Clean Power from Deserts[1]

Michael Düren, II. Phys. Inst., Univ. Giessen, Heinrich-Buff-Ring 16, 35392 Giessen, Germany

E-Mail: michael.dueren@uni-giessen.de

Abstract

Solar power from deserts can contribute significantly to a future renewable energy system. The technically accessible solar potential in deserts exceeds the global energy demand by a factor of 20. In the DESERTEC concept, a smart super grid based on HVDC technology interconnects wind, solar and other renewable energy sources with distant consumers on a scale of several thousand kilometres. The large grid averages out the natural fluctuations of renewable energy sources to a large extend. Remaining fluctuations have to be compensated by storage systems. Two competing technologies, CSP and PV, are available for large-scale solar power production in desert countries. CSP technology can be combined with thermal energy storage and water desalination. A large-scale production of solar energy in desert countries has important socio-economic implications. The interconnection of continents by large power grids introduces new economical interdependencies, which can help to reduce the North-South gradient of economic wealth.

1 Introduction

For 200,000 years, mankind had a sustainable energy system, based on biomass, wind, sun and water for cooking, heating, mobility and mechanical work. 250 years ago, during the period of industrialization, fossil fuels became available at large scale, and today, they cover 85% of the world energy system. The combustion of fossil fuel caused a steep rise of the concentration of CO_2 in the atmosphere by 40% from 280 ppm in the preindustrial era to 390 ppm in the year 2011 [2]. If - in view of the anthropogenic climate change - mankind decides to replace fossil sources within a short time scale of 20 to 50 years, an energy concept is needed that works globally and that can be put to practice with limited resources of manpower and material in a short time. The abundant solar power that is available in the deserts of the world can play a key role for a future renewable energy supply. The “clean power from deserts” or “DESERTEC” [3] concept is an inherently international, transcontinental approach, where the central technical starting point is a super grid that distributes electric power over distances of thousands of kilometres and averages out fluctuations of the renewable sources as well as of the energy consumption. The original DESERTEC white paper proposes to import 15% of the European electricity demand from deserts in Africa. The challenge to replace coal, oil and gas also in the non-electricity sector is often forgotten in the public discussion about local renewable energy systems. This paper gives an overview of basic technical and non-technical aspects of the approach to use the deserts of the world for a sustainable energy system.

2 Mission impossible - the increasing world power demand

Today, the world power consumption is approximately 15000 GW, averaged over day and night and over the whole year [15]. The world is facing an increasing world population and an increasing energy demand per capita, what may lead to an expected global power demand of approximately 24000 GW in 2050 [16]. This figure corresponds to a projected average power consumption of 2.6 kW per capita, which is less than half of today's energy consumption of 6

[1] This paper is an excerpt of a review published in GREEN.2011.025 [1].

kW per person in the OECD countries. Fig. 1 illustrates how the primary power divides into fossil, nuclear and renewable energies. Taking the climate goals serious, the fossil contribution has to be reduced by at least 50% in the coming decades to have an significant effect on the accumulated CO_2 at all. This means that capacities of 30000 GW of primary power have to be newly installed without exploiting the remaining fossil resources. The above numbers are only approximate and ignore additional energy saving potentials and energy conversion factors. Today, we convert fossil fuels to electricity and loose part of the energy due to the limited efficiency of the power plants. In future, we might want to produce synthetic fuels from electrical power, e.g. for applications in aviation, and again we have to take into account the corresponding conversion factors. Nevertheless, ignoring the various conversion factors that are hard to compare, the above numbers illustrate the order of magnitude of additional capacities that have to be installed in the very short time of 40 years. For illustration, one should keep in mind that 1 GW corresponds to the electrical power of one nuclear power plant. To build and run 15000 additional nuclear power plants (fission or fusion) in the next 40 years (i.e. 1 new reactors per day) is simply impossible from the point of view of the qualified manpower that is needed to do so. To build 15000 GW of PV-modules is only possible, if the amount of rare chemical elements needed for the production of the modules is significantly reduced.

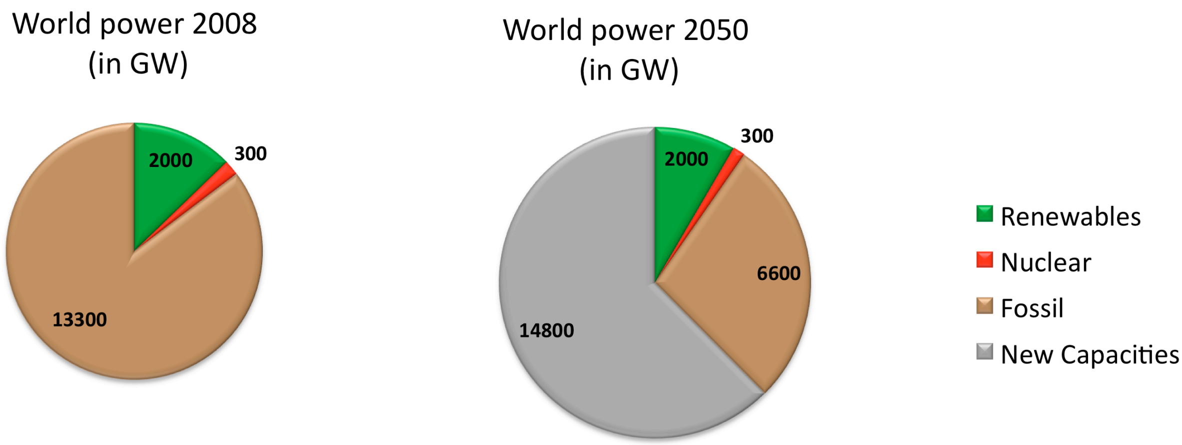

Figure 1*: It is assessed that the world primary power demand may increase in the coming 40 years by about 50% from an average of 16000 GW to about 24000 GW [16]. A reduction of the fossil fuels by 50% requires the installation of additional 15000 GW, corresponding to the capacity of one additional nuclear reactor every day for the next 40 years.*

This illustrates that the future energy system will not be defined by what technology is possible in principle, but by what technology is available in short time and is feasible from the point of view of human and material resources.

