# 5 Environmental Impacts

The environmental impacts of the different energy technologies used in our scenario have already been summarized in /MED-CSP 2005/, pp. 159 ff. and the respectively quoted references, and will not be repeated here. However, the impacts resulting from the specific TRANS-CSP electricity mix in Europe and the environmental impacts related to the power transmission lines from MENA to Europe will be discussed in more detail.

## 5.1 Environmental Impacts of the TRANS-CSP Scenario

The goal of our study was to demonstrate the possibility of a sustainable power supply system in the analysed EUMENA countries with considerably reduced greenhouse gas emissions without creating other serious environmental, societal or economic problems. The major environmental impacts resulting from the scenario are related to the emissions of greenhouse gases, land use and other local impacts. They are summarised in the following:

**Emission of Greenhouse Gases**

The emissions of renewable energy technologies are mainly occurring during the production of the plant's components, because most plants are produced within today's industrial production schemes that use mostly fossil energy. Thus, the emission occurs from fossil power plants that are at present used to provide energy for the production of plant components. The life cycle emissions are valid for a power park with average $CO_2$ emissions of 700 g/kWh. During operation, only biomass and geothermal plants produce emissions. The emission of greenhouse gases ($CO_2$ equivalent) of renewable energy technologies are by orders of magnitude lower than those of fossil fuelled technologies. Coal plants usually have emissions of 900 – 1100 kg $CO_2$/MWh, oil plants around 600 - 700 kg $CO_2$/MWh. Even coal plants with $CO_2$ sequestration would still emit more $CO_2$ than solar or wind power plants, as about 15-20 % of their emissions would still reach the atmosphere. Moreover, it is not yet clear for how long $CO_2$ reservoirs of sequestration would remain isolated from the atmosphere. Other emissions that mainly occur during combustion like nitrates $NO_x$ and sulphates $SO_x$ as well as phosphoric acids are also avoided in the same proportion as carbon dioxide. They can lead to acidification and over-nutrition of soils and water bodies. Emissions of CSP plants in hybrid operation will gradually be reduced with time applying increased solar thermal storage capacities. For the future fuel-based power generation in Europe, an increasing share of $CO_2$ sequestration was considered as discussed in Chapter 2.

At present, the total carbon emissions of electricity generation of all countries analyzed in the study amount to approximately 1400 million tons per year. Instead of growing to 2350 million tons per year that would be expected for the year 2050 in a business as usual case maintaining the mix of the year 2000, our scenario achieves a reduction of emissions to 350 million tons within that same time span (Figure 5-1). Of the 2000 million tons avoided every year, 12 % are avoided by carbon capture, 22 % by rational use of energy and energy efficiency, and 66 % by using new renewable energy sources. The scenario avoids a total cumulated 18 billion tons of carbon dioxide until 2050. It is interesting to note that this number is lower than the potential avoidance of the quickly growing MENA countries described in /MED-CSP 2005/.

The scenario reaches a per capita emission of 0.59 tons/cap/y in the electricity sector in 2050. This is acceptable in terms of the maximum total emission of 1-1.5 tons/cap/y recommended by /WBGU 2003/ and /IPCC 2002/. The carbon emission data for every country analysed within the TRANS-CSP study is given in the Annex.

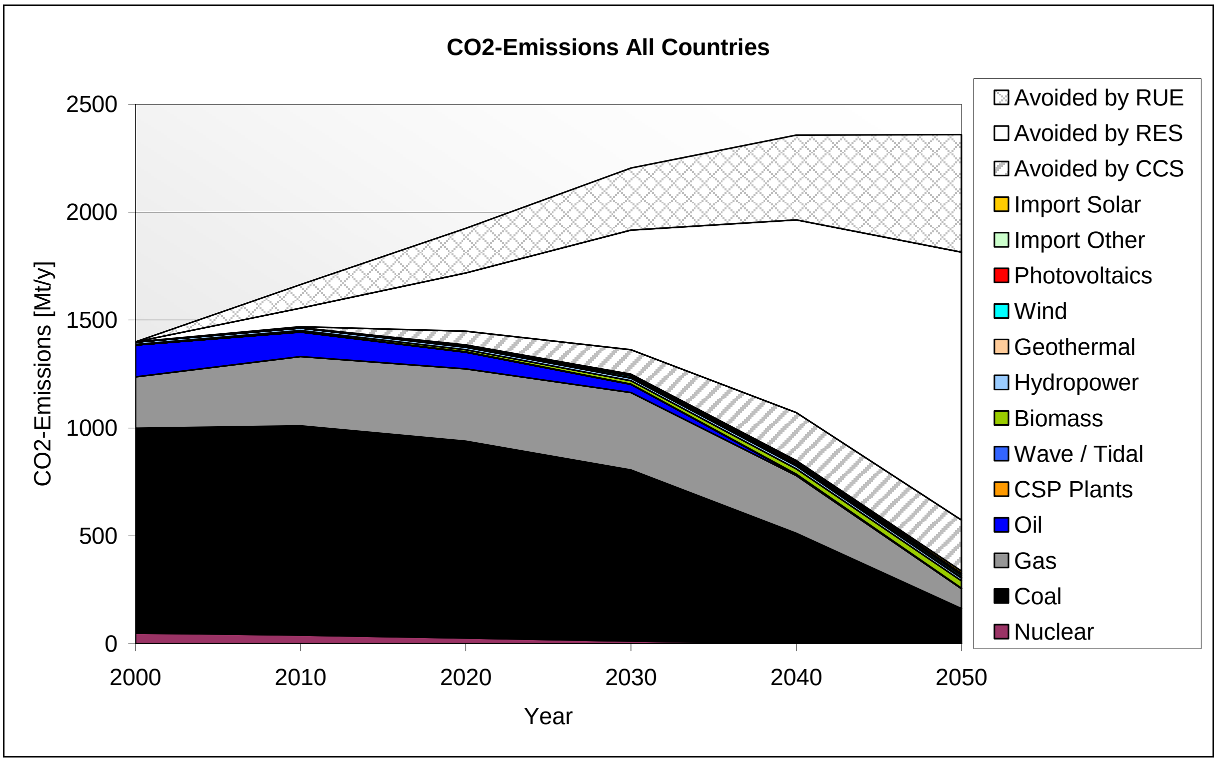


**Figure 5-1: $CO_2$-emissions from electricity generation in million tons per year for all countries of the TRANS-CSP scenario and emissions avoided by Rational Use of Energy (RUE 22 %), Renewable Energy Source (RES 66 %) and by Carbon Capture and Sequestration (CCS 12 %) with respect to an electricity mix equivalent to that of the year 2000. For single countries please refer to the Annex.**

## Land Use

The specific land requirement of hydropower ranges between 10 km²/(TWh/y) for river runoff and micro-hydropower plants and over 400 km²/(TWh/y) for very large schemes like the Aswan dam in Egypt. In Europe, the values range from 10 to 100 km²/(TWh/y). The average value for Europe resulted in 35 km²/(TWh/y) for the total analysed region, which is only 25 % of the value resulting for MENA /MED-CSP 2005/. Geothermal power requires little land (1 to 10 km²/(TWh/y), average 2 km²/(TWh/y)), and the areas affected are in the subsoil at thousands of meters depth. In our scenario, biomass is produced mainly by agricultural and municipal residues (no extra land use) and from wood, resulting in an average land use of only 3.3 km²/(TWh/y). Energy crops – with a very high land use – were not considered in the MENA countries, as they would compete with food and water supply. For wind power, the average land use was 41 km²/(TWh/y), considering only onshore power generation. The specific values differ considerably according to the different performance indicators in each country.

Concentrating solar thermal power plants in Europe have a specific land use of 8-10 km²/TWh. For the CSP plants in MENA installed for export solar electricity, the land use is 5-6 km²/(TWh/y). However, land could be gained from waste land, if multi-purpose CSP plants are applied as described in Chapter 2. This would mean winning additional land rather than land consumption. Photovoltaic energy has no additional land use if installed on roofs, and a slightly higher land use than CSP if installed in large installations. An average land use of 10 km²/(TWh/y) was assumed, considering that many PV installations will be realised also in Central and Northern Europe, while CSP will only be installed in the Southern countries.

The total energy mix in 2050 within the TRANS-CSP scenario has an average land use of 25 $km^2/(TWh/y)$. The total land required for the renewable energy mix amounts to 1.1 % of the total area, which is comparable to the land used for transport and mobility.

For comparison, the land use of gas, oil or coal fired steam cycles ranges between 25 and 100 $km^2/TWh$. Considering the long time during which areas are affected by nuclear waste disposal and uranium mining, nuclear plants also have a high land consumption in the order of 100 $km^2/(TWh/y)$, not accounting for nuclear accidents like in Tschernobyl. On a global level, the change to renewable forms of energy will lead to a more efficient land use for power generation.

## Other Environmental Impacts

Any power technology has an impact on the environment, which must be evaluated very carefully in order to avoid harmful results. Wind plants may have a negative impact on bird habitats and, through visual effects and noise, on recreational and municipal areas. Offshore wind parks may additionally affect marine habitats in their vicinity. Geothermal hot dry rock technology will establish a water cycle from the depths, which will contain a lot of minerals harmful to the surface environment. Therefore, it must be secured that the water cycle used for extracting the heat from the ground is always returned and not infiltrated into surface or groundwater bodies. The disposal of biomass residues is in fact a positive contribution to the environment. Using wood for energy purposes is more critical in terms of avoiding over-exploitation. Plants must be carefully designed and distributed to not overexploit the natural resources. It must be considered that the use of biomass for electricity will compete with other use for heat and fuel in the mobility sector. All in all the environmental impacts of most renewable energy technologies is manageable if there is a careful prior analysis and design.

The environmental impact of large hydropower schemes is well known and documented world wide. Large dams may affect severely the natural habitat of many species, as they usually dwell in the narrow and shaded canyons of the river beds which are set underwater by the dam. Therefore in most cases large hydro dams must be considered as questionable in terms of environmental compatibility. Anyway, the potentials in Europe not exploited so far are very scarce.

The effects of large scale sea water desalination plants connected to CSP in MENA as proposed in Chapter 2 must also thoroughly be evaluated in order to avoid damages by the salty brine and by chemical additives used against scaling and fouling. Due to the large demand of desalination that can be foreseen, intensive research and development for environmentally compatible desalination technologies is of high priority in order to avoid the overload of the local environment.

All in all, it can be stated that the TRANS-CSP scenario reduces the environmental risks related to electricity generation when compared to the present European supply system. The emission of carbon dioxide is reduced to an acceptable level recommended by the International Panel for Climate Change /IPCC ed. 2001/, /IPCC 2002/, together with other pollutants originating from conventional power generation.

