by human egos and can be replaced by new rules any day. Let's hope our society manages to either stabilize and control the markets and their managers or replace early enough the concept of global free markets by something sustainable, so that the human race will not have a similar fate as the voracious dinosaurs in the times of prehistoric climate change.

4.3 Paradigm Change in Energy Economy

The transition from fossil and nuclear energy to renewable energies will have a direct impact on the economy. A few aspects are mentioned here.

Decentralization

The production of renewable energies is always more or less decentralized, as energies from sun, wind, water, biomass or others do not have the energy density as e.g. coal or nuclear energy, where the power of several Giga-Watt can be produced in one building. This argument, often brought up by engineers as being a structural drawback of renewables, is of course only half of the truth, as energy carriers like e.g. coal or uranium require vast fields of mining in remote areas. The real economical difference between renewables and conventional sources is twofold: While mines and the corresponding conventional energy carriers can be owned and sold and they lose their value when they are exhausted, renewable energy sources like wind and sun cannot be owned, and the harvesting and trading of the energy does not lead to a loss of value of the property: sun and wind will be back every day. This has an essential economic impact as illustrated in the following example: If a consortium dominates the oil market, it can reduce production to increase the fair market value and to save the oil for later when prices might even be higher. This way the profit is maximized and at the same time economic and political power is generated. In contrast, if a solar or wind power station reduces its power output, it will lose money and the earnings of that day are lost forever.

A second economical difference of renewables compared to conventional sources is that renewable energies typically require large initial investments while the "harvesting" of the energy is for free, except for maintenance costs and depreciation. In many cases, the dominating costs of renewables are banking costs while for conventional fossil power generation the fluctuating, and over decades typically increasing fuel costs dominate.

The decentralized nature of renewables is intrinsically incompatible with monopoly-like business models of e.g. the traditional international oil companies where a few consortia own the major mines and oil fields. Instead, renewable energy companies try to get market dominance in technology, licenses, or distribution networks, which is much harder to achieve due to competition and regulation.

Democratization

Today, power production is feasible for anybody. This is especially true for PV, but also for wind, biomass, and small hydropower. It turns out, that a large number of individuals and communities favour the idea of producing their own power. These people invest a large amount of money for owning their own power generation for a feeling of being independent, environmentally friendly and sustainable. In many cases they invest more than they will ever earn back from the investment. This kind of behaviour is well known in the car market, where people spend a large amount of money for the feeling to own something which is a status symbol and that makes them independent, even if public transportation or getting a taxi is cheaper and more convenient in many large cities.

In Germany, the Renewable Energy Act (EEG) has been brought forward to support the energy transition [13]. The EEG is based on three pillars:

i. Small and medium sized power producers are allowed to connect to the grid and sell their power with priority and for a guaranteed, stable feed-in tariff over 20 years. The tariff is technology specific. This enables the government to promote certain technologies, which are not necessarily the most suited ones for a given site and/or application.
ii. The investments are private and do not charge the public purse. Instead, the costs are redistributed to all consumers over 20 years by a surcharge on the electricity price. This way, the costs of today's energy transition are effectively moved to our children and grandchildren. To avoid a migration of industry, many of the large power consuming companies in Germany do not have to pay the EEG surcharge. As a consequence, the surcharge on the electricity price for the private household is extraordinary high.
iii. While feed-in tariffs for existing power producing facilities are constant, they decrease for new installations in regular intervals in order to foster innovations and price reduction.

Energy and Power Transition

Currently, energy economy is in a transition period and large parts of the energy debates are influenced by the concerns of fossil and nuclear industry that still have a dominant economic and political power in many countries. Renewable energies are publically propagandized, but at the same time fossil and nuclear energies are subsidized in a direct or an indirect way. In addition, industry antagonizes carbon trading and CO_2 taxes and also feed-in-tariffs and the priorities of renewables are disputed.

For countries that own nuclear bombs or plan to become engaged in nuclear weapons in future, the “peaceful” use of nuclear energy is of special importance, as that allows them to share the costs for the whole chain of nuclear fuel production and expertise between the military and the civil applications.

An indicative example for the subtle discouragement of renewables is a plan of a European government to make private owners of PV modules subject to income tax even if the owners consume their self-produced power themselves. Many people object this proposal, they label it “sun taxes” and they compare it to paying taxes for tomatoes that you grow in your own garden. Possibly, it was not even seriously planned to realize this proposal, but by bringing it up, it achieved already the effect to unsettle and discourage potential small investors of PV modules and to delay the energy transition.