2.1 The future is electric

If fossil fuels are drastically reduced in future, they will have to be replaced by other energy carriers. Options are synthetic fuels (liquid, or gaseous like hydrogen), or electricity. Electric power is a prime choice, as the transport and distribution of electric power is very efficient and simple and the demand of electric power by the consumer is increasing. This is not only due to the increasing use of electronics, electric lights, microwaves etc, but electric power can be a prime choice even for room heating, if heat pumps are used that deliver thermal energy at a rate which is 3 - 5 times larger than the electrical power consumption of the device [17]. For mobile applications, where the storage capability of energy plays a prime role, the situation may be different, and synthetic fuels may play an important role in future. An efficient way to produce synthetic fuels by renewable energy sources has to be studied in parallel to the already intense research on better batteries for e-mobility.

3 The solar potential in deserts

The total solar irradiation in the deserts of the world is immense. The solar constant, i.e. the solar radiation that the sun delivers to an area at the entrance of the earth atmosphere is 1.37 GW/km^2. Using current technology of thermal concentrated solar power plants (CSP), the technically accessible power is 340000 GW_{el} [18], which exceeds the world energy consumption by a factor of 20. This number corresponds to the day and night, all year average and is based on an conservative estimate of the average efficiency of 12% to convert solar irradiation into electrical power and a land use fraction of 37% for the mirror field. Suitable desert areas are areas with high direct solar radiation. Areas not suitable for standard technology, e.g. mountain areas, are excluded in this estimate. Fig. 2 shows a map of those desert areas that are well suited for standard CSP technology. Overlaid is a satellite photo of the earth at night. The yellow lights indicate areas where there is a high consumption of electricity at night. It illustrates the concentration of electrical power consumptions in the USA, Europe and Japan and also the lack of electrical power in the populated areas of Africa and South America.

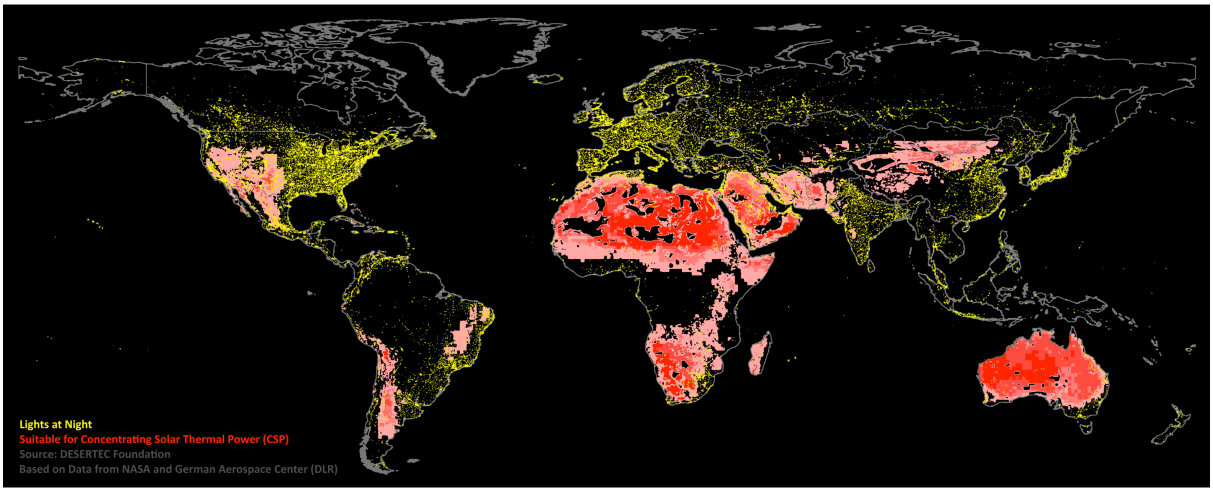

Figure 2: *The red colour indicates desert areas that are well suited for solar power plants due to large direct solar irradiation. Overlaid is a satellite image of the earth at night. The yellow lights indicate the areas with concentrated electricity consumption (Source: DESERTEC; based on data from NASA and DLR).*

4 Solar power plants in deserts

Two competing technologies are available for converting solar radiation into electricity: thermal concentrated solar power (CSP) and photovoltaics (PV). The CSP systems consist of a mirror system that follows the position of the sun, an absorber that converts the solar radiation into heat and a steam engine with generator that converts the heat into electricity. Optionally, CSP plants can have heat storage and a possibility to run in hybrid mode by firing fossil fuels at night or all day in addition. PV systems convert the solar irradiation into electricity without the detour of thermal energy. They are capable to make use of diffuse light in addition to the direct solar radiation. The following sections give an overview of the concepts of solar power plants. Details are found e.g. in [7], [10] and [12].

4.1 The parabolic trough

There are several technological realizations for CSP. The most mature one uses a parabolic trough that follows the position of the sun by a one-axis rotation. It focuses the solar radiation in one dimension onto an absorber pipe. An alternative similar system, the Fresnel system, replaces the large rotating parabolic mirrors by small strips of almost-flat mirrors that follow the position of the sun and focus the light onto a fixed absorber pipe.