The main impacts are related to the use of land and to visibility, e.g. of large wind parks. However, compared to the risks related to the use of nuclear power, the unsolved problem of nuclear waste disposal, and the risk of the proliferation of plutonium, those impacts have a totally different dimension, although they can and should not be neglected. However, with a sound, well balanced mix of technologies and resources, the local impacts to the environment and society can be limited to an acceptable level, with the benefits more than compensating the drawbacks.

| | Hydro | Geo | CSP | Bio | Wind | PV | Total | Country | Area Used |
|---|---|---|---|---|---|---|---|---|---|
| | km² | km² | km² | km² | km² | km² | km² | km² | % |
| Austria | 461 | 6 | 0 | 12 | 73 | 29 | 581 | 83860 | 0,7% |
| Cyprus | 30 | 0 | 0 | 0 | 56 | 1 | 87 | 9251 | 0,9% |
| Denmark | 2 | 0 | 0 | 5 | 591 | 13 | 610 | 43093 | 1,4% |
| Finland | 1289 | 0 | 0 | 66 | 293 | 17 | 1664 | 338145 | 0,5% |
| France | 3597 | 22 | 0 | 138 | 12088 | 234 | 16079 | 544000 | 3,0% |
| Czech Republic | 133 | 0 | 0 | 8 | 203 | 11 | 354 | 78864 | 0,4% |
| Belgium | 27 | 0 | 0 | 7 | 485 | 21 | 540 | 30518 | 1,8% |
| Ireland | 63 | 0 | 0 | 7 | 690 | 11 | 770 | 70284 | 1,1% |
| Luxembourg | 46 | 0 | 0 | 0 | 1 | 8 | 55 | 2586 | 2,1% |
| Netherlands | 6 | 2 | 0 | 4 | 238 | 43 | 293 | 41864 | 0,7% |
| Sweden | 4329 | 2 | 0 | 81 | 1542 | 37 | 5991 | 449964 | 1,3% |
| Switzerland | 383 | 0 | 0 | 4 | 0 | 37 | 424 | 41290 | 1,0% |
| United Kingdom | 395 | 0 | 0 | 26 | 2096 | 78 | 2595 | 244000 | 1,1% |
| Poland | 389 | 3 | 0 | 47 | 2475 | 31 | 2944 | 312684 | 0,9% |
| Bulgaria | 263 | 1 | 0 | 11 | 148 | 20 | 443 | 110994 | 0,4% |
| Slowac Republic | 285 | 5 | 0 | 6 | 31 | 20 | 347 | 49036 | 0,7% |
| Slowenia | 236 | 1 | 0 | 3 | 13 | 10 | 263 | 20252 | 1,3% |
| Germany | 1300 | 45 | 0 | 54 | 795 | 234 | 2428 | 357022 | 0,7% |
| Hungary | 228 | 26 | 0 | 14 | 101 | 20 | 389 | 93032 | 0,4% |
| Greece | 322 | 9 | 28 | 32 | 606 | 39 | 1037 | 131957 | 0,8% |
| Italy | 2318 | 30 | 40 | 60 | 3044 | 176 | 5667 | 301300 | 1,9% |
| Malta | 0 | 0 | 3 | 0 | 2 | 1 | 5 | 316 | 1,7% |
| Portugal | 790 | 9 | 64 | 19 | 232 | 39 | 1152 | 92289 | 1,2% |
| Spain | 1958 | 36 | 240 | 144 | 3102 | 195 | 5675 | 504982 | 1,1% |
| Turkey | 3058 | 150 | 520 | 61 | 2501 | 156 | 6446 | 779452 | 0,8% |
| Macedonia | 104 | 0 | 0 | 1 | 6 | 6 | 116 | 25713 | 0,5% |
| Croatia | 348 | 1 | 0 | 5 | 144 | 8 | 506 | 56600 | 0,9% |
| Romania | 898 | 1 | 0 | 20 | 263 | 20 | 1201 | 238391 | 0,5% |
| Serbia & Montenegro | 750 | 4 | 0 | 9 | 17 | 10 | 789 | 94000 | 0,8% |
| Bosnia-Herzegowina | 482 | 0 | 0 | 7 | 6 | 6 | 500 | 51129 | 1,0% |
| Iceland | 148 | 48 | 0 | 0 | 6 | 3 | 204 | 103000 | 0,2% |
| Norway | 1510 | 0 | 0 | 27 | 199 | 10 | 1745 | 323878 | 0,5% |
| Total km² | 26144 | 401 | 895 | 876 | 32044 | 1539 | 61900 | 5623746 | 1,1% |
| Electricity TWh/y | 749 | 201 | 112 | 496 | 784 | 154 | 2495 | | |
| Relative km²/(TWh/y) | 34,9 | 2,0 | 8,0 | 3,3 | 40,9 | 10,0 | 24,8 | | |

**Table 5-1: Land area for renewable electricity generation in 2050 in the TRANS-CSP scenario. The two columns at right show the total area of each country and the percentage of this area used for power generation by the renewable energy mix in 2050. Hydropower surface demand varies strongly between countries. Photovoltaic surface demand considers only 50 % of the total because many plants will be installed on roofs. Wind power and CSP surface demand is calculated as if exclusively used for power generation. Biomass surface only considers fuel wood. For comparison, the transport system in EU 15 requires 1.2 % of the land area.**

## 5.2 Environmental Impacts of Overhead Lines

The environmental impacts of high voltage transmission lines have been assessed and described extensively by /May 2005/ and the related references. Within this chapter we will summarise the main results of this analysis.

The space requirement of an overhead line can be subdivided in a permanent use while the line is operated and a temporary use during the construction phase. Areas are occupied permanently by the fundament of pylons, for example approximately 22 m² by the massive concrete fundament of medium-sized ton mast. A typical Danube mast with four pedestal fundaments can have a local space requirement of nearly 64 m². /Knoepfel 1995/ states an enclosed area of 50 m²/km for a ±500 kV DC pylon and 100 m²/km for a 750 kV AC pylon. Further space requirement through transformers and rectifiers must be added. A rectifier station with a capacity of 5000 MW requires an area of 800 m x 700 m (560,000 m²) /Normark 2005/, whereas a medium-sized transformer station needs 10,000-15,000 m².

Moreover, there are time-limited places for barrels and winches every 2-3 km nearby the line and repositories every 20 km with a size of 5000 - 6000 m² where wires, isolators and armatures can be stored. Here a reserve of oil absorber of at least 100 kg is also held /APG, 2004/. In addition to this, there is a temporary working stripe with a width of 5 m per month along the line /Knoepfel, 1995/.

The actual width of the line depends on the pylon construction, the voltage level and the correlative safety distance, which must be observed between the conductor wires themselves and the surrounding area. For reasons of safety a ± 800 kV double-dipole ought to be separated into two lines. Typical pylon constructions for this voltage level and the associated width of the line are shown in Figure 5-2. The size and distances of the pylons are defined by the required security margins to avoid electric discharges and health impacts to the population.

| Capacity 10 GW | 800 kV HVAC | ± 800 kV HVDC |
|---|---:|---:|
| **Number of circuits/conductor** | **5/15** | **2/4** |
| **Pylon height [m]** | **1-level pylon 30 - 40** | **30 - 40** |
| | **Danube pylon 40 - 80** | |
| **Pylon width [m]** | **40** | **15** |
| **Fundament [m²/km]** | **100** | **50** |
| **Line width [m]** | **5 x 85** | **2 x 50** |

**Table 5-2: Sizes of a HVAC and HVDC overhead line /Knoepfel 1995/, /Arrillaga 1998/.**

Impacts on the landscape-image, which are caused by a high voltage overhead line, are unavoidable. Large impacts through overhead lines exist in the open plain. Due to the strong restricted possibility of finding new lines in the Central European region, multiple lines with up to six circuits are used almost exclusively in the high voltage area /Kießling et al. 2001/. The very robust, more conspicuous guyed pylons can considerably reduce the recreation value of the environment. Therefore it is aimed at a bundling of lines. It means that high voltage overhead lines are built preferably along the existing infrastructure like highways, railways and other overhead lines.

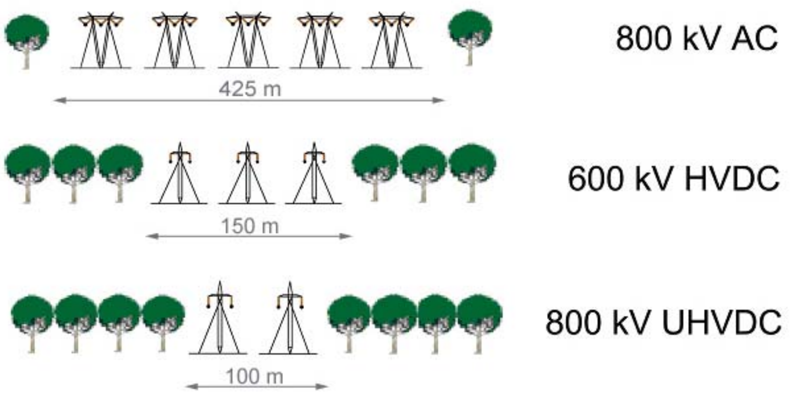


**Figure 5-2: Required number of parallel standing pylons to transfer 10 GW /May 2005/.**

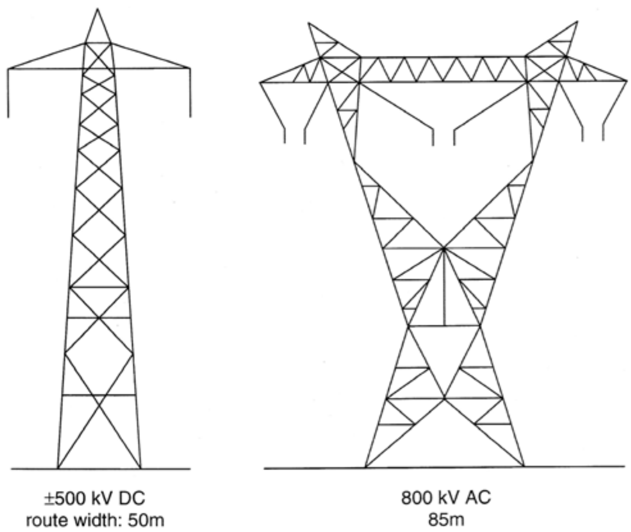


**Figure 5-3: Typical pylon constructions of a HVAC and HVDC overhead line /Arrillaga 1998/.**

Moreover, it is also attempted to achieve a better integration of steel lattice pylons in the surrounding landscape, although the construction is already transparent. The easiest way of integration is a coat in 'Camouflage-Green'. Routing along natural lines and shapes is advantageous for the landscape-image but has a higher expenditure. The visibility of lines can also be reduced considerably within woodlands. Lower and less pylons have a favourable effect on the landscape-image, but a rise in distance between pylons also causes a rise in the amount of pylons since a threshold of 10 m above the ground is prescribed for the maximum conductor sag.

The normal ratio of guyed pylon to carrying pylon is 1:4 in flat terrain. Here the distance between several pylons is an average of 400 m. The more difficult the ground is and the more often the direction of the line changes, the higher the number of guyed pylons.

A DC pylon carries only two conductors per circuit in comparison to an AC pylon with three conductors per circuit and therefore is characterized by a lower height and width. The better integration of a DC line into the environment could also have positive influences on the acceptance of the population.

Acceptance for high voltage transmission projects is particularly low in surroundings of cultural assets, religious places and tourist destinations as the typical landscape-image is affected. Under this point of view a GIS[1]-based analysis of the line visibility can be helpful.

An endangering of the avifauna by high voltage overhead lines hardly exists by a direct electroshock in touching the voltage-carrying conductors or grounded components. Isolators of the hanging type make sure that the distance between conductor and pylon is large enough so that even birds with a large wing range are not able to bridge it. Different to the medium voltage area these hanging isolators cannot be used as raised stand.

Rather it comes to collision accidents with the badly visible ground wire due to it's smaller cross-section, while birds are trying to approach the conductor or to make way for the same. This particularly concerns inexperienced young birds. The use of bird spirals and flutter bands at the earth wire or the lower one-level masts can contribute to a better visibility at very dangerous line sections. This way the annual death rate could be reduced by almost 90 %.

