1 Solar Electricity Transfer from MENA to Europe

The option of producing solar[1] electricity under the ideal meteorological conditions in the sunbelt countries of the Middle East and North Africa (MENA) and transferring part of this electricity to Europe (EU) has been discussed and proposed in many occasions in the past /Knies et al. 1999/, /TREC 2006/, /Asplund 2004/, /Czisch 2005/, /DPG 2005/, /WBGU 2003/.

It also has been proposed to use hydrogen as energy carrier to produce storable renewable energy comparable to fuel oil and natural gas to supply electricity, heat and transportation. However, as brought to the point by /Bossel 2005/, a solar electricity transfer by hydrogen would force three quarters of the solar power generators to work exclusively for covering the energy losses of the hydrogen conversion chain (Figure 1-1). Under this perspective, the use of hydrogen as an energy carrier for solar electricity from North Africa to Europe must be discarded.
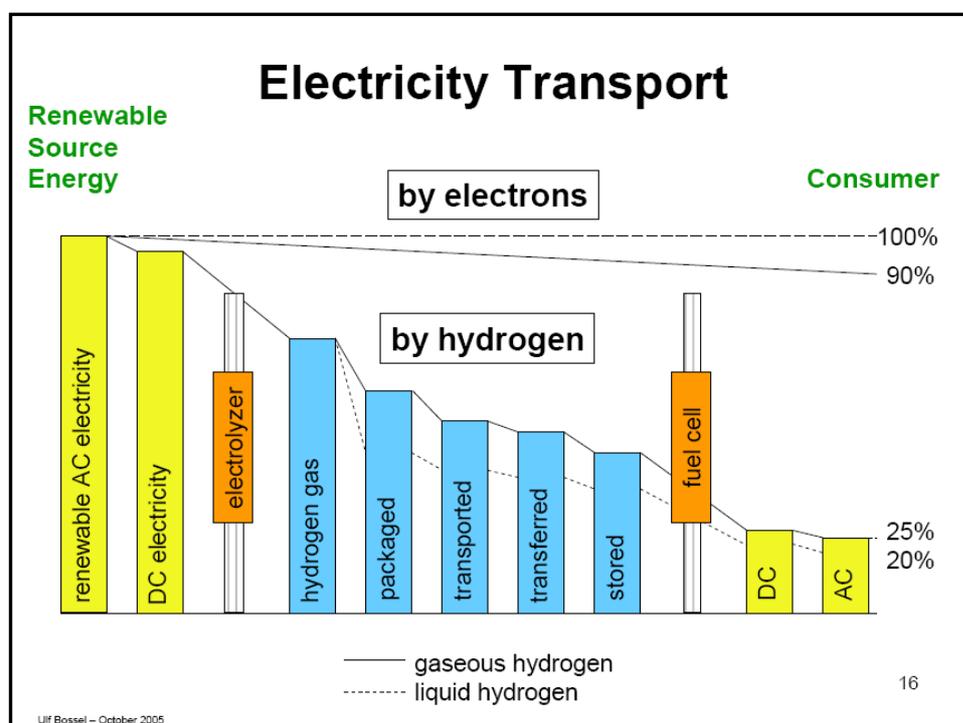

Figure 1-1: Comparing the losses of electricity transport by electrons and by hydrogen /Bossel 2005/

This chapter describes the technical possibilities of solar electricity transfer through the conventional alternating current (AC) electricity grid and by means of an additional future backbone grid based on high voltage direct current (HVDC) technology.

1.1 Present Electricity Transfer Capacities in EUMENA

The interconnected synchronous European network of the Union for the Coordination of Transmission of Electricity (UCTE) supplies about 450 million people with electric energy.

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1 This does not exclude wind energy or other renewables, as they will be part of a future electricity mix. However, solar energy is the only renewable energy source that is superior to the expected future electricity demand in MENA and thus the only source that could produce significant surpluses for export to Europe /MED-CSP 2005/.

Europe has a very dense network of high voltage power lines of different capacity, from 132 kV to lines with 750 kV (Figure 1-2). Currently, the union counts 23 member states, 33 transmission providers and 230,000 km in the high voltage network supplying 2300 TWh/y at an installed plant capacity of 560 GW. In wide parts of the UCTE 380 kV is the highest voltage level, whereas transmission voltages of 500 kV, 750 kV and even 1200 kV are used in other countries outside the UCTE, for instance Russia, in order to bridge very long distances. At a voltage over 800 kV it is also spoken of ultra high voltage /Kießling et al. 2001/.
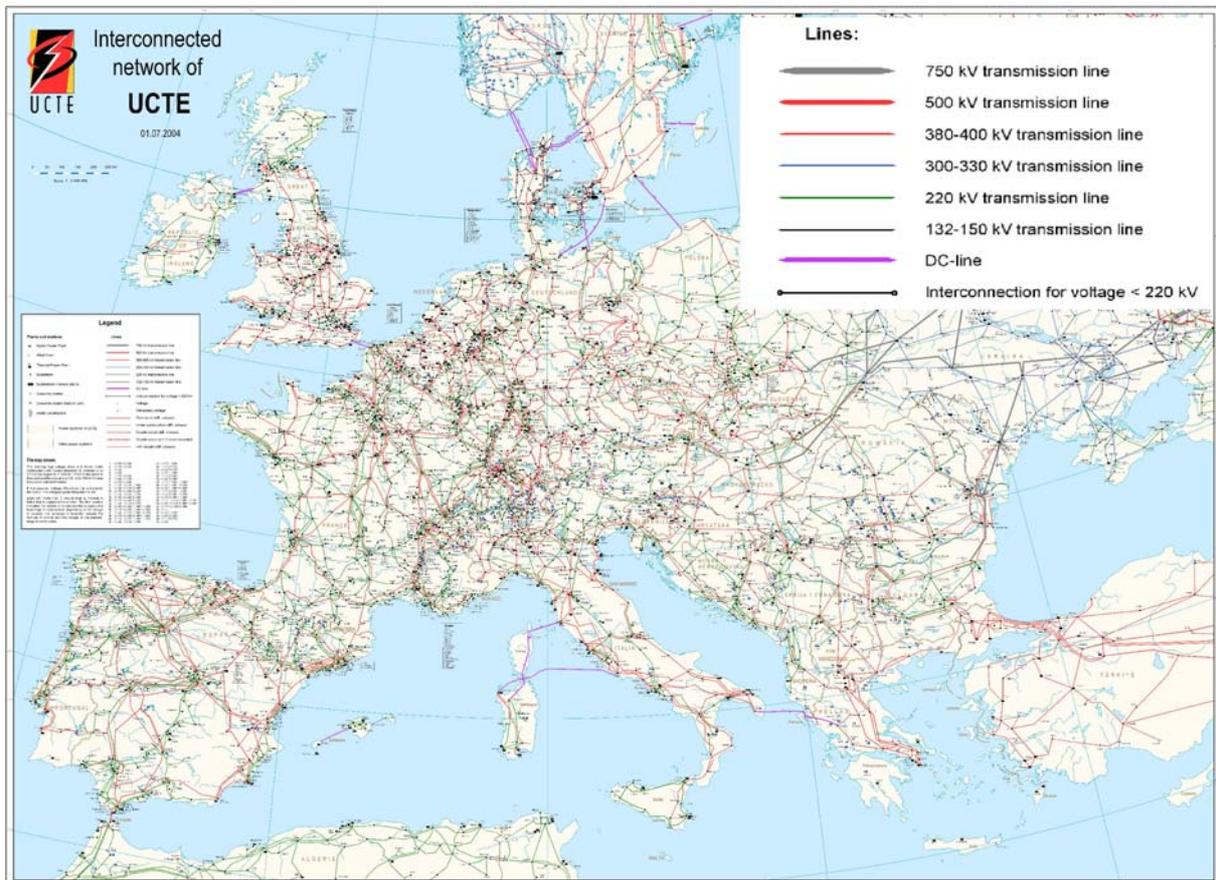