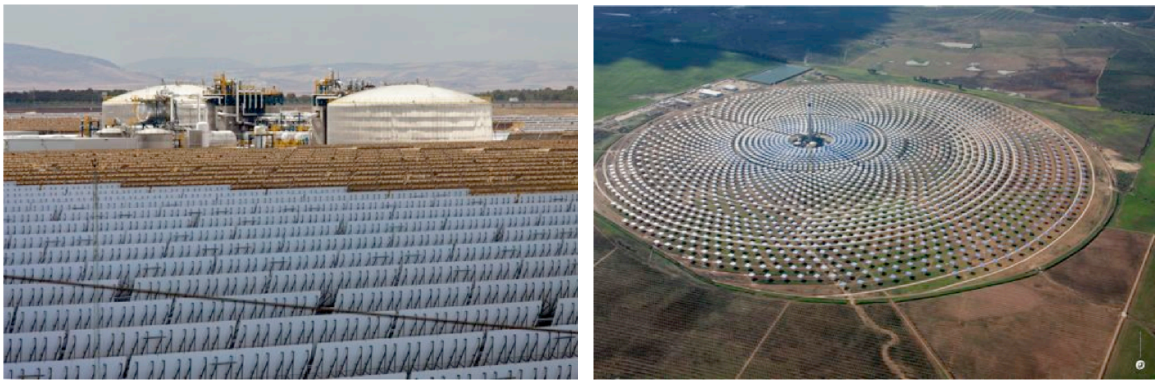

Figure 3: Left**: A concentrated solar power station with a field of parabolic troughs (front) and with two large thermal storage tanks (rear). The tanks contain liquid salt that is heated up by the solar field during day. They provide power for electricity production during the night (Photo: Solar Millennium).* ***Right: *The 20 MW Gemasol plant in Andalucia/Spain uses molten salt as heat carrier. Storage tanks for hot molten salt permit an electricity generation of up to 15 hours without sun, which allows for an uninterrupted operation day and night (Photo: Torresol Energy).*

The absorber pipe has the purpose to absorb light (IR, visible and UV radiation) and to convert it into heat. The absorber pipe is usually made from special, double walled glass with a vacuum in between (like a thermos jug), to minimize heat dissipation. The inner part of the absorber pipe has a special coating, which absorbs light but has a small radiant emittance in the infrared to minimize losses by heat radiation. A special technology uses molten salt at temperatures of 550 °C as heat transfer medium, which has the great advantage that the hot molten salt can directly be stored in a tank for a later energy use on demand.

The steam engine with a generator converts thermal energy into mechanical and electrical power. To optimize the efficiency, most steam turbines use water-cooling. For desert use air condensers are needed that have a closed-circuit water-cooling system, leading to a loss of about 10% of efficiency compared to water-cooled systems. An alternative to air-cooling is cooling with seawater. Sites directly at the coast are usually not suitable for CSP due to the fog in the air, but an option is to build seawater pipelines, which transport seawater for cooling from the coast to the optimal sites in the inland. This may pay off, especially when the residual heat of the power station is used for seawater desalination and local fresh water supply.

Parabolic trough systems are a proved, mature technology (see Fig. 3 left). Commercial systems have been operational in the desert for over 25 years in a reliable way. CSP power plants use components that can, to a large extent, be produced in desert countries themselves. The materials used are mainly glass, steal, concrete and copper and those are sufficiently available on the world market, also for large-scale production. The energy repayment period of a parabolic trough system is 5-6 months for a location in Spain and shorter in sites of higher solar irradiation as e.g. in North Africa [11].

4.2 The power tower

While the parabolic trough and Fresnel systems focus the sunlight in one dimension, power towers focus in two dimensions and can therefore reach higher temperatures and higher Carnot efficiencies. Higher temperatures also mean a more efficient heat storage. The technology of power towers is very promising for the future, but currently there is little commercial experience, as only very few power stations are in operation (see Fig. 3 right). One big advantage of the power tower compared to the parabolic trough is that the power tower can be built in a hilly area whereas the parabolic trough needs a flat surface. The size of the mirror field is limited due to the limited height of the tower and due to light losses at large distances. Therefore the power of a single device is not scalable and is limited to about 100 MW [12]. The technological challenge of power towers is the receiver that has to convert solar power in the 100 MW range in a limited volume and to transfer it to a heat circle at a high temperature of about 600-1200 °C [12]. The heat carriers that have been investigated are steam, liquid sodium, and others. The research tower in Jülich/Germany uses ambient air that is aspirated through the absorber.

4.3 Dish Stirling plants

A very efficient way to convert thermal energy into mechanical energy is the Stirling engine. A dish Sterling system is a device that consists of a large parabolic mirror, an absorber, a dish Sterling engine and a generator. The whole system follows the position of the sun by rotation around two axes. Commercial systems produce typically 10-50 kW [12] of electric power with a solar-to-electric power efficiency up to about 16%. An advantage of a dish-sterling system compared to a PV system is that it is a low-tech product that can be constructed in any (non-developed) country without large investments.

4.4 Photovoltaic panels

The modern, high-tech method to produce electricity from light is to use photovoltaic cells (PV). The various PV technologies, from monocrystalline silicon to thin films and spray-on solar panels make up a large and fast moving field of research. The reader is referred to more comprehensive reviews for technical details [13]. PV has the following clear advantages compared to CSP:

- It makes efficient use of diffuse light.
- It needs (almost) no water during operation (except for cleaning the panels).
- It needs (almost) no qualified manpower for operation.
- It has no movable parts and needs (almost) no maintenance.
- It is modular and scalable.

The sensitivity to diffuse light makes PV the prime choice for areas like the north of Germany, where the portion of diffuse light is up to 50%. But also for desert-like areas with dust or for coastal areas with fog the diffuse component of the light is an important factor in the decision for or against concentrating systems. Currently the costs of CSP and PV are at a similar level and both technologies have a large potential for cost reduction. Depending on the application, the decision will favour one or the other technology. To satisfy high power demand for air conditioning during the day, PV is currently the technology of choice whereas for covering power demand after sunset, CSP with thermal storage is appropriate. For an application at large scale it is important to develop a technology that is not only cost effective but also effective in terms of the material budget of rare elements, in terms of the energetic payback time and in terms of the local value added in the country during the construction and operation of the power plant.

4.5 Concentrated PV

To reduce the amount of semiconductor material in PV panels, arrays of lenses are used which focus the light on small, highly efficient PV cells. Similar to dish-Sterling systems these PV panels follow the position of the sun in two dimensions.