Major investments in fossil and nuclear industry and infrastructure will unavoidably lose their value in future, and some of the companies will face huge decommissioning and liability costs. Some energy companies are currently starting to separate the companies into an independent renewable sector and a deeply indebted conventional part, with the hope to recover the profit and to dispose the debt to the public. This is the commercial analogy to the invention of “bad banks” in the financial crisis.

4.4 The Global Union

It is beyond the scope of this book to design possible future economic or political systems. However, as a consequence of the scientific analysis, it seems clear that the political, economic and environmental system as of today is diverging and likely to approach a break down, which actually may mean the death of millions or billions of people or even a breakdown of major parts of the biosphere on our planet that is the basis for human food production. It also seems clear that especially the financial system needs further stabilizing elements. The global market may not continue to act without political control.

From the scientific point of view, it is likely that any uncontrolled complex system will collapse if the feedback loops are not well tuned. This is the case when the timescales of change are too fast compared to the response of the system or when the amplitudes of the changes, i.e. the power of the stakeholders are not well balanced. Therefore, from the humanistic point of view, the author sees no alternative to some general regulation of the markets:

Any agreement on tariffs and trade must be complemented with a political agreement that makes sure that economy is not only profit oriented but also serves the people and future generations.

It needs a kind of global government or global trade union that effectively incorporates the needs and concerns of the people and of future generations in the regulations of the market.

A viable option would be to add a new body to the organisations of the United Nations. This body—let's call it the **Global Union**—would consist of a kind of parliament or commission that has direct binding legislative power over all the member states of the Global Union concerning certain global issues. In case a member state does not accept a majority decision of the Global Union, there is no "veto right" for certain privileged countries, but of course a country may leave the Global Union at any time. The "Global Union" could be set up in a similar way as the "European Union". Any government on our planet would be allowed to join the "Global Union" if it accepts its basic rules. One might even think about expanding the membership to sub-states like Scotland or California and to geographical regions or even communities of NGO's. By doing so, members could have great trade advantages while governments outside the "Global Union" could be sanctioned economically in case they violate certain standards of humanity or if they devastate the biosphere and the global resources.

It is not unlikely, that already in the coming decades millions of people will have to migrate due to climate change, water and food scarcity and/or the breakdown of domestic economy. This can boost xenophobia, nationalism and populism. Local political leaders will have to balance the right compromise between demarcation, integration and the promotion of global solutions. To the author's opinion, the most important characteristic of any political party should be the following: It needs to have practicable visions for a future life on this planet. These visions must esteem the people and their work and must be compatible with their moral concepts. They must include the protection of the living condition of future generations. I believe, a lot of today's power structures in politics and economy are far away from this basic footing.

Concerning the long-term effects of climate change a trial-and-error economy will be fatal. There is no reason to hope that the creative mechanisms of the free market will handle the energy transition by itself. Large parts of the energy transition will have to be carefully thought through. A global policy will have to set the right stimuli and penalties, and a coordinated international effort is needed in research and development. Energy flows in power lines or pipelines have to be coordinated and regulated by international agencies and cannot be left to companies or countries that only want to maximize their profit.

Finally, when it comes to the point that fossil fuels will be rationed and owners of fossil fuels will not be allowed to sell or use it, international conflicts will be inevitable, unless our society has reached the next level of human development by then. Let us hope that we do not have to go through another world war to reach it:

We are all in the same boat, sitting on the same powder-keg!

Table 4.1 Examples for economic stimuli and penalties to foster a global energy transition. Some of them are taken from Germany as one of the pioneering countries

Aim	Measure	Function and Remarks
De-carbonization of energy industry	CO_2 taxes	Taxes are imposed on the extraction, production, vending, import, export and/or consumption of fossil fuel (coal, oil, gas) according to the associated amount of CO_2 during the combustion of the fuel. The advantage of taxes compared to other measures is that public money becomes available to reduce negative socio-economic side effects of the CO_2 taxes and to foster further measures for the energy transition
	Carbon trading	Carbon Emission Trading and the Clean Development Mechanism were the measures of choice in the Kyoto protocol. Up to now these measures were not very effective because the allowed CO_2 limits are too high, the prices too low, and many companies invented ways to circumvent or misuse the regulations
	Stop subsidies for fossil and nuclear energies	Direct or hidden subsidies for the conventional energy industry are widespread. This weakens the chance of renewables to compete in a common market. The money that is freed by stopping subsidies for the conventional market can be invested in sustainable technologies
Foster energy research	Coordinated global research	Increase public funding and international coordination for research of technical and socio-economic aspects of the energy transition. The constitution and funding mechanisms of CERN in Geneva can be used as blueprint for a dedicated research organisation with these goals
	Revision of rights on intellectual properties	Patents are rights to exclude others from using inventions and innovations. This aspect is inherently counterproductive for a fast technological development. Three examples: (I) Ten researchers at ten different companies have ten clever ideas, but they keep their invention secret over years and fail to make a profitable product from it. Bringing the ten ideas together might solve the problems of the developers immediately. (II) A company buys a patent not in order to use it but in order to stop competing companies from using the innovation e.g. because it endangers their

