Future long distance electricity transmission using HTS HVDC cables

O. A. Chevtchenko, R. Bakker and J. J. Smit*

HTS-powercables.nl B.V., Koperweg 45, 7335 DS Apeldoorn, The Netherlands

Corresponding author: O. A. Chevtchenko, info@hts-powercables.nl
*J. J. Smit can be contacted at: j.j.smit@outlook.com

Publication date: 17 November 2015 (in the final form: 25 November 2015)

Abstract
In this paper a need is identified for 250-2000 km-long transmission links with capacity of 10-75 GW for the future high voltage direct current (HVDC) overlay grid connecting e.g., EUMENA countries, for which the costs of 500 B€ are foreseen. Transmission options available for such links are carefully selected and compared. A concept of high temperature superconducting (HTS) HVDC cable cooled with liquid nitrogen (LN_2) is proposed that addresses the identified challenges. The proposed cable concept is described and main specifications of such cable are derived. In conclusion, we expect that proposed HTS HVDC cable in many cases will be superior to conventional overhead line, elpipe or MgB_2 superconducting cable cooled with liquid hydrogen (LH_2).

1. Introduction

A comparison of alternatives to deliver electricity from the energy source (coal in this case) to the customer at 1-5 GW over 1000 km distance indicates that a high voltage direct current (HVDC) link using overhead line (OHL) is the most appropriate economically and environmentally, further reading is available [1-2]. Meanwhile a question arises how this statement applies to the power range of 10 to 75 GW and assuming other remote energy sources: such as hydro-, wind and solar. For example, from fig. 1 it is clear that for the future overlay HVDC grid the links (many up to 1000 km-long) will be required with capacities between 10 and 75 GW.

Long HVDC links using OHL exist up to 6.4 GW and under consideration between 10 and 30 GW. On the other hand, conventional cables are limited in capacity by 1-3 GW and are 5-6 times more expensive than OHL ([2.1], Table 1 therein). Underground el-pipes are designed for capacities up to 24 GW [3], but they are more expensive as it is clear from Table 1 below. Therefore as it follows from Fig. 1 in a "business as usual" scenario, Europe one day will be covered (at the cost of 500 B€ [2]) by an additional grid of HVDC OHLs. To give an idea, a tower of a 6.4 GW bipole OHL is physically 50 m tall and 20 m wide (requiring a corridor at 100% annoyance level of 50 m tall and 300 m wide for a single 20 GW bipole).