4.6 Thermal storage

Solar thermal power stations use heat as intermediate energy medium and allow for a cost effective storage of energy at large scale. During the day the molten salt from the "cold" container is pumped into the "hot" container using a heat exchanger that transfers the thermal energy from the thermo oil coming from the solar mirror field to the molten salt. After sunset the salt is pumped back to the original container through a heat exchanger that gives the energy to the steam system. This way the steam turbine can continue to operate during night. The investment of the heat storage system pays off for two reasons: it allows an electricity production on demand when the electricity price is highest and it allows to operate the steam turbine at full load for a longer time every day without having to cut the solar peak power during midday. To bring the costs down, the storage material has to be cheap and available in large quantities. For obvious reasons, sand is an attractive medium for solar power stations in deserts. At the solar tower lab in Jülich, the option to use sand as storage material is investigated. The heat is transferred to the sand sufficiently fast by blowing 900 °C hot air through the sand. The hot sand can be stored in a silo. On demand, the energy is extracted from the sand using a flow bed exchanger where the heat is transferred to steam that is used to run a steam turbine. One m^3 of sand at 900 °C contains about 300 kWh thermal energy what means that, neglecting losses and efficiencies, the storage of 10 hours solar power of a 1 GW solar field requires a sand cube of 30 m size.

4.7 Hybrid power stations

As CSP power stations use conventional steam turbines, one can combine solar power and fossil power in the same power plant without doubling the investments for the power block. Even though CSP stations with heat storage can deliver power day and night, there may be reasons to operate a CSP station with fossil fuels, e.g. to bridge a bad weather period. Another reason for building hybrid power stations is to minimize initial investments. Starting from an existing modern combined cycle gas turbine, the fossil fuel can be replaced by solar energy step-by-step by adding a solar field that delivers part of the exergy.

4.8 Seawater desalination in desert countries

For many desert countries the future fresh water supply is an even more serious issue than the energy supply. Today, many desert countries exploit fossil water reservoirs for drinking water and for agriculture. The fossil water sources are limited and the demand for water is increasing due to the population rise. The problem may be intensified in future by reduced rainfalls due to climate changes, especially in many regions of Africa.

Seawater desalination can mitigate the problem. As seawater desalination is inherently energy intensive, about 4 kWh_{el} are needed for one cubic meter of water [3], it is important to integrate seawater desalination into an overall energy concept. An elegant way to combine electricity production and seawater desalination is to use the waste heat of CSP stations for desalination [4]. As already mentioned, sites at the coastline are not optimal for CSP because of fog and clouds, therefore the seawater should be transported to inland CSP plants by seawater pipelines.

4.9 Wind power in deserts and off-shore

In many desert countries there are trade winds that allow for an efficient and reliable production of wind power. Modern wind power stations are a highly cost efficient way to produce renewable energies. Due to the fluctuating nature of wind, wind power has to be integrated into a large grid to average out fluctuations and it has to be combined with other sources of renewable energy in a common concept. Naturally, wind energy is not limited to deserts. There is a large unused energy potential offshore that is waiting to be harvested. Wind power increases with the third power of the wind speed, and therefore offshore wind power is significantly larger than on-shore wind power. What the desert is for solar energy, the sea is for wind energy.

4.10 Synthetic gas and liquid fuels from deserts

Today, mobile applications rely on fossil fuels to almost 100%. In spite of efforts to build reliable and light batteries, for many applications, especially in aviation, synthetic fuels will still be needed on the long run. It seems that CSP offers a largely unexplored field to synthesize fuels using catalytic reactions at high temperatures. A prominent example is the generation of alcohol using synthesis gas that is generated in a solar oven from CO_2 and water. Although this technology has been proved only at the laboratory scale and with an efficiency of 0.8%, there is hope that this technology can be brought to industrial scales at high efficiencies of e.g. 16-20% or more [19]. The production of hydrogen from water is also possible with catalytic reactions in CSP without making the detour of electricity generation. For the transport of synthetic fuels from the desert to the consumers, the existing pipeline system can be reused.

4.11 Further methods to produce power in deserts

There are other ways to produce electric power in the deserts. A prominent example is the solar chimney power plant. Despite the height of the chimney of 1000 m and more, the efficiency of such a power plant is as low as about 1%.

Solar heat can be used directly without the detour of electric energy in many local applications. Examples are process heat for industry and air conditioning of houses using absorption refrigeration machines that produce cooling energy from heat.

4.12 The ideal solar thermal power station

To summarize, the ideal solar thermal power station in the desert focuses the light by a large concentration factor, reaches highest temperatures, stores the heat using a large volume of cheap storage material, and uses the stored heat to produce electricity on demand. Seawater, brought in by a pipeline, serves as heat sink to increase the Carnot efficiency. The waste heat is used for seawater desalination and as process heat for industrial processes. In future, CSP technology may become a key technology for the large-scale production of synthetic fuels using catalytic reactions.

5 Power to the people - the super grid

The electric power produced in deserts has to fulfil first the growing power demand of the local population in the desert country. The large potential will exceed the local demand by far and can be used to export electrical power to the neighbouring countries [6]. About 90% of the world population lives within 3000 km from a desert. How is the power brought to the people? Modern high voltage technology allows for an efficient way to transport the power by electric cables over thousands of kilometres. By the use of a super grid that spans continents, all kind of distant, renewable energy sources can be interconnected among each other and with the consumers.

5.1 Local vs. central

When the DESERTEC concept was born, it met strong opposition by part of the established solar power community, especially in Germany. The competing concept is the idea of energy autonomy, where individual houses or small communities produce their own energy and are self-sufficient. A main benefit is anticipated from the avoidance of power losses in the grid and especially from the economical and political independence from large power companies and the corresponding large investments. From the technical point of view - ignoring the political issues here - it seems obvious that the decision for a local or a central energy concept depends on the situation. In a village in a rural area with little energy demand, e.g. in Namibia with a population of 1 person per km^2, it is obvious that the energy supply has to be local, using a combination of dish-Stirling, PV panels, wind power or biomass. The extension of existing grids to all villages will not pay off. In a big city like Cairo, Frankfurt or Chicago, a grid is the most economic, ecologic and reliable way to provide power 24 h a day to every household and to industrial centres. The grid is needed to supply energy when the fluctuating solar and wind power does not deliver. Ideas to use local batteries, local hydrogen production or bio fuels are not practical at a global scale where thousands of GW have to be provided. In contrast to a battery, an electric cable does not need large amounts of chemicals and is the easiest and cleanest solution to provide power to a region of dense power consumption. Therefore in industrialized and populated areas a dense power grid is needed. The idea of DESERTEC is to interconnect the local grids on a scale of thousands of kilometres for three reasons: to transport energy from deserts to distant consumers, to average out fluctuations of renewable energy sources, and to minimize expensive local storage and back-up capacities.