(continued)

Table 4.1 (continued)

Aim	Measure	Function and Remarks
		own business model. (III) Two competing companies own a patent each and they stop each other from producing the ideal product that combines the two patents The rights on intellectual properties have to be revised such that research results and inventions are either public domain or can be licensed by paying a reasonable fee to an international organisation that handles these fees (e.g. similar to what GEMA in Germany does for musical performance rights). A reimbursement for the inventors and research institutes has to be guaranteed by this international organisation. Such a move could greatly improve the worldwide cooperation in energy research. Also here the example of the particle physics community at CERN is a reference for an open, well-working and productive research community with rapid progress. It is based on the finding, that real researchers are intrinsically motivated and money is secondary. Only businessmen need patents
Transition of the power market	Priority of renewables	The German renewable energy law grants priorities to renewable energy sources. This is a good move, however there is a side effect that grids are overloaded or electricity prices become negative. The law should be changed such that renewable sources can be switched off remotely in this case, however their owners still have to be reimbursed for this time by the causer of this situation (e.g. the conventional power station that could not be switched off in time or the grid operator that failed to provide the power lines that are necessary for a smooth operation)
	Feed-in tariffs	Feed-in tariffs are useful to foster investments in renewables. However, in Germany the money to finance the feed-in tariff mainly comes from private consumers. Large-scale industrial power consumers, companies that produce their own power, and consumers of fossil fuels are excluded from the feed-in surcharge. This perverts the original idea. It encourages the energy-intensive industry to continue with fossil fuels and with business as usual, while the average private user gets the

(continued)

Table 4.1 (continued)

Aim	Measure	Function and Remarks
		impression that the energy transition is really expensive Instead, the users or producers of conventional energies should finance the feed-in tariffs for renewable energy, because they are the cause for the environmental problem Paying feed-in tariffs may lead to the situation that renewables become profitable, that do not use the best suited technology or the best sites for this technology. Therefore feed-in tariffs have to be carefully chosen and should be valid only during very limited transition periods
Transition of the heat market	Insulation and heat recovery	Investments in insulation and heat recovery must have highest priority and have to be regulated by law for (new) buildings and industrial products. Some of the current laws allow playing the quality of insulation off against the method of heating. That may be counterproductive on the long term
	Priority of heat pumps	Today, electrical heat pumps in Germany are burdened with large taxes and surcharges for feed-in tariffs of electrical power. In comparison, simple gas burners do not have these high surcharges. In future this has to be inverted and heat pumps have to become the standard for heating applications
	Power-heat cogeneration	The small-scale cogeneration of power and heat is strongly privileged in Germany. In many cases, there is no justification for that, because heat pumps and combined cycle gas power stations would be the better choice. Therefore power-heat cogeneration should be used only in exceptional cases where heat pumps are disadvantageous
Transition of the mobility market	Public transport	In many regions, public transport has many negative attributes: Not all locations are easily accessible, it is too infrequent, too expensive, and it has too little comfort. One has to realise that all these attributes are a consequence of the fact that individual motorcar traffic is the standard and public transport is the exception for large parts of the population. This has to be inverted and public long distance and local transport must have great political priority wherever it is suitable

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Table 4.1 (continued)

