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.

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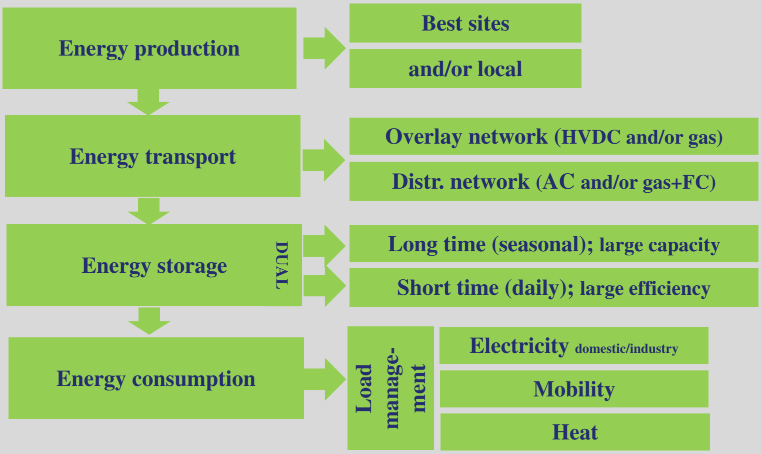
3.1 Overview of the Future Energy System

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.

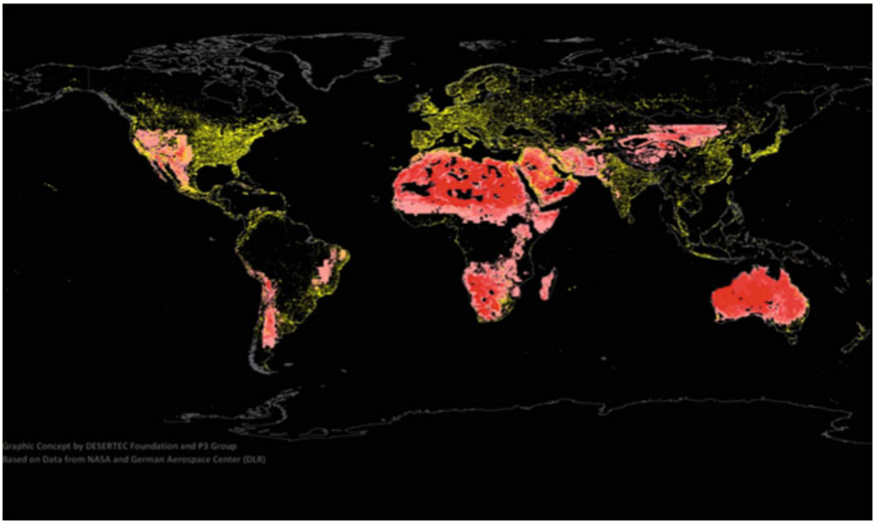
A dual energy-storage system is needed: one system that has large (but cheap) capacity and one that has high efficiency. The highly efficient storage with limited capacity is needed to absorb daily fluctuations. A second, large-capacity storage is needed for seasonal storage. It may have low efficiency, 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



Graphic Concept by DESERTEC Foundation and P3 Group
Based 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]

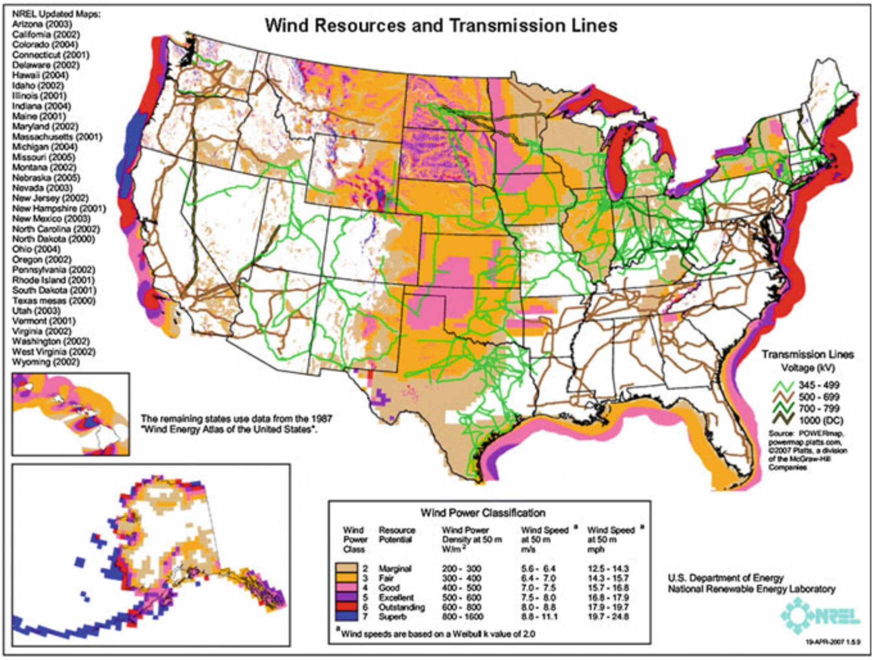


Fig. 3.2 Wind power can be harvested anywhere, but the most suited areas are regions with strong average wind, especially in coastal areas. The map shows a compilation of wind resources of the US, taking environmental and land use issues into account [9]

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

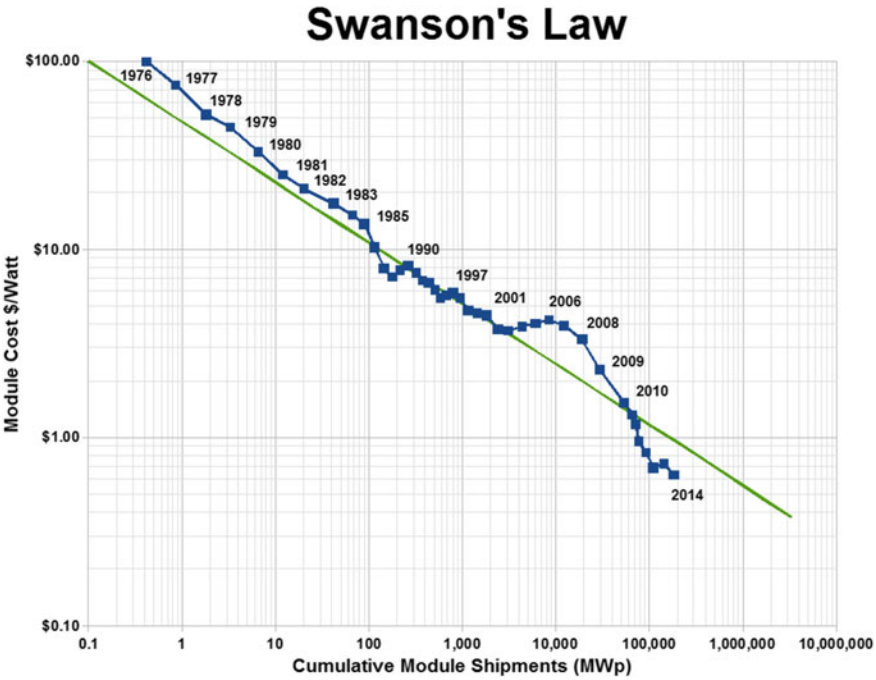


Fig. 3.3 In agreement with the economies of scales, the prices for PV modules dropped by about 20% for every doubling of cumulative shipped volume, which corresponded to about halve costs every 10 years. The module production is given in the unit MW_P which is defined as the (peak) power of the modules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

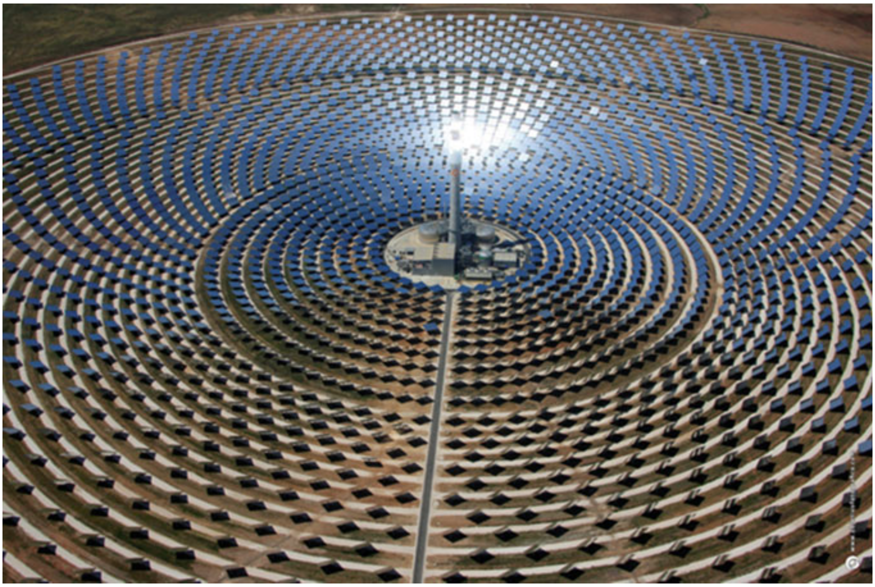


Fig. 3.4 The Power Tower technology focuses solar radiation onto a central tower where the high temperatures of the focus are used to generate electricity with high efficiency. Tanks with molten salt store the solar thermal energy to allow for a continuation of electricity production after sunset. The 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:

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

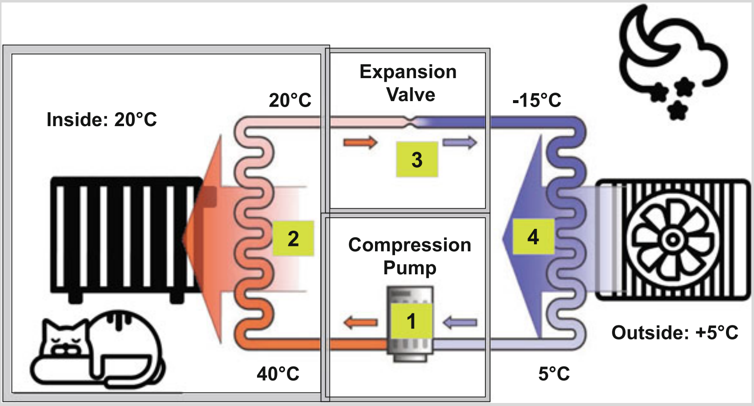
Here, η is the Carnot efficiency, i.e. the maximum efficiency that a cyclically operating technical device can have when it uses heat energy at high and low temperatures T_H and T_C to produce electrical energy. $T_0 = -273.15$ °C is the absolute zero, the lowest possible temperature. The efficiency 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.

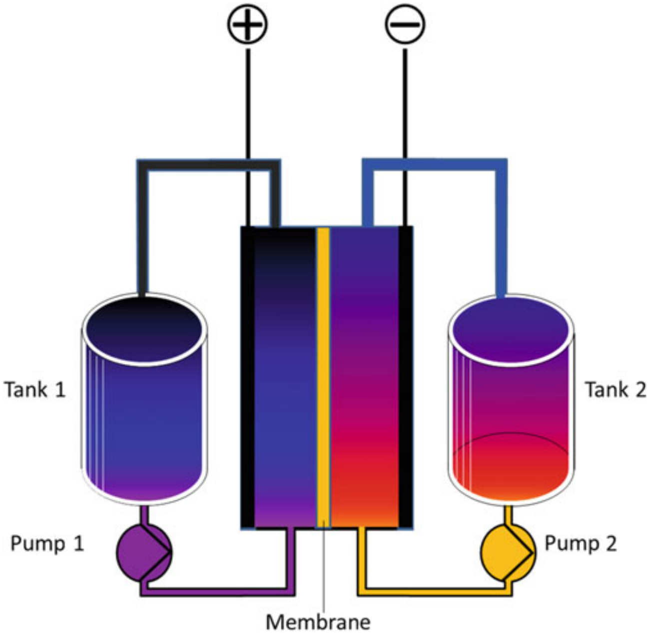


Fig. 3.9 Flow batteries are batteries where the electrolytes (which contain the energy) are stored in tanks separately from the device that converts the chemical energy into electrical power. The capacity of a flow battery can be enlarged unboundedly by larger electrolyte tanks. While maximum power of 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 $1000 \times 1000\ \mathrm{km}^2$ 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]

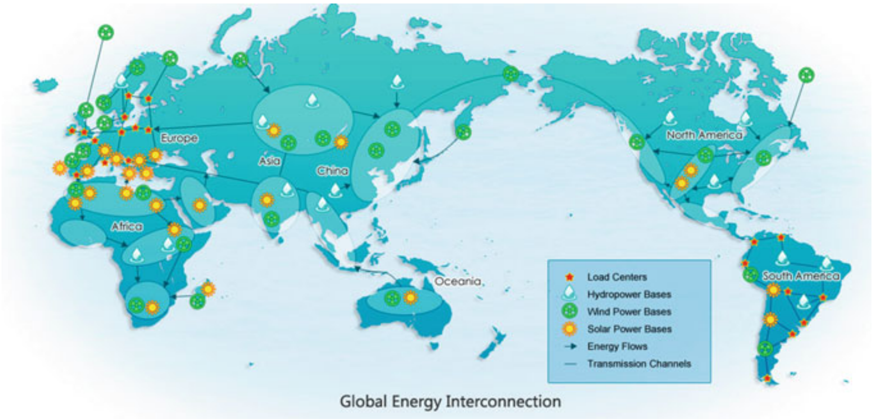


Fig. 3.11 The global power grid. In future, overlay grids will connect more and more countries and allow for efficient international trading of power. At that point it starts to make sense to interconnect all these grids to a single global net and to make use of sun from deserts, wind from polar regions, 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

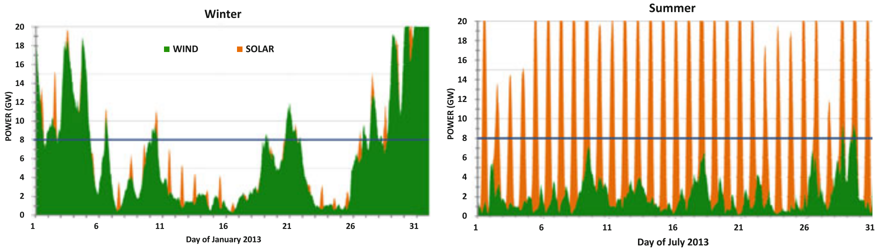


Fig. 3.12 The renewable energy production by wind (*green*) and PV (*red*) in January (*left panel*) and July (*right panel*) in Germany 2013 show the typical mix of periodic and random fluctuations. The blue line indicates the average annual renewable power production [50]

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 $P_{\text{in,max}}$ for loading. The total capacity C divided by the average output power $P_{\text{out,ave}}$ 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 $\sim$365, i.e. a 50% inefficiency of a Long-Term Storage corresponds to a 0.14% inefficiency of a Short-Term Storage.

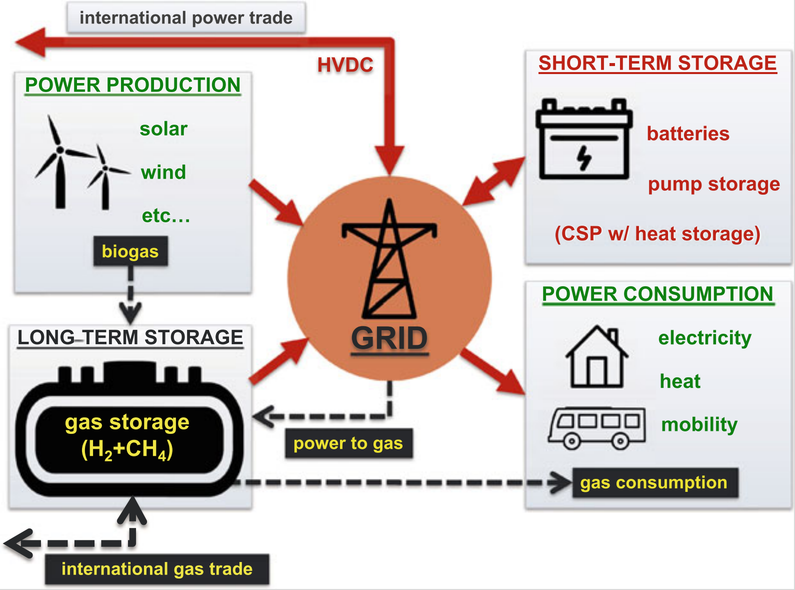
New business models are needed in the future energy system. The new business models have to account for the different tasks of the storage systems, because otherwise there is no way for a Long-Term Storage to compete with a Short-Term Storage, because that one is used all day while the Long-Term Storage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

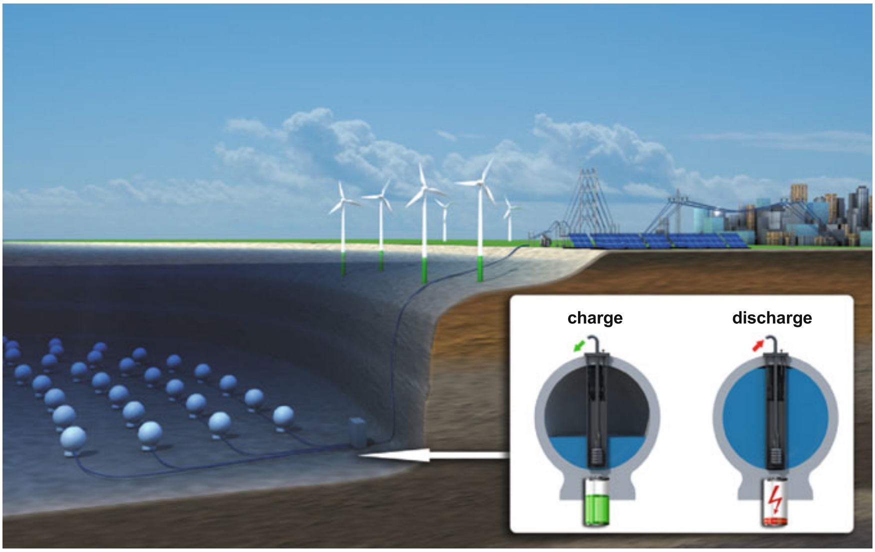


Fig. 3.14 A new idea for pump-storage are large sub-marine bowls that are anchored in deep-sea and which act as efficient pumped-storage hydropower station [61]

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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