5.2 HVDC technology

The super grid became feasible by recent progress in the technology of high voltage direct currents (HVDC). Electric power can be transported using direct current (DC) or alternating current (AC). A draw back of the three-phase alternating current technology are problems with inductive and capacity reactance of long distance cables and possible black-outs due to phase instabilities in large area grids. In contrast to AC technology, modern HVDC technology allows for point-to-point connections with small losses of about 2.5% every thousand kilometres. The loss in the AC-DC converter stations is of the order of 1% or below [6]. In addition, modern HVDC connections work bidirectional and can stabilize the existing AC networks by adjusting and stabilizing the phases of the AC currents.

It is not the technical challenge of HVDC that is regarded as the main difficulty of the DESERTEC concept. Many people regard the long approval processes for new power lines as a major obstacle. As the energy supply of a country is of national interest, legislation has to be adjusted accordingly. To minimize the interference with the environment and with third parties, one can use ground cables that are placed parallel to railway routes or highways. Ground cables are more expensive than overhead lines, but compared to the production costs of electric power, the cost for the net are still moderate. The cost for a line from Africa to Europe (sea cable and overhead line) has been estimated to 0.01-0.02 €/kWh [6]. The losses of HVDC lines are typically less than 3% every 1000 km [8].

5.3 Averaging out fluctuations

Sun and wind are fluctuating energy sources. The sun has a daily and a yearly cycle, and due to clouds and weather conditions there is a stochastic behaviour in addition to the predictable oscillations. For wind energy the stochastic fluctuations dominate the cyclic variations. The fluctuations are spatially correlated, and the correlations decrease with distance. By interconnecting a large number of fluctuating energy sources, part of the fluctuations are averaged out. A simple example for three almost uncorrelated sources are the daily fluctuations of wind power generation in the North Sea, and the generation of wind power in North Africa using trade winds, and the fluctuations of the PV power production in the south of Germany. In general, renewable wind or solar energy sources are not at all uncorrelated and a detailed investigation of time series is needed to evaluate the overall performance of the super grid [9].

5.4 Demand control and smart grids

Standard grids distribute the power of a few power sources to a large number of consumers and adjust the production of the power plants to the need of the consumer of the power. Smart grids do not only adjust the production to the consumption, but in addition they adjust the power consumption to the availability of power. A technical requisite to do so is a communication line between the power company and the power consumers that allows switching off certain devices for certain periods, e.g. short times during daily peak hours or longer time periods e.g. during calms of wind power. Economically that can be introduced by special power tariffs that make electric power cheaper for consumes at certain times or under certain operating conditions. Short power breaks are uncritical for a certain class of devices like air conditioning systems, refrigerators, and heat pumps. Longer power breaks may be uncritical for water desalination, for water pumps in agriculture, and even for energy intensive industrial production where energy prices are a dominant factor and more relevant than e.g. manpower costs. Up to now there are many ideas about how a smart grid could work. A classical example is to run the washing machine remote controlled during the night, but there is little practical experience about how well the concept is accepted in daily life and what the final benefit will be.

6 Energy security

Energy has to be available 24 h/d, every day in the year. Our current fossil energy system based on coal, oil and gas uses storage capacities to ensure permanent availability. If in future a major fraction of the electrical power comes from sun and wind, the fluctuations and the daily and yearly cycles of these renewable energy sources have to be taken into account for a secure energy supply. The main ingredients for a stable, renewable energy supply based on energy from deserts are:

i. A large-scale smart super grid
ii. CSP thermal storage
iii. Overcapacities and a "fine-tuning" of the selection of various power sources
iv. Large scale water pump storage
v. Power to gas production
vi. Back-up power stations

The large-scale grid, sufficiently dimensioned, averages out stochastic fluctuations of the energy sources and of the consumption over a scale of a thousand kilometres. In addition, due to being "smart", it allows to reduce the power demand in periods of power shortage. The daily cycles of solar energy can be handled by thermal storage in CSP, provided the HVDC lines have overcapacities that match the power consumption during peak hours. Overcapacities of power stations, especially of wind power stations, are also needed to minimize the required storage capacities. The idea of "fine-tuning" comes from the fact that every source of renewable energy as well as every type of consumer has a specific daily and yearly cycle. By adjusting the number of power stations of each type to each other, the daily or yearly net variations of power demand and of power consumption can be compensated to some extent. If, for example, an area needs extensive electric power for air conditioning during the hot hours of the day, local PV is the ideal power supply, which matches the daily cycle of the demand. Another example: there are areas which have supplementary wind in winter, like the regions of the North Sea and the Baltic Sea, and areas which can produce more power in summer, like CSP and wind power in North Africa. By adjusting the number of power stations in the north with those in the south the overall variations can be minimized.

6.1 Water pump storage

The most efficient way to store electric power at large scale is to use water pump stations. A water pump station consists of two large water basins at different heights that are connected by a turbine which can pump up the water if there is an excess of electric power and that can run in generator mode when electric power is needed. Water pump stations have a high efficiency of typically 70-85% [10]. Pump storage systems are characterized by the maximum power they deliver and the maximum energy they store. Large systems reach a power of about 1 GW and a capacity of about 8 GWh. Much larger systems could be built by using the ocean as one of the basins. For example, a Fjord in Norway with a size of e.g. 400 km^2 that is converted into a barrier lake by a 25 m high dam could store 340 GWh. Another suitable geographic area is a large lowland in Morocco, up to 60 m below sea level that could be flooded and used as the lower basin with the Atlantic being the upper basin in this case.

