Meshed HVDC Transmission in the Content of Sustainable Power Transmission for the Future and its Environmental Impact

Sven Bohn, Fraunhofer IOSB-AST, Germany
Anne-Katrin Marten, Ilmenau University of Technology, Germany
Michael Agsten, Fraunhofer IOSB-AST, Germany
Dirk Westermann, Ilmenau University of Technology, Germany

The North American Conference on Sustainability, Energy & the Environment 2014
Official Conference Proceedings

Abstract
When talking about the future of power systems, power transmissions cannot be omitted. While it makes sense to generate renewable energy where the potential is highest, it often means that renewable plants will be far from industrial zones or load centers. Hence, volatile renewable energy has to be transmitted over long distances. Because direct current (DC) transmission has less line losses and the AC/DC grid couplings (converter terminals) are fully controllable, high voltage direct current (HVDC) transmission is favored for modern long distance power transmission to reinforce existing AC transmission. In America, Europe, and around the world, HVDC transmission is discussed and implemented in grid expansion studies and plans. These plans range from point-to-point HVDC links, multi-terminal radial HVDC systems towards meshed HVDC grids. Some studies even introduce a complete transition from AC to DC power systems. This paper, based on previous work, explores meshed HVDC grids, and their ability to transmit volatile renewable energy in bulk and over long distances. Using these grids is shown to prevent a massive AC grid expansion, and therefore can positively impact the environment. The ideas introduced in this paper are applied in a feasibility study of a pan-European-North African HVDC transmission grid.

Keywords: meshed HVDC grid, renewable energy, power transmission, smart transmission, grid operation, environmental impact, management of resources

Introduction

Due to the increasing in-feed of renewable energy (RE) and the reduction of conventional power plants, power grids must be reinforced. While RE is generated where the potential is highest, it often means that renewable plants will be far from industrial zones or load centers (Platzer, 2011),(DESERTEC Foundation, 2014),(Sahara Wind Energy Development Company, 2014). Hence, volatile renewable energy has to be transmitted over long distances and transmission grids will play an important role in the future.

Because DC transmission has less line losses and the AC/DC grid couplings (converter/terminals) are fully controllable, high voltage direct current (HVDC) transmission is favored for modern long distance power transmission to reinforce existing AC transmission (Meah & Ula, 2007). In America, Europe, and around the world, HVDC transmission is discussed and implemented in grid expansion plans and studies. These plans range from point-to-point HVDC links (Bundesnetzagentur, 2013), multi-terminal radial HVDC systems towards meshed HVDC grids (CIGRÉ WG B4-52, 2012),(Krontiris & Benz, 2013),(Bohn, Boie, Kost, Agsten, & Westerman, 2013). Some studies even introduce a complete transition from AC to DC power systems (R. W. De Donker, 2013).

This paper, based on previous work (Bohn, Agsten, et al., 2014),(Marten & Westermann, 2012), explores meshed HVDC grids, and their ability to transmit volatile renewable energy in bulk and over long distances. Using these grids it is shown to prevent a massive AC grid expansion, and therefore positively impact the environment. The ideas introduced in this paper are applied in a feasibility study of a pan-European-North African HVDC transmission grid.

Power Transmission

Power grids are divided into the transmission grid and the distribution grid. While the transmission grid transmits bulk power over long distances, the distribution grid distributes power in local regions. Today’s power transmission grids mainly consist of the alternating current (AC) transmission in tri-phase at high voltages (HVAC transmission). Voltages range between 220 kV and 765 kV, and above for ultrahigh voltage (UHV) transmission, e.g. 1000 kV UHVAC in China (Liu, 2013).
High voltage direct current (HVDC) transmission has several advantages over AC transmission (Meah & Ula, 2007), and is more efficient, particular for wide-area transmission. In (Paris et al., 1984) the longest cost-effective distances for HVAC and HVDC transmission was determined. For HVDC transmission 7,000 km (4,300 mi) was determined. For AC it was 4,000 km (2,500 mi), although transmission lines in use today are shorter than this. In the study on a pan-European-North African electricity infrastructure (Boie et al., 2013) the existing AC transmission grid and the developed HVDC grid was modeled. The histogram of line length was determined afterwards, as shown in Figure 1.