Migrants and passage migrants are more endangered than sedentary and breeding birds. They rest preferably in the area around waters, wetlands and open grasslands and sometimes take a lot of space in order to start and alight. Therefore high voltage overhead lines ought not to be erected in such areas. Up to now measures to defuse line sections with a particular risk potential for alighting birds are not legally prescribed and can be carried out voluntarily by the energy supply companies /Schuhmacher 2002/.

Especially what concerns the protected meadow breeders species like European curlew (*Numenius arquata*) and lapwing (*Vanellus vanellus*) it could be proved that breeding areas were depreciated or not so often visited after the erection of a high voltage overhead line. Probably overhead lines impair the environment in a visual way. It happens now and then that the animals keep a distance of 100 m to the line, what in the end amounts to a loss of the breeding area. The sky-lark (*Alauda arvensis*) also showed a significant preference to areas far away the line /Schuhmacher 2002/.

Quite another kind of influence on ground breeders is the utilization of the pylon alienated from its purpose as hatchery by diurnal prey birds. The raised standing predators cannot be chased away from the nest environment and therefore are a permanent danger for the juvenile waders. Consequently, the shift of the predator-prey-relation for the benefit of the predators could lead to the loss of the population in case of a critical size /Schuhmacher 2002/.

Danger of soil compacting by the use of heavy equipment and machinery particularly exists for heavy soils. However, after finishing the project a depth aerator can be used to counteract this danger. If necessary, the use of helicopters is recommended in areas which are difficult to access.

A high danger is represented by erosion processes at the place where the soil is not covered with vegetation. For that reason there is an urgent need in restoring the initial condition as far as it is possible. This also contains the equalization of a possible subsidence.

Where ever fuel and oil consuming devices are used there is a fundamental risk of contaminating the soil and later the groundwater with hazardous substances. Therefore it calls for special care if the aquifer is affected by constructional measures in the range of waterworks. Heavy metal emissions of the pylon can be neglected since modern pylons, whose hot-dip galvanized steel framework is coated with a protective lacquer, are used /Knoepfel 1995/. The professional disposal of waste, such as a contaminated excavation, and the curative dismantling and recycling of disused components is presumed and therefore not be further discussed.

1 GIS Geographic Information System

## 5.3 Environmental impacts of underground cables

The acceptance of the population for overhead lines has heavily decreased because of the unavoidable impairment of the landscape-image. Both in congested areas and also in semi-natural landscapes people are bothered by the high mast constructions, although often on a subjective emotional level. But also lack of space in congested areas and the strict prevention of impairments of special worth protecting areas lead to an intensified use of underground cables in these areas. If a project has effects on the characteristic region, such as high voltage power lines, protracted permit procedures have to be passed through until the construction can be started.

Furthermore, most of the impacts typically caused by overhead lines can be eliminated with ground cables. First of all this concerns the distinct lower space requirement in comparison with an overhead line. Anyhow, a forest aisle of 5 m width is unavoidable. The placing depth of the cable amounts to nearly 1 m and even after finishing of construction works a radius of 1 m around the cable must not be built over or planted with deep-rooted plants on safety grounds /VDEW 2001/.

The cable isolation shields the electric fields almost completely. Magnetic fields remain uninfluenced by this and can only be minimized if several cables are buried in closer neighbourhood to each other so that fields eliminate themselves mutually. The magnetic field strength rapidly decreases with the increasing distance to the cable and reaches the background value after 5 m.

Another effect of an underground cable is the local dehydration of the surrounding soil. That is because of the reduced quality of heat removal in dependency on the soil texture and humidity. The resulting, minimized heat emission impairs the operating safety of the cable, but affects the vegetation cover, fruit ripeness and vegetation period only in the closest environment of the cable. The specific influences on the microbiology, flora and fauna are still unknown for the most part.

In case of accident there is an acute risk for the environment by the contamination with hazardous substances, especially for the groundwater. The risk potential by leakages is dependent on the used cable type. In the high voltage area low pressure oil filled cables and mass-impregnated cables are preferably employed. The former must be checked regularly for leakages even after placing out of operation and an alarm and measure plan must be made. For that reason it is better to remove the cable at once, whereas the closure of mass-impregnated cables is not such a danger as the endings are sealed and the high-viscosity paper-oil isolation gets more viscous after the cooling down of the cable. PVC cables, which release heavy metals at a $pH < 3$ or hazardous hydrogen chlorides such as dioxin in case of fire, are not used any more in the high voltage area /VDEW 2001/.

## 5.4 Environmental impacts of submarine cables

Up to now the deepest DC submarine cable in the world has been laid in a depth of maximum 1000 m between Italy and Greece. Figure 5-4 shows the very rough profile through the 'Street of Otranto'. The HVDC line starts on the Italian side as a 43 km long underground cable. Then it follows a 160 km long submarine cable section where the cable is rinsed into the seabed on the continental shelf or is simply put down on the sea bottom in deeper areas. On the Greek mainland the transmission line runs as 100 km as overhead line. Impacts and influences on the environment respectively occur by the laying of the submarine cable. In the offshore area the cables are directly put down on the sea bottom while they are rinsed in a depth of 1-2 m into the seabed of the shallower coastal zone.

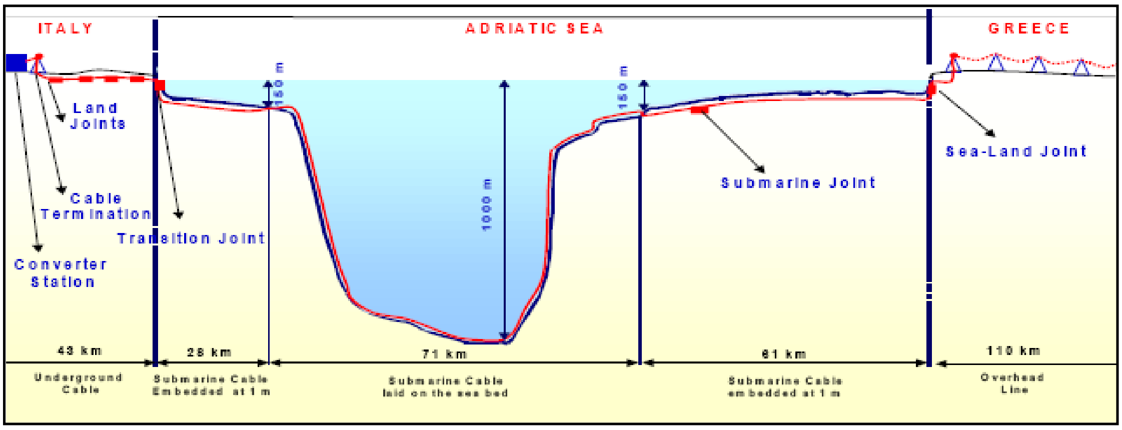


**Figure 5-4: Profile through the 'Street of Otranto' /Cigre 2002/**

In areas with highly dynamic morphology, such as in tide-ways and in front of islands, cable-laying is recommended up to a depth of 3 m to avoid possible free-rinsing. Because of large sediment transfers the loss or influence of the benthic bio co enosis or fish living nearby the ground cannot be avoided /Wirtz, Schuchardt 2003/. The duration of resettlement amounts to at least two years. Furthermore, the fine grain fraction mobilized by sediment transfers also causes a higher turbidity of water, which is separated in time and space. On one hand the activity of the primary producers and the phytoplankton is impaired and on the other hand the simultaneous release of nutrients supports the growth of algae. The latter occurs especially in spring and summer when there is usually a lack of nutrients. The impairment of the marine mammals and avifauna depends on the extent of disturbances in the form of vibration and noise, but altogether it is considered to be low. Nevertheless, the building measures ought not to be carried out during the breeding time and formation of colonies as a precaution /Wirtz, Schuchardt 2003/.

Electric and magnetic fields arise around the conductor during operating. The electric field cannot permeate good cable isolations. First of all the magnetic field of a bipolar DC cable affects the environment, which in turn can induce secondary, electric fields owing to the sea current. In this way also natural, electric fields are generated by moving of water through the earth's magnetic field. For example, the Gulf Stream produces an electric field with a strength of 50 µV/m /Kullnick & Marhold 2000/. Up to now most of the submarine cables have been performed as mono-polar conductor with back current via seawater so that sea-electrodes are required. The electric fields in a distance of 10 km to such electrodes move on a level of $10^{-4}$ V/m, what is comparable to natural electric field strengths in the sea.

The electrode is operated as cathode with a surface of 400 m² and 1500 Amperes DC. The resistance of the seawater amounts to 0.8 Ω*m. Because of the rapid decrease of the field strength with the increasing distance towards the electrode an influence of fish is hardly expected after 10 cm. Alternatively, the use of land instead of sea-electrodes would be feasible. Although it is known that the biological activity is connected with weak electric field events, the effect of the weak electric fields arising by the transmission of electricity are largely unexplored /Debus 1998/. Fishes are equipped with special electro-receptors and can react more sensitively as they are able to even perceive electric fields around 1 µV/m. Strong electric fields have field strengths of more than 1 V/m and current densities of at least 5 mA/cm². Such fields produce a galvanic-tactical and anaesthetic effect and have been used as fishing assistance since 1925 /Debus 1998/.

The magnetic field of a HVDC line is the strongest at the cable surfaces and decrease with an increasing distance. At a power of 500 MW the field strength in 6 m distance is equivalent to the natural magnetic field /Söderberg, Abrahamsson 2001/. The magnetic field strength can be reduced by overlapping of two reverse-polarised fields. Therefore it is recommended using closely lying, bipolar conductors (‘Touch-Laying’), in future also in a joint cable (‘Flat-Type’). Additionally, the transmission capacity can be doubled this way and sea-electrodes can be given up. An influence on the orientation of far-migrant fishes like eel (*Anguilla anguilla*) and salmon (*Salmo salar*) could be given as they are still able to perceive the field of a 500 MW HVDC cable in a distance of 160 m /Debus 1998/. However, previous examinations outdoor and in the laboratory provided no clear indications of a barrier effect, deflection or influences on communication of fishes (shy and deflection effect). Most likely a multi-factorial orientation during the fish migration is assumed, in which the natural magnetic field represents only one component. The natural magnetic field becomes more and more important for migration if other factors like sunlight, temperature, salinity and velocity of flow appear not so strong.

Even the migration of animal groups like molluscs (snails and mussels), crustaceans, marine mammals and zooplankton is controlled by several factors. Altogether there is a considerable need in research with regard to the perception and utilization of the natural magnetic field by marine organisms. Therefore possible influences on migration by technical-generated fields cannot be excluded fully /Kullnick, Marhold 2000/.

Beside the fields an increase in temperature can also be observed in the immediate environment of the cable. In case of a 600 MW bipolar cable buried in a depth of 1 m an increase in soil temperature of 3 °C in within a radius of 50 cm can be measured. The change in temperature at the surface of the sediment amounts to 1 °C at most. This local warming of the soil leads to an intensification of the bacterial metabolic rate and a reduced mortality of invertebrates in winter. Moreover, the settlement of thermopile organisms is possible /Wirtz, Schuchardt 2003/.

Here it is just mentioned that theoretically trawl nets and anchors could get caught by free-rinsed cables. The probability of such an accident lies at 1 event in 200 years at a 12 km long cable section /SEP 1997/. It should therefore be aimed at bundling and multiple-shift usage of submarine lines.

## 5.5 Low Impact Solar Electricity Links

The methodology of finding ecologically optimised lines for the interconnection of sites with high solar electricity potential in MENA with centres of massive electricity demand in Europe was developed and described in detail by /May 2005/. In the following we will present the main results of the analysis of three exemplary lines of a possible future trans-European HVDC electricity grid, interconnecting Western Algeria with Germany, Southern Libya with Italy, and Central Egypt with Poland for the purpose of exporting solar electricity from concentrating solar power plants.

Three exemplary sites for solar electricity generation were simply found by looking at the solar irradiance map of the MENA region and selecting three sites with major solar irradiance potentials of over 2800 kWh/m²/y. In the real world, such an assessment would be made considering much more parameters for site selection, taking into account e.g. political and social constraints, economic performance, accessibility etc. The chosen sites are quite remote and thus constitute something like a worst case for solar power transmission.

On the other side, we had to find out the targets of solar electricity transfer. This is defined on one side by the results of the scenario analysis in Chapter 2, that shows the deficits of firm renewable power capacity in most central European countries and also on the British Island. The other end of the power lines was thus placed in the major centres of electricity demand in Central Europe, in order to effectively backing and taking off some load from the conventional AC electricity grid with firm DC power capacities, and effectively using local AC grids for the distribution of imported solar electricity.

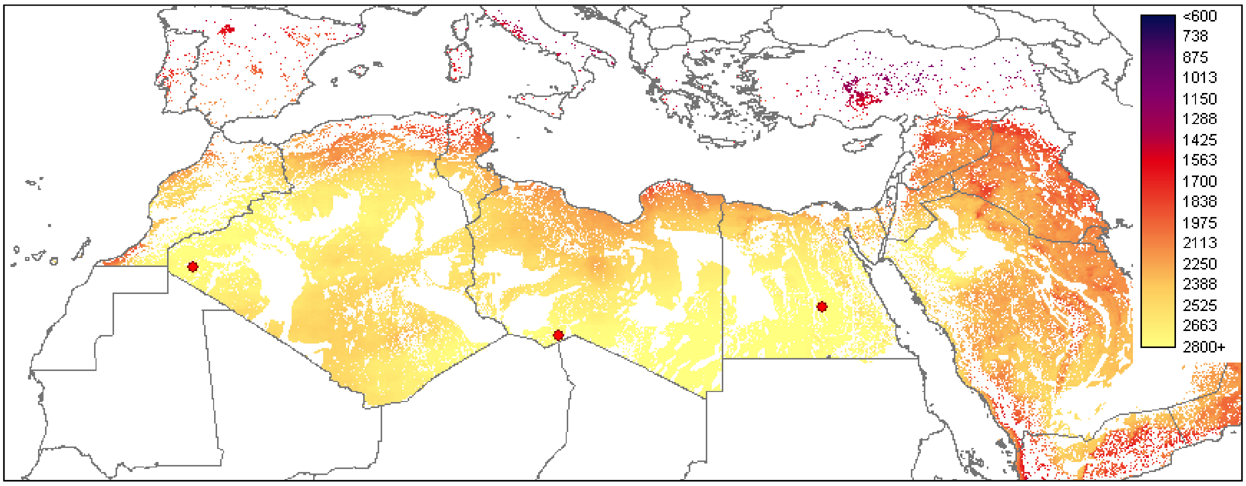


**Figure 5-5: Annual solar irradiance atlas in kWh/m²/y with sites excluded for the erection of CSP plants generated in the frame of the study /MED-CSP 2005/. The red dots indicate the sites chosen exemplarily for solar power generation.**

The major centres of electricity demand in Europe can easily be found looking at the density of the UCTE electricity grid in Figure 1-2, the population density in Figure 5-6 and the nightly light emission from Figure 5-7 as major indicators for electricity demand. Looking at those maps, we have selected the Ruhr area in Germany, London in the UK, Milan in Italy and Warszawa in Poland as possible headers of the HVDC links coming from MENA.

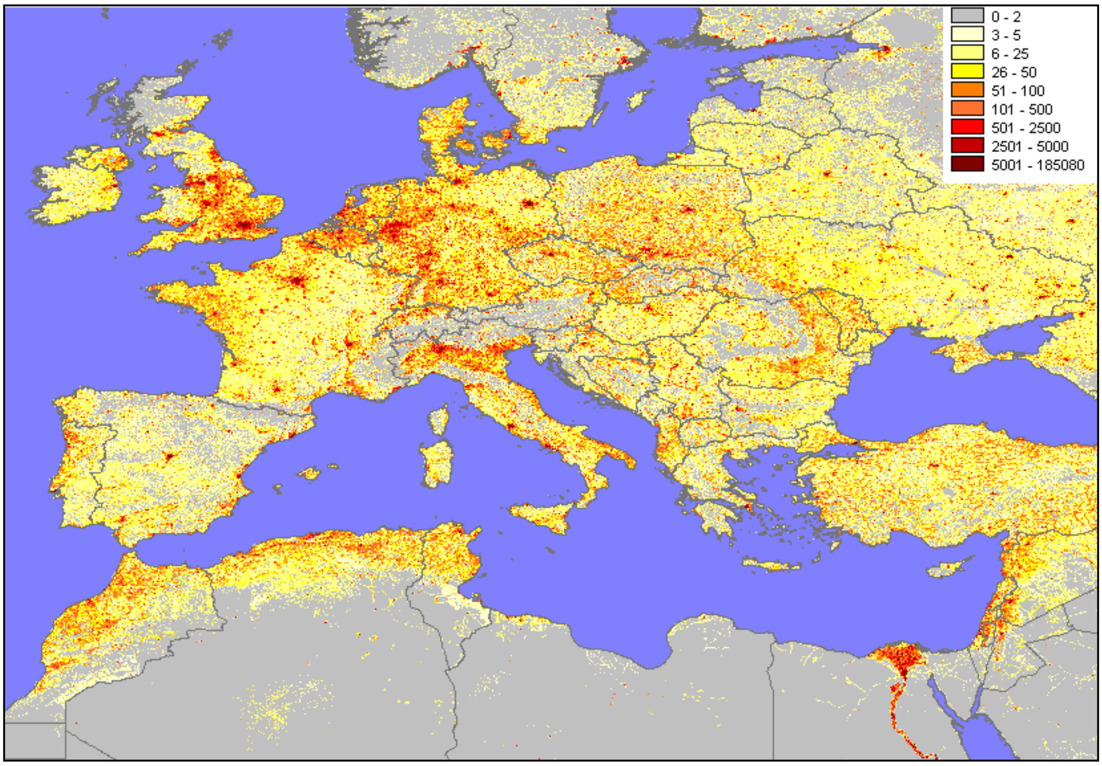


**Figure 5-6: Population density in EUMENA in Persons/km² /ORNL 2003/.**

**Figure 5-7: Satellite view of the EUMENA region at night showing the intensity of light emissions as indicator for electricity consumption /Brockhaus 2005/.**

After defining the starting and end point of the three exemplary interconnections Algeria – Germany, Libya – Italy and Egypt – Poland, a thorough analysis of the shortest (most economic), but ecologically most compatible way was undertaken using a geographic information system (GIS) for that purpose (Figure 5-8). The analysis considered the topography of the landscape, protected areas, land cover, population density and infrastructure, cultural and religious sites and natural hazards to find the shortest viable interconnection of both terminals with minimum environmental impact for three lines with 5-10 GW capacity each /May 2005/.

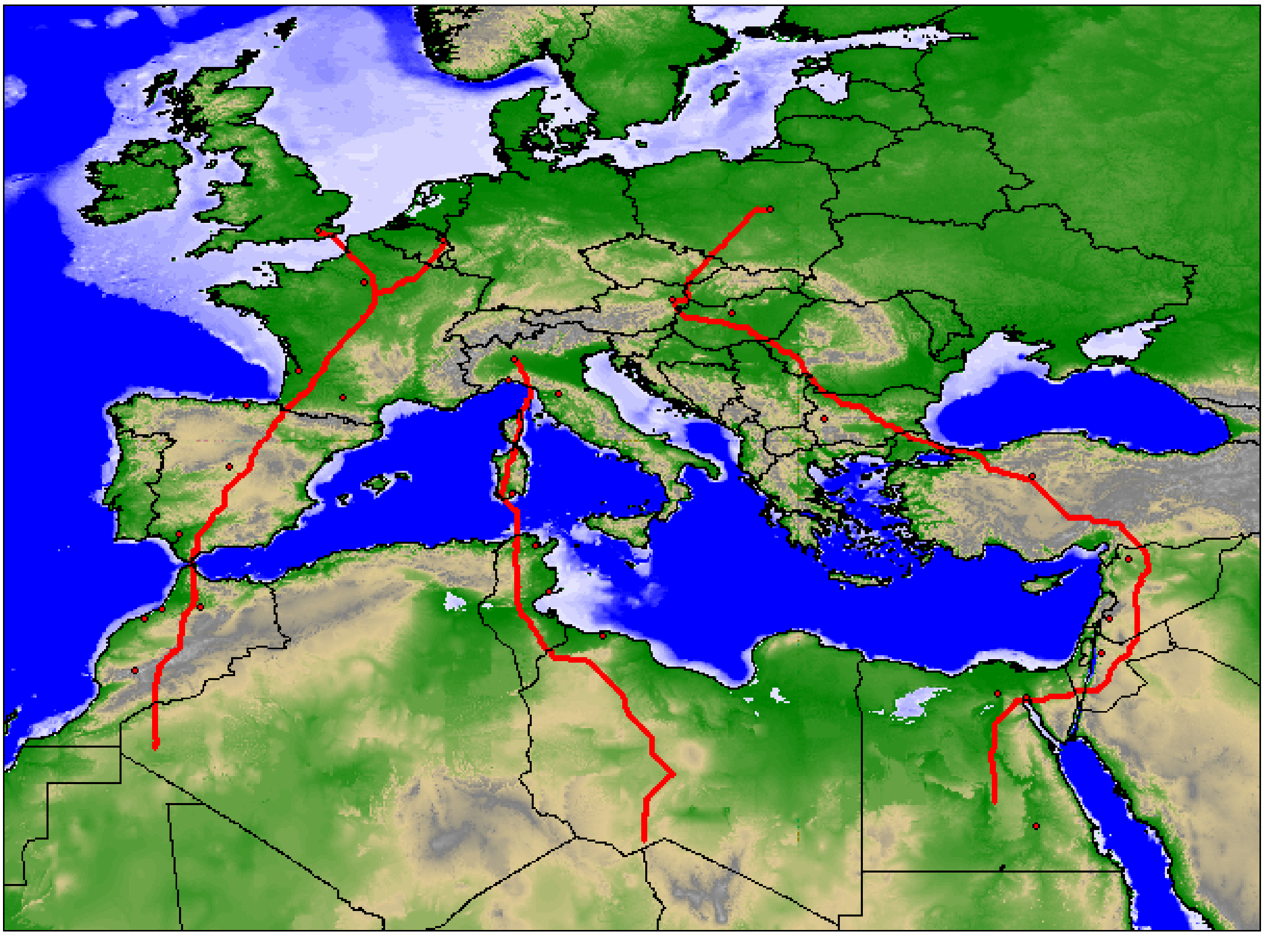

**Figure 5-8: Three analysed samples of EUMENA interconnections with HVDC lines with a capacity of 5 GW each. The red dots indicate further centres of demand that are close to the line and could be interconnected, too. The background map shows the topographic features of the landscape /May 2005/**

### Line 1: Western Algeria - Aachen

The first line starts in the western part of Algeria approximately 100 km to the east of *Tindouf*. From there an overhead line leads exactly in a northerly direction through the desert to Morocco, crosses the *Atlas Mountains* and reaches the *Strait of Gibraltar* after nearly 1090 km. Then the line must be performed as submarine cable on a length of 18 km. At the European coast again it is connected to an overhead line. On the further course the line has to get past the Spain wildlife sanctuaries *Los Alcornocales* and *Sierra de Grazalema* to the east and then to cross the Iberian Peninsula on a length of about 930 km, where the land cover varies heavily between woodlands, grasslands, croplands and semi deserts. On the latitude of the *Pyrenees* the French border is passed. Then the line runs almost straight in a north-easterly direction as only a few areas are excluded in France. The residual area is mainly used for agriculture. After a total of 3117 km the destination *Aachen* in Germany is reached.

Figure 56 shows the ground profile from the centre of demand in the north to the plant site in the south. Along the line a maximum height of 3500 m in the *Atlas Mountains* and a maximum depth of -750 m while the *Mediterranean Sea* must be overcome. The hypsographic summarized curve makes clear that over 50 % of the areas lie between sea level and 500 m above sea level and just 5 % in the high mountain region above 1500 m.

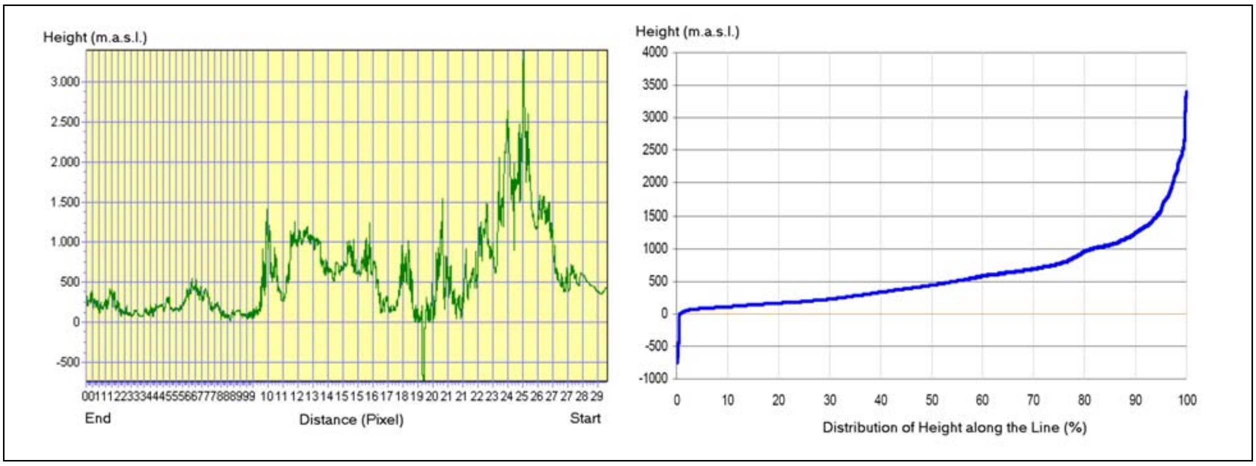


**Figure 5-9: Ground profile [height above sea level] of line 1 from Western Algeria to Aachen, Germany and the associated hypsographic elevation model**

### Line 2: Southern Libya - Milano

The second line has a total length of 3108 km and begins in the south-western part of Libya around 80 km south-easterly of *Al Wigh*. The first 1330 km leads through the *Libyan Desert* in a north-west direction. There the course of the line is mainly determined by geomorphologic features like dunes and fields of lava around *Al Haruj*. Tunisia is centrally passed on a length of 700 km because of the large sand deserts of the *Sahara* (*Erg*) in the west. Altogether over 50 % of the line lies in desert areas. In the northern part of Tunisia areas are hardly excluded due to a low population density and a lot of cropland and grassland. Then comes a 220 km long submarine cable to the Italian island *Sardinia*. On the Mediterranean islands the line follows the course of the already existing HVDC line *SACOI*. The large *National-Regional Park of Corsica* forces the line to go easterly. In order to connect the line with the Italian mainland a submarine cable with a length of nearly 130 km is used. The national park *Arcipelago Toscano* remains untouched. Afterwards the line has to pass the woodlands of the *Apennines* and croplands in the *Plain of the river Po* until the destination *Milano* is reached after 180 km.

The largest heights about 1200 m can be found on *Sardinia* and in the *Apennines*. The deepest point of the line lies at -1968 m in the *Mediterranean Sea*. Along the whole distance no high mountain regions are crossed and almost 90 % of the areas lie between sea level and 1000 m above sea level.

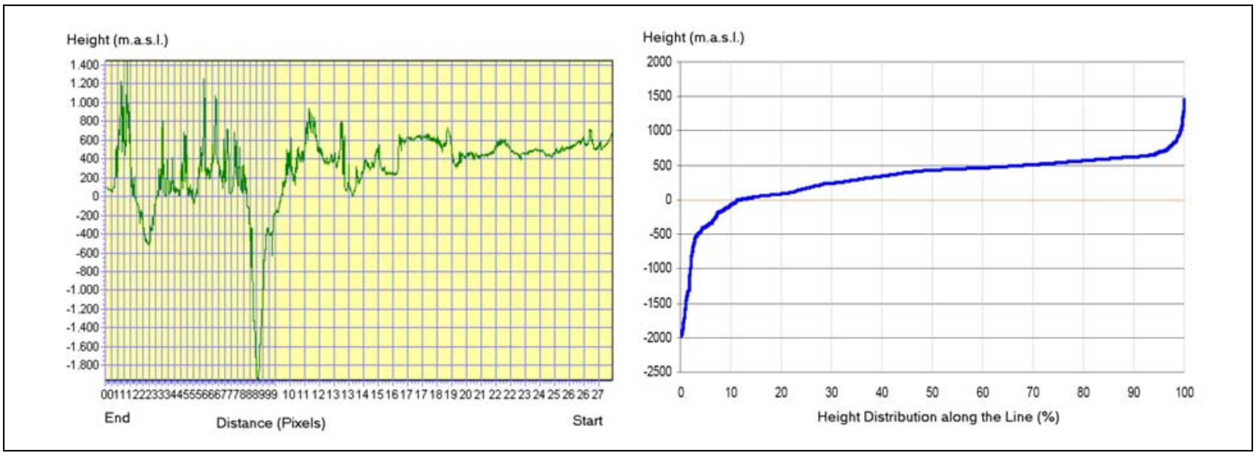


**Figure 5-10: Ground profile [height above sea level] of line 2 from Southern Libya to Milano, Italy and the associated hypsographic elevation model.**

## Line 3: Central Egypt - Warszawa

The solar thermal power plant, which is the starting point of the third line, is located approximately 50 km in the east of the oasis *Kharga* in Egypt. From there the overhead line runs 860 km through Egypt first in northerly and then in easterly direction. On the way the *Nile* is crossed nearly 35 km in the north-west of *Asyut* and afterwards also the *Gulf of Suez* as the populated places of the city *Suez* and dunes in the northern part of *Sinai Peninsula* are excluded.

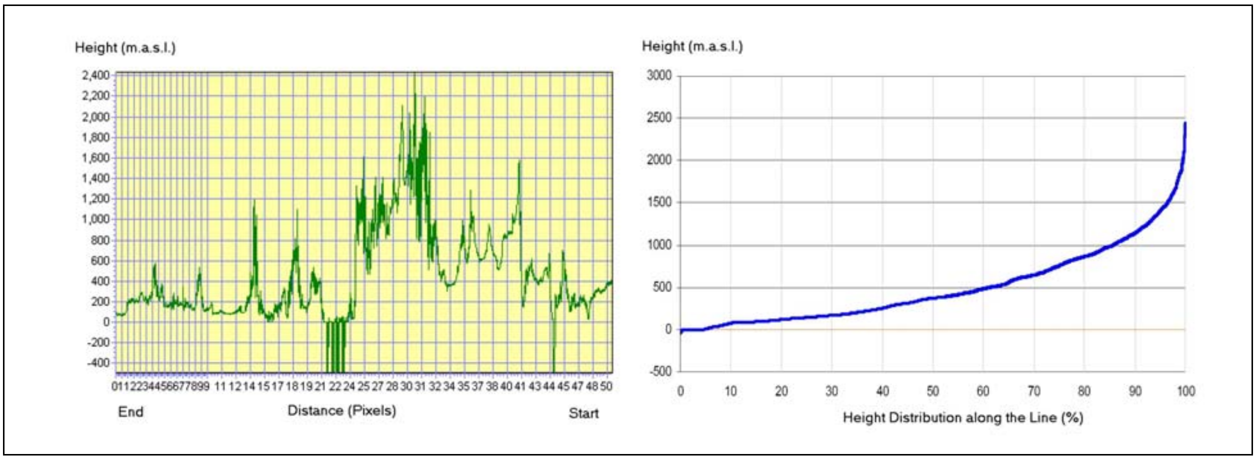


**Figure 5-11: Ground profile (height above sea level) of line 3 from Central Egypt to Warszawa, Poland and the associated hypsographic elevation model.**

On a distance of 60 km the southern part of Israel is passed exactly between the three natural reservations *Har Ha Negev*, *Ashosh* and *Nehalim Gedolim Uqetura* and afterwards the line leads to *Ma'an* in Jordan. After a total of 380 km the national border to Syria is reached. From there the line runs around 500 km through the *Syrian Desert* and then gets past westerly the water reservation *Buhayrat al Asad*. On a distance of 1300 km the line leads further through the Anatolian part of Turkey, past *Ankara* and *Istanbul* and then runs along the coast of the *Black Sea* over the *Bosporus* and through the European part of Turkey called *Thracia*. Afterwards the countries Bulgaria, Romania and Hungary are passed in a north-westerly direction until *Vienna* is reached after 1370 km. The river *Danube* is first crossed 60 km in the south-west of *Craiova* in Romania and then 60 km in the south of *Budapest*. Then the line goes on to the border of Slovakia and follows that border north to the Czech Republic. From there it crosses the Czech Republic and Poland and reaches Warszawa after further 632 km.

The line has a total length of 5143 km and has to overcome large heights of around 2000 m especially in the *Balkan Region*. More than 90 % of the line lies between 0 and 1500 m above sea level.

### Comparative Evaluation of the Three Lines

In the following the lines are submitted to analysis and the results are evaluated regarding their accuracy among others.

#### *Length of the Lines*

In Table 5-3 the total length, the shared length of all countries and the sea sections are listed. Accordingly, line 2 has the longest submarine section of 373 km, that corresponds to 12 % of the line. Line 1 has to cross the *Strait of Gibraltar* on a length of 18 km and the 30 km long submarine sections of line 3 lie in *Gulf of Suez* and at the *Bosporus*. However, what concerns line 3 the length of the submarine section has been overestimated. As the line leads along the coast, an overlapping with areas of the *Black Sea* is possible. Line 3 has the longest overhead line section with 5113 km.

| **Line 1** | | **Line 2** | | **Line 3** | |
|---|---|---|---|---|---|
| **Country** | **Length [km]** | **Country** | **Length [km]** | **Country** | **Length [km]** |
| Algeria | 256 | Libya | 1326 | Egypt | 858 |
| Morocco | 835 | Tunisia | 701 | Israel | 59 |
| Spain | 932 | Sardinia/Italy | 313 | Jordan | 378 |
| France | 907 | Corsica/France | 216 | Syria | 495 |
| Belgium | 164 | Italy | 178 | Turkey | 1324 |
| Germany | 5 | | | Bulgaria | 448 |
| | | | | Romania | 361 |
| | | | | Hungary | 518 |
| | | | | Austria | 72 |
| | | | | Slovakia | 50 |
| | | | | Czech Republic | 195 |
| | | | | Poland | 355 |
| Overhead line | 3099 | Overhead line | 2735 | Overhead line | 5113 |
| Submarine cable | 18 (0.6 %) | Submarine cable | 373 (12 %) | Submarine cable | 30 (0.6 %) |
| **Sum** | **3117** | **Sum** | **3108** | **Sum** | **5143** |

**Table 5-3: Line shares of the concerned countries in kilometres.**

#### *Land use*

The calculation of the respective forms of land use concerned by the lines shows that in all three cases areas are mainly used which have been intended for that. Rice fields and wetlands are not touched by the lines and also agglomerations are almost always omitted (details in /May 2005/). The share of forest does not exceed 10 % (Figure 5-12). This is essentially equivalent to a typical land use of an overhead line mentioned in /Knoepfel 1995/.

Only what concerns line 2, about 10 % of the crossed areas lie in the visual range of certain cultural sites. The shares of the other lines are lower; however, this analysis is based on a database afflicted with a higher uncertainty.

If a line width of 100 m for a 10 GW line is estimated, the space requirement below the line amounts to 100 km² per 1000 km.

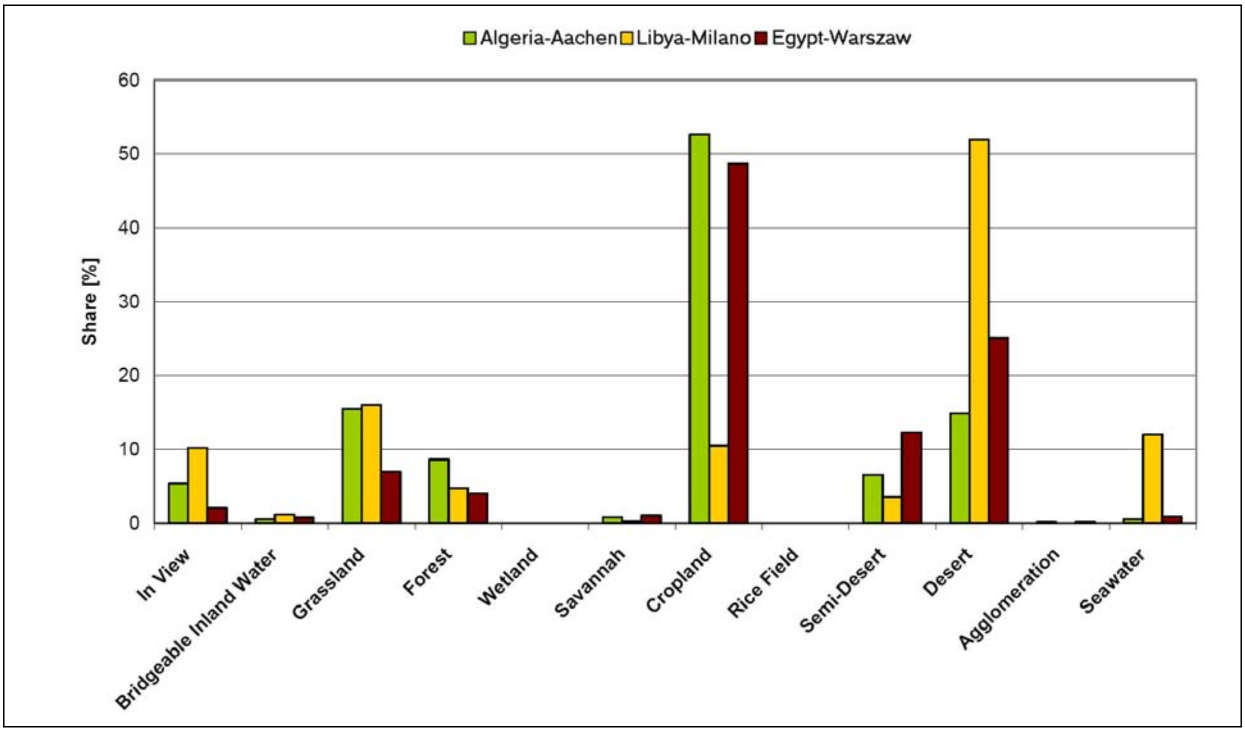


**Figure 5-12: Share of land use and visibility of the three analysed lines.**

### *Distance to Highly Populated Areas*

In case that it is intended to deliver power to other places in future, provided that the lines would be operated as multi-terminal, the direct distances to important cities along the lines are listed in Table 5-4. Branch line for HVDC can only be realized by a further rectifier terminal. If larger loads are taken out, the line should be extended so that following demand centres can be supplied with electricity.

### *Accuracy of the Results*

The accuracy of the course of the three lines depends on the underlying datasets, especially on their completeness. Especially what concerns the protected areas within the European Union, better datasets could be provided by the cataloguing of the 'Natura 2000' areas after their finalization in the near future. Regarding the infrastructure there has not been provided an updated and topographically correct dataset together with attributes up to now. The difficulty lies chiefly in the spatial reproduction of these structures.

Furthermore, the dataset used for the visibility analysis is rated uncertain. Anyhow, it concerns a subjective criterion so that the impacts on the landscape-image should be clarified at another scale and with another method. Here just an approximate estimation for this criterion can be done. For the residual datasets it is assumed a sufficient accuracy with regard to the formulation of the question and the scope of this study. It has been attempted to take a scientific method as a base for the determination of the optimal path, otherwise reasonable estimates were taken.

Altogether it seems that the results, especially with regard to the land use, are plausible and fulfil the requirement of a general representation. The multitude of possibilities to visualize the results within a GIS can contribute to give a clear imagination of the topographic course of the lines. If it is considered on country level, the results could also be interesting for political decision maker. Nevertheless, this analysis does not substitute a detailed planning

| **Line 1** | | **Line 2** | | **Line 3** | |
|---|---|---|---|---|---|
| **City** | **Distance** | **City** | **Distance** | **City** | **Distance** |
| Marrakech | 96 | Tripoli | 141 | Aswan | 233 |
| Casablanca | 152 | Sfax | 128 | Cairo | 83 |
| Rabat | 92 | Tunis | 79 | Suez | 12 |
| Fes | 39 | Cagliari | 40 | Amman | 82 |
| Sevilla | 70 | Florence | 104 | Damascus | 108 |
| Madrid | 57 | Genua | 62 | Aleppo | 72 |
| Zaragoza | 96 | | | Ankara | 12 |
| Toulouse | 132 | | | Istanbul | 19 |
| Bordeaux | 78 | | | Sofija | 99 |
| Paris | 105 | | | Budapest | 55 |

**Table 5-4: Distances of the HVDC lines to selected major cities in km**

## 5.6 Eco-Balance of Solar Electricity Imports

Generally accepted guidelines for the preparation of a Life Cycle Assessment (LCA) can be found in ISO 14040 ff. /ISO 2005/. Modelling of material and energy flows is carried out within the database and modelling tool Umberto® by means of material flow networks. The procedure of the Federal Environmental Agency (UBA) was used for the preparation of the impact assessment /UBA 1999/, /IFEU/IFU 2005/. The results are normalized to 1 kWh (electricity) and compared with a reference electricity mix. In a broad sense the question should be answered if environmental impacts associated with the provision of electricity from fossil primary energy carriers can be reduced by an electricity import from renewable energy resources. Furthermore, it is also interesting to what extent a changed electricity mix for the production of the facilities could have an effect on the balance.

Within the balancing of the plant exploration, mining, processing and transportation of the fuels, especially for the electricity mix as well as the required infrastructure, are covered. Furthermore, the production of single components is considered. This comprises the solar field, the steam generator, the mechanical and electrical engineering, the constructional engineering, the storage and the steam turbine. Certain recycling quotas are given for steel, aluminium and copper. Modelling of the facility operation includes maintenance, i.e., cleaning and material exchange. The disposal of the facility is composed of the demolition (except the buildings) and the depository.

Modelling of the HVDC line comprises the winning of the raw materials, the production and transportation of the materials and components with respect to their destination. Besides, emissions arising during the operating time of the facility are incorporated. There is no reliable data available about maintenance, cleaning measures and the final disposal.

A solar thermal power plant (type Parabolic Trough Solar Electricity Generating System 'SEGS') with thermal storage and dry cooling tower is used for the generation of electricity. The transmission line is a ±800 kV HVDC system performed as double-dipole. Plant location and course of the line correspond to the respective lines from the GIS analysis. Both systems are designed for a capacity of 10 GW. The year 2030 is defined as temporal reference for the facility construction. Accordingly, the electricity mix, the manufacture of steel, aluminium, copper, rock wool, ceramics and flat glass are extrapolated to this year.

An existing model for an 80 MW SEGS power plant with reference to the year 2010 from the SOKRATES project was adjusted to a 10 GW SEGS power plant /Viebahn 2004/. The quality of the original data from the year 1996 is rated high because it concerns information of the producer. Besides, it was updated and added. Input data for the modelling of overhead lines and cables is primary data from the producer ABB /Normark 2005/. In some places it is supplemented with own calculations and bibliographical references /Knoepfel 1995/, /ESA 2004/. In addition, the process database of Umberto® and partially the ecoinvent database 2000 was used /ecoinvent 2003/.

For the long-distance transport of 10 GW a ± 800 kV double-dipole system on two separate lines with a capacity of 5 GW each is used. The conductor deployed is an aluminium-steel compound wire (Al/St 805 mm²/102 mm²). In a 4-string-bundle 2500 MW per Pole can be transmitted with it. The pylons are steel lattice pylons with a concrete fundament and long-rod ceramic isolators.

In order to cross the sea a ± 800 kV mass-impregnated cable with a central copper conductor (2100 mm²) is used. Altogether 8 cables are required to transmit 10 GW.

The rectifier stations and transformers are composed of many different materials, for which no data was available, but they are of no consequence for the balance due to the large length of the HVDC line.

Power plant operating time is defined as 30 years. Thus, just 60 % of the HVDC line, which has an operating time of 50 years, is considered for the balance. The electricity mix of Germany of the year 2030 was taken as reference for the calculation of emissions during construction.

| | Unit | Site Algeria | Site Libya | Site Egypt |
|---|---|---|---|---|
| DNI | kWh/m²/y | 2835 | 2802 | 2865 |
| Capacity | $GW_{el}$ | 10 | 10 | 10 |
| Solar field size | Mio m² | 227.0 | 227.0 | 227.0 |
| Thermal storage | $GWh_{th}$ | 590.5 | 590.5 | 590.5 |
| Electricity production | TWh/y | 77.1 | 76.2 | 77.9 |
| Full load hours | h/y | 7710 | 7620 | 7790 |

**Table 5-5: Performance data of 10 GW base load solar thermal power plants in 2030 at the three starting points in Northern Africa, derived from /ESA 2004/, /May 2005/, as used for the eco-balance.**

| HVDC | ± 800kV Overhead line (2 lines) | ± 800kV Submarine cable (8 cables) | Source |
|---|---|---|---|
| **Technical Data** | | | |
| Length | 3099 km | 18 km | |
| Conductor | 4 | 8 | /Normark 2005/ |
| Line losses | 3.7 %/1000 km | 1.7 %/1000 km | |
| Station losses (2x) | 1.4 % | 1.4 % | /ESA 2004/ |
| Durability | 50 a | 50 a | /Pehnt 2002/ |
| $O_3$-emissions | $4.0 * 10^{-9}$ kg/$MJ_{el}$ * km | | /Knoepfel 1995/ |
| $N_2O$-emissions | $0.4 * 10^{-9}$ kg/$MJ_{el}$ * km | | /Knoepfel 1995/ |
| **Materials** | | | |
| Aluminium | 2 x 17.4 t/km | | /Normark 2005/ |
| Steel, high grade | 2 x 6.4 t/km | 8 x 24 t/km | " |
| Steel, low grade | 2 x 75 t/km | | " |
| Concrete | 2x 200 t/km | | " |
| Ceramics | 2 x 2 t/km | | " |
| Copper | | 8 x 19 t/km | " |
| Lead | | 8 x 17 t/km | " |
| Polypropylen | | 8 x 2.3 t/km | " |
| Paper | | 8 x 6 t/km | " |
| Impregnation | | 8 x 1 t/km | " |

**Table 5-6: Parameters for the long-distance transport of 10 GW line capacity /May 2005/.**

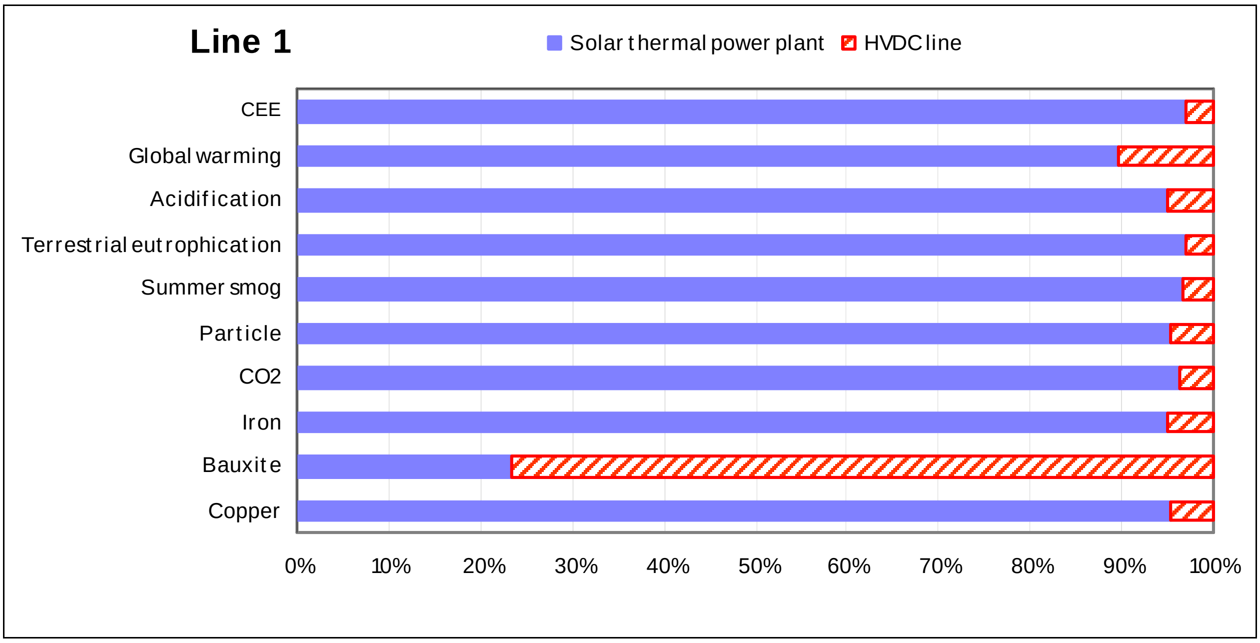


**Figure 5-13: Proportional shares of the plant and the line in environmental impacts (line 1, reference year 2030). CEE = cumulated energy expenditure.**

The proportional shares of plant and line in the environmental impacts of the entire facility is given in Figure 5-13. It is evident that the impacts are mainly caused by the solar thermal power plant. Only the aluminium demand is significantly higher for the HVDC line. If the submarine cable link is just long enough, approximately 300 km, the need of copper also increases (Figure 5-15).

### Solar Thermal Power Plant Impacts

Negative impacts and resource consumptions are mainly caused by the production process of the solar field, which requires a considerable material expenditure because of a size of 15 km x 15 km for a 10 GW installation. Altogether 91 % of the iron flows into the production of the steel girder for the solar field and 97 % of the copper is used for the production of pumps and control lines. About 93 % of the bauxite is meant for the alloy of high-grade steel, which is mostly needed for the absorber tube of the solar heat collecting element. The material expenditure of the residual components of the facility is low in comparison to the solar field (Figure 5-14).

The cumulated energy expenditure (CEE) mainly accounts for 47 % of the construction of the solar field, of that nearly 41 % are used for steel, 30 % for the heat carrier oil phenol and just 15 % for flat glass.

In a high degree also the construction of the thermal storage, the material transport and the plant operation beside the solar field participate in emissions. Thus global warming potential of the solar field comes to 46 % and of the large storage capacity contributes with 27 %.

However, the material transport dominates the terrestrial eutrophication potential with 48 % and the summer smog with 37 %, the transport by trucks due to a large transport capacity.

The acidification potential of the solar field amounts to 43 %. The share of the ship transport is 10 % and is caused by using heavy oil as fuel.

Particle of the size < 10 µm are especially released during the steel production, accordingly high is the share of the solar field (69 %).

During the plant operation impacts arise chiefly in the form of summer smog. Furthermore, a certain need in energy must be met, which follows for the most part from the substitution of phenol. Every year 4 % of it is lost /Viebahn, 2004/.

Besides, the entire facility engineering, the constructional engineering and the steam turbine are not so important in the considered spectrum of impacts and material expenditures.

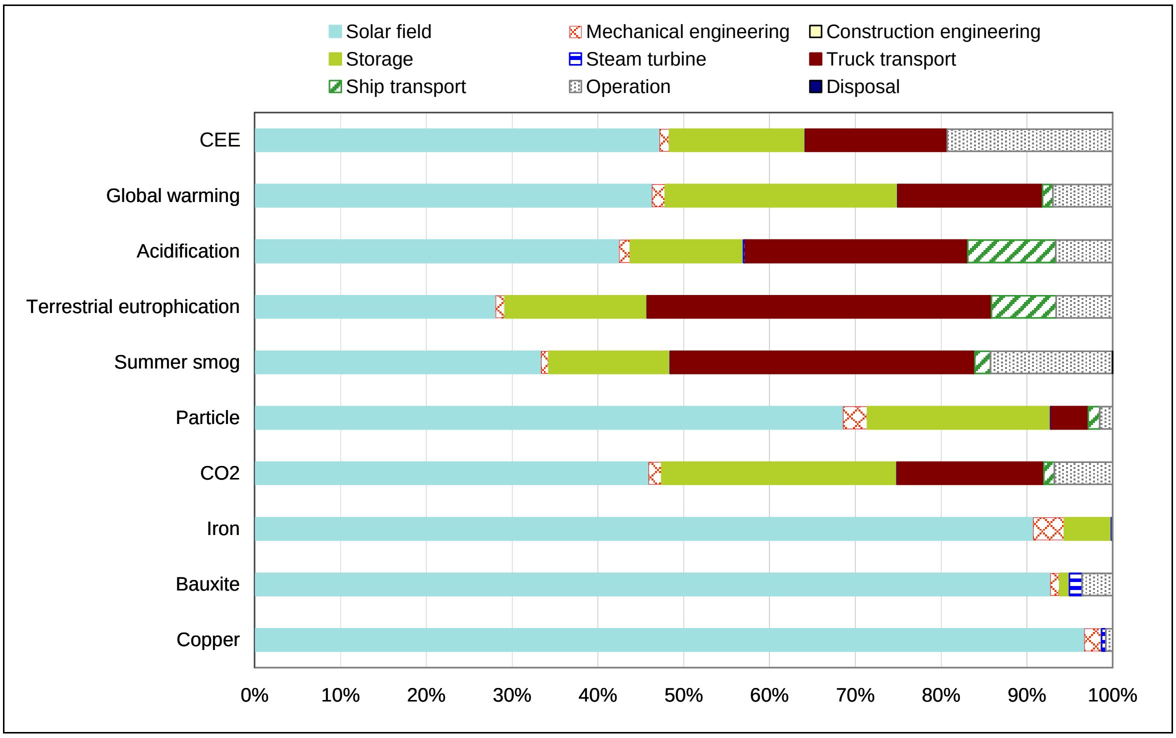


**Figure 5-14: Impacts and resource consumptions of single plant components and life cycle phases of the plant respectively (line 1, reference year 2030). CEE = cumulated energy expenditure.**

## HVDC Transmission Line Impacts

According to the low submarine cable share of 0.6 % in the total line the environmental impacts of the overhead line predominate (Figure 5-15).

About 67 % of the global warming potential is solely caused by the operation of the overhead line. The importance of the ionization of air molecules along the high voltage overhead line for the climate is normally rated as low. Because of the large length of the overhead line a distinct higher influence emerges. First of all it is because of the formation of the laughing gas (N2O), which is a 310 times more effective climate gas than $CO_2$.

About 75 % of the acidification potential is caused by the manufacture of the overhead line and only 6 % by the submarine cable manufacture. Altogether the transport amounts to 19 %.

The terrestrial eutrophication potential is dominated by the overhead line with 55 %, but the share of transport (43 %) becomes important as well, especially the truck transport with 36 %.

In the category summer smog the influence of the overhead line predominates; it adds 34 % to the steel production and 32 % to the aluminium production. The direct formation of ground near ozone because of ionization processes could not be represented with the underlying evaluation procedure yet.

Associated with the steel production it turns out that the overhead line again dominates the particle formation. Just 16 % go into the production of aluminium and concrete. Iron and bauxite resources are almost exclusively used for the manufacture of conductor wires and pylons, whereas the main portion of the copper consumption is caused by the submarine cable link in spite of its shortness.

About 84 % of the cumulated energy expenditure lies at the overhead line manufacture, of which 59 % go into the steel production and 21 % into the aluminium production. Within the submarine cable manufacture the considered impacts have to be added to the copper and lead production beside the steel production. The share of lead in the eutrophication potential amounts to 43 %, followed by steel (20 %) and the ship transport (19 %). The other components of the submarine cable such as paper, impregnation and synthetic envelopments have a smaller share in impacts. Their share in the cumulated energy expenditure comes to just 12 %, in summer smog due to a higher share of impregnation to 23 %. This picture looks different for the other lines because of a longer transport distance (see Figure 5-16). A detailed description of the complete analysis and the data for the other two lines can be found in /May 2005/.

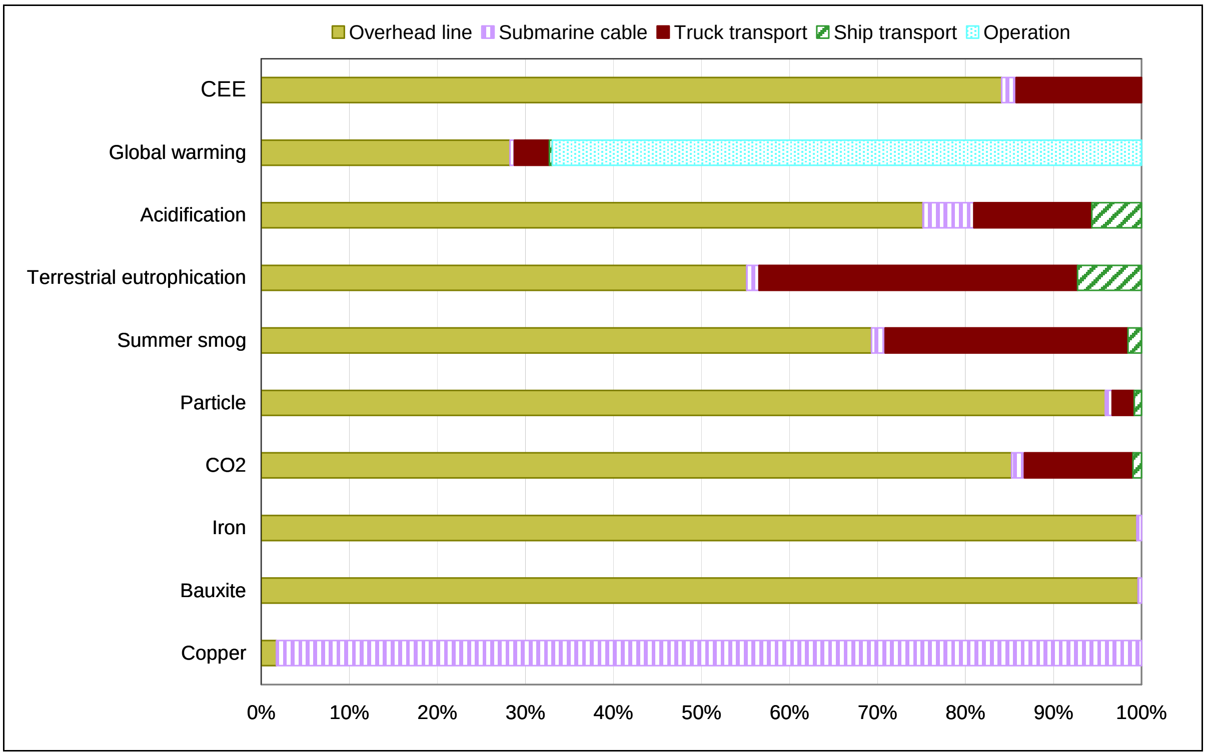


**Figure 5-15: Impacts and resource consumptions in the phases of life of the HVDC transmission line (line 1, reference year 2030). CEE = cumulated energy expenditure.**

### Comparison of the balances of all three lines

The environmental impacts of all three lines are normalized to 1 kWh free network electricity supply and depicted in Figure 5-16 and Table 5-7 for a comparative representation of the impacts categories and the energetic and material resource consumptions respectively.

Line 2 has the highest cumulated energy expenditure with 0.21 MJ/kWh because more energy must be raised for the truck transport. It looks similar for the global warming potential, which is also the highest by line 2. If the emissions arising during the operation of the HVDC transmission lines are considered, the differences in the length of single overhead line sections become clear.

Transport participates considerably in the acidification and eutrophication potential and in summer smog, in case of line 2 even to more than 50 %. The impacts of the ship transport increase according to the distance to North African harbours from line 1 to line 3.

In the acidification potential of line 2 the long submarine cable section turns out. The particle load is the highest in case of line 3. As all values have been normalized to 1 $kWh_{el}$, the higher losses of line 3 affect the results.

Altogether the impacts of the solar power plant dominate in comparison to the line. This concerns also the iron consumption, only the bauxite consumption is mainly defined by the length of the overhead line section. The share of the line of the copper consumption increases if the submarine cable section is just long enough.

The *cumulated energetic expenditure* for the single HVDC transmission lines depends on the length of the line and the transport capacity. Line 2 requires the highest *cumulated energetic expenditure* regarding plant construction due to a high transportation capacity, particularly in North Africa. The differences in the solar electricity generation also depend on the irradiance on-site.

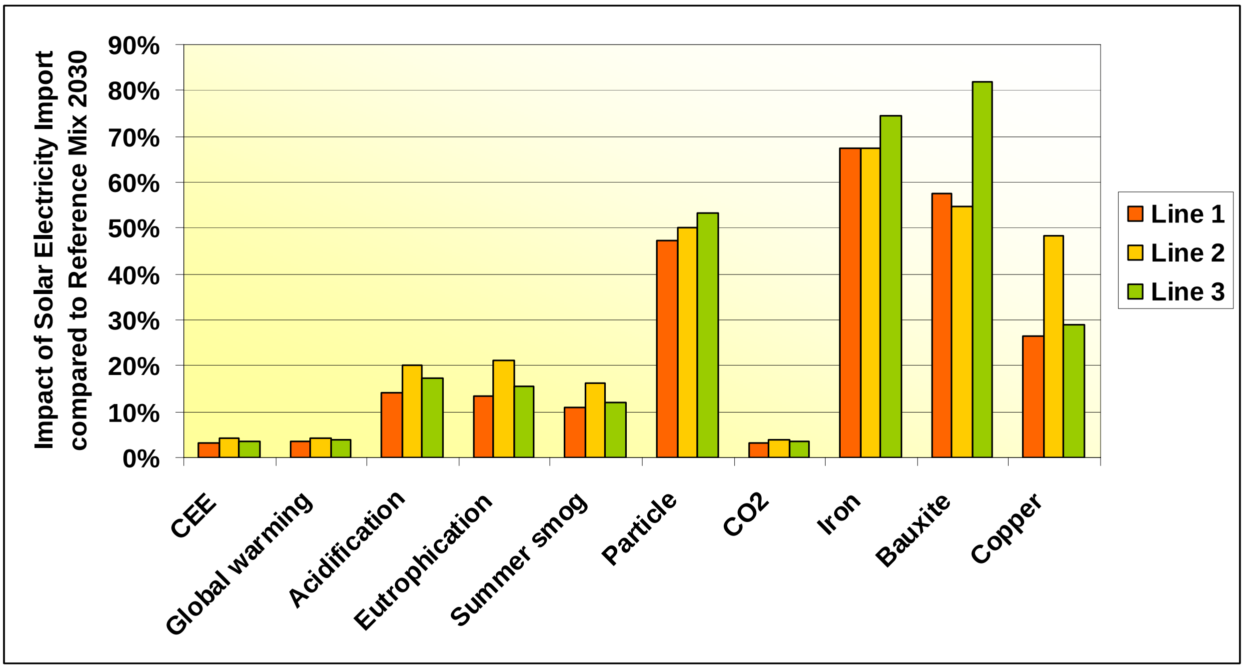


**Figure 5-16: Impact of solar electricity transferred from North Africa to Europe compared to the reference electricity mix in the year 2030 /May 2005/**

| Impact category | Unit per $kWh_{el}$ | Line 1 | Line 2 | Line 3 | Electricity mix 2030 | Line 1 | Line 2 | Line 3 |
|---|---|---|---|---|---|---|---|---|
| CEE | MJ | 0,17 | 0,21 | 0,18 | 5,17 | 3,3% | 4,1% | 3,5% |
| Global warming | g $CO_2$-Equi. | 13,78 | 16,50 | 15,00 | 403,54 | 3,4% | 4,1% | 3,7% |
| Acidification | mg $SO_2$-Equi. | 65,50 | 93,00 | 80,00 | 463,11 | 14,1% | 20,1% | 17,3% |
| Eutrophication | mg $SO_2$-Equi. | 6,87 | 10,80 | 8,00 | 51,32 | 13,4% | 21,0% | 15,6% |
| Summer smog | mg Ethylene | 2,57 | 3,80 | 2,80 | 23,26 | 11,0% | 16,3% | 12,0% |
| Particle | mg | 22,09 | 23,50 | 25,00 | 46,80 | 47,2% | 50,2% | 53,4% |
| $CO_2$ | kg | 0,012 | 0,015 | 0,013 | 0,38 | 3,2% | 3,9% | 3,4% |
| Iron | g | 1,50 | 1,50 | 1,65 | 2,22 | 67,6% | 67,6% | 74,3% |
| Bauxite | g | 0,019 | 0,018 | 0,027 | 0,033 | 57,6% | 54,5% | 81,8% |
| Copper | g | 0,005 | 0,009 | 0,006 | 0,019 | 26,3% | 48,4% | 28,9% |

**Table 5-7: Results of the life cycle assessment of required materials and emissions of solar electricity transferred from North Africa to Europe within the three analysed HVDC lines**

The energetic amortization time EAT states how long it takes until all energetic expenditures for the construction of the facility are compensated by the own electricity production. The mathematical equation reads:

$$EAT[a] = \frac{CEE_H}{\left(\frac{E_{net}}{g} - CEE_B\right)}$$

| | |
|---|---|
| $CEE_H$ | Cumulated energetic expenditure for the facility construction [MJ] |
| $E_{net}$ | Annual generated net energy amount [MJ/y] |
| $g$ | mean degree of utilization of the German power plant mix [%] |
| $CEE_B$ | Cumulated energetic expenditure for the facility operation [MJ/y] |

For *g* a value from literature of 31.4 % is used /Viebahn, 2004/. In Table 5-8 the amortisation times for all three solar thermal power plants including the HVDC transmission lines are listed (reference year 2030). Altogether the energetic expenditure amortizes after 4-6 months.

| | Unit | Line 1 | Line 2 | Line 3 |
|---|---|---|---|---|
| $CEE_H$ | [MJ] | 2.76E+11 | 3.50E+11 | 3.12E+11 |
| $CEE_B$ | [MJ/y] | 2.16E+09 | 2.20E+09 | 2.46E+09 |
| $E_{net}$ | [MJ/y] | 2.42E+11 | 2.42E+11 | 2.63E+11 |
| g | [%] | 31.4 | 31.4 | 31.4 |
| EAT | [year] | 0.36 | 0.46 | 0.42 |
| **EAT** | [month] | **4.3** | **5.5** | **5.1** |

**Table 5-8: Energetic amortization time (EAT) for the three lines.**

One important result of the life cycle assessment and eco-balance is that each installation composed of solar thermal power plant and associated HVDC line causes distinct lower environmental pollution than the reference electricity mix, even taking as reference the enhanced electricity mix of 2030. The energetic expenditure makes up a very small fraction of the reference electricity mix related to one kilowatt-hour. Merely the demand in iron is increased at 40 % due to the erection of the new infrastructure, but this does not represent any limitation regarding the feasibility of such a project.

Differences in performance of the three HVDC lines concerning the share of overhead line and submarine cable hardly influence the result. Only in case of a distinct longer submarine cable section (line 2) or overhead line section (line 3) appears a higher demand in material resources like copper, iron and bauxite.

By means of these results it turns out that, even in an integrated consideration from the provision of original materials over the production and operation of the installation to its disposal, the cumulated environmental impacts are many times lower than the impacts through the conventional energy supply system. Besides, no highly risky waste products are produced, which survive in the long-term such as nuclear waste, whose consequence for the future, anyway, can be hardly estimated.

Besides, it is also a cheap kind of energy supply possible if solar thermal power plants are used in a large scale and all cost reduction potentials are exhausted. Nevertheless, its expansion decisively depends on political framework conditions. At the end of this paper the general statement can be formulated that, from an ecological point of view, nothing is opposed to the expansion of solar thermal energy in North Africa and a transmission of the generated solar electricity to Europe.

Finally it is remarked that the different forms of renewable energy in their great variety show together a major capacity, what does justice to a secured, independent, socially and environmentally compatible and affordable, global energy supply in the long-term.