An alternative option for water pump storage is to go underground and use old, unused mines as lower basins. Recently it was proposed not to reuse old mines but to build new wells for the purpose of water pump storage. These wells would have a depth on the order of 2000 m, the water would be pumped up and down using existing pump station technology and they could be build at a location of choice with almost no impact on the landscape [20].

Another new concept for pump storage is to exploit the high water pressure in deep sea. It is proposed to build large hollow concrete balls that are stationed at submarine ground at a depth of 1000-2000 m. They are equipped with a turbine that is able to evacuate the balls. A power cable connects the balls with the power grid. The hollow spheres act as pump storage by evacuating them. By floating with seawater the energy is recovered. At a depth of 2000 m the potential energy density of water is 20 MJ/m^3. The electrical energy output obtained from such a ball equals the one from a natural gas storage of the same volume at normal pressure.
It was proposed to tune the wall thickness of the balls such that its weight compensates the upwelling, and that a fully evacuated sphere can resurface for maintenance [21].

6.2 Chemical storage

It has been proposed to use batteries of cars as storage capacity of the grid. This concept is appealing at first sight, but it has some deficiencies. Due to the limited cycles of batteries and the requirement that the battery has to be full when the car is needed, not everybody will accept that the battery of his car is emptied every day during peak electricity demand, especially when the peak demand in winter coincides with the morning rush hour where the car is needed. Using batteries for buffering grid energy at large scale requires a huge number of cars that are unused most of the time. Such a concept of individual motor traffic with cars that are parking most of the time is not a very ecological mobility concept - even though it is fact today. More ecological concepts like car-sharing or public transport are not compatible with the idea of using batteries of cars as free storage capacity.

6.3 Power to gas

An alternative to batteries is the production of hydrogen, methane or other synthetic fuels for energy storage. Hydrogen can be produced from water using electrolysis with an efficiency of about 60% [22]. Using fuel cells or gas turbines, 60-70% of the energy can be retrieved as electricity [10], which means that the overall efficiency of the storage medium hydrogen is about 40%, using current technology.

Recently, an appealing concept is promoted using the label *wind gas*: Excessive wind power is used to generate hydrogen, which is then feed into the existing natural gas pipeline network. There, the gas is stored using the existing gas storage capacities. Due to diffusion and its chemical properties, the fraction of hydrogen in the standard gas pipelines has to be limited to a few vol.-%. In order to overcome this capacity limit, the hydrogen is chemically converted to methane by the addition of CO_2. This *renewable* methane perfectly replaces natural gas and can be stored and distributed by the existing gas infrastructure [23]. Currently, the production of hydrogen or methane has still large conversion losses and future R&D will show if gas production becomes an option for large-scale energy storage.

6.4 Back-up power stations

In a future energy system based on water, solar and wind power, power stations based on biomass can be used as buffer and back-up for the case that water, wind, solar, and pump storage power are insufficient. Also natural gas power stations can play this important role in the coming decades during the transition time from the fossil and nuclear energy system to a renewable energy system. The still existing coal and lignite power stations should be preserved as back-up power stations. They cannot serve as short-term resource to compensate for daily fluctuations, but their existence reduces the vulnerability of a country against power cuts, for example in case of a political crisis in one of the solar power generating countries. Putting fossil power plants into operation for a limited time is a way to overcome power shortages on the scale of weeks or months.

7 Environmental issues

Numerous large-scale solar power stations, wind parks, overhead lines, and large pump storage stations certainly have an impact on the environment that has to be carefully studied. Nevertheless, all conceivable impacts of this renewable energy concept are put into perspective compared to the impact of global warming, air pollution, oil pollution, nuclear accidents, or coal and uranium mining and radioactive waste repositories.

8 Socio-economic and political issues

The socio-economic and political preconditions for and implications of a transition to a sustainable society exceed the scope of this paper and the reader is referred to more comprehensive reviews [14], [25], [26], [27], [28], [29], [30], [31]. Nevertheless a few key aspects related to a switch over to renewable energy supply from desert areas will be discussed.

8.1 The learning curve and the internalization of external costs

The change of our global energy system requires huge investments. Conventional power plants, like e.g. gas turbines, need a comparably small initial investment, and a large proportion of the electricity costs comes from the costs of the fossil fuel. Renewable energy systems have small running costs and the major part of the electricity costs are investment costs, i.e. manpower and material during construction and the interest of the investor. In addition, there is a learning curve to pay in the coming years, as the required technologies are partially still in the pre-commercial development phase and not yet in mass production. All that makes the switch from an exploiting energy system to a renewable energy system economically difficult, and political regulations or incentives are needed so that renewable energies can compete with the old technologies on a free market. Possible political tools are feed-in tariffs, carbon certificate trading or energy taxes. A first and overdue measure is the cancellation of governmental subsidies for the mining or use of fossil fuels.

A more difficult step is the internalization of the external costs. Examples for external costs of fossil fuels are the long-term costs of global warming, the costs of air pollution to the health of the population and the costs of oil pollution by accidents during drilling and transport of the oil. Examples for external costs of nuclear industry are the long-term costs of nuclear accidents, the costs for keeping nuclear radioactive waste repositories safe over centuries and the costs to prevent the proliferation of nuclear weapons.

A first political measure to bring the old and the renewable energy industries to an equal footing would be to force energy companies to re-insure those risks. A full risk assessment and insurance against costs of possible terroristic attacks in nuclear industry would certainly make nuclear power economically unattractive. The same will be true for oil and coal companies if the impact of global warming is internalized.