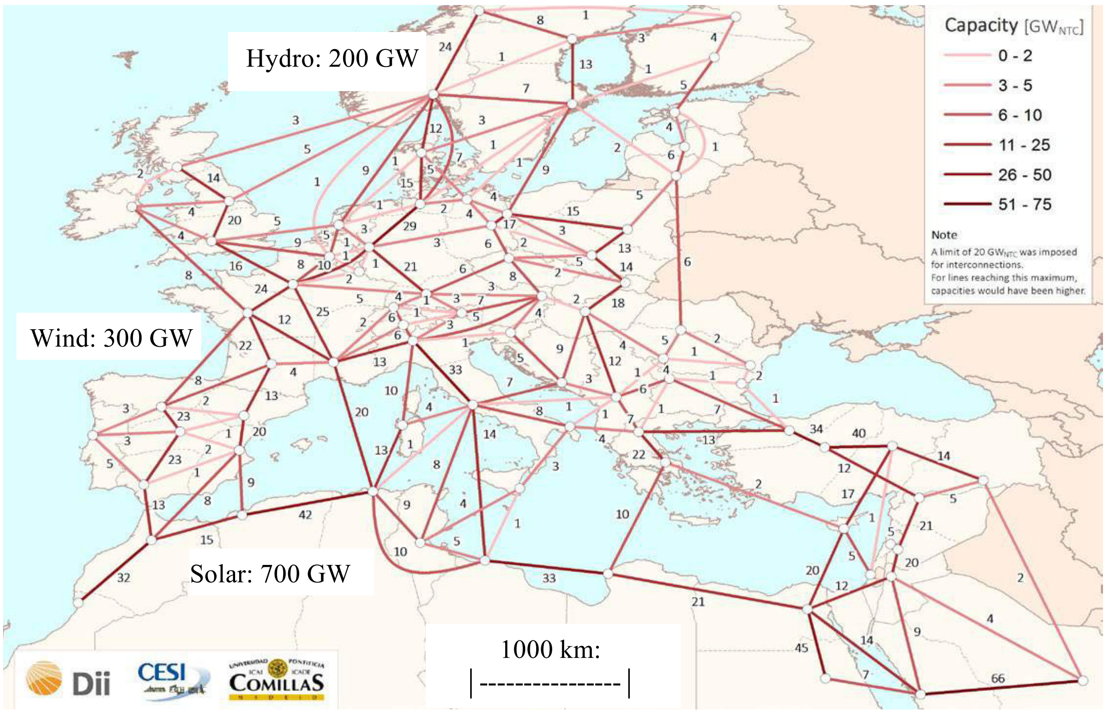

Figure 1. Expected HVDC overlay grid (with the line capacities) by year 2050 in EUMENA countries, according to [2] (the renewable energy sources are indicated, see fig. 5 in [2] for details)

To address this problem, also the designs of superconducting cables for HVDC transmission can be used [4-6]. We exclude [4] from considering here, because the cost estimate is not provided, the design clearly aims at relatively short distances (5 km mentioned), so that the provided cable diameters (e.g., corrugated cryostat: 180 mm, HTS core 100 mm for ±500 kV version, Table 1 in [4]) only allow a distance of up to 50 km between two cooling stations (our estimate) and furthermore cable terminations are needed for each cooling station to access the inner flow of nitrogen.
To our opinion, the HTS cable design of [5] was a remarkable step at the time. Authors use the idea that the same power (e.g., 10 GW) can be delivered more efficiently at lower voltage (±50 kV as compared to ±800 kV for alternatives). This idea however is not supported by their own data: e.g., at the lowest assumed HTS tape price of 5 $/kAm, the superconductor core costs 0.6 M$/km while the dielectric costs under 0.2 M$/km, see Tables C2 and C-4 [5] and the resulting costs of HTS cable are above optimal. Also, the distance of 20 km between two cooling stations is hardly acceptable (e.g., 240 cooling stations for a 1600 km long, N-2 redundant link). And no clue is presented on how currents this high (100 kA) can be handled (switching, terminations, short circuit event, forces, magnetic fields, etc.). We will use here the data of [5], but exclude this design from consideration and the interested reader can consult [6] for a comparison on this matter.
Authors of [6] state that a unique combination of MgB_2 and LH_2 properties allows for a very competitive design of superconducting cable. We compare characteristics of such cable to that of optimally designed HTS cable and to other selected transmission options in Table 1. The cable design [6] is sufficiently clear, it allows a comparison to alternatives and for these reasons it is included in Table 1.
Therefore, in this paper we compare the selected options to transport 20 GW of electricity over a distance of 1000 km at N-2 redundancy (Table 1), optimise HTS cable design and propose a concept of HTS HVDC cable (Fig. 2) that addresses the challenges of such transport.

2. Comparison of selected transmission options

Reliability and redundancy

Reliability of a transmission system is of prime concern for a transmission system operator (TSO). A known feature of HVDC bipole system is that when one pole fails, the other (operated as a monopole) can deliver (somewhat lower) power for some time (for OHL: 22 minutes) sufficient for a modern grid to engage the alternative transmission route. We do not think this is an acceptable mode for a future grid (since in the case when monopole operation is permitted, a blackout is replaced by a grayout of some sort with a light degree of electrocution of nearby areas). More generally (to our opinion) a HVDC link with three independent poles is N-2 redundant. On the other hand, when a mast collapses, both poles (of a bipole) go out of service, so when supported by the same mast, the poles of a bipole are not really independent. Therefore, we conclude that only a link with three independent bipoles (each rated for the same power as the link) is N-2 redundant.
Similarly, when the superconducting cable bipole is in the same cryostat and cooling fails, operation in monopole mode is impossible and such link fails. Subsequently, a link containing three independent cryostats (each with independent cooling system and each with two superconducting poles) has the same redundancy (N-2) as the link with three independent OHL bipoles. For a 20 GW link high reliability and therefore N-2 redundancy is preferred and on the other hand, a minimal cost of the link is essential.