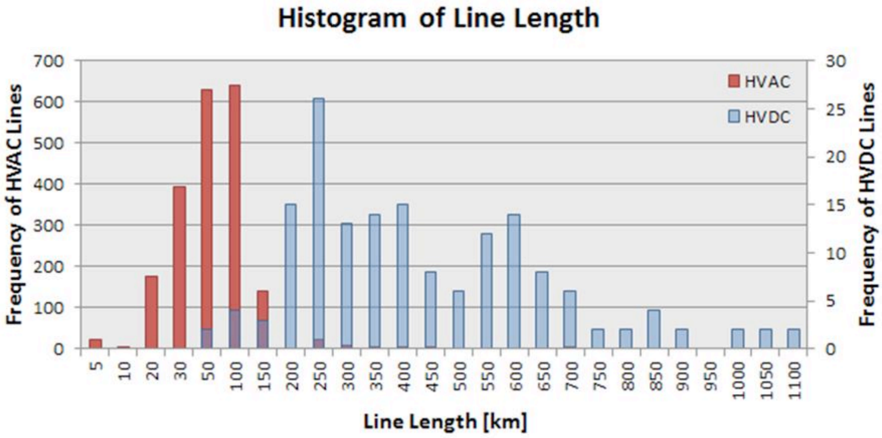

Figure 1. Frequency of transmission line length for HVAC and HVDC lines

It can be seen that the AC transmission system has more lines and the lines are shorter compared to the HVDC system. AC transmission lines range between 30 – 100 km while HVDC lines mainly range between 200 and 600 km, and above. This is because HVDC transmission is used when it comes to overlaying the AC transmission grid (DESERTEC Foundation, 2014), (CIGRÉ WG B4-52, 2012), (Krontiris & Benz, 2013), at higher voltages (e.g. ±800 kV DC). An overlaying HVDC grid is supposed to relieve the underlying AC transmission grid from bulk energy transmission over long distances. Figure 2 shows the AC power transmission infrastructure and the overlaying HVDC grid in a meshed manner.

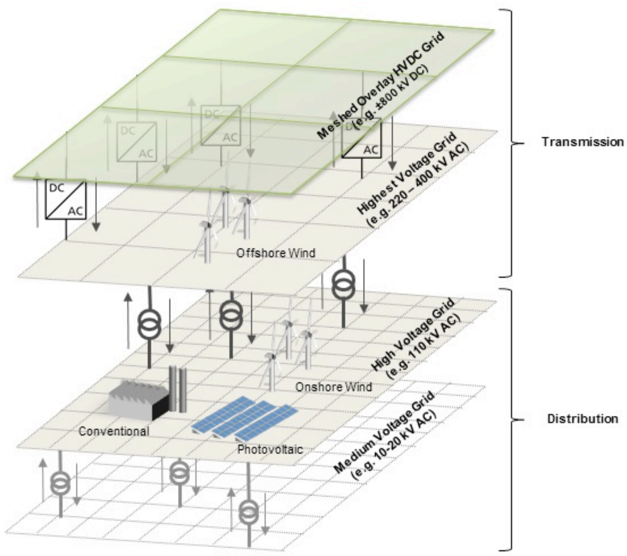

Figure 2. Power grid infrastructure

For the transmission of bulk power over long distances there are basically four technologies available; HVAC through overhead lines, HVAC through cable, HVDC through overhead lines and HVDC through cable. HVAC transmission through overhead lines exists already worldwide and is a mature technology. However, HVAC transmission has a disadvantage over HVDC due to the alternating current and its reactive power demand (Meah & Ula, 2007). This reactive power demand increases over distance. Also, HVAC transmission through overhead lines through water is not feasible. HVAC transmission through cable is doable but demands even more reactive power due to the proximity of the AC current-carrying conductors. HVDC is the preferred method for transmitting bulk power over long distances, even, and particularly, when using cable technology. HVDC does not have a reactive power demand due to the absence of a system frequency.

RE Potential for a pan-European-North African Electricity Exchange

In the project SUPERGRID (Platzer, 2011) three Fraunhofer institutes have evaluated the potential for RE deployment, strategic location planning for renewable energy plants in North Africa (NA) and the power transmission infrastructure for a European-North African electricity exchange (Boie et al., 2013). The study was done for the year 2050 and four possible scenarios with differences in CO_2 reduction goals, increases in local electricity consumption, energy efficiency and availability of a transmission grid infrastructure, were evaluated.