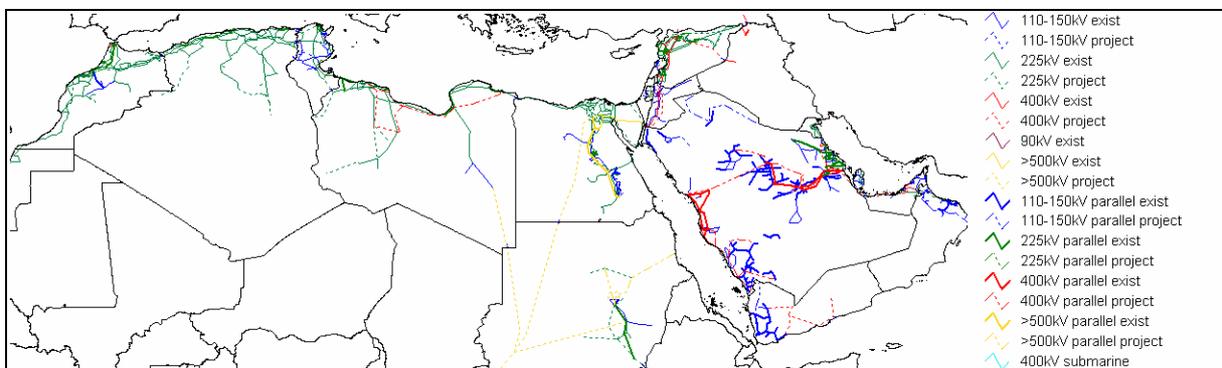**Figure 1-2: Present interconnected network of UCTE and neighbouring regions /UCTE 2005-2/.**

Figure 1-3: Present interconnected network of the North African and Middle East countries /NERC 2004/.
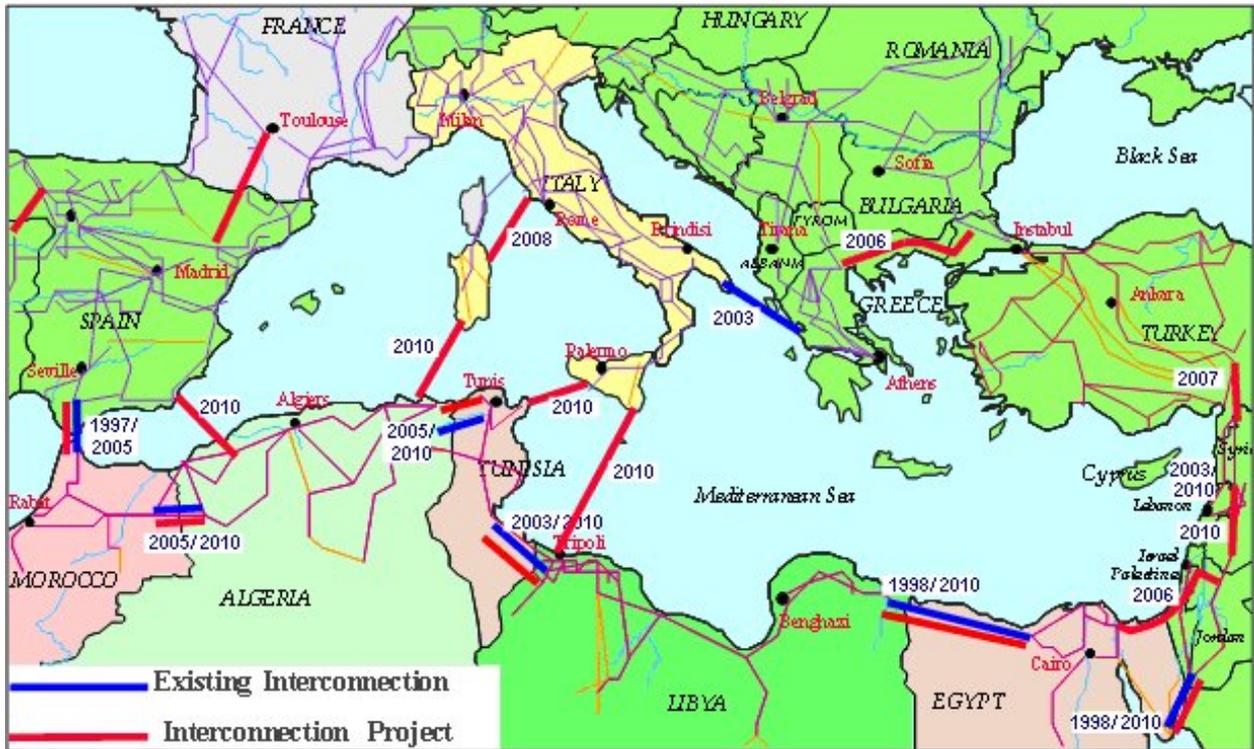
Figure 1-4: Networks and interconnection projects until 2010 in the Mediterranean region /Hafner 2005/

Project	Thermal limit [A]	Length [km]	Voltage [kV]	Design	Year of operation
Spain-Morocco	960	28,5	400 AC	Submarine cable	2005
Spain-Algeria	2000		500 DC	Submarine cable	2005/2010
Italy-Algeria			400/500 DC	Submarine cable	2010
Italy	Tunisia	500	500 DC	Submarine cable	2010
Algeria-Morocco	2 x 1720	250	220 (400) AC	Submarine cable	2003/2005
Algeria-Tunisia	1720	120	220 (400) AC	Submarine cable	2004/2010
Tunesia-Libya		210	400 AC	Submarine cable	2010
Libya-Egypt			400/500 AC	Overhead Line	2010
Reinforcement (ELTAM)			400 AC	Overhead Line	2010
Egypt-Jordan	880	20	500/400 DC	Submarine cable	2008
Egypt-Palästina	1440		220	Overhead Line	2005
Palästina (WB-Gaza)	1440		220/240	Overhead Line	2006
Palästina-Jordan	1450		400	Overhead Line	2006
Jordan-Syria		210	400 AC	Overhead Line	2010
Lebanon-Syria	1660	22	400 AC	Overhead Line	2003/2010
Syria-Turkey	1440	124	400 AC	Overhead Line	2007
Turkey-Greece	2165/2887	250	400 AC	Overhead Line	2010

Table 1-1: Planned interconnections between Mediterranean neighbouring states /OME, 2003/.

Both the British island network and the Scandinavian network of NORDEL are linked to the UCTE network by submarine cables. Since 1994 some European states have been able to make use of the major hydropower potentials of Scandinavia. The CENTREL states have been connected to the interconnection network since 1995 and have been full members only for short time. Since 1997 the interconnection with the Maghreb states has been realized by a submarine cable, through which approximately 1.5 TWh/y have been exchanged. Rumania and Bulgaria

have been the latest members since 2003. UCTE 2 as a former part of the synchronous network was separated by the war in former Yugoslavia in the year 1991 and has been integrated again recently.

The electricity grid in North Africa and the Middle East is much less dense than in Europe, and – following human activities – concentrated to the coastal regions and the Nile valley (Figure 1-3). The major part of the existing MENA network is based on 220 kV. Only between Egypt, Jordan and Syria and between several Mediterranean neighbouring states of the EU exist 380 kV lines. Since 2003 there has been a single 630 kV interconnection between Libya and Tunisia. The so-called 'MED-Ring-Project' of the South Eastern Mediterranean Countries (SEMC) and the North Mediterranean Countries (NMC) is aimed at closing the networks around the Mediterranean Sea (Figure 1-4 and Table 1-1). Final closing of the ring by coupling the Turkish block and the UCTE block will result from the connection between Syria and Turkey scheduled in 2006 /Eurelectric 2003/. The ring will have an overall net transfer capacity of about 400 MW in 2010.
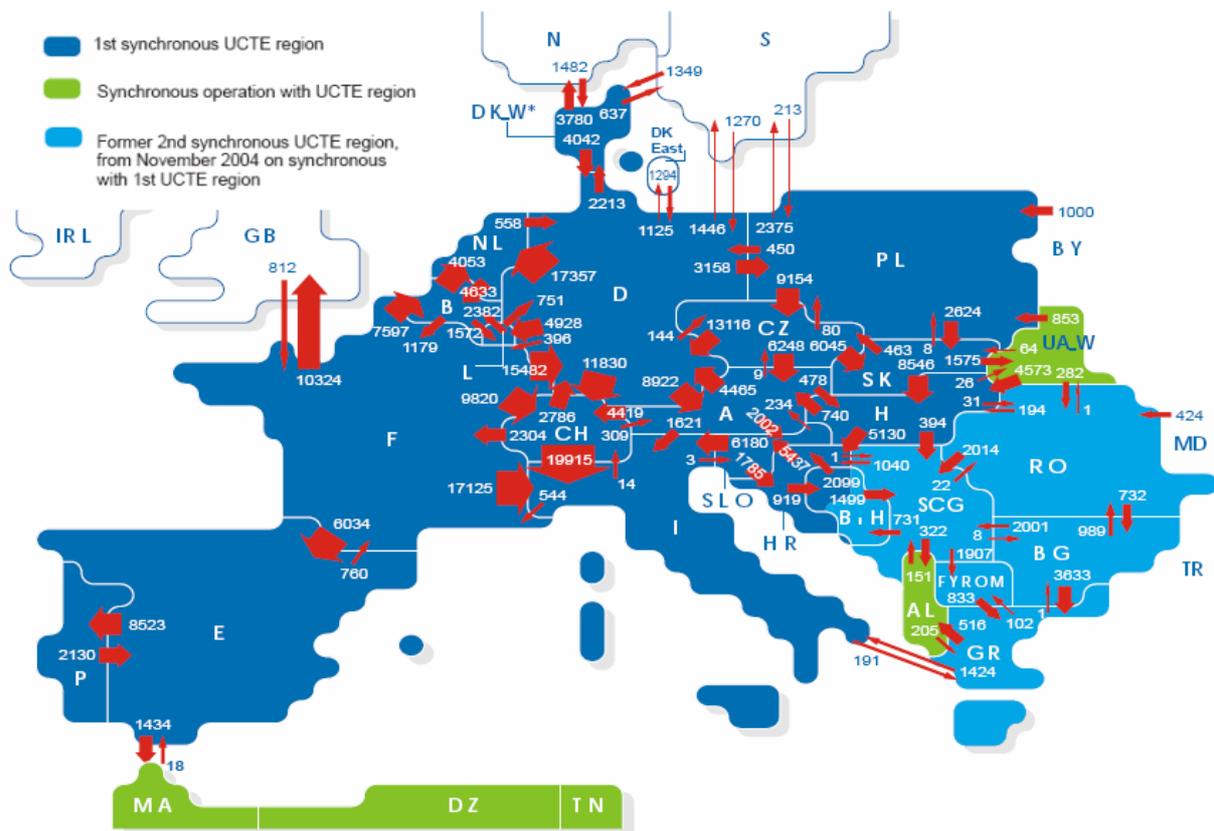

Figure 1-5: Physical electricity exchanges in GWh/y in the UCTE grid in 2004 /UCTE 2005-1/

The benefits of such a large grid interconnection are the gain of additional reserve capacity and the compensation of local power and plant outages respectively. The so-called 'n-1 criteria' guarantees a secure supply by substituting one broken plant for another intact. Within a large grid there is a higher utilisation of the single power plants, and the electricity exchange over national borders is easier (Figure 1-5). In the year 2004 electricity exchanges inside the UCTE interconnection network amounted to approximately 270 TWh for import and 281 TWh for export /UCTE, 2005a/. The largest amounts of electricity are transferred from Germany to Netherlands and from France and Switzerland to Italy, ranging in the order of 17-20 TWh/y.

Looking at the net power transfer capacities in northern direction (Figure 1-6) it becomes clear that the capacity of the conventional electricity grid for solar electricity from North Africa is very limited. Although there are very large transfer capacities across the borders of Switzerland, there are limitations within the rest of the grid, with about 2500 MW in the central European region and about 400 MW limiting the interconnections between Europe and MENA. Even assuming that MENA will expand in the medium and long term it's electricity grid to achieve values comparable to those in Europe today, this would restrict the net transfer capacities to the order of 3 GW or 15 TWh/y (or two times this value accounting for both the Western and Eastern interconnection). In view of the required capacity of around 600 GW or 2500 TWh/y in terms of annual electricity consumption, a solar electricity transfer from MENA to Europe in the medium and long term through a mature, conventional AC electricity interconnection would therefore be restricted to about 1 % of the European demand. If we assume that all six EUMENA interconnections shown in Figure 1-4 would be empowered to a net transfer capacity of 2500 MW each, solar electricity transfer through the common AC grid could reach about 3.5 % of the European demand under the condition that those links would exclusively transfer electricity from South to North and not be congested by other uses.
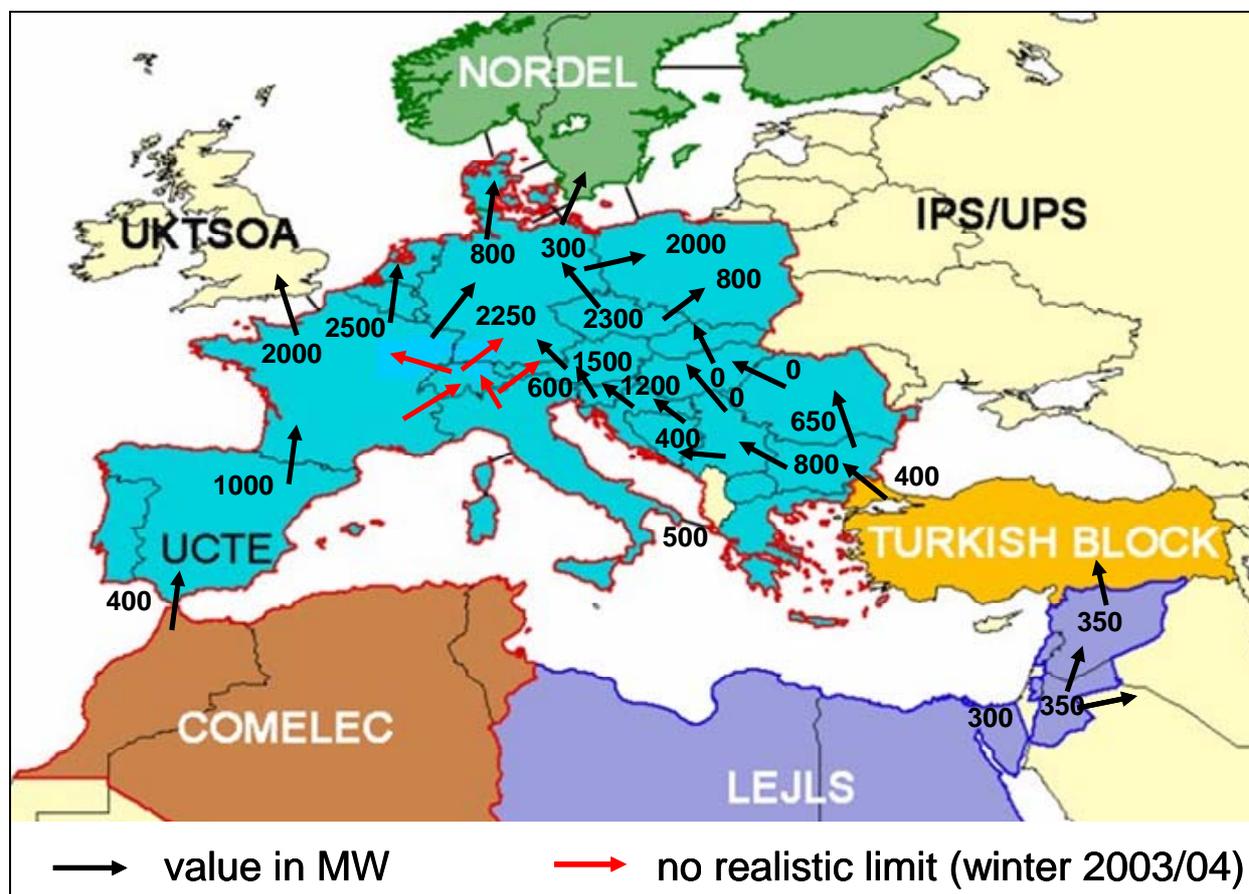

Figure 1-6: Present net transfer capacities in EUMENA in Northern Direction. Source: /etso 2004/, /Eurelectric 2003/. The bottleneck of transfer capacity from MENA to Europe is at present about 400 MW. Assuming that EUMENA would achieve a transfer capacity standard as Central Europe today, it could increase to about 2500 MW by 2050. This would allow an annual electricity transfer of less than 15 TWh/y through each north-south interconnection.

1.2 High Voltage Alternating Current Transmission (HVAC)

In the European high voltage area electric energy is mainly transmitted in the form of three-phase alternating current, whose direction and amount changes with a sinusoidal periodicity. The frequency of the European electricity supply network amounts to 50 oscillations per second, which means, that the current flows 50 times per second in the same direction. Here, the current is also called three-phase alternating current because of three time-shifted phases. Single-phase alternating current is mainly applied in public railway traffic.
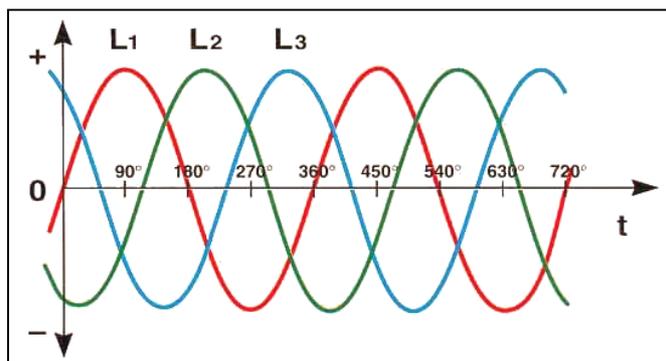

Figure 1-7: Three-phase alternating current /Leuschner 2005/.

Alternating current is produced in a power plant by a generator, whose magnet is driven mechanically and passes three 120°-shifted coils during one rotation. Accordingly, the induced alternating currents are also 120°-phase-shifted. Each current is forwarded by the respective conductor. Because with symmetrical load the sum of the three currents amounts to zero at every moment, there is no need to have a return wire like in case of single-phase alternating current.

The decisive advantage of three-phase alternating current is the simple regulation of voltage and frequency. The voltage can be stepped up and stepped down with few losses by a transformer and everywhere it is possible to branch off electrical power with the same. In addition, engines driven by alternating current can be produced small, compact and cheap /Leuschner 2005/.

One disadvantage is that the synchronicity of producer and consumer voltage is absolutely necessary. Otherwise, unwanted swings could lead to serious problems with the network stability. The failure of one conductor results in the total failure of the whole circuit.

Losses of alternating current

The current-carrying conductor produces a magnetic field around itself. If it concerns alternating current, this magnetic field changes periodically and induces a voltage. Thus the power line behaves like a coil and puts up resistance to the alternating current through self-induction, that in turn causes a decrease in current. This is called the inductive reactance when the voltage runs in front of the current at a maximum phase angle of 90°.

In the opposite case alternating current is intensified because of the capacitive reactance so that the voltage runs after the current. The problem of storage of electric charges especially occurs with cables, which behave like a condenser due to their multi-layered structure.

These resistances cause no heat losses in contrast to the Ohmic resistance, but they create a un usable reactive power which swings permanently between generator and power source and reduces this way the effective power capacity.

The maximum transferable load and transmission length are more limited by the drop of voltage along the line than by the thermal power rating of the conductor. That is why in practice installations for the compensation are used every 600 kilometres /Rudervall et al. 2000/.

Losses of Overhead Line

In addition to current-dependent losses there are also voltage-dependent losses in the form of gas discharges in areas of heavy curved surface and high field strength. These requirements are fulfilled by the conductors. If then the electric field at the conductor surface (fringe field) exceeds the disruptive field resistance of air, the ionization of air molecules is possible. Electron-impact ionization can happen if previously released electrons hit neutral molecules. The energy needed for that is taken from the electric field.

Such corona discharges can be perceived as a luminous appearance and crackling sounds. Therefore bundle conductors restricting the field strength at the fringe are utilized from 110 kV upwards. At the same time the transferable load increases because the cross-section of the conductor is apparently enlarged by overlapping of the single fields.

In the annual mean the corona losses amount to approximately 2-3 kW/km for a 400 kV-system /Laures 2003/. /Knoepfel 1995/ states 1-10 kW/km for a 380 kV system and 2-60 kW/km for a 750 kV system that strongly depends on the respective atmospheric conditions and can be neglected in this order of magnitude.

Altogether losses in high voltage AC-systems come to 15 %/1000 km (380 kV) and 8 %/1000 km (750 kV) respectively. In addition to this, each transformer station can loose 0.25 % of the energy /Knoepfel 1995/.

Losses of Ground Cables

In case of ground or sea water cables it is also distinguished between current-dependent losses, which only appear while electricity flows, and voltage-dependent losses, which appear under the effect of an electric field in the isolation and therefore are described as dielectric losses.

Heat losses in the conductor and additional losses in the metallic sheath, screen and armour belong to current-dependent losses. Current heat losses increase with the power of 2 with the current. For that reason it is generally aimed at keeping the current as small as possible by raising the voltage. Nevertheless, there are ohmic heat losses caused by the conductor material, which increase proportionally to the transmission length and furthermore depend on the conductor cross-section and the operational temperature. These current heat losses increase more if the frequency rises due to self-induced turbulent currents in the magnetic field of the conductor. As they are directed to the opposite of the operational current, this current is displaced at the edge of the conductor ('Skin-Effect'). Thus it cannot use the whole cross-section of the conductor and, in addition to this, the risk of exceeding the maximum allowable temperature of the conductor increases because of the high current density in the outer rim.

Moreover, turbulent currents can be generated by magnetic field emissions of adjacent cables, which become more intense with an increasing distance of cables ('Proximity-Effect'). Here a triangle arrangement of phases has a better effect than side by side laying of cables.

Additional losses can occur in the residual metallic components of the cable. Induced current losses (longitudinal-voltage induction) and turbulent current losses in the jacket and the same losses together with magnetisation losses in the steel armour belong to it. Applicability of an alternating current cable is limited by two aspects /Peschke, Olshausen 1998/:

Maximum transmission length

The capacitive charging current increases proportional to the cable length and overlays the actual effective load at the same time. This is especially the case of cables with a multi-layered isolation. The capacity of a cable rises with the increasing relative permittivity and rated voltage. The maximum transmission length of a 380 kV-cable with 1000 mm² copper conductor and paper isolation amounts to just 35 km due to the capacitive charging current. A VPE[1]-cable has a reach of 50 km instead. If dielectric losses are included, this length is more reduced. The resulting reduction of the voltage endangering stability along the line must be counteracted by compensational measures (which is of course very difficult for underwater cables).

Maximum transmission capacity

The transmission capacity only increases up to a certain voltage level, which depends on the dielectric properties, and after that decreases again. The higher the dielectric loss and the smaller the heat removal, the sooner the economic cut-off voltage is reached. Accordingly, the cut-off voltage of a 1600 mm² copper conductor with paper isolation comes to approximately 500 kV and with a VPE-isolation to more than 1200 kV. The transmission capacity of an underground cable is particularly limited by the removable heat lost. On optimum conditions a maximum heat removal rating of 90 W/m can be realized. Hence there is a thermal breakeven performance of approximately 1000 MVA for an oil-paper cable with 2500 mm² copper conductor and approximately 1450 MVA for a VPE-cable at a transmission voltage of 500 kV. Altogether an AC-cable system can only reach 50 % of the capacity of an overhead system in spite of lower heat losses. For the same transmission capacity it calls for a double cable system, an artificial cooling or a completely different transmission technology.
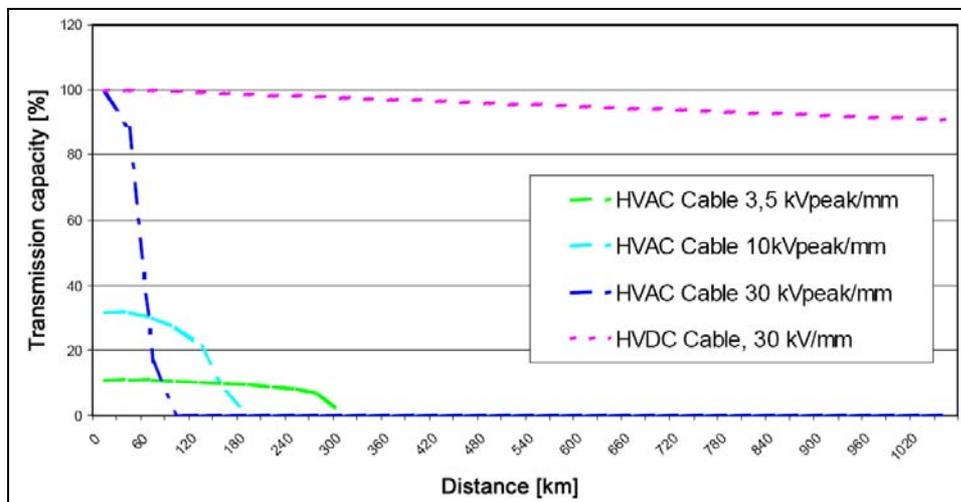

Figure 1-8: Comparison of transmission capacities of AC- and DC-cables (Source: Asplund, o. J.).

Figure 1-8 shows how the transmission capacity of an AC sea cable is rapidly reduced with increasing distance. Moreover, it becomes clear that with an AC-cable at a lower voltage it is possible to bridge long distances, but only transmitting less energy. Therefore compensational measures would be required, which are not realizable with submarine cables in practice.

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1 isolation with polyethylen grid structure

1.3 High Voltage Direct Current Transmission (HVDC)

Direct current flows continuously in one direction with a constant amperage. It can be generated by electrochemical processes or by rectification of alternating current. In case of rectification the amount of amperage can change periodically because of a rest of ripple.

Capacity and losses

The utilization of direct current has diverse advantages if compared with alternating current. First of all the transmission length is only limited by ohmic resistance. The cheaper the power input is, the less important the heat losses are. Besides, there are no capacitive, inductive or dielectric losses which would result in a drop of voltage along the line. Current displacements at the edge of the conductor, which are typical for alternating current, do not matter as well so that the whole cross-section of the conductor can be used up to the thermal breakeven point.

The circumstance that no reactive power is transmitted with direct current causes a further increase in power by transmitting sheer effective power. Reactive power must only be provided for the inverse transformation by the rectifier.

In comparison with a three-phase AC-system of three conductors a high voltage direct current transmission requires only two conductors (bipolar case) or just one conductor (monopolar case) while the current flows back via earth (Figure 1-9). This leads to lower costs for the lines, especially at long distances. The requirements on the line also turn out lower regarding pylon height and width.

If one conductor of a bipolar HVDC fails, a short-term back current is possible for approximately 10 minutes via earth while the transmission capacity is halved. This way much more time is available to bridge areas concerned than in case of a conventional system where failures occur within split seconds /Peschke, Olshausen 1998/, /Schymroch 1985/.

Stability and controllability

HVDC can contribute to security of the network stability, for instance by connecting power plants with a high energy rating. Because no short-circuit currents can be transmitted, the short-circuit current is equal the nominal current in fact.

A direct current system has no problems with stability in principle and is quickly adjustable via rectifiers. However, rectifiers cannot be overloaded. The controllability of the power flow in amount and direction is gaining increasing importance in decentralized electricity markets. Since the source voltage and the voltage at the load are allowed to be asynchronous, HVDC as back-to-back station is predestined to couple networks with different frequencies /Schymroch 1985/.

Disadvantages

Direct current has the disadvantage of not being directly transformable to another voltage, by which the erection of networks with different voltage levels becomes difficult. Besides, it is not easy to switch off the current with conventional switches at a high network voltage. A subsequent branching of power is also difficult in an existing direct current system and is only possible via an additional rectifier, which shows higher investment costs and a higher space requirement than usual power substations /Beck 2000/.
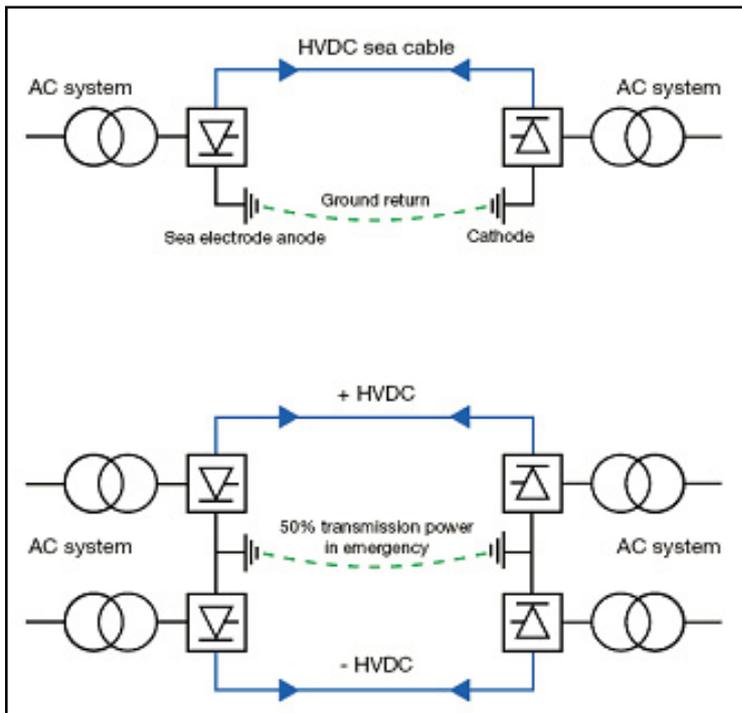
Figure 1-9: Schematic diagram of the interconnection of a monopolar (above) and bipolar HVDC system (below) with the conventional AC grid /Söderberg, Abrahamsson 2001/.
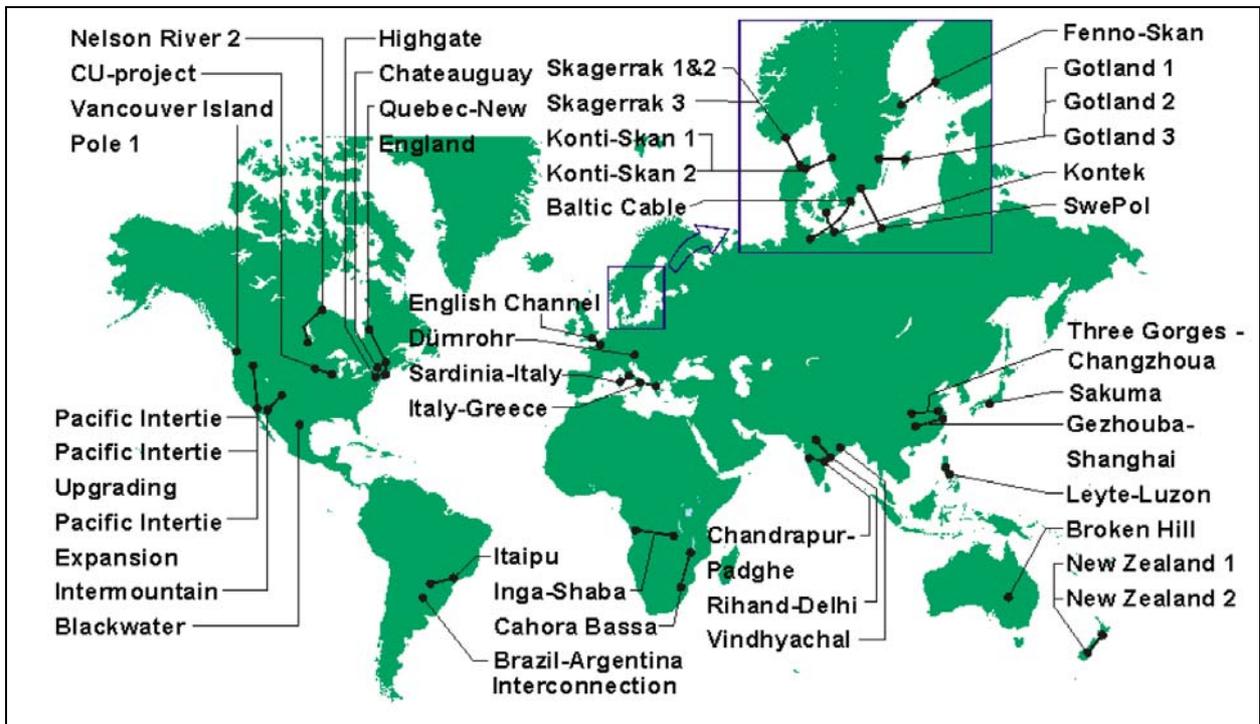

Figure 1-10: World wide HVDC transmission lines cumulate today to a total cpacity of over 75 GW in more than 90 projects. Put in one line, they would reach around the globe. Many of them connect renewable power sources from hydropower (e.g. Inga-Shaba, China, Brasil, New Zealand) or geothermal power (e.g. Phillipines) with distant centres of demand. Others are used to interconnect countries over sea (e.g. SwePol, Baltic Cable, Italy-Greece, Sardinia). (Source: www.abb.com).

Nowadays a power of about 75 000 MW is transmitted by HVDC lines in more than 90 projects all over the world (Figure 1-10 and Table 1-2). Nevertheless, the potential of this transmission technology is not fully utilized. For the long-distance transmission of electricity with overhead lines the voltage level will increase at 800 kV in the near future. This means that one pole will have a capacity of 2500 MW. In this context it is also spoken of 'Ultra High Voltage Direct Current' (UHVDC).

The development to higher transmission voltages is also foreseeable in the ground and sea cable manufacture. Thus a bipolar ±600 kV mass-impregnated cable would be able to transfer 2000 MW. Oil-pressure cables would be able to transfer 2400 MW at the same voltage level. Indeed, they can only be used for middle distances. Lately, HVDC-light cables are built in the range of ±150 kV which are also able to transfer 700 MW (bipolar case) over long distances /ABB 2005/.

Hence, the following applications for HVDC are feasible:

• 2-point transmission over long distances

• Utilization as submarine cable

• Utilization as underground cable in congested areas

• Connection of asynchronous networks via back-to-back station

• Connection of power plants

• Multi-terminal system (> 2 stations)

HVDC/country	Design[*]	Start of operation	Power [MW]	Voltage ±[kV]	Length [km]	System
SACOI/Sardinia-Corsica-Italy	SC, O	1967	300	200	423	Bipole, Multi-terminal
Cahora Bassa/ Mozambique-South Africa	O	1977-79	1930	533	1420	Bipole, 2 lines
Inga-Shaba/Congo	O	1982	560	500	1700	2x Monopole
Itaipu/Brasilia	O	1984-87	6300	600	800	Double-Bipole
Québec-New England/Canada-USA	O	1990-92	2000	450	1480	Bipole, Multi-terminal
BalticCable/Swe-Ger	SC	1994	600	450	250	Monopole
SwedPol/ Sweden-Poland	SC	2000	600	450	260	Monopole, Metallic return
Italy-Greece	UC, SC, O	2001	500	400	310	Monopole
Murraylink/Australia	UC	2002	220	150	177	Bipole, HVDC Light
NorNed/Nor-NL	SC	2007	700	450	580	2x Monopole

*O – overhead line, SC – submarine cable, UK – underground cable

Table 1-2: Selection of HVDC Links /ABB 2005/

1.4   Performance, Economy and Impacts of High Voltage Transmission

The cost of transferring electricity is dominated by the investment cost of the transmission lines and by the electricity losses during transmission. Table 1-3 compares the losses and investment cost of AC and DC transmission lines at comparable voltage levels for a transmission of 5 GW.

At present, overhead lines predominate since the cost of an overhead line amounts to only 15 - 20 % of the cost of a ground or sea cable /Schlabbach 2003/. The transmission losses of HVAC overhead lines are roughly twice as high as those of HVDC. The cost of overhead lines is similar for the lower voltage level, but at 800 kV HVDC lines are much less expensive than comparable AC lines. On the other hand, rectifier stations of HVDC links are considerably more expensive than the transformer stations of AC systems. Therefore, for shorter distances and lower voltages AC is often the preferred choice, while HVDC lines are applied at distances well over 500 km (Figure 1-11). The high losses and cost of HVAC sea cables limits their applicability to about 30 kilometres, however HVDC is preferably applied for this and for longer distances.

Parameter	Unit	HVAC		HVDC	
Operation Voltage	kV	750	1150	± 600	± 800
overhead line losses	%/1000 km	8%	6%	5%	2.5%
sea cable losses	%/100 km	60%	50%	0.33%	0.25%
terminal losses	%/station	0.2%	0.2%	0.7%	0.6%
overhead line cost	M€/1000 km	400 - 750	1000	400 - 450	250 - 300
sea cable cost	M€/1000 km	3200	5900	2500	1800
terminal cost	M€/station	80	80	250 - 350	250 - 350

Table 1-3: Cost and performance parameters of high voltage alternate current and direct current transmission systems from different references according to /May 2005/ and own calculations for 5000 MW rated transmission capacity.
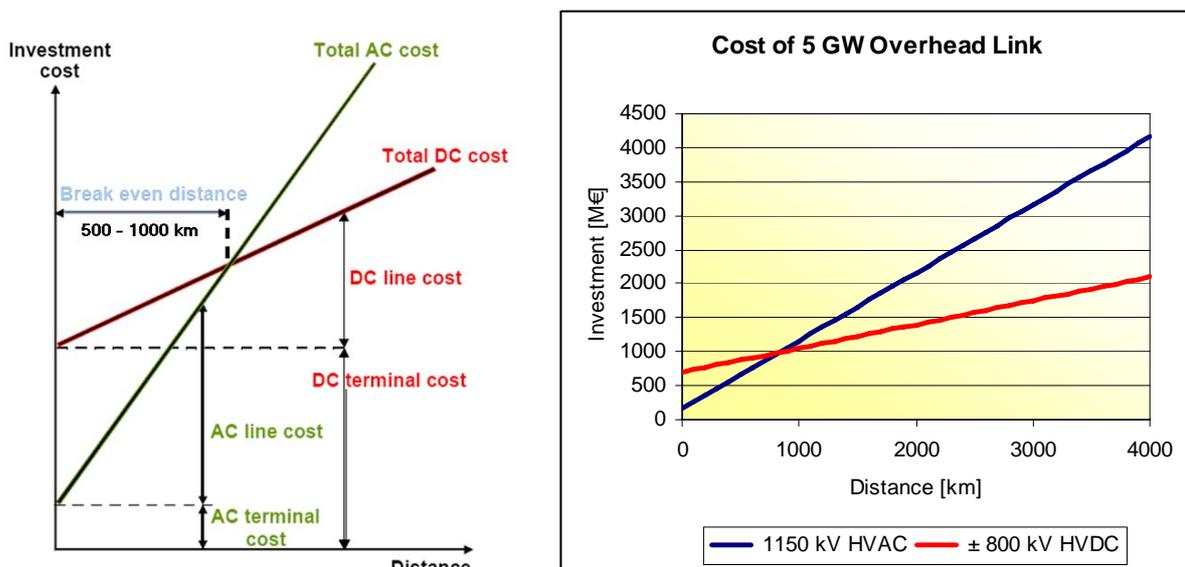

Figure 1-11: Comparison of AC and DC investment costs /Rudervall et al. 2000/ (left) and cost model used here for a 5 GW interconnection with overhead line (right). Break even point is at 830 km distance.

The so-called 'Break-Even-Distance' terms the shortest distance where the investment costs of a direct current transmission are identical with the costs of an alternating current transmission. It depends on the transmission capacity and topography of the area in detail /Heuck, Dettmann 2002/. In the beginning high investment costs of the rectifier make a significant difference compared with the lower cost of transformers. With an increasing transmission length the total costs of HVAC are affected by the higher costs for conduction and network losses so that many advantages result from the use of HVDC from the 'Break-Even-Point' upwards. In addition, the maximum transferable loads are not restricted by the thermal limit of the conductors, but by the guaranty of a stable voltage along the line. In contrast in case of HVAC, additional costs must be added for compensational measures realized every 600 km /Rudervall et al. 2000/.

In the TRANS-CSP model the following assumptions have been made for costing HVDC:

➢ Voltage ± 800 kV, Unit Capacity 5 GW

➢ Overhead Line Investment 350 M€/1000 km

➢ Sea Cable Investment 2500 M€/1000 km

➢ Converter Stations Investment 350 M€/Station

➢ Overhead Line and Cable Losses 2.5 %/1000 km, Stations 0.9 %/Station

➢ Economic Lifetime 40 years

➢ Discount Rate 5 %/y

➢ Operation & Maintenance Cost 1 % of Investment per year.
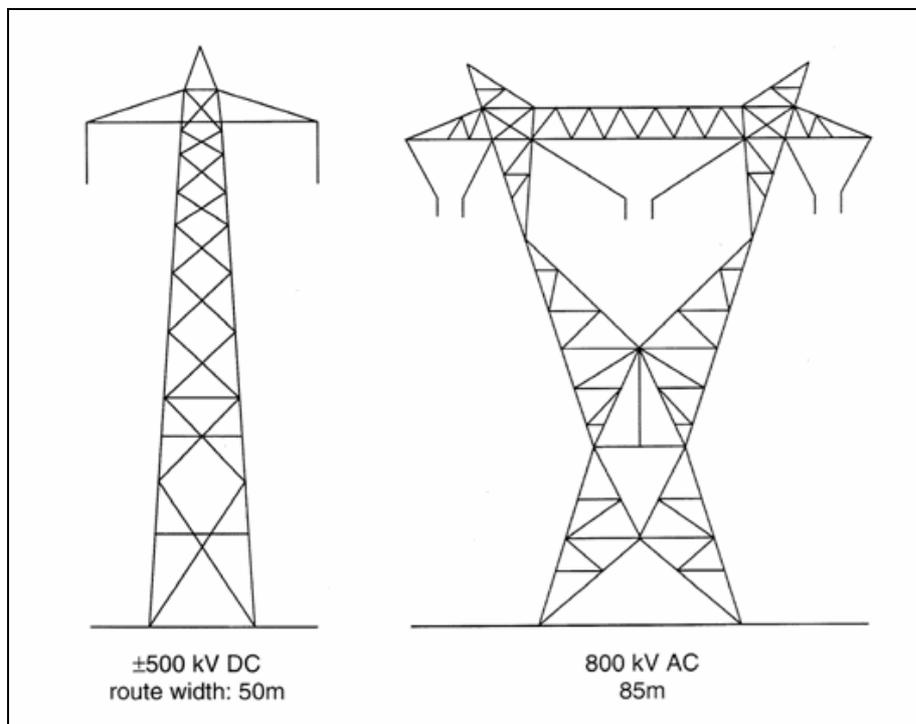

±500 kV DC
route width: 50m

800 kV AC
85m

Figure 1-12: Typical pylon constructions of a HVAC and HVDC overhead line (Source: Arrillaga, 1998).

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 a ton mast medium-sized. 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 takes up 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 1-12.
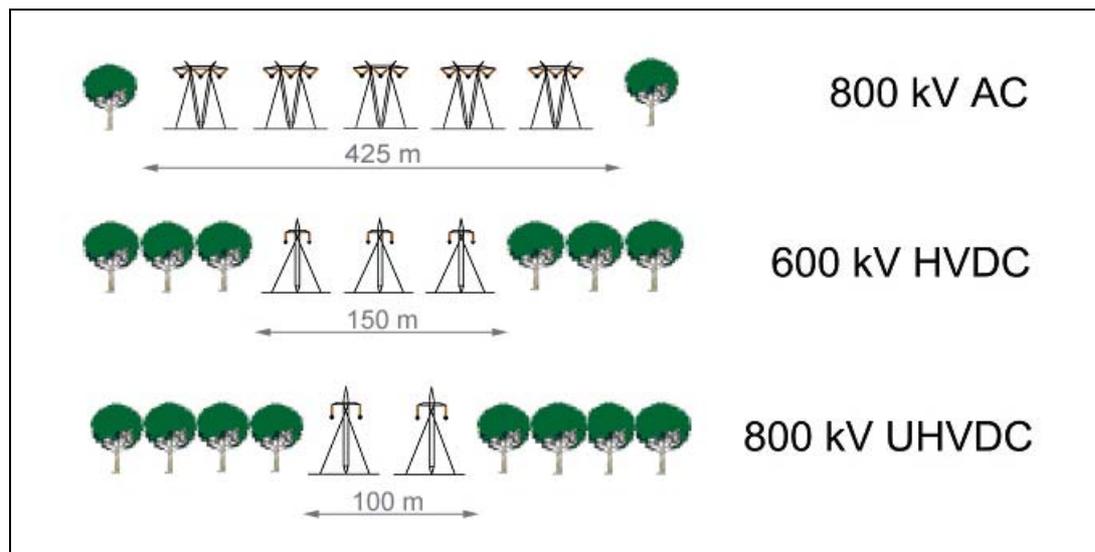

Figure 1-13: Comparison of the required number of parallel pylons and space to transfer 10 GW of electric capacity. Adapted by /May 2005/ from /Asplund, 2004/

For a given transfer capacity, the space requirement of HVDC overhead lines can be four times lower than that for HVAC lines (Figure 1-13). While a 800 kV HVAC line would require a width of 425 meters over the total length of a power link of 10 GW, a HVDC line of the same capacity would only require a band of 100 meters width. This leads to considerable differences in the environmental impact of both technologies (see also Chapter 5).

As a conclusion, High Voltage Direct Current (HVDC) technology is the best choice for long distance solar electricity transfer from MENA to Europe, bridging several thousand kilometres with electricity losses of only 10 – 15 % and providing stable, high capacity transfer at reasonable cost and with low environmental impact.

1.5 The Vision of EUMENA Electricity Highways

The Swedish island of Gotland is situated in the middle of the Baltic sea. It earlier got all its power though two HVDC cables from the Swedish mainland. Actually, Gotland had in 1954 the first commercial HVDC project in the world.

As the wind conditions on the island are excellent a large number of wind power stations were built on the southern part of the island. This made it possible to reduce electricity imports. However, the AC network on the island was not designed for feeding power from the south to the centre of the island. This could have been solved by constructing a new AC line, but due to the crossing through a bird protection area it was judged to be less suitable with overhead lines. Instead a HVDC system using underground cables was built (Figure 1-14). This solved the problem to transmit the power and made very important contributions to stabilize the voltage in the AC network on the whole island. With this reinforcement of the AC grid on Gotland wind power can be further expanded on the island. In fact, already today it happens that more power is produced by the wind mills on the island than what is consumed (there are around 50 000 inhabitants) and the surplus is exported to the mainland. So Gotland already today could be taken as an example of what might in happen in the future on international level /Asplund 2004/.

HVDC has also attracted interest in Denmark, both for transmitting large amounts of offshore wind power, but also to supply the wind generators with reactive power. As most wind generators are asynchronous machines, they consume a lot of reactive power and this can cause voltage stability problems in the generator end. In the other end where the transmission line is connected to the AC grid, there might also be problems as the short circuit power of that point is usually not very strong.

It is also favourable if one can adopt the frequency of the wind generators to the wind speed as this increases their efficiency. All this together led to the construction of a demonstration plant in conjunction to a small park of four wind generators. This plant has demonstrated operation with variable frequency and serves as a demonstration for a bigger wind park far out at sea.

HVDC technology is becoming increasingly important for the stabilisation of large electricity grids, especially if more and more fluctuating resources are incorporated to that grid. HVDC over long distances contributes considerably to increase the compensational effects between distant and different renewable energy sources like wind and solar energy, makes possible the use of Norwegian hydropower storage for compensation of power demand in Germany, and allows to compensate blackouts of large power stations through distant backup capacity. HVDC electricity highways will considerably increase the redundancy and stability of the future Trans-European power grid /Fischer et al. 2004/.

As a spin-off effect of this development, the import of solar electricity from MENA will become an attractive diversification of the European power generation portfolio. Solar and wind energy, hydropower, geothermal power and biomass will be generated in the regions of best performance and abundance, distributed all over Europe through a highly efficient HVDC grid on the upper voltage level, and finally delivered to the consumers by the conventional interconnected AC grid on the lower level (Figure 1-15).

Analogue to the network of interstate highways, a future HVDC grid will have a low number of inlets and outlets to the conventional AC system, as it will primarily serve long distance transfer, while the AC grid will have a function analogue to country roads and city streets.
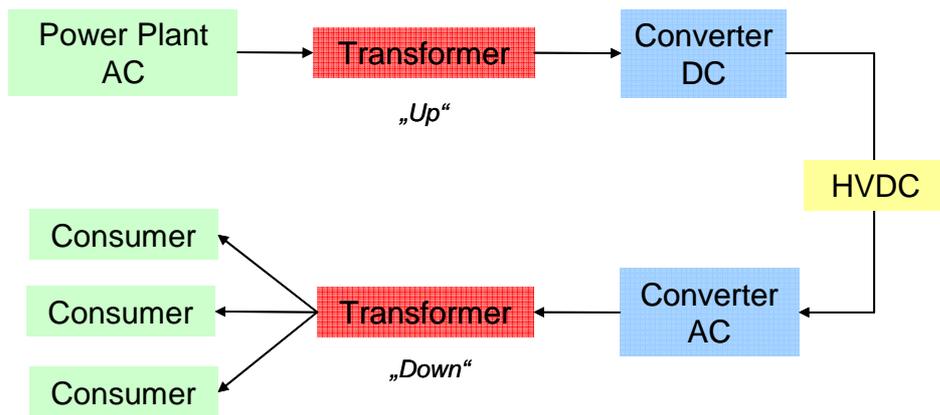
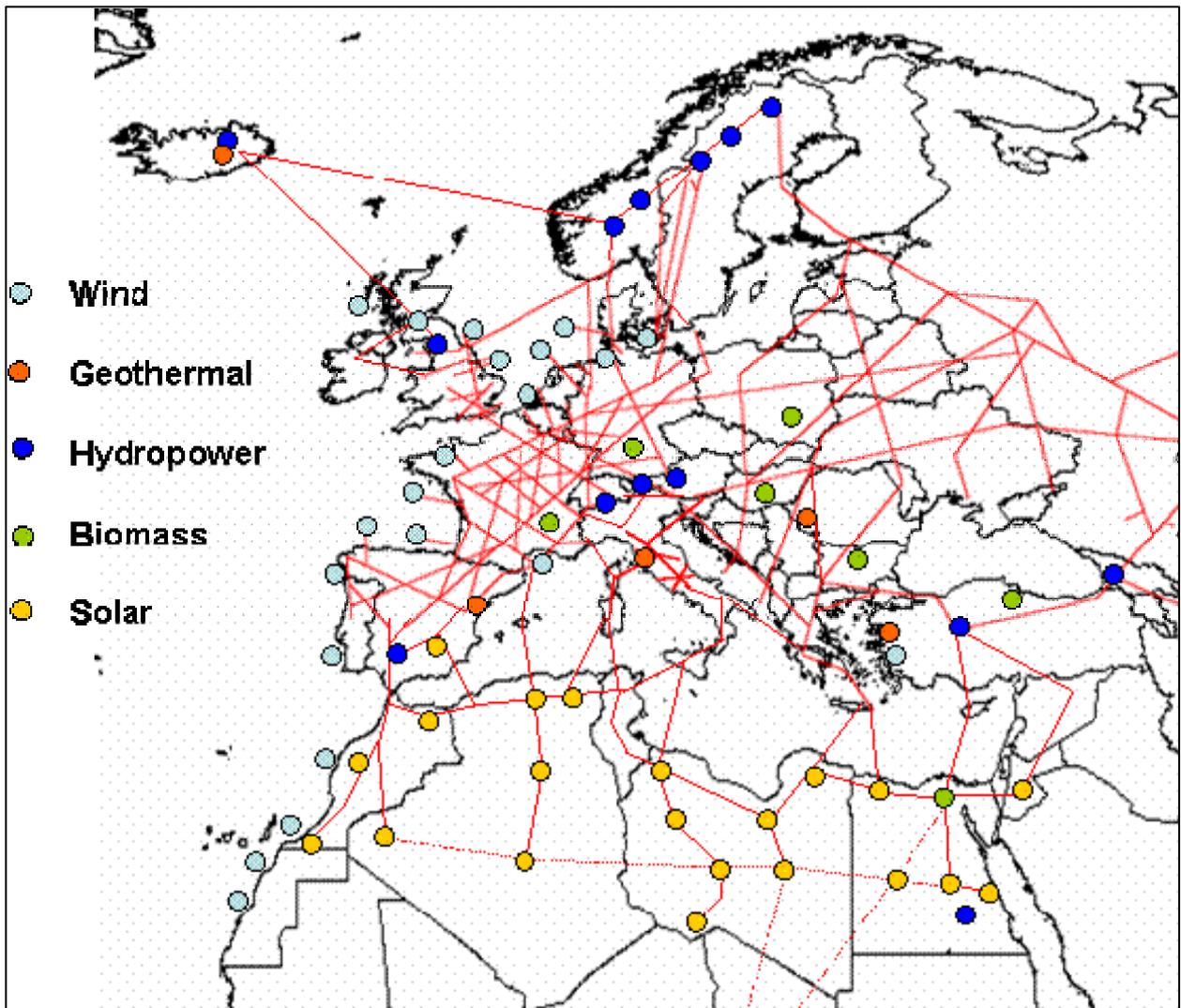**Figure 1-14: Schematic diagram of interconnecting HVDC and AC technologies.**

Figure 1-15: Vision of an EUMENA backbone grid using HVDC power transmission technology as "Electricity Highways" to complement the conventional AC electricity grid. Based on /Asplund 2004/