Aim	Measure	Function and Remarks
	Railway infrastructure has to be financed	In many cases railways are the most sustainable mean of transportation due to the little friction resistance, the electrification without the need to transport heavy electricity storage and due to the high degree of automation. Today's economical hindrance of railways is the fact that the railway infrastructure has to be paid by the small number of railway customers, while the road infrastructure is paid by the community and/or a very large number of car and truck drivers. Also here the concept of financing has to be inverted: The railroad infrastructure should be paid by the community while the privilege to use expensive highways and to produce excessive noise and pollution in towns and landscapes should be discouraged by environmental taxes
	Car sharing, e-bikes, new communication technologies	Car sharing, e-bikes and new communication technologies provide a new market that is able to minimize transportation cost, time, and energy consumption. Many new ideas are emerging and have to be fostered by politics
	Video conferences; home offices; 3-D printing	Modern technologies allow for minimizing the need of transportation. Videoconferences and home offices, as well as home shopping are examples to avoid travel. 3-D printers and video-instructions allow for local repair shops and the local production of goods. A fast and area-wide coverage by high speed internet is required to allow for that
	EVs	The infrastructure for EVs has to be provided by the public. There should be economic stimuli or penalties that foster the use of EVs compared to cars with fossil fuels

(continued)

Table 4.1 (continued)

Aim	Measure	Function and Remarks
Capitalism and globalization	Revision of trade agreements	The problem of global warming is too big and urgent to be handled by small adjustments of the current economic system. Global problems require global solutions, i.e. solutions that are agreed on by the majority of the countries. There are two general approaches: 1. Strengthen globalisation and economic interdependency. This forces global thinking and makes any economic or conventional warfare unprofitable. However, there must be a global political consensus about standards in human and environmental questions, otherwise the globalisation will be counterproductive 2. Demarcation and protective tariffs. This allows for local changes in certain sectors of economy and certain groups of countries, even when there is no global consensus on questions that are regarded as important. It is probably easier to humanise economy on a limited scale by a “coalition of the willing” instead of finding free trade agreements that improve the human standards globally. This demarcation can be combined with fair trade agreements in the international domain In today’s world with different ideologies and political systems there is no obvious solution, neither for approach 1 nor 2. Nevertheless, it is of eminent importance to find solutions where mankind is not divided any further and where it becomes possible to act together in the fight against a collapse of civilization

4.5 Conclusions

Today, the global economy is largely decoupled from the political systems of the individual countries and there are hardly any political instruments to control world economy. By numerous agreements on tariffs and trade, global business competition was set-up in a way that it leads to a decline of taxes and to public debt. In the last decades, the classical capitalism converted to a financial capitalism, which trades large amounts of money in short timescales and allows companies and people to become super-rich, while the corresponding huge negative amounts of money are accumulated as public and private debts. A political counter force is needed that sets up rules to stabilize the financial markets and to reinvest the profits of the companies in the communities.

Today's free economy maximises short-term profit regardless of its effects on future generations. To manage the global energy transition, a coordinated international research and planning is needed, as well concerning technologies and energy passageways as stimuli and penalties that regulate the market. Effective international agreements have to be negotiated to protect our climate and to pursue a global energy transition. Ways have to be found to enforce these international agreements. It seems clear that nationalism cannot solve global problems, instead we need strong international organisations as for example the proposed "Global Union".

It is beyond the scope of this book to re-design global economy, but as a basis for further discussions Table 4.1 lists a number of political measures that could help to foster a global energy transition. It is up to the reader to discuss the political pros and cons of these options. Let's take the climate change as a chance to redefine our living together on our planet!

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Chapter 5
Closing Remarks

The book has been written with the intention to give the reader an overview of today's energy problem, which is caused by the demographic, sociologic and economic conditions of our modern human society and which is embedded in the complex ecosystem of the earth's biosphere. It is written from the viewpoint of a physicist who is educated in studying complex systems. The proposed solutions for the energy transition are based on general physical considerations and take recent developments in technology into account. The political aspects of the book are based on the conviction of the author, have no stringent scientific validity and are meant as stimuli in the search of the reader for valid solutions.

Most of the statements in the book are common knowledge and can be found in many books and publications; some of them are recent or unpublished, and some are a synthesis of different ideas from various discussions and conference talks.

Writing a book like this is a tightrope walk for a scientist. On the one hand the book should have a clear, up-to-date analysis of the situation so that it is useful as basis for political and economic decisions and for general education. On the other hand, a scientist likes to publish only statements that are 100% provable and indisputable. Unfortunately, the described matter is multidisciplinary and too complex for a full scientific analysis. And it is changing rapidly over the years. Therefore, the reader should take this book as a field report of the author on his lifelong way to understand the complexity of the problems, their relations and possible solutions. The author is looking forward for feedback, so that in a possible second edition of this book errors can be corrected and novel proposals and solutions can be included.

M. Düren, *Understanding the Bigger Energy Picture*,
SpringerBriefs in Energy, DOI 10.1007/978-3-319-57966-5_5