(1) Moderate CO_2 reduction targets of 50% relative to 1990 levels for both EU and NA; high electricity demand in both regions, no integration of EU-NA transmission networks.
(2) Ambitious CO_2 reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; high electricity demand in both regions, no integration of EU-NA transmission networks.
(3) Ambitious CO_2 reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; high electricity demand in both regions; EU-NA transmission networks are interconnected.
(4) Ambitious CO_2 reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; low electricity demand in both regions; EU-NA transmission networks are interconnected.

Renewable energy potentials were determined using a geographic information system (GIS). Moreover, the power consumption of the five NA countries (Morocco, Algeria, Tunisia, Libya and Egypt) was estimated for the year 2050. Based on this data and assumptions for technology cost developments, cost-optimized generation mixes and power flows among the five NA countries, and between Europe and NA were determined by applying a linear optimization model (Boie et al., 2013). Results are shown in Table 1 and Table 2. For a European-NA electricity exchange eight cost-optimized interconnectors were determined between Portugal-Morocco, Spain-Morocco, Spain-Algeria, France-Algeria, Italy-Algeria, Italy-Tunisia, Italy-Libya, Greece-Libya. . It was found out that the potential for RE generation in NA exceeds the local demand by approx. 1/3. Hence, electricity export to Europe is possible and economically viable. The results for the RE generation mix and net energy flows are shown in Table 1and Table 2. The RE generation is dominated by wind, followed by concentrated solar power (CSP) and photovoltaic (PV).

Table 1. Possible electricity generation portfolios in NA in 2050 (Boie et al., 2013)

	Generation per technology in 2050 [TWh/a]			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wind	618	737	965	735
PV	97	86	118	94
CSP	199	303	416	222
Gas -GT	8	3	3	4
Gas-CCGT	125	68	21	38
Coal	47	0	1	3
Hydro	50	50	50	50
Total	1143	1247	1575	1146
RE-share	83%	93%	98%	96%

Table 2. Net electricity exchanges in 2050 (Boie et al., 2013)

	Net Electricity Exchanges [TWh]		Total
	Within NA	NA-EU	
Scenario 1	28	Per definition not possible	28
Scenario 2	37	Per definition not possible	37
Scenario 3	117	347	465
Scenario 4	68	191	259

These results were further used in a next modelling step for strategic location planning and short-term operation of individual RE generation plants (Kost, Schlegl, & Möst, 2013). In this modelling the five NA countries were further detailed into 23 regions. For each region a modelling for short-term operation was conducted. As results, further detailed generation mixes (c.f. Figure 3) and generation and consumption profiles (c.f. Figure 4) for each region were generated.

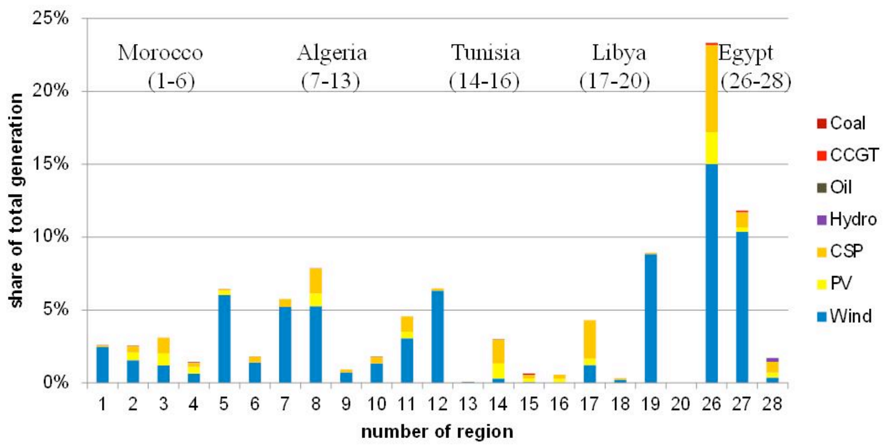

Figure 3. Generation mix per region in NA

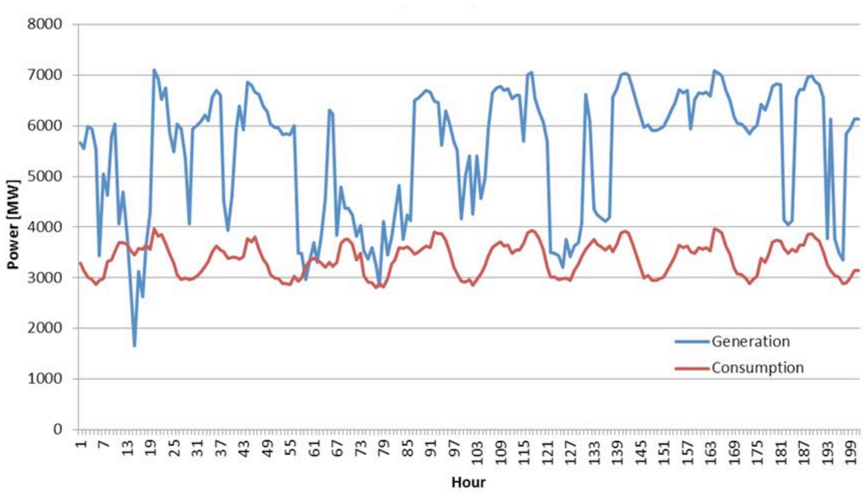

Figure 4. Excerpt of a generation (blue) and consumption (red) profile

A pan-European-North African Electricity Infrastructure

The generation and consumption profiles from the previous modelling were used to evaluate the existing power transmission grid and to further develop the required power transmission infrastructure. To do so the existing AC transmission infrastructure was modelled and evaluated for the pan-European-North African electricity exchange. The currently existing transmission grid of the 220 kV voltage level and above was modelled as shown in Figure 5.

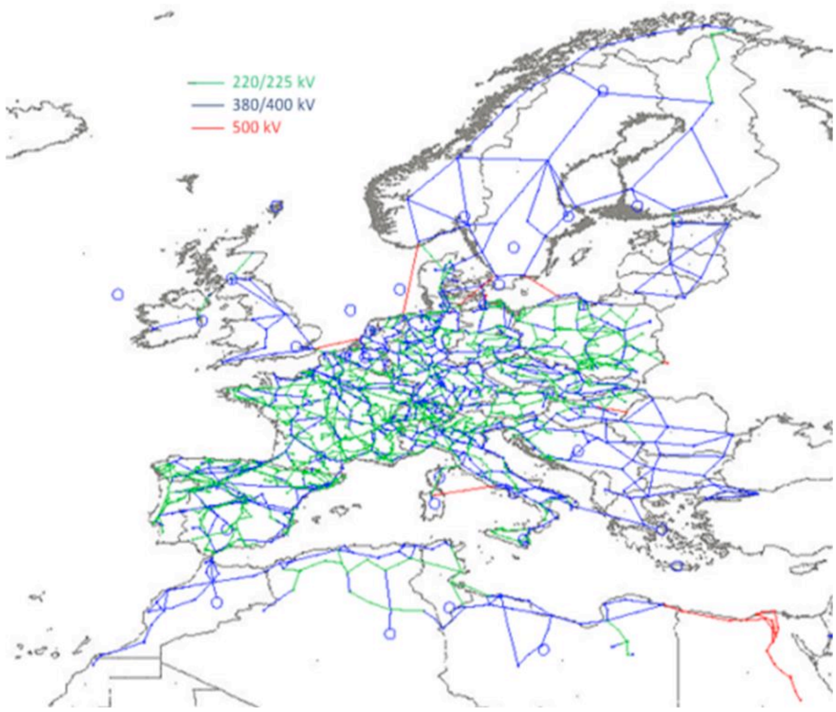

Figure 5. European and North African AC transmission grid infrastructure

In this power grid model the aforementioned generation and consumption profiles were applied to each power grid node of the model. Then power flows for each step (8760 steps in total, each for one hour of the year 2050) were observed in order to determine overloading of the power grid. The analysis of the existing AC transmission grid revealed that the current transmission infrastructure is not able to transmit the predicted amounts of electricity. The transmission grid has to be expanded.

As mentioned before the HVDC transmission is the favored method for transmitting bulk power over long distances. Therefore, an HVDC grid from a feasibility study (CIGRÉ WG B4-52, 2012) was implemented first in the modelling. This HVDC grid enables the electricity transmission throughout the Mediterranean See and to the load centers in Europe. Based on this HVDC grid the AC grid expansion in NA was determined.

The total transfer capacity (TTC) is commonly used to quantify grid expansion needs. The TTC represents the maximum transmittable power through a power grid. It is the sum of the maximum transmittable power of each transmission line of the transmission infrastructure. The results are shown in Table 3.

Table 3. AC transmission grid expansion needs in NA until 2050

Scenario	TTC [MVA]	Expansion Needs	Total Length of Lines [km]	New Lines [km]
Base Grid (Status Quo)	390,184	-	24,320	-
Scenario 1	801,840	206 %	69,680	45,359
Scenario 2	919,690	236 %	87,589	63,269
Scenario 3	2,805,746	719 %	310,580	286,260
Scenario 4	2,696,822	691 %	290,886	266,566

An AC grid expansion of approx. two-times its actual capacity is required for the two scenarios that do not have a transmission infrastructure between Europe and NA. This grid expansion is required to cover the local demand in NA only. The scenarios that do allow electricity export to Europe require a grid expansion of approx. 7-times its actual grid capacity. This is an enormous grid expansion that has to be deleled with by 2050. Assuming one km of new transmission line cost approx. 1 Mio. Euro this results in a massive investment.

On the other side, disadvantages of the AC transmission remain. The utilization of the transmission lines is low due to the demand of reactive power and the transmission of volatile renewable energy (caused by the Ferranti effect). Hence, transmission lines have to be installed to carry the total transmission power which is the sum of active (P) and reactive power (Q) but active power can be used only. It also means that transmission lines need to be financed fully while the return of investment can be calculated on the utilization of approx. 20-30% only. Also, the volatile power transmission generates a volatile reactive power demand which need to be compensated. Hence, controllable compensation devices have to be installed which increases the cost of transmission further.

Table 4. AC transmission grid utilization and reactive power demand

Scenario	Utilization [%]	Average Q/P Ratio	Max. Average Q/P Ratio
Scenario 1	21.4 %	4.47	69
Scenario 2	21.5 %	1.48	12
Scenario 3	27.7 %	2.07	37
Scenario 4	31.0 %	2.06	56

As HVDC transmission is the favored method the actual modelled HVDC grid was expanded in order to reduce AC transmission grid expansion. To expand the HVDC grid the results from the first modelling were used to place the identified cost-optimized interconnectors between Europe and NA, and the generation profiles for each region in NA were analyzed for the highest electricity export (c.f. Figure 6).

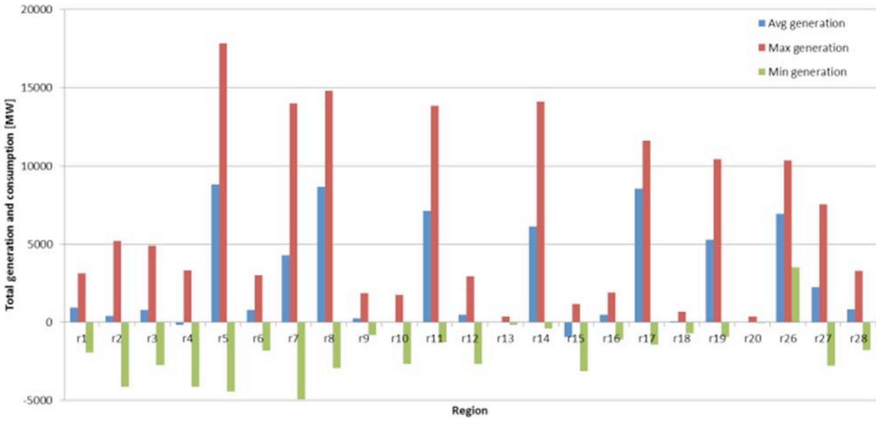

Figure 6. Total excess generation of each region (scenario 3)

Then the interconnectors between Europe and NA were placed in the regions with the highest electricity export. Additionally, AC/DC converter terminals were placed in these regions to connect the AC and HVDC grid. Also, based on the results of power flows among NA countries and the high reactive power demand of remote regions, some kind of collector grid was formed. The finally expanded HVDC grid is shown in

Figure 7.

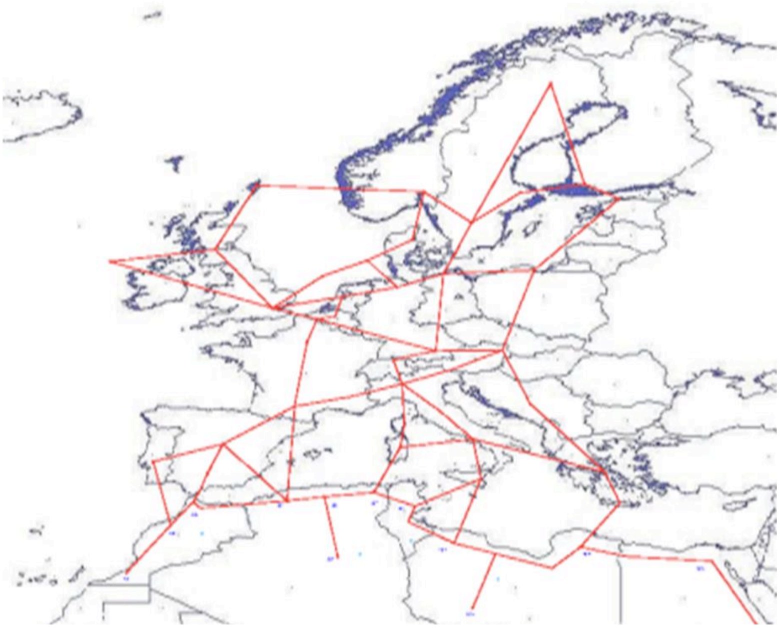

Figure 7. Pan-European-North African overlay HVDC transmission grid

The proposed HVDC grid enables the electricity export of RE from NA to Europe and is able to reduce AC grid expansion. The HVDC grid is designed in a meshed way, but meshed HVDC grids do not exist as of today. Hence, further investigation and development has to be undertaken in terms of grid operation of meshed HVDC grids, e.g. (Marten & Westermann, 2012),(Bohn, Fetisova, Agsten, Marten, & Westermann, 2014), which shall not be part of this contribution.

Environmental Impact

The construction of new and the reinforcement of existing power transmission lines is usually refused by the relevant public and environment protection organizations. However, new and expanded transmission is required due to the increasing in-feed of RE (Energie-Forschungszentrum Niedersachsen, 2012). The expansion of transmission grids is foreseen in many power grid expansion plans worldwide. Hence, grid development and reinforcement plans have to respect ecological, environmental and territory considerations (Kühne, 2014).

In 2012 the German energy research center Niedersachsen did a study to evaluate the options for transmission grid expansion based on HVAC and HVDC from an environmental perspective. Special focus of the study was the comparison of overhead lines and underground cables and its environmental, ecological, and territorial impact. One result of the study is that it is difficult to compare HVAC and HVDC in general. There are technological, operational, and economic considerations that have to be taken into account and require a case-by-case comparison. HVAC using overhead lines is a well-established technology compared to the relatively new VSC HVDC technology with cables. Due to the underground work and more complex composition of cables the cable technology is more costly than overhead lines. HVAC transmission with cables requires compensation, already after a few 10 km, and is not feasible for the bulk power transmission over long distances. Advantages of VSC HVDC are the independent controllability of reactive power on the AC side, the controllability of the (active) power flow and the low voltage drop across conductors. Also HVDC with cables is feasible for bulk power transmission over long distances. HVDC transmission using overhead lines even requires narrower power transmission routes which impacts the environment positively. The study, however, concludes that HVDC has an economic advantage over HVAC for transmission lines 130-280 km and above, even when using cable technology. (Energie-Forschungszentrum Niedersachsen, 2012)

The study further shows that electro-magnetic fields, which may impact humans and other creatures, are below the safety limits of the German 26. BImSchV provision if the appropriate geometrical alignment is chosen. HVDC using cables is the favored method in terms of electro-magnetic fields. They do not have an electric field outside the cable and have a static magnetic field due to the usage of DC current which does not exceed the magnetic flux of the earth magnetic field. Besides the note that HVDC in a meshed way is not useable today, and for the short distances in Germany, the study concludes that HVDC should be used where its advantages can be released – for the bulk power transmission over long distances, for interconnectors through a see, to connect off-shore wind parks, and for a German or European-wide overlay grid. (Energie-Forschungszentrum Niedersachsen, 2012)

Besides these technical aspects, environmental aspects were looked at directly. The workgroup “environment” looked as aspects like

- Human health
- Animals, plants and biological diversity
- Ground
- Water
- Air and climate
- Landscape
- Cultural and other assets

Conclusions

The study on a pan-European-North African electricity exchange revealed that there is enormous potential for the deployment of RE technologies in NA and the generation exceeds the local consumption by far. Hence, electricity export to Europe’s load centers is possible. Furthermore, the existing AC transmission infrastructure was evaluated, which is not able to support a pan-European-NA electricity exchange, and an overlaying transmission grid was developed using HVDC technology. The results and assumptions of the study were compared to the environmental impact of available transmission technologies, and it was found out that the technically preferred method – HVDC – is also the technology with the least environmental impact.

Acknowledgment

This work was supported by the Fraunhofer Internal Program »Markets of Tomorrow« under Grant No. 823 813 Project »Supergrid«.

References

1. Bohn, S., Agsten, M., Marten, A.-K., Westermann, D., Boie, I., & Ragwitz, M. (2014). A Pan-European-North African HVDC Grid for Bulk Energy Transmission – A Model-based Analysis. In 2014 IEEE PES Transmission & Distribution Conference & Exposition. Chicago, USA. doi:10.1109/TDC.2014.6863272
2. Bohn, S., Boie, I., Kost, C., Agsten, M., & Westerman, D. (2013). „SuperGrid " – Das europäisch-nordafrikanische HGÜ-Overlay-Netz der Zukunft. In Internationaler ETG-Kongress (pp. 1–8). Berlin, Germany.
3. Bohn, S., Fetisova, M., Agsten, M., Marten, A.-K., & Westermann, D. (2014). A continuous DC voltage control function for meshed HVDC grids, and the impact of the underlying future AC grid due to renewable in-feed. In 6th International Conference on Modelling, Identification and Control (ICMIC2014), (accepted). Melbourne, Australia.
4. Boie, I., Pudlik, M., Ragwitz, M., Sensfuß, F., Bohn, S., Agsten, M., … Westermann, D. (2013). Scenarios for Renewable Energy Deployment in North African Countries and Electricity Exchange with Europe – A Model-based Analysis for 2050. International Journal of Smart Grid and Clean Energy (IJSGCE), 3, 299–306.
5. Bundesnetzagentur. (2013). Netzentwicklungsplan Strom 2013, Zweiter Entwurf.
6. CIGRÉ WG B4-52. (2012). HVDC Grid Feasibility Study.
7. DESERTEC Foundation. (2014). DESERTEC Concept. Retrieved July 07, 2014, from www.desertec.org
8. Energie-Forschungszentrum Niedersachsen. (2012). BMU Studie - Ökologische Auswirkungen von 380-kV-Erdleitungen und HGÜ-Erdleitungen.
9. Kost, C., Schlegl, T., & Möst, D. (2013). Integration of renewable energies in North Africa to supply European electricity markets. In 13th European IAEE Conference. Düsseldorf, Germany. Retrieved from http://static.gee.de/cgi-bin/download.cgi?dl=1&id=1363257374
10. Krontiris, A., & Benz, T. (2013). Vorteile einer Vernetzung von HGÜ-Verbindungen. In ETG-Kongress 2013. Berlin, Germany.
11. Kühne, O. (2014). Landschaftsbild und Akzeptanz beim Netzausbau. In Umwelt & Akzeptanz beim Netz- und Speicherausbau. Berlin, Germany.
12. Liu, Z. (2013). Electric Power and Energy in China (p. 400). John Wiley & Sons.
13. Marten, A.-K., & Westermann, D. (2012). A novel operation method for meshed HVDC overlay grids and corresponding steady state and dynamic power flow calculation principle. In The 10th International Conference on AC and DC Power Transmission (ACDC 2012). Birmingham, UK.
14. Meah, K., & Ula, S. (2007). Comparative Evaluation of HVDC and HVAC Transmission Systems. In IEEE Power Engineering Society General Meeting. Tampa, FL.
15. Paris, L., Zini, G., Valtorta, M., Manzoni, G., Invernizzi, A., De Franco, N., & Vian, A. (1984). Present Limits of Very Long Distance Transmission Systems. In International Conference on Large High Voltage Electric Systems. Paris.
16. Platzer, W. (2011). Supergrid: Efficient generation, storage and distribution of electricity. Fraunhofer Project Web Page. Retrieved from http://www.fraunhofer.de/en/research-topics/energy-living/energy-efficiency/supergrid.html
17. R. W. De Donker. (2013). Elektrische Netze der Zukunft. In VDE-Vortragsreihe. Ilmenau, Germany.

18. Sahara Wind Energy Development Company. (2014). Sahara Wind. Retrieved January 09, 2014, from www.saharawind.com

Contact email: sven.bohn@iosb-ast.fraunhofer.de