Comparison of the selected options for a 20 GW and 1000 km-long HVDC link

This is taken into account in Table 1 where the costs are presented of the selected transmission options for a 20 GW, N-2 redundant, 1000 km long HVDC link. When acceptable, such link can deliver respectively 40 and 60 GW being N-1 and N-0 redundant. The selected HVDC options are: 1- proposed HTS cable cooled with LN_2 (this paper, see Fig. 2 for details); 2- overhead line [1-3]; 3 – elpipe [3] and 4 – MgB_2 cable cooled with LH_2 [6]; UGC stands for underground cable. The listed options are ranked by the capital (initial investment) cost of the link and the lowest is listed first.

Voltage

In a conventional cable, the power capacity is often limited by the thermal properties of dielectric and/or soil (heat generation and removal are proportional respectively to the conductor cross-section and to cable outer diameter). Furthermore, in a conventional cable with extruded insulation the voltage can be increased from the 525 kV to 800 kV by reducing the DC conductivity of insulation and capacity of 2.6 GW is reported for a 3000 mm^2 copper cable pair [7]. To our opinion, an advantage of HTS HVDC cable is that it is free of the thermal limit, since most of the energy loss is outside of the insulated cable core, namely, through the outer cryostat wall. Therefore, to our opinion, it should be easier to make a step from 525 to 800 kV in HTS cable than in conventional cable. Furthermore, a cable and OHL operated at the same voltage are compatible allowing hybrid connections without additional conversion. Moreover, a cable transporting the same power and operated at higher voltage needs less of superconductor (new technology, but more of dielectric-established technology), which to our opinion reduces overall risk.

Table 1. Specifications of the selected options for a 20 GW, 1000 km-long, N-2 redundant HVDC link

Specification	Transmission by: HTS UGC	OHL	Elpipe UGC	MgB_2 UGC
Reference	this paper	[1-3]	[3]	[6]
Voltage, ±kV	800	800	800	125
Current, kA	12.5	12.5	12.5	80
Capital costs of the link:				
per unit length, M€/km	8.3	14.6	21.3	26.9
full length, B€	8.4	15.7	21.5	28.2
full length with converters, B€	16.6	24.1	29.8	36.6
as addition to that of the power plant, €/W	0.8	1.2	1.5	1.8
Technology status	unproven	proven	unproven	unproven
Energy loss, % of the delivered, excl. converters	0.24	2.5	1	1.5
Conductor and cooling detail				
Conductor and cooling	ReBCO+LN_2	AlCSR+ air	Al+Na+soil	MgB_2+LH_2
Operating temperature core, K	66.5	350	358	16
Min. number of cooling stations per 20 GW bipole	2	n.a.	n.a.	10
Max. spacing of two cooilng stations, km	1000	n.a.	n.a.	300

On the other hand, when costs/km of superconductor and of dielectric are comparable, using more of conductor and less of dielectric leads to smaller pole diameter and more compact design [5, 6]. To our opinion, this advantage (of having lower voltage level) must be carefully balanced with the disadvantage of having higher currents (see Table 1) and higher overall risk.

Current

For the same power and at the same voltage level the currents are the same, which simplifies the current management (switching, terminations, short circuit conditions, etc.) through the whole variety of available options. A deviation from this [5, 6], see option 4 in Table 1 has a disadvantage of having higher currents, magnetic fields, etc.

Power

In Table 1 we compare expected specifications of the selected transmission options for a 20 GW link (redundancy of N-2 is provided by assuming such link is always comprised of three independent bipolar circuits). Further analysis reveals that in the power range from 10 to 75 GW the capital cost of the link using proposed HTS cable depends only slightly on the transmitted power (far less than that for OHL), Fig. 3, left.

Capital costs

For each option the costs are added of the power plant compensating for the respective energy loss. For each (of the three) installed 20 GW HTS bipole cable estimated capital, manufacturing (material and production) and the laying costs are respectively: 2.78, 2.14 and 0.64 M€/km. As shown in Fig 3, left the costs of the proposed HTS cable depend less on the power capacity that that of OHL and they are equal to each other at the capacity of 5 GW, at higher power capacity costs of HTS cable are lower. For an OHL the cost from [3] is used. It should be noted that in literature one could find both higher and lower values of the cost [1-3]. The cost of a 20 GW elpipe is interpolated from [3]. For each 20 GW MgB_2 bipole cable (comprised of two 10 GW cables [6] laid in the same trench) estimated here capital, manufacturing (material and production) and the laying costs are respectively: 4.49, 3.84 and 0.64 M€/km.

Energy loss

In Table 1 the energy loss of the link operated at full load is presented for each transmission option (excluding the converters, for two LCC converters at full load 1.5 % should be added). For superconducting cables the energy loss includes heat inputs through the cryostat walls, in joints, in terminations, the pump work, etc. times the cooling penalty.

3. Cable arrangement, operation and components

Layout of the proposed HTS cable is shown in Fig 2. Longer cable length is obtained by increasing the HTS cable outer diameter D_0. For instance, the cable length of: 500, 1000, 2000 and 4000 km can be achieved at $D_0 = 0.23$, 0.33, 0.45 and 0.67 m (using the same cooling scheme as in [6]). For these values of D_0 respectively for the inner and the outer flows the derived heat inputs are: 27, 25, 27 and 28 mW/m and 0.33, 0.35, 0.41 and 0.4 W/m, while the mass flow rates are taken equal to each other and amount respectively: 2.2, 4.6, 9.0 and 18.8 kg/s (as follows from the hydraulic analysis explained below). The outer and the inner cryostats provide respectively the heat leaks of 0.3-0.4 W/m and 10 mW/m in the temperature ranges from 300 to 67 K and from 77 to 65 K.

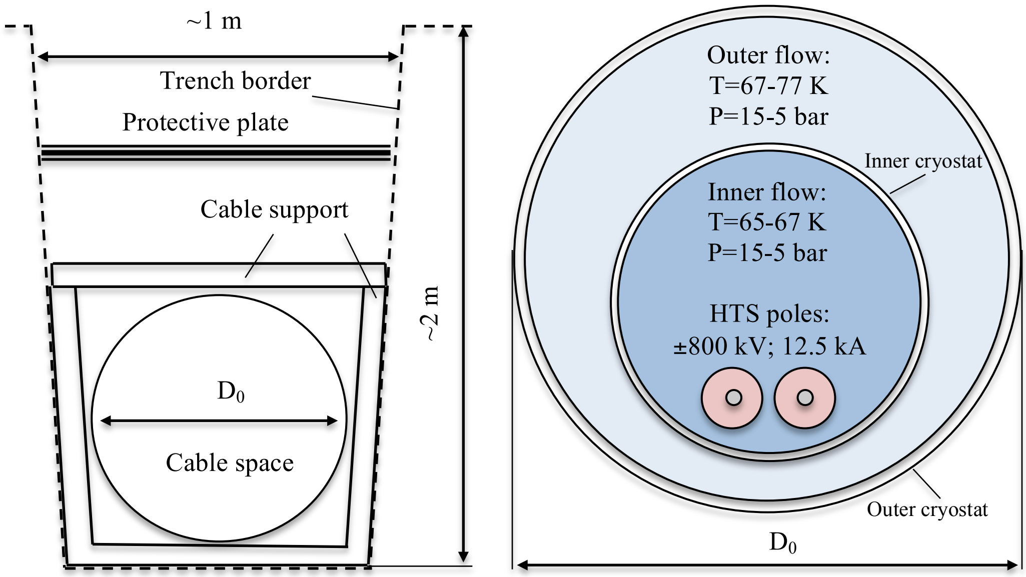

Figure 2. Left: schematic trench and support arrangement for the proposed HVDC HTS cable (where needed stray magnetic fields can be reduced e.g., by integrating a ferromagnetic shield / yoke in the support; security cameras and sensors foreseen respectively above, around and inside the cable support structure). Right: cross-section of the proposed 20 GW, ±800 kV single bipole cable with the outer diameter D_0 = 0.23, 0.33, 0.45 and 0.67 m depending on the preferred cable length: 500, 1000, 2000 and 4000 km (respectively; the latter case is depicted in the figure at the zero altitude change).

Therefore the outer and the inner cable cryostats are each made of two (mainly rigid, mm-thin) stainless steel shells with static vacuum, thermal multilayer insulation, getters, etc. in between. The two HTS poles are positioned in the inner cryostat (the bottom area in Fig. 2, right). Each pole has the outer diameter of about 80 mm and consists of a screen (e.g., [4]), layer of electrical insulation for 800 kV (conductor to the ground: e.g., 30 mm thick layer of PPLP) with HTS cable core inside: e.g., a 20 mm diameter CORC [13] (or other core arrangement, similar to that described in [4, 5]).
To give an idea of what was possible 3-4 years ago: the HTS CORC with the critical current of 15 kA at 65 K (sufficient for the 20 GW cable), has outer diameter of only 10 mm, is wound on a copper former of 5.5 mm and has 17 layers of HTS tapes [13]. We therefore think that currents from 15 to 60 kA at 65 K (sufficient for 20 to 75 GW HTS cables) can be obtained in a superconducting pole as described above without substantial increase of the outer diameter (estimated between 70 and 90 mm). Short circuit protection of the HTS cable is provided by a hybrid DC switch (e.g., similar to [14]) that disconnects the cable from the grid within 5 ms.

Superconductor
At the operating temperature (Table 1), the cost of 6 and 5 €/kAm for YBCO (ReBCO) and for MgB_2 superconductors respectively are assumed.

YBCO (ReBCO)
A major challenge of the proposed HTS cable is reduction of coated conductor price to the level of 15 €/kAm (at 77 K, self-field). This challenge is addressed e.g., in [11]: a relatively small factory (staff of 56) can produce 5 Mm/year of 4 mm wide YBCO tape with the critical current of 200 A at 77 K, self-field condition at the cost-price of 6 €/kAm. To our opinion, this leaves a reasonable margin for the scale-up business. Indeed, for the 3100 km long, 20 GW link using three parallel HTS cables (N-2 redundant) from Table 1, seventeen such factories (each producing 10 Mm/year) can supply enough tape within 3 years. Using 28% of the profit, the whole investment (estimated at 1.7 B€) can be returned within 3 years. Therefore, no investment from HTS cable manufacturer is required to start this scale-up process, only a commitment to buy HTS tape at 15 €/kAm (which must be supported by a TSO). The challenge of (and the risk of not) meeting the target cost price can be addressed by running a pilot factory ahead of the whole process. To our opinion, reduction of the coated conductor price is not anymore a scientific and not so much a technical question, but one of the proper investment and of scaling up existing technology. Moreover, when YBCO tape is operated in the cable core at 16 K (instead of MgB_2 wires), it provides much higher stability (due to much higher current sharing temperature and the heat capacitance). For YBCO tape the lift factor is 6 (from the standard: 77 K, self-field to the operating condition: 16 K; 0.1 T perpendicular, 0.5 T parallel external magnetic field [12]), the tape price at

operating conditions is therefore 2.5 €/kAm, which is comparable to that of MgB_2 [6]; anyway at this level it does not dominate anymore material cost of superconducting cable, Fig. 4.

MgB_2
According to [6], the main advantage of MgB_2 over HTS is that at the operating temperature of 16 K the superconductor price of about 5 €/kAm (at 16 Kelvin, self-field condition) is visible.

Dielectric
Electrical insulation for 800 kV (conductor to the ground) in the proposed design is comprised of 30 mm thick cold lapped dielectric, made of e.g., PPLP layers.

4. Cryostat, hydