Concentrated Solar Power in Sahara

Renewable Energy in Practice 2009, CA

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Submitted: August 20, 2009
Abstract

Today around 2900 TWh/year of the electricity produced in Europe comes from non-renewable resources. In year 2030 the demand is increased to 3300 TWh/year. This project considers replacing non-renewable energy sources in Europe with radiation from the sun in the North African desert. Captureradiation in roughly 11,000 km² of desert, convert the irradiance into electricity in 900 of 500 MW power plants, transport it by DC transmission and distribute it to the customer with an efficiency of about 15 %. Each plant will be equipped with 126,000 m³ thermal heat storage with molten salt.

Currently eight concentrated solar power technologies are available (only few of them commercialized) with a levelized electricity cost from 0.14 €/kWh. They all have the potential to be competitive to conventional coal fired power plants in the future.

High Voltage Direct current (HVDC) transmission lines have a big potential for transporting electricity over long distances and implementing energy from renewable energy sources. The loss is only 2.5 % per 1000 km. A disadvantage is that the transmission lines constitute a very big part of the startup investment.

The cost-analysis shows that concentrated solar power in the Sahara demands massive initial investment, and that producing electricity through this technology is not competitive in the near term. The financial conclusion implies that political regulation to support investment might be needed. The possibility for EU-regulation is therefore examined. It is shown that creating positive incentive structures could speed up the transition process towards more renewable energy sources.
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Introduction [DRN; KFM; MBN]

The world is facing an enormous challenge of reducing the CO₂ emission in order to leave up to the recommendations set by the IPCC. The EU has decided to reduce CO₂ emissions by at least 20 % in 2020 compared to 1990-levels. This can be done by energy savings and shift from fossil fuels to renewable energy resources.

Currently 2900 TWh of power a year are produced in Europe by nuclear and fossils fuels. A large amount of the energy consumed is imported from Russia (natural gas) and the Middle East (oil). These fossils energy resources are very limited and give rise to concern about security of supply.

Solar energy has the potential to solve the two problems - Within 6 hours the world deserts receives more energy than the whole world consumes in a year. The idea is to produce electricity where the renewable energy resources are available and transport this energy to the consumers.

A new foundation called Desertec wants to promote this idea in the Sahara Desert by making a network between stakeholders in the EU-MENA (Europe, Middle East and Northern Africa) region. The network seeks to affect the energy policy of this region and find a way to finance the enormous investments. The goal is that a major part of the electricity generation would be based on solar energy in the Sahara Desert and consumed in the whole EU-MENA region.

The main challenges are to develop new renewable technologies which are competitive to the conventional fossil based ones, implement an electrical transmission grid and set up a political framework which gives incentives to invest in these technologies.

The aim of this report is to further research and assess the Desertec project by looking more carefully into the technological, economical and political assumptions and conditions. Since the Desertec project is very complex it has been chosen to take its most important elements and put those into a simplified system in order to investigate its feasibility and prospects. A simple system consists of several production facilities in the Northern African countries (Morocco, Algeria, Tunisia and Libya), an electrical transmission grid to the EU and the electrical demand of the EU.

Several concentrated solar power (CSP) technologies for large scale production seems to be promising renewable energy options. Only the concentrated solar thermal power technologies are investigated. Solar chimneys are not considered in this report. Other solar power systems such as photovoltaic are more efficient and could be an alternative way to convert radiation from the sun into power, but it is estimated that the expenses for materials and production are too high compared with the CSP systems and they do not have the opportunity to store energy.

The existing CSP technologies will briefly be described in terms of how they work advantages, disadvantages, the electricity costs and the annual solar efficiency.
The technology of transmission lines is briefly described. Advantages of HVAC and HVDC are discussed and also a rough estimate of cost is determined.

The energy demand of the EU is estimated for 2030, the solar irradiance in the Sahara Desert is estimated and the needed area to produce the required electricity will be calculated. The size of thermal storage will be estimated.

After looking into the technical aspects, an economic analysis investigates the capital requirement needed to implement the technology in a sufficient scale and the prospects of private investment. The main issue at stake is, if electricity generated in the Northern Africa will be competitive to the conventional produced electricity in the near and long term.

The third element to be considered is the possibility of political involvement on EU-level. The purpose of political regulation would be to create a more favorable investment environment, compensating for the near-term financial challenges. Creating a more aggressive incentive structures could promote a quicker shift towards solar-energy from Sahara.

At last, other political and economic considerations are shortly discussed.
Potential and technical feasibility [KFM; MSN; DRN]

Concentrated solar power technologies [KFM]

Concentrated solar power (CSP) plants, which convert sunlight into heat and then into electricity, can be divided into four main groups due to how the solar energy is captured [K3], [K4].

- Central receiver system (CRS)
- Parabolic trough (PT)
- Linear Fresnel (LF)
- Parabolic dish (PD)

Some of these concepts can be divided into sub categories depending on the: fluid (media) which is transporting the heat, and the thermodynamic process. These processes are briefly described in the next section. Another important characteristic is the ability of storing the energy in the form of heat – this has only been applied to some of the concepts. The cost of each state-of-the-art CSP-technology has been estimated by ECOSTAR – European Concentrated Solar Thermal Power Road-Mapping [K3] in 2005. As far as possible, commercialized technology (also demonstration and pilot project) has been applied to assess each technology in terms of state of development and the levelized cost of electricity production, see Figure 1. To compare these technologies, a reference system for each system has been calculated i.e. all plants have been scaled to the same size (50 MWe). It is assumed that the reference systems produce at full load from 9am to 11pm. The CSP concepts are briefly described after a short introduction to the thermodynamic processes.

![Definition of “Levelized Electricity Costs” (LEC)](image)

\[
LFC = \frac{crf \cdot K_{\text{invest}} + K_{\text{O&M}} + K_{\text{fuel}}}{E_{\text{net}}}
\]

with

\[
crf = \frac{k_d (1 + k_d)^n}{(1 + k_d)^n - 1} + k_{\text{insurance}} = 9.88\%
\]

- \(k_d\) real debt interest rate = 8%
- \(n\) depreciation period in years = 30 years
- \(k_{\text{insurance}}\) annual insurance rate = 1%
- \(K_{\text{invest}}\) total investment of the plant
- \(K_{\text{O&M}}\) annual operation and maintenance costs
- \(K_{\text{fuel}}\) annual fuel costs
- \(E_{\text{net}}\) annual net electricity

Figure 1: Definition and assumption for levelized electricity costs (LEC). Source [3]
**Thermodynamic processes.**

All the CSP plants produce heat which must be converted into electricity. A machine converts the heat into mechanical work by a thermodynamic process. The mechanical work is converted into electricity by a generator. Three different thermodynamic processes (and a combination of these) are applied in the different CSP concepts.

- Rankine cycle
- Brayton cycle
- Stirling Engine
- Combined cycle (Brayton + Rankine)
**Rankine cycle**
A Rankine cycle is a traditional steam/water cycle used in coal, oil, gas and nuclear power plants. It is a closed cycle, which is a loop where water is recycled. A simplified Rankine cycle consists of four components: Pump, Boiler (steam generator), Turbine and condenser. The processes in the cycle will be explained in the following, see Figure 2.

![Simple Rankine cycle](image)

1 \(\rightarrow\) 2: water is pressurized by the pump (P) to a pressure in the range of 100-300 bars.

2 \(\rightarrow\) 3: the water is heated in the boiler (B) and transferred into steam (500-600 C).

3 \(\rightarrow\) 4: the steam is expanded in a steam turbine (ST) which performs mechanical work. The pressure and temperature drops.

4 \(\rightarrow\) 1: In the condenser (C) Heat is removed from the steam which condensates (liquid water). Temperature/pressure is not changed.

**Brayton cycle**
This open cycle is used in small to medium size power plants and in jet engines for aircrafts. The thermodynamic process is briefly described in the following, see Figure 3.

1 \(\rightarrow\) 2: Air is compressed to a pressure in the range of 5-30 bars by a compressor (COM).

2 \(\rightarrow\) 3: The compressed air is heated either by burning a liquid or gaseous fuel, or by another heat source, e.g. concentrated sun light in a combustion chamber (CC), to a temperature in the range of 1000-1400 C.

3 \(\rightarrow\) 4: The hot air is expanded in a gas turbine (HPGT), which provides mechanical work to a generator (G) producing electricity. The exhaust temperature of the air/gas is in the range of 400-600 C.
**Stirling engine**

The Stirling engine is a piston machine like a normal internal combustion engine (ICE) in a car. The most important difference is that the heat source is *external* – not *internal* as for the ICE. The thermodynamic process has four steps (or strokes), see Figure 4. The model has two cylindrical chambers which are connected. Each chamber has its own piston.

![Figure 4: The cycle of the Stirling engine. Source: [K14]](image)

(a) 1 → 2: Heat ($Q_h$) is added by an external source (e.g. solar radiance) to the left chamber. This expands the gas and the left piston is moved down (the right piston is fixed).

(b) 2 → 3: The left piston moves up while the right piston moves down – the volume remains the same. The hot gas in the left chamber heats up a wire mesh (regenerator/heat recovery) on its way to the right chamber.

(c) 3 → 4: The gas in the right chamber is cooled by an external source (e.g. cooling water or air) – heat is removed ($Q_c$) and the gas contracts which move the right piston upwards.

(d) 4 → 1: The right piston is moved further upward while the left piston is moved downward. The gas is moved from the right chamber to the left chamber. On the way it receives heat from the wire mesh.
**Combined cycle**
The term “combined cycle” normally refers to the combination of a Brayton and a Rankine cycle. The Rankine cycle utilizes the hot exhaust gas from the gas turbine in a heat recovery steam generator (HRSG), which increases the overall thermal efficiency, see Figure 5.

![Figure 5: Combined cycle - the combination of a Brayton and a Rankine cycle.](image)
Central receiver system (CRS)

CRS is also called a “power tower”. Solar radiation is reflected by heliostats (moveable mirrors) to a receiver, which is placed on top of a tower, e.g. 100 m tall, see Figure 6. The solar radiation is absorbed by the receiver and transferred to a fluid, which can be:

- Molten salt
- Saturated steam
- Atmospheric air
- Pressurized air

**CRS - Molten salt**

![Process flow diagram of CRS-molten salt cycle.](source)

Figure 6: Central receiver system - PS10 in Seville, Spain. Source [K13].

Figure 7: Process flow diagram of CRS-molten salt cycle. Source: [K3].
The molten salt is a mixture of 60% sodium nitrate and 40% potassium nitrate and heated from 290°C to 565°C in the receiver, see Figure 7. The salt transfers the heat to Rankine cycle (conventional EPGS) by a steam generator [K3].

The produced heat can be stored in salt storage. This makes it possible to produce electricity in periods when the sun doesn’t shine, e.g. during night or on cloudy days.

Solar Two is an upgraded version of Solar One. It is the largest demonstration plant of this type. The capacity is 10 MW. It is located near Barstow in California and has been in operation from 1996-1999. It includes a thermal storage of 110 MWh/ and 154 hours of non-stop production has been demonstrated [K3]. The overall peak efficiency (solar to electricity) is 13.5 %, the receiver efficiency 88 %, the thermal storage round-trip efficiency 97 % and the Rankine thermal efficiency 34 %. The major problem is corrosion of the heliostats and a reliable movement of these. The availability of the plant is uncertain due to freezing of the salt, which delays the startup [K3].

The first commercial plant GEMASOLAR (former known as Solar Tres) is under construction near Seville, Spain. It has a capacity of 17 MW producing approximately 110 GWh/y [K5]. This plant (like Solar Two) depends on natural gas, which is used for co-firing.

The estimated cost of produced electricity is 0.1545 €/kWh_e [K3].

**CRS – Saturated steam**

Water is directly heated in the receiver which is an advantage compared to the CRS-molten salt, because the relatively expensive heat exchanger (steam generator) is not necessary. Surplus steam is stored to provide steam for the turbine in case of a lack in the solar irradiance (clouds). The disadvantage is that steam is not very
dense which makes the storage relatively expensive and therefore only feasible for short-term storage purposes, e.g. half an hour.

PS10 and Solar One have demonstrated this technology [K3].

Sierra Sun Tower, the first commercial plant in the US of this type, started operation on August 6, 2009. The capacity is 5 MW. It is expected that the next generation is equipped with a much larger thermal storage, e.g. molten salt [K6].

The electricity production cost of this plant, when scaled up to 50 MW is estimated to 0.1681 €/kWh [K3].

**CRS – Atmospheric air**

![Flow diagram of the atmospheric air central receiver system. Source: [K3]](image)

The CRS-atmospheric air principle is to some extent similar to the molten salt principle. Air is heated in the receiver and a steam generator transfers the heat to a Rankine cycle. The storage works differently. Since atmospheric air has a very low heat capacity by volume, a porous ceramic material takes up the heat when the hot air is send through the storage. When the receiver cannot produce enough heat, cold air is send through the storage to recover the heat stored and then further to the steam generator.

The capacity of the storage is limited to 3-6 hours, which is small compared to the molten salt principle (15 hours).

A plant called CESA-1 (generating steam only) was built in 1991 in Spain, demonstrated steam production at 700°C with a startup time of only 20 min [K3].

Advantage: Very simple system compared to molten salt CRS.

Disadvantage: Limited storage.

The levelized costs of electricity produced by a 50 MW<sub>e</sub> plant is estimated to 0.1787 €/kWh
This central receiver system applies a gas turbine (and a Rankine cycle) to convert heat to mechanical work/electricity, see Figure 10. The atmospheric air is compressed by a compressor driven by a gas turbine. The air is heated in four steps: from 25 to 420 C by the compression, to 600 C in one type of receiver and to 800 C by another type. In order to operate the gas turbine, the air must be 1020 C. The last step of heating is provided by combustion chamber [K3].

The advantage of this configuration is high thermal efficiency of the combined cycle, which gives higher electricity production and reduced need for cooling. In future systems it should be possible to operate the plant by solar energy only. A prototype has reached almost 1000 C before the combustion chamber [K7]. A high temperature thermal storage will also be implemented in the future [K3].

The levelized cost of electricity produced by a hybrid configuration (solar + natural gas) is estimated to 0.0819 €/kWh - for solar only it is 0.1385 €/kWh.
Parabolic trough (PT)

Figure 11: A 30 MW parabolic trough power plant. Source: [15].

The linear parabolic trough collector has a single axis tracing system. The sun is normally tracked from east to west. The incoming solar radiation is reflected by the collector to a pipe filled with a heat transfer fluid. There are two types:

- Thermal Oil
- Water/steam (DSG, direct steam generation)

Figure 12: Schematic of parabolic trough. Source [4]
The thermal synthetic oil (red lines) is heated to about 400°C in the parabolic trough collectors – marked with yellow in Figure 13. The heat is transferred to a Rankine cycle (blue lines) by a steam generator (red boxes). Excess heat is stored in a two tank molten system (green). The heat can be recovered when the solar irradiance is insufficient to run the Rankine cycle alone [K3].

The first commercial plant of this type, a 13.8 MWₑ Solar Electric Generating System (SEGS-1), was built in the Mojave Desert, California in 1985. In the period 1986-1991 eight more have been built (SEGS-2 to SEGS-9) in the same area with a total capacity of 354 MWₑ. These are still in operation, despite the fact that the company was bankrupted in 1991 – each plant is owned by separate investors [K3].

The first European commercial plant AndaSol is located in Spain. It has been in operation since November 2008 and has a capacity of 50 MWₑ [K9]. Two more sections are under construction [K8].

The overall solar to electricity efficiency is 10.6% on average of the nine SEGS power plants. It is expected to be increase to 14.0% in the near future [K3].

Based on the nine plants in the Mojave Desert (SEGS) and the expected efficiency, the levelized electricity cost have been estimated to 0.1720 €/kWh [K3].

The disadvantage of the technology is the synthetic oil, which has a maximum temperature of 400°C, is expensive and makes a risk of fire. In addition it is harmful to environment.
Parabolic trough with the Direct Steam Generation (DSG) is much simpler than the system with oil. Because steam is produced directly in the collector, it is not necessary to apply a heat exchanger (steam generator) which is fairly expensive. Also the solar to electricity efficiency will be increase because it is possible to go to higher temperatures (no longer limited by the max temperature of the oil). In addition, the losses in the heat exchanger are avoided [K3].

The challenge of DSG is to control the flow of water/steam in the absorption pipes of the collector, because an uneven distribution of fluid will result in thermal stress of the pipe material. It has been tested that this is possible to do by recirculation of the fluid. A pre-commercial plant of 5 MW_e called INDITEP has been tested. This plant was not optimized with respect to thermal efficiency, which would be the case for a real commercial plant [K3].

A disadvantage is that there is not technically feasible way to store the heat.

The levelized electricity cost (operated by solar only) is estimated to 0.1870 €/kWh.
Linear Fresnel

The linear Fresnel technology is similar to the parabolic trough direct steam generation. The difference is the collector system. Several flat very long mirrors tracks independently the sun in order to reflect sunlight onto a boiler tube placed above. This type of collector is cheaper to produce than a parabolic trough [K3].

A 5 MWₚ pilot plant built by Ausra started power production in October 2008 [K10].

The disadvantage of the linear Fresnel technology is that only some of the reflected light hits the boiler pipe – this decreases the efficiency.

The levelized electricity cost is estimated to 0.1620 €/kWh. This is not based on a real plant but a model [K3].
Parabolic dish (PD)

The parabolic dish collector is inspired by a traditional parabolic antenna – either a single dish or a collection of dishes, see Figure 16. The solar radiation is reflected by the dish(es) and concentrated to an absorber placed in front of the dish(es). The heat from the absorber is sent either to a Stirling engine or a gas turbine, see Figure 17.

Figure 16: Parabolic dish with Stirling engine. Source: [K12]

Figure 17: Parabolic dish combined with Stirling engine (left) and gas turbine (right). Source: [3]
The size of the Stirling Engine is in the range of 10-25 kW and the corresponding dish has a size of 40-120 m². Several systems have been tested for many hours and demonstrated reliable operation. Even though, lack of a Stirling engine industry (there is only one in the world with a small series production) and the price of the dishes are the main reasons why this technology is not yet commercialized [3]. The capacity of this technology makes it more feasible for distributed purposes rather than central generation [4].

Another possibility is to apply a recuperated (recover waste heat) gas turbine. Dishes of up to 400 m² have been produced which fit well to a gas turbine. Small gas turbines in the range of 30-100 kW are reliable and already commercialized. The gas turbines are equipped with a combustion chamber which makes it possible for hybrid operation (gas and solar) [K3].

As hybrid the levelized electricity cost is 0.2811 €/kWh while the solar-only is 0.3835 €/kWh [3].

**Overview of CSP-technologies**

The maturity of the technologies differs a lot, but the estimated levelized electricity cost is in the range of 0.14 to 0.19 €/kWh, except the parabolic dish, see Table 1. The electricity cost of the parabolic dish could be reduced significantly if the Stirling engines are mass produced [K3].

<table>
<thead>
<tr>
<th>CRS Molten salt</th>
<th>CRS Saturated steam</th>
<th>CRS ATM. air</th>
<th>CRS Press. Air</th>
<th>PT Oil</th>
<th>PT Water/steam</th>
<th>Linear Fresnel</th>
<th>Parabolic dish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levelized costs (€/kWh) [K3]</td>
<td>0.1545</td>
<td>0.1681</td>
<td>0.1787</td>
<td>0.1385 (0.0819)</td>
<td>0.1720</td>
<td>0.1870</td>
<td>0.1620</td>
</tr>
<tr>
<td>Solar capacity (%) [K3]</td>
<td>33</td>
<td>26</td>
<td>33</td>
<td>11 (55)</td>
<td>29</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Annual solar net efficiency (%) [K3]</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
<td>14.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual solar net efficiency (%) [K4]</td>
<td>8–10 (d) 15–25(p)</td>
<td>8–10 (d) 15–25(p)</td>
<td>8–10 (d) 15–25(p)</td>
<td>8–10 (d) 15–25(p)</td>
<td>10–15 (d) 17-18 (p)</td>
<td>10-15 (d) 17-18 (p)</td>
<td>9-11 (p)</td>
</tr>
</tbody>
</table>

*Table 1: Comparison of Central Receiver System (CRS), Parabolic Trough (PT), Linear Fresnel and Parabolic dish. All levelized electricity costs are for solar only production – hybrid production (natural gas + solar) is given in parentheses. The solar capacity is valid for southern Spain. For the annually solar net efficiency: (d) = demonstrated, (p) = projected.*
The annual net efficiency (solar irradiance to net electricity) is not estimated for all the technologies in [K3]. Numbers from the MED-CSP report [K4] have also been taken into account, see Table 1. From these numbers it is estimated that an annual efficiency of 15% is reasonable.

None of the eight technologies investigated in the ECOSTAR report should have higher priority in terms of research and development. They all have the potential to be competitive to the fossil electricity in the future, and it should be left to the market power to make this decision [K3].
Transmission [MSN]
The electrical grid in Europe is right now divided into five power systems. The major one in Europe is UCTE and in Scandinavia it’s NORDEL. Denmark is actually divided in two when you looking at the power systems. The western part with Jutland and Fyn is a fraction UCTE and Zealand is a fraction of NORDEL. 

![Image of Europe's power systems](image)

*Figure 18: the different power systems in Europe. Source [MO1]*

The five power systems have a lot of transmission lines connecting the different countries see Figure 18. Within each power system all the countries are connected via AC (alternating current) transmission lines. Europe has a dense high power electrical network. The voltage in the transmission system ranges from 0.23kV up to 750kV with multiple steps in between. Then you talk about the high voltage transmission systems which are controlled by the TSO (Transmission System Operator) of each country the voltage will be between 110kV up to 750kV. It is not possible to connect to power systems with an AC transmission line if they are not synchronized. E.g. in Denmark it is not possible to connect the western and eastern part. The AC electricity is a sinusoid wave. It is shown in Figure 19.
This is the power distributed in the transmission lines. The signal there is in Figure 19 could for example be from UCTE and the signal from NORDEL is then a phase shifted compared to the electricity from UCTE. This is the reason that you can’t connect the power systems with AC power. To connect two systems that are not synchronous you have to use DC (Direct Current). This leads to Desertec vision on the future transmission system in EUMENA (Europe, Middle East, Northern Africa). In Figure 19 you can see a DC signal.

**Desertec’s Vision**

Desertec has the vision that Europe, Northern Africa and Middle East should be connected with HVDC (High Voltage Direct Current) transmission lines. They compare it with the road system. They see the HVDC lines as the Interstate or Highway, where you can get around quick but there are not a lot of exits or access points. And as it is right now we don’t have the highways in the transmission system. We have HVAC lines but they are not capable of crossing different power systems and their loss is bigger over long distances as will be shown later in this report.
On the map above you see that these HVDC lines cross a lot of countries and different power systems. With this system it is possible to produce renewable energy where it is best suited for it. It could for example be wind power in Denmark and solar power in Africa. This system spans over many time zones so as the sun goes up in the Middle East they will be able to send power to the rest of the system although the sun hasn’t risen yet. So this system would be very flexible and make the security of supply much better. With this system it would be possible to implement a lot more renewable power. An example could be wind power. The possibility for no wind in this huge region is very small. And with solar power there is not a lot of possibility that hole the region of EUMENA should be cloudy.

**AC vs. DC**

Some of the advantages of using DC compared to AC in big electrical distribution systems are already mentioned, for instance the way to connect different power systems. There are a lot of other advantages with using HVDC over long distances. HVDC gives lower losses then HVAC [MO1] when using overhead lines. The loss is 8%/1000km for AC voltage 750kV compared to 2.5%/1000km for DC voltage 800kV. When looking on sea cable the different in loss is significant. For AC voltage 750kV the loss is 60%/100km and for DC voltage 800kV it is 0.25%/100km. The loss in the terminals¹ there have to be in each end or in the middle or the transmission line is also to be considered. The loss for a 750kV AC terminal is 0.2%/station and for DC 800kV it is

¹ This could for example be transformer stations and converter stations when talking about HVDC.
You have to make a long transmission line before it’s worth it. The lower loss in DC compared to AC, and that it is possible to connect multiple power systems together is the main reason why using HVDC to this project. There are also some economic advantages with DC but it will be shown later in this report.

HVDC technology

HVDC is not a new technology. The first commercialization goes back to 1954 where Mercury Arc Valve constructed a line between Sweden and the island Gotland [MO5]. The technology has of course developed since then. The big producers of HVDC\(^2\) are able to transmit more and more power through the lines. Right now ABB is able to transmit 6400MW at a voltage of \(+800\text{kV}\) through one transmission line.

In Figure 21 the concept of HVDC transmission is sketched. AC is converted to DC by a converter station and then the electricity is transmitted to where it is needed. Then it is converted back to AC through another converter station.

\(2\) For example Siemens and ABB
The expensive part with HVDC, which isn’t necessary for HVAC, is the converter station. A converter station consists of lots of components which detailed description is beyond the content in this report. On Figure 22 is a picture of a converter station to give an overview of its content. You can see that the input and output of the station is AC and DC.

![Converter Station Diagram](image)

Figure 22: This picture shows a HVDC converter station. This station represents the two blue triangles on figure 4. Source: [MO7].
Figure 23 shows how much space you have to use to transfer 10 GW of electricity when you build HVAC compared to HVDC. This shows that to transmit the same amount of electricity you can use much less space with HVDC. This is important because it is very difficult to get permission to build transmission lines. It also takes a lot of time to get the permission to build them. The fact that HVDC is more compact also has the effect that the impact on the environment is smaller.

![Diagram showing space required for transfer 10GW of electricity](image)

Figure 23: Shows the space required for transfer 10GW of electricity when using HVAC compared to HVDC. Source: [MO4].

**Existing HVDC lines**
There is a numerous number of HVDC transmission lines all over the world. On the figure under here the current HVDC lines is shown:
A lot of these HVDC lines connect power systems which are not synchronous with each other. An example could be the line between Denmark and Germany or the line between UK and France, see Figure 24. There are also lines that connect a big hydropower plant with its consumers. An example of that could be Pacific HVDC Intertie [MO9] which connects a big hydropower plant in Oregon with Los Angeles area. The line is 1360km long with a capacity of 3100MW. In Denmark they also get a lot of cheap hydropower from Norway and Sweden. So Denmark is connected with Norway and Sweden with multiple HVDC connections.

Cost of HVDC transmission lines
The cost of transmission lines is impossible to give a direct answer to. It depends on a lot of parameters. It is for example much more expensive to build 100km transmission line in an area with a dense population concentration compared to a remote area without people. There is also a different cost in building transmission lines in mountains or in flat areas. The price to building 1000km of transmission lines differ from project to project, taking that into account. In Table 2 under here is an estimation of cost on HVDC transmission lines from a report concerning the Desertec’s vision.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>HVAC</th>
<th>HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Voltage</td>
<td>kV</td>
<td>750</td>
<td>+600</td>
</tr>
<tr>
<td>Overhead line cost</td>
<td>M€/1000 km</td>
<td>400-750</td>
<td>1000</td>
</tr>
<tr>
<td>Sea cable cost</td>
<td>M€/1000 km</td>
<td>3200</td>
<td>400-450</td>
</tr>
<tr>
<td>Terminal cost</td>
<td>M€/station</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 2: Estimation of cost of HVDC.

If you are building short transmission lines the cheapest solution is AC lines. The AC overhead lines or AC cables are actually more expensive then DC overhead lines and cables but with HVDC you have to build expensive converter stations in each end of the transmission line. If you are building inside a power system it can be cost effective to invest in HVDC compared to HVAC. If the line has a certain length it is cheaper to build HVDC than HVAC. The figure below shows that:
With HVDC you have a higher start price but the cost per kilometer is cheaper so the two lines intersects at some length of the transmission where it begins to be cheaper to build HVDC than HVAC. Example where only overhead line is used to find the transmission line length, where the cost of HVDC and HVAC is the same:

**AC Overhead line (750kV) + 2 terminal stations:**

$$\text{costHVAC} = \frac{575 \text{M€}}{1000 \text{km}} \cdot x + 2 \cdot \text{station} \cdot \frac{80 \text{M€}}{\text{staion}}$$

**DC Overhead line (800kV) + 2 terminal stations:**

$$\text{costHVDC} = \frac{275 \text{ M€}}{1000 \text{km}} \cdot x + 2 \cdot \text{station} \cdot \frac{300 \text{ M€}}{\text{staion}}$$

where \( x \) is the length of the transmission line and it is assumed to apply two terminals only - one in each end of the transmission line. If you equal the two equations you can find the length.

$$\frac{575 \text{M€}}{1000 \text{km}} \cdot x + 2 \cdot \text{station} \cdot \frac{80 \text{M€}}{\text{staion}} = \frac{275 \text{ M€}}{1000 \text{km}} \cdot x + 2 \cdot \text{station} \cdot \frac{300 \text{ M€}}{\text{staion}}$$

\( x = 1467 \text{ km} \)

This example shows that the transmission line has to be reasonably long before HVDC is cheaper than HVAC. The example is of course very simplified because the loss in the lines is not included in the calculation and the cost for the transmissions lines and terminals are only estimates but it gives a good idea about the considerations you have to make before you build a transmission line. 1467km is probably a bit high because the losses in the transmission lines are lower with HVDC.

In the report Trans-Mediterranean Interconnection for Concentrating Solar Power [MO4] they have made an estimation of the cost of the transmission lines in the Desertec project. They estimate the cost 20*5GW HVDC transmission lines to be 45 billion € in 2050. They will start building 2 out of those 20 transmission lines in 2020 at the cost of 5 billion €.
You can compare this with the new gas pipeline they have agreed to construct. Its name is Nabucco and it is 3300km long pipeline. Its cost is estimated to be around 7.9 billion € [MO10].

**HVDC network potential and prospects**

In this chapter on transmission it is obvious that HVDC has a bright future. In the future more renewable energy will be integrated into the power grid. To do so we need a more flexible power grid where it’s possible to transmit power over long distances at low losses. With a HVDC power grid implemented the electrical power market would be more similar to that of other products. It would be possible to build the renewable power where it is most effective. For example it is foolish to put up solar panels in Germany when these solar panels would have been much more effective in Spain or in Africa. With a huge area and smart HVDC transmission it is possible to make even wind energy a stable renewable energy source.

We think that the prospects for HVDC are good. The HVDC network Desertec is talking about has definitely long prospects but it has the potential to solve our future energy demand in a very clever way. In the long term it has the potential to supply all of EUMENA with renewable energy.
Energy consumptions [DRN]

To see how much area that should be used for solar capture, it is necessary to analyze the demand of electric power in Europe. Furthermore it would be considerable that regular coal and oil power plants in Northern Africa also should be replaced with solar systems, maybe even before the power grid connection between Africa and Europe is installed.

Figure 26 shows the total electricity demand in Europe the last 15 years and from what energy sources the demand is satisfied with and how the forecast for the power consumption and distribution looks like within the next 20-25 years. It should be mentioned, that the model was made in 2005 [D2].

The model does not contain exactly these data. The amount of electricity produced from thermal energy sources do only appear as one number, what means that sources like solids (coal with more), oil, gas, biomass, waste and geothermal are all calculated as one value.

The magnitude of each source input used for electricity production in Europe all appears in the report/spreadsheet. In that context we have assumed, that all electricity production from all thermal sources has the same efficiency, and therefore the biomass/waste for electricity production constitutes the same percentage of the thermal production as the input for thermal production.

![Figure 26: Power demand in Europe. Source: [D2].](image)

The power coming from nuclear and thermal (others) are to be replaced with solar systems. In 2010 this number is 2,900 TWh/year and in 2030 the forecasts tells us that power of 3,300 TWh/year comes from non-renewables in Europe.
As mentioned it has been considered to use some of the generated electricity in Northern Africa before exporting the electricity to Europe. In our analysis this contains countries like Morocco, Algeria, Tunisia and Libya with a total electricity consumption of 75 TWh in 2005 [D1]. Figure 27 shows the electricity consumption for some countries in Middle East, South Europe and Northern Africa and a forecast for the next 40 years development. As seen in the figure the mentioned countries in Northern Africa increases the consumption 5-10 times within the next 20-25 years.

Figure 27: Future electricity demand. Source: [D3].
**Irradiance/resources**

"Within 6 hours the world desserts receives more energy than the whole world consumes in a year. That is what motivates us to build solar systems in the Sahara and transport electricity to Europe. “

![Figure 28: Solar irradiance. Source: [D3].](image)

Figure 28 shows the intensity of the irradiance in Northern Africa, Middle East and South Europe. As seen the radiation from the sun is around 2.5 MWh/m²/year.

Assuming that 85% of the energy from the irradiance is loss, such as reflection, heat loss in the thermal systems, losses in turbines or other kind of conversion from heat to mechanical energy, generator loss when producing the electricity and loss at AC-DC-, DC-AC-converting, transporting and distribution. Just 15% of the total solar energy radiation is distributed as electricity to the customer in Europe.

Within the next 20-25 years the European and North African electricity demand will be in an order of around 4000 TWh/year corresponding to an average of 450 GW electricity productions. That means that an area in order of 11,000 km² (D4) of is needed in the dessert to produce the electricity demand in Europe and Northern Africa. Assuming the plants are in the order of 500 MW an amount of 900 power plants is needed.

As it appears from Figure 28, it is no problem to find the radiation energy to fill out the electricity demand. The next step is to find enough usable space in the desert, which is not already being used for habitation, agriculture, industry and other applications or is unusable because of landscape and geography. Another issue will be to have access to water for cooling. If the plants are located without access to water cooling, the efficiencies of the plants will decrease, and more area and plants will be needed.

Figure 29 shows the usage of land in Northern Africa. Considering the space for putting up solar systems may not be a problem in its self. Another important perspective is the political issues in order to use big areas of
land for electricity production. Depending on the instability in the respective countries, this issue could prevent a startup of the project. This issue is out of scope of this report.

![Figure 29: Land usage. The red square corresponds to the area needed to meet electricity demand of Europe. Source: [D3]](image)

**Molten salt storage**

As long as the sun only shines during the day, and the electricity demand also exists at night, some of the energy needs to be stored. Usually the electricity demand varies a lot during the day and becomes lower during the night.

Already existing concentrated solar plants uses the molten salt storage, which is a good way to store thermal energy. One of them is Andasol solar power station in Granada, Spain, completed in November 2008. The plant has a size of 50 MW, the molten salt storage has a tank volume of 14,000 m³ (corresponding to a cylinder tank of 30 meter diameter and 20 meter height) and contains 28,500 tons of salt, enough to store energy for 7.7 hours electricity production at full load.

Assuming that storage for 7.7 hours is enough for the whole night (not at full load), the needed capacity of storage for the total electricity production in Europe and Northern Africa will be 126,000 m³ for each 500 MW power plant.
Part conclusion [MSN]

Eight concentrated solar power technologies are described. Seven of them with a cost rate of 0.14-0.19€/kWh, but reductions in costs are expected in the future.

To transport the electricity from Africa to Europe a high voltage direct current transmission line is needed. The lines and the converter stations require a very big startup investment, but it has very low losses and makes it easy to implement renewable energy sources to the grid.

900 power plants each producing 500MW electricity and receive sunlight in a total area of 11,000km², will be enough to produce the estimated electricity demand in Europe and Northern Africa in 2030 of 4000TWh/year.
Economic considerations [AH]

The technical analysis has shown that several Concentrated Solar Power technologies exist and are viable for large scale implementation, as envisioned in the Desertec Project. These paragraphs will assess the economic and financial aspects of implementation. First, how much initial financial capital is needed to kick-start the project in the relevant scale and what is the estimated price per kWh? Second, what technology advances can be expected in the future and how will they affect production costs. The cost analysis gives an indication on the technology’s competitive nature in both the near and long term.

Capital Analysis

Initiating a massive Concentrated Solar Power project in the Sahara Desert would require an equally massive amount of financial capital. Interested parties have to purchase equipment, land, hire labor, and most importantly, secure transmission lines. The Desertec project, which is looking at solar power in the Sahara to meet 15% of the EU’s total consumption, costs over an estimated 400 billion € [A1]. Transmission lines from the Sahara to Europe alone cost an estimated 45 billion € [A2]. The capital required to begin construction of a single Concentrated Solar Thermal plant is noticeably higher than that of other alternative energy solutions (only the Photovoltaic Solar Cell is more expensive). Despite the very high cost of founding a CSP plant, the benefits of this technology are many. It is one of the few alternative energy sources to offer energy storage. Even though the plant is placed far away from the consumer, connection to transmission lines requires the same equipment as conventional power plants. The Concentrated Solar Power designs are the most efficient of solar energies [A3].

Power fields with generating capacity from 25-200 MW are the goal of the Desertec project. A 2003 Central Receiver System project in Australia for 200 MW [A4] was estimated to cost 585 million Euros (“one billion Australian Dollars”) [A4]. More recently, prices for CRS projects have been quoted at 566 million Euros (AUS800 million) [A5].

The AndaSol Solar Trough fields, generating 50 MW power in Granada, Spain, and with energy storage capabilities of up to three hours, cost around 300 million Euros [A6]. The general equipment costs alone were around 150 million Euros [A7]. Getting a CSP plant off of the ground takes considerably more money per kilowatt hour than conventional power.

The Moss Landing Power Plant burns Natural Gas. When Duke Energy acquired the plant, they spent 370 million Euros [A8] (US$525 million) to upgrade the plant from 1,500 to 2,560 MW. The cost of this upgrade was nearly a third cheaper for twice the amount of power than that of a Concentrated Solar Power plant.

The previously estimated levelized economic cost (LEC) for the CSP technology at 15 € Cent per kWh (2005-prices) makes CRS the second most expensive alternative energy source [A9], trumped only by Crystalline Solar Photovoltaic.
Further, estimated LEC’s for traditional energy sources are shown in Table 3:

<table>
<thead>
<tr>
<th>Energy sources</th>
<th>LEC benchmark (2008-prices)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>5.1 – 9.2 Euro Cent per kWh</td>
</tr>
<tr>
<td>Gas</td>
<td>5.0 – 6.8 Euro Cent per kWh</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6.7 – 8.6 Euro Cent per kWh</td>
</tr>
</tbody>
</table>

Table 3: LEC estimates for traditional energy sources. Source: [A11].

As shown, concentrated Solar Thermal technologies are simply not competitive with conventional energy sources at this time.

**Future Technologies**

The ECOSTAR Report has numerous projections on how to lower the cost of Concentrated Solar Thermal in the near future. Focused Research and Development will drastically lower equipment and assembly costs. Investing in concentrator technology for Parabolic Trough Systems could drop the LEC up to 11%. A storage system for the trough could drop the LEC another 6%. Increase in Helioestat size and structure can drop prices by 11%. Most impressive, scaling up existing trough plants to 50 MW systems (most are ~15MW) would drop the LEC 14%. The report lists multiple other ways for CSP technology to lower its costs.

Computing the cost of CSP technology using the LEC parameters given in the Ecostar report allows for up to a 65% LEC drop with significant technologic advancement in the next 10 years. This means 40-65 € per MWh or 4-6.5 € cents per kWh. Ecostar believes this technologic progress can become operational within the next 15 years. The initial capital to build a 200 MW station would only be around 350 million Euros.

**The cost of transmission**

Distances from North Africa to Regional Transfer Operator’s in Europe span thousands of kilometers. As discussed in previous sections, transmission lines are exceptionally expensive. As stated previously, the choice between AC or DC lines depends on the final distance; AC lines are cheaper for lines short than 1470 km and DC for longer lines. If we assume a CSP plant in Northern Algeria, AC is the best option for Spain and Southern France. The rest of Europe is farther from the CSP Plant than is economical for an AC line. Thus, a DC line is in fact the best option for Europe.

The cost of transmission has been estimated to approximated 0.007€/kWh. In this estimation is assumed; 50 years lifetime on the transmission lines, 2*5GW transmission lines at a cost of 5 billion €, full load at all time on the transmission line, 10% loss in the lines and converter stations, constant price on electricity: 0.05€/kWh. 0.007€/kWh includes the loss in the transmission line and the investment in the transmission lines. The investment cost spread out on the kWh cost 0.0011€/kWh, see appendix “A.1: Estimation of transmission costs” on page 52.
Part conclusion
The economic analysis has shown that major initial capital investment is needed to start-up up a large-scale solar-energy project in Sahara. Yet, private investors are discouraged due to the high cost of producing energy through CSP technology, which at this time is too expensive compared with conventional energy resources and other alternative energy sources. The lack of competitiveness is expected to diminish over time as technology advances, making solar-energy in Sahara profitable. Some kind of financial push in the near time could speed up the process of technology development and help define incentives for future financiers.
The potential of political regulation [MBN]

The large amount of financial capital needed to implement a massive CSP project in the Sahara desert at a sufficient scale to meet EU goals, and the inability for the pricing of said technology to compete commercially requires political intervention. As long as the economic side of the project is only profitable in the long term, it is unreasonable to expect that private investment will function as the sole initiator of this process. Taking into account additional technical uncertainties the expectation becomes even more doubtful.

The Desertec Foundation is not oblivious to these problems. Political commitment to make an environment favorable to investment in the near term is often mentioned as a head premise to get the project started. The political effort needed to initiate Desertec is being compared to the Apollo Program of the 1960s. However, more concrete suggestions of political initiatives are also put forward, some of which will be discussed in the following [M2; M3].

The main political actor – the European Union (EU)

The primary purpose of the Desertec-project is to serve the European continent with clean and renewable energy. In this light, the EU will be the main political actor. The competence of the EU varies according to the policy area. In some policy areas, the legislative abilities still lie with national authorities, implying that the EU’s regulatory power is limited to standard setting and coordination [M1]. In other fields, such as energy and climate change, EU has been given binding legislative competences, so that the individual member states must act according to the given policy framework.

Of course, EU’s energy and climate change policies consist of and intertwines with several particular policy fields, for example transport or agriculture, which are all subject to different levels of individual regulation. However, to limit the complexity of the analysis, focus here will be restricted to the common, strategic action plan regarding energy and climate change, adopted on EU-level.

EU’s energy and climate change objectives – why would EU get involved?

The European Union has been developing its integrated climate change and energy policy over several years. In 2002, EU collectively (and all member states individually) ratified the Kyoto Protocol, which implied a commitment to reduce the GHG emissions by 8% compared to 1990 levels during the first commitment period between 2008 and 2012. Since then, EU has made significant efforts to adopt and implement different policy schemes in order to be able to meet this commitment. Most importantly, EU has introduced an internal emission-trading scheme (EU-ETS), which will be further discussed below. In general, EU is well on its way to fulfill its Kyoto obligation [M4].

The second major turning point as regards EU’s climate change and energy policy took place in December 2007 with the adoption of a comprehensive common framework of middle and long term objectives and commitments. The so-called “Energy and Climate Change Package (ECCP)” sets out precise, juridical binding
goals for future GHG emissions, the share of renewable energy sources and energy efficiency, see Table 4: Main long term targets as set out in the ECCP. Source: [M5; M6]. Table 4.

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GHG emissions</strong></td>
<td>An independent reduction of at least 20% compared to 1990-levels.</td>
<td>EU shall work for an international agreement which prescribes a 50% global reduction in compared to 1990 levels. For the industrialized countries this entails a reduction of 60-80% compared to 1990-levels.</td>
</tr>
<tr>
<td></td>
<td>However, a reduction of 30% compared to 1990-levels if an international agreement is reached, which implies that other developed countries commit them self to similar reduction targets.</td>
<td></td>
</tr>
<tr>
<td><strong>Share of renewable energy</strong></td>
<td>At least 20% of EU’s energy consumption</td>
<td>No target, but the ambition is that by 2050 the transition to low-carbon technology will be executed with a mix of energy sources that rely on a great share of renewable energy sources</td>
</tr>
</tbody>
</table>

Table 4: Main long term targets as set out in the ECCP. Source: [M5; M6].

Both the 2020 and 2050 emission reduction target is directly extracted from the scientific recommendation of the IPCC, which states that a global temperature increase of more than 2 degrees Celsius would be detrimental and should be avoided by the above mentioned CO2-reductions [M5].

From an international perspective, the adoption of the ECCP has put EU in a leadership position. EU is acting as a progressive policy driver within the negotiations of a post-Kyoto climate change regime [M5; M6]. At the same time, the rationale behind the ambitious EU-goals has been politically framed in a macro-perspective indicating that the transition to a low-carbon- and low- energy-society is in the interest off the EU’s long term economic performance and thereby also in the overall interest of all EU-citizens (i.e. maximizing the net gain to society) [M9; M11; M8]. In other words, sustainability, security of supply and independence from unstable oil and gas suppliers have been effectively presented as conditions for EU’s future, competitiveness, growth and employment (which also are the goals in the Lisbon-strategy). Judging from EU’s own strategic analyses, the political conviction is rather strong [M5; M6].

**Creating an favorable investment environment for solar energy – the switch point theory**

EU already adopted early targets for their share of renewable energy sources. In fact, related to the creation of the Kyoto Protocol in 1997, the EU set a target of 12% of total consumption by 2010. However, it is now evident that this target will not be met. The Commission views it unlikely that renewable energy sources will be providing more than 10% of the total EU energy consumption in 2010 [M5].
In its proposal for the ECCP, the Commission concludes in similar lines as the economic analysis above that the lack of progress in this field is partly due to the fact that:

- Renewable energy sources are still relatively too expensive and that there is a lack of an overall political framework to insure stability for investors [M5].

Taking into account the ambitious objectives of the EU and the overall potential of using solar energy from the Sahara, the question then is: What can the EU do to speed up the energy transition process, moving away from the traditional carbon-intensive fossil fuels towards using relevant renewable energy sources, in this case concentrated solar energy from Sahara? Or in other words, how can EU increase the competitiveness of solar energy from the Sahara and thereby establish one important condition for securing investment?

To answer these questions it is fruitful to analyze the marked situation by applying the so called switch point theory. The purpose is to show how a market-based incentive approach, which is already favored by the EU, could be the regulatory solution to promoting the wished for investments already in the near-term.

The switch point theory takes its starting point in the expectation that the shift from fossil fuels to renewable energy will take place eventually, because the marginal cost of producing fossil fuels will rise over time and at some point exceed the marginal cost of the given renewable energy. The assumption of a rising marginal cost curve for fossil fuels is based on the fact that resources are limited and will eventually be exhausted. At the same time, the marginal costs of various renewable energy sources can be assumed to at least stay constant and most probably fall over time due to technology advances and scale economics [M9; M5].

![Figure 30: The switch point theory Source: [M9]](image-url)
However, when exactly the shift takes place is unknown and may not, as in the case of solar energy, be within the time frame wished for. Therefore, political regulation could be used to speed up the process, for example by adding or subtracting negative and positive externality cost to the marginal cost of either energy resource.

Figure 30 illustrates the shifts from coal to solar energy both without and with political regulation. In this example the marginal cost of solar energy is assumed to be constant making it the upper limit of the energy price \( p^* \). Without political regulation, the shift from coal to solar energy takes place at \( t^* \) when the \( m_{\text{coal}} \) exceeds \( m_{\text{solar}} \).

With political regulation, in this case a tax/permit price on a unit of carbon emission and a subsidy on solar energy, the shift takes place faster at \( t_s \), since the marginal curves of the two energy alternatives has been moved up and down respectively.

As stated, the EU has traditionally been in favor of using economic mechanisms to internalize external costs, so that the market reacts in the most cost-effective way [M5]. The internal emission-trading scheme is the prime example in this regard. Through this system, it has been possible to put a price on emission of GHG in the EU. The system is also cost-effective in the sense that it insures that abatements take place where it is cheapest (firms with low abatement costs sell their permits to firms with high abatement cost) [M11].

The EU-ETS was first implemented in 2005 and has run a trial period through 2007. One of the main elements in the Commissions strategic proposal for meeting climate change objectives is to optimize the workings of the system. It has been a problem that too many initial emission permits was given, making the price of permits too low [M6]. Heavy lobbying can serve as an explanation for this error [M10]. In the future, when the amount of permits is set to decrease, the permit price is expected to increase significantly [M6]. This should increase the overall effectiveness of the system and hence the incentive structure.

The other option, i.e. creating some kind of common subsidy framework on specific renewable energy sources has not yet been explored on the EU-level. So far, the EU's strategic renewable energy policy is built on a common share target but implemented through obligatory national action plans on renewable energy development, which are to take into account local potential and conditions. However, the national governments have been given the authority to support the renewable energy sector through a wide range of remedies, including subsidization [M6].

The most common form of subsidy in the member states have been feed-in tariff systems. A feed-in tariff implies that a legal obligation is placed on the regional or national electricity utilities to purchase electricity from renewable energy installations. The tariff rate is guaranteed, and in the best examples, for a long period - say 20 years. The tariff rate is scientifically determined for each technology, to ensure profitable operation of the installation [M7]. When the given renewable energy source has reached the envisioned marked penetration, the tariff is often phased out.
Feed-in tariff regulation has resulted in impressive results in Spain, Denmark and Germany. The share of the relevant renewable energy technology has rapidly increased after introduction of the system [M7]. The German case is especially interesting, since it has been possible to increase the use of solar energy significantly despite the fact that the potential of solar energy is quite low.

Returning to the case of EU-level regulation, one basic option in this case would be to introduce a common feed-in tariff system directly upon solar energy from Sahara. Implementation could still take place on national level.

Of course many other subsidy systems could be imagined.

**Part conclusion**

The political analysis has shown that the EU certainly has the commitment to combat climate change and to create a future low-carbon and energy society. Expanding the share of renewable energy sources is one very important approach to reach these goals. So far, the existing policies regarding renewable energy have not been as successful as hoped, so for the EU to actually fulfill its 2020 renewable energy target, new thinking and strategies might be needed. As shown, the solar energy project in the Sahara can be promoted through a more aggressive regulatory system, including both a carbon-trading and subsidization.
Other considerations [MBN; AH; KFM]

So far the analyses have been focused on the technical feasibility and political-economic issues involved in implementing a solar energy project in the Sahara. However, many other considerations should ideally be taken into account, when discussing such a large scale and cross-country and even cross-continent project. In the following, a few of the most pertinent implications are discussed in short.

Energy production outside EU [MBN]

An important part of the European Union’s long-term, strategic energy plan is establishing independence from energy imports and security of energy supply. Europe is becoming more dependent on foreign carbon-hybrids; projections put imports reaching 65 % of total energy supply in 2030; gas being at 84 % in 2030 and oil reaching 93 % in 2030 [M5; M6].

World energy resources are diminishing as the world demand increases. In this scenario, the EU is completely dependent on fuel producing areas such as Russia and the Middle East, regions which have already complicated relationships with the EU-region. Further, international incidents often result in significant price fluctuations; see Figure 31. Lately, gas conflicts between Russia and the Ukraine have resulted in gas cut-offs in several eastern EU-countries.

One could argue that the solar-energy in Sahara project does not solve the energy dependence problem. Energy would still be produced outside Europe. Further, by importing solar-energy from Northern Africa, EU will need to deal with the fact that several of the involved countries are subject to both internal and external tensions. Further, since transmission lines would have to either cross ocean, or go through multiple country boundaries a certain amount of unpredictability in supply would be inevitable. Maritime issues, such as storms, rogue waves, oil spills etc. would have to be taken into consideration and guarded against. A trans-continental transmission line would give any country it passes through a certain amount of political leverage against the EU.
The Desertec Foundation does not consider this accusation of vulnerability valid. First, solar energy from Sahara would in fact increase the diversity of EU’s energy mix. The foundation foresee that, in the long term, 15 % of Europe’s total energy supply would come from this Sahara project, 65 % from localized renewable energy production and 18 % from traditional energy sources. In this scenario, it will be possible to compensate a loss of 20 % from alternative energy sources. Second, the solar energy would not come from one big power plant, but several hundred smaller ones spread out in different countries and owned by different operators, making the supply less vulnerable to attacks, accidents or cut-offs. Third, it would have political and economic spill-over implications, if one country was to hinder production or transmission. Lack of confidence would trigger less investment etc [M2; M3].

A main challenge will be to create some sort of institutionalized cooperation structure between EU and the MENA country which helps develop a symbiotic relationship between the supply countries and consumer countries. This structure could help interested financiers enter the solar energy project with a minimum of roadblocks. It could stimulate trade between the two regions, basing its actions on the connections already made while developing the project. These and other objectives set by a cooperative structure would create and incentive for all parties to maintain and foster the Solar plants and transmission lines.

**Growth and Development [AH]**

The European Solar Energy in Sahara project could provide a wealth of development opportunities for both European and Northern African nations. Mainly, the structuring and implementation of such a massive project would create thousands of new jobs in both markets.. Initiating this project would be a great way to jump start years of positive economic development.

Europe provides an abundance of educated laborers interested in the success of this project. The current economic stagnation will make it easy to hire college graduates and professionals who are having a hard time finding jobs in already established industries. The workforce of the African countries are also ready to work and struggling to find new jobs. People will need to compile data, write reports, study said reports, and make demonstrations of all this information before any real capital investment has even begun. When the project is operational, and many individual companies are competing with each other to sell their electricity, researchers will be needed to increase efficiency and maintain plant competitiveness.

Laborers in Africa would be essential to construct and maintain the acres solar fields. It takes thirty trained men to operate a CSP plant, and another seven to maintain the fields [K3]. These are not jobs that can be done from remote facilities in Europe. These jobs would be sourced directly from countries where the construction is taking place. Local employees would receive the training for long term operation.

Financial development in all countries associated with a large scale infrastructure effort is assured. When the infrastructure being built is power plants, there is the added benefit of long term security.
**Liberalizing the EU’s energy market [MBN]**

To fully implement the potential of concentrated solar-energy in the Sahara, the EU needs to establish a fully liberalized internal energy market. So far, fair competition and cross-border trade of electricity has been hampered by various national support and regulation schemes, such as price caps on gas and electricity. In its proposal for a new energy policy in 2007 the Commission concludes that the existing liberalization policies and measures have not been successful and hence that further, and more radical measures are needed. It also concludes that the current situation is prohibiting the entry of new, alternative energy providers [M5].

In August 2009, the EU finally adopted its third liberalization package for gas and electricity. Most importantly, it has been decided to establish a proper separation between producers and distributors of electricity and gas. Also, better consumer information and effective regulation and control on EU-level will be effectuated, hopefully increasing transparency and implementation respectively [M5, M12].

In all, the package can be assumed to have a positive impact for the possibilities of new solar-energy producers to enter into the market.

**Environmental impacts [KFM]**

There has been some concern about how large scale CSP will affect the local environment in the Northern Africa. This issues has not been treated in this report, and it is not possible to state weather it is relevant or not.

Also other environmental impacts cours ed by e.g. transmission lines are not discussed either.
Conclusion [All]

The purpose of this report has been to further research and assess the idea promoted by the Desertec Foundation, i.e. using concentrated solar energy from the Sahara Desert to supply the EU-Mena region with clean and renewable energy. To simplify the analysis in this report, it was chosen to look primarily at the potential for supplying European demand.

Eight concentrated solar power technologies have been described, seven of which can be implemented in large-scale as envisioned in the project. It is not possible at this stage to recommend one of the seven technologies, and it is not clear which technology will at some point dominate the CSP-marked. Further technology advances will show.

To transport the electricity from Northern Africa to Europe a high voltage direct current transmission line is needed. On one side, it is clear that establishing the lines and the converter stations require a very large startup investment. On the other side, this type of transmission has very low losses and makes it easy to implement renewable energy sources to the grid.

The analysis has shown that 900 power plants, each producing 500 MW of electricity and receiving sunlight in a total area of 11,000 km², will be enough to produce the estimated electricity demand in Europe and Northern Africa in 2030 of 4000TWh/year.

The conclusion about the technical feasibility and potentials is therefore rather positive.

At this point, however, the economic and financial aspect is a big challenge. Taking into account the large initial capital needed to implement the technology in the relevant scale, and the estimated cost rates of the electricity produced, 0.14-0.19€/kWh, the technology will not be competitive to conventional energy resources in the near term. Expectations are that future technology advances will bring down the cost of CPS significantly. At the same time, oil-, coal, and gas-price increments will make the CPS technology more profitable in the long term. However, to kick-start implementation at this point would probably need financial support of some kind, most likely through political regulation.

The European Union serves as the main actor in this regard. The EU has set very ambitious, collective climate change and energy targets, reducing CO2 emission and expanding the share of renewable energy supply by 2020. To meet these objectives, the EU has introduces several policy instruments, most prominently the internal carbon-trading Schemes. Through even more aggressive policy measures, such as a subsidy-incentive scheme, it would be possible for the EU to create a more favorable investment environment, making the shift to solar-energy happen faster. However, the EU would also have to consider if importing some of its renewable energy from the MENA-region would in fact solve the problem of energy dependence. At least, a stabile, institutionalizes co-operation structure would have to be established between the different stake holders. On the other hand, the project could have significant development benefits in the Sahara Region.

In all, producing solar-energy in Sahara does seem to be the most efficient single method to reach Europe’s and maybe later on, the world’s climate change and energy problem.
References


[A7]: Ecostar Roadmap; see [K3]


[A11]: Average exchange rate $/€ in 2008: 0.68331 (http://www.oanda.com/convert/fxaverage_result)


[D2]: European country data for the STREAM model (KIM you may have the link where you got this, xls-file)

[D4]: Appendix, calculations.xls

[D5]: Doerte Laing, German Aerospace Center, Solar thermal energy storage technologies,


[K1]: Franz Trieb; Technologies for large scale seawater desalination using concentrated solar radiation; http://linkinghub.elsevier.com/retrieve/pii/S0011916408005833; 2009


[K6]: David Biello; Scientific American - Sierra Sun Tower; http://www.scientificamerican.com/article.cfm?id=first-us-power-tower-lights-up-california; 2009

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[K12]: Digtheheat.com; Picture of parabolic dish with Stirling engine; http://www.digtheheat.com/geothermalpics/dish_stirling.jpg; 2009

[K14]: http://www.physics.ubc.ca/outreach/phys420/p420_08/Hiroko%20Nakahara/Pictures/Stirling%20cycle.jpg


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[M6]: European Commission (EUC) (2008): To gange 20 % i 2020 Europas muligheder i forbindelse med klimaændringerne


[M8]: Olsen, Mancur (1965): The logic of collective action, Harvard University Press


[MO1]: http://en.wikipedia.org/wiki/File:ElectricityUCTE.svg
[MO2]: http://upload.wikimedia.org/wikipedia/commons/2/27/Dcigraph.png
[MO5]: http://en.wikipedia.org/wiki/High-voltage_direct_current
[MO9]: http://www.abb.com/cawp/gad0218/c1256d71001e0037c1256b800371e41.aspx
[MO10]: http://en.wikipedia.org/wiki/Nabucco_pipeline
Appendix

A.1: Estimation of transmission costs

Price for transmission without loss

Price for two 2*5GW: 5 billion euro, Lifetime 50 years, expected full load at all time

```
> restart:
> with(Units):
> AllyearsTransmit:=2*5000000000*Unit(W)*50*365*24*Unit(hour)*0.001*k;

AllyearsTransmit := 4.3800000001012 [W] [h] k
> PriceOnInvestmentkWh:=5000000000.0*euro/%;

PriceOnInvestmentkWh := 0.001141552512euro

```

Price for transmission with loss, price on electricity 0.05euro/kWh, assumed constant price over 50 years

expected loss through the transmission line equal to 10%

Price of loss:

```
> ElectricityLoss:=2*5000000000*Unit(W)*50*365*24*Unit(hour)*0.001*k*0.1;

ElectricityLoss := 4.3800000001011 [W] [h] k
> PriceOnLoss:=(0.05*euro/(Unit(W)*Unit(hour)*k))*%;

PriceOnLoss := 2.19000000010euro
```

This is the price on the loss on electricity over 50 years.

```
> AllElectricityTransmitted:=AllyearsTransmit-ElectricityLoss;

AllElectricityTransmitted := 3.942000000012 [W] [h] k
> PriceOnLosskWh:=PriceOnLoss/AllElectricityTransmitted;

PriceOnLosskWh := 0.005555555556euro
```

Total price with loss and investment:

```
> total:=PriceOnLosskWh+PriceOnInvestmentkWh;

total := 0.006697108068euro
```

An estimation on transmission of 2*5GW HVDC transmission lines over a period of 50 years:
cost of transmission per kWh = \frac{0.007 €}{kWh}

This estimation is without maintenance.
A.2: Calculation of electricity demand and irradiance

<table>
<thead>
<tr>
<th>Year</th>
<th>Electricity generation</th>
<th>Nuclear</th>
<th>Thermal</th>
<th>Thermal (Biomass/waste)</th>
<th>Thermal (other)</th>
<th>Hydro+wind</th>
<th>Nuclear</th>
<th>Thermal</th>
<th>Thermal (Biomass/waste)</th>
<th>Thermal (other)</th>
<th>Hydro+wind</th>
<th>Nuclear</th>
<th>Thermal</th>
<th>Thermal (Biomass/waste)</th>
<th>Thermal (other)</th>
<th>Hydro+wind</th>
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<td>1995</td>
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<td>881,662,00</td>
<td>328,160,00</td>
<td>1,499,495,00</td>
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<td>1,442,325,05</td>
<td>2,323,987,05</td>
<td>2,323,987,05</td>
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<tr>
<td>2000</td>
<td>2,993,400,00</td>
<td>944,822,00</td>
<td>376,697,00</td>
<td>1,671,876,00</td>
<td>88,082,38</td>
<td>1,583,793,62</td>
<td>2,528,620,62</td>
<td>2,528,620,62</td>
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<tr>
<td>2005</td>
<td>3,280,583,00</td>
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<td>110,304,01</td>
<td>1,741,139,99</td>
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<tr>
<td>2010</td>
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<tr>
<td>2015</td>
<td>3,903,270,00</td>
<td>962,326,00</td>
<td>711,003,00</td>
<td>2,306,076,00</td>
<td>185,521,84</td>
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<tr>
<td>2020</td>
<td>4,163,708,00</td>
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<td>2025</td>
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<td>2030</td>
<td>4,564,417,00</td>
<td>857,785,00</td>
<td>875,430,00</td>
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**CALCULATING BIOMAS/WASTE RATE OF THE THERMAL INPUT (the efficiency is assumed the same for all thermal)**

<table>
<thead>
<tr>
<th>Fuel Inputs for Thermal Power</th>
<th>16109132</th>
<th>15800102</th>
<th>16862506</th>
<th>17944750</th>
<th>18942298</th>
<th>19739840</th>
<th>20432128</th>
<th>21275980</th>
<th>21570434</th>
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<td>Solids</td>
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<td>9840361</td>
<td>9426035</td>
<td>9919659</td>
<td>9549798</td>
<td>8835111</td>
<td>9024564</td>
<td>10213598</td>
<td>10853682</td>
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<tr>
<td>Oil (including refinery gas)</td>
<td>2349130</td>
<td>2192794</td>
<td>1829297</td>
<td>1518511</td>
<td>1414217</td>
<td>1261860</td>
<td>1014797</td>
<td>902590</td>
<td>842929</td>
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<tr>
<td>Gas</td>
<td>2275156</td>
<td>3039449</td>
<td>4596851</td>
<td>5132996</td>
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<td>6711649</td>
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<tr>
<td>Biomass &amp; Waste</td>
<td>428645</td>
<td>602397</td>
<td>888397</td>
<td>1069100</td>
<td>1328288</td>
<td>1588053</td>
<td>2274949</td>
<td>2831324</td>
<td>2941730</td>
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<tr>
<td>Geothermal heat</td>
<td>116100</td>
<td>125227</td>
<td>132050</td>
<td>134229</td>
<td>154242</td>
<td>172538</td>
<td>192886</td>
<td>209005</td>
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<td>RATE</td>
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</table>

**Power demand in Europe**

- **Thermal (Biomass/waste)**
- **Hydro+wind**
- **Thermal (other)**
- **Nuclear**

**Demand 2030**

- 4000 TWh/year

**Irradiance energy**

- 2.5 MWh/m²/year

**Converted to electricity 15%**

- 375000 MWh/km²/year

**Needed space**

- 10666,6667 km²

1km²2  50 MW
1km²/year  438000

9132,42009