It can be predicted that even without internalizing external costs and without special feed-in tariffs, wind, CSP and PV power stations will be economically competitive in many areas of the world in the coming decades, due to the rising costs of fossil fuels and due to the cost reduction by mass production of components for renewable energy power stations. This fact makes investments in new fossil or nuclear power stations uncertain already today, as a power station that is constructed today will not be competitive during its whole life span any more. In addition, future investments in fossil and nuclear industry will face an increasing risk of penalties (taxes, re-insurance, environmental conditions, etc.) due to the decreasing acceptance in the public opinion. Therefore, feed-in-tariffs and other political measures are not needed to make the energy revolution happen, but they are urgently needed to make the energy revolution happen in time, i.e. before humanity runs into serious problems of energy shortage and climate change.

8.2 The special situation of MENA and Europe

The USA, China, Australia and other countries have their own deserts. For many countries in Europe, Africa, Asia and South America the use of energy from deserts relies on international cooperation, which is challenging in many cases, as for example in the case of Europe and Africa. In MENA (Middle East and North Africa) the population and the need for electricity are growing rapidly. There is little industry in North Africa, a high unemployment rate and a lack of prospects for the young generation. The idea of DESERTEC is to construct solar and wind power stations in MENA. The excess of energy that is not needed in the country itself can be exported to Europe. That creates an economical interdependence between MENA and Europe and is a basis for a stronger future collaboration. It is a classical win-win situation. Europe has the knowledge how to build the power plants and the HVDC grid. It also has the money to pay for the learning curve. MENA has the optimum sites for solar energy power stations and the manpower to construct them. Europe can profit from a cost-effective clean solar power generation, from a political stabilization of North Africa due to the economic growth, and from a new business market in its vicinity. The rising problem of migration and extremism can be mitigated by a close collaboration of Europe and Africa. Africa has the advantage of getting sustainable energy, fresh water from seawater desalination, new possibilities for industrial growth and a large number of new jobs and perspectives for the future of the young population. The power connection of the continents can bring the continents closer together in an economical and may be even in a cultural way. Representatives from North-Africa have expressed that they do NOT want turnkey power stations made by European companies any more, but that they want to gain the know-how themselves how to build solar power stations and have local value added. The DESERTEC foundation supports this concept and has set up an academic and a university network where institutes from most of the North African countries are represented [24]. A large number of (local) engineers is required, so that the goal to build a large amount of power stations in the coming decades can happen sufficiently fast.

8.3 Requirements of a future energy system

From the political point of view, the future energy system has to fulfil three criteria (see Fig. 4): reliability, economic efficiency and environmental sustainability. Concerning the environmental sustainability the renewable energy systems obviously beat the fossil and nuclear energies, provided that renewable energy systems are chosen that have a good eco-balance concerning the amount of energy and material needed to construct the renewable energy systems. The reliability issue is obviously fulfilled by the DESERTEC concept in the global sense, as there is no fuel needed, sun and wind will not run out and the fluctuations can be handled. From the point of view of a certain country that has to import electricity from a neighbouring country, the situation looks different at a first glance, as there is an obvious dependence on the neighbouring country. However, this situation is not new for most of the industrialized countries. Already today, Europe's energy security depends on a few suppliers of oil and gas. The credo of the DESERTEC concept is that the economic interdependence of the involved countries introduces a partnership that finally is the best guarantor for a safe neighbourhood far beyond the aspect of a safe energy supply.

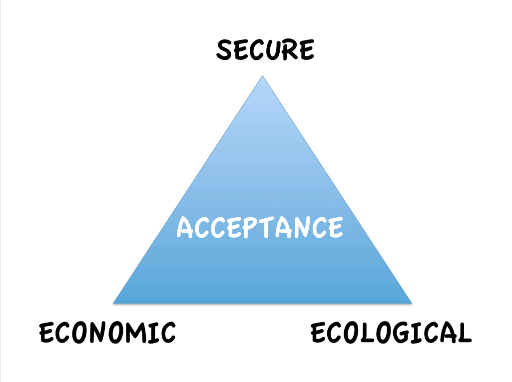

Figure 4: *Energy security, economic efficiency and environmental sustainability are the three main criteria for the political and public acceptance of an energy concept.*

A big economical advantage of renewable energies compared to fossil energies is that they do not depend on a fluctuating world market of fossil resources. The product "electricity from the desert" is not suited for long-term storage. An African desert country that cuts the electric power line to Europe will not be able to bunker the electricity to sell the energy at another month to a different customer. It will simply loose the benefit of its investments. Therefore, it is in the interest of both partners to maintain good long-term business relations.

The economic efficiency of renewable energy sources is still an issue today, because the external costs of the competing energy sources are not internalized. It is the prime duty of political leaders today to negotiate national and international agreements that stop the apparent cost advantage of fossil and nuclear energies and to support the renewable energies by feed-in tariffs, by paying the learning curve and by organizing and financing intense research and development on renewable energy systems to bring the costs down.

More and more important, beyond all economical and political considerations is the acceptance of a technology by the people. Here, the protagonists of the idea of the "clean power from the desert" still need to do a convincing job, to overcome the scepticism against a new technological concept that, in the view of many people, seems to have a large risk of generating new dependencies as well for the industrialized non-desert countries as for the developing countries.

9 Conclusions

Clean power from deserts is ready to go. It has an overwhelming potential for a sustainable world energy supply. Basic concepts and technologies are available to be implemented. Nevertheless, the way to an almost 100% renewable, carbon free energy supply still requires huge efforts of technical R&D, and more important, significant changes in the political and socio-economic boundary conditions. Looking at today's economical and political decisions, it seems that many people either ignore or underestimate the range of the required changes of the world energy system.

Acknowledgements

The above ideas were developed by many people and organisations and I have to thank those who studied the ideas and those who discussed them with me, especially Gerhard Knies, Franz Trieb, Gregor Czisch, Hani el Nokrashy, Mouldi Miled, Robert Pitz-Paal, Thiemo Gropp, Rolf Linkohr, Walter Blum, Gerhard Luther, the DESERTEC foundation, the working group on energy at the German Physics Society (DPG), the German Aerospace Center (DLR), the DESERTEC Industrial Initiative (Dii), the DESERTEC University Network (D.U.N.), the Solarinstitut Jülich, all my colleagues at the working group Solar Energy Partnership Africa Europe (SEPA) at the Univ. Giessen, and many others.

References

1. M. Düren, Green, Vol. 1 (2011), pp 263-275, DOI 10.1515/GREEN.2011.025
2. IPCC, NOAA ESRL, *Trends in Carbon Dioxide* , 2010. http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html\#global
3. G. Knies, U. Möller and M. Straub, editors, *Clean Power from Deserts, The DESERTEC Concept for Energy, Water and Climate Security*, White paper, 3rd edition, ISBN 978-3-929118-67-4, Protext Verlag, Bonn, 2008. http://www.desertec.org
4. F. Trieb et al., DLR-AQUA Study Team, *Concentrating solar power for seawater desalination*, final report (AQUA-CSP), DLR Institute of Technical Thermodynamics, Stuttgart, Germany, 2007. http://www.dlr.de/tt/aqua-csp
5. F. Trieb et al., DLR-MED Study Team, *Concentrating solar power for the mediterranean region*, final report (MED-CSP), DLR Institute of Technical Thermodynamics, Stuttgart, Germany, 2005. http://www.dlr.de/tt/med-csp
6. F. Trieb et al., DLR-TRANS Study Team, *Trans-mediterranean interconnection for concentrating solar power*, final report (MED-TRANS), DLR Institute of Technical Thermodynamics, Stuttgart, Germany, 2006. http://www.dlr.de/tt/trans-csp
7. M. Mohr, P. Svoboda and H. Unger, *Praxis solarthermischer Kraftwerke*, Springer, Berlin, 1999.
8. Siemens AG, *High Voltage Direct Current Transmission - Proven Technology for Power Exchange* , Erlangen, 2011. http://www.siemens.com/energy/hvdc
9. D. Heide, M. Greiner, L. von Bremen, and C. Hoffmann, *Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation*, Renewable Energy, Volume 36, 2515 (2011).
10. E. Rebhan, editor, *Energiehandbuch*, Springer, Berlin, 2002.
11. H. Gladen, *Solar Thermal Power Plants - Firm Capacity with 100% Renewables*, Solar Millennium AG, CUEN 3rd Annual Energy Conference, 22nd June 2009. http://www.srcf.ucam.org/cuens/
12. W. Vogel and H. Kalb, *Large-Scale Solar Thermal Power*, Wiley-VCH, Weinheim, 2010.

13. R. Brendel, *Silizium-Wafer-Solarzellen - Neue Horizonte*;
M. Powalla, H.-W. Schock, U. Rau, *Dünnschichtsolarzellen - Technologie der Zukunft?*;
V. Dyakonov, C. Brabec, J. Hauch, *Photovoltaik - Neue Konzepte*;
in *Themen 2010 Forschung für das Zeitalter der erneuerbaren Energien* and references therein, FVEE Renewable Energy Research Organisation, Berlin, 2010. http://www.fvee.de/publikationen/
14. I. Werenfels and K. Westphal, *Solar Power from North Africa*, SWP Research Papers, German Institute for International and Security Affairs, ISSN 1611-6372, Berlin, (2010). http://www.swp-berlin.org
15. IPCC, SRREN, *Special Report on Renewable Energy Sources and Climate Change Mitigation SRREN*, 2011. http://srren.ipcc-wg3.de
16. IPCC, SRREN, *Potential of Renewable Energy Outlined in Report by the Intergovernmental Panel on Climate Change* , 2011. http://srren.ipcc-wg3.de/press/content/srren-press-release-updated-version.pdf
17. DPG Studie, *Elektrizität: Schlüssel zu einem nachhaltigen und klimaverträglichen Energiesystem*, Deutsche Physikalische Gesellschaft, Bad Honnef, 2010.
18. F. Trieb, C. Schillings, M. O'Sullivan, T. Pregger, C. Hoyer-Klick, *Global potential of concentrating solar power*, SolarPaces Conference Berlin, September 2009.
19. W. C. Chueh, et al. *High-flux solar-driven thermochemical dissociation of CO_2 and H_2O using nonstoichiometric ceria*, Science 330, 1797 (2010);
20. G. Luther and H. Schmidt-Böcking, *Schacht-Pumpspeicherkraftwerk* , Patent DE 10 2011 105 307, (2011).
21. H. Schmidt-Böcking and G. Luther, *Pumpspeicherkraftwerk* , Patent DE 10 2011 013 329, (2011).
22. B. Diekmann, K. Heinloth, *Energie*, Teubner Studienb\"ucher Physik, Stuttgart.
23. M. Sterner, M. Jentsch, and U. Holzhammer, *Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes*, Expertise by Fraunhofer IWES (2011).
24. http://www.desertec.org
25. H. Graßl et al., *Über Kioto hinaus denken - Klimaschutzstrategien für das 21. Jahrhundert*, WBGU Berlin, (2003). http://www.wbgu.de
26. H. J. Schellnhuber et al., *Welt im Wandel - Gesellschaftsvertrag für eine Große Transformation*, WBGU Berlin, (2011). http://www.wbgu.de
27. S. Erdle, *The DESERTEC Initiative*, DIE, German Development Institute, Bonn, (2010). http://www.die-gdi.de
28. N. Supersberger et al., *Algeria - A Future Supplier of Electricity from Renewable Energies for Europe*, Wuppertal Institute, Wuppertal, Germany and CREAD, Rostomia, Alger (2010). http://www.wupperinst.org
29. A. Gazzo et al., *Middle East and North Africa Region Assessment of the Local Manufacturing Potential for Concentrated Solar Power (CSP) Projects* , Ernst & Young et Associes, Fraunhofer Institutes ISE and ISI, and The World Bank, Washington DC (2011).
30. N. Supersberger et al., *The Impact of Clean Energy Innovation*, An Analysis by Google.org using McKinsey \& Company's US Low Carbon Economics, (2011). http://www.google.org
31. J. Lilliestam and S. Ellenbeck, *Energy security and renewable electricity trade - Will Desertec make Europe vulnerable to the 'energy weapon'?*, Energy Policy 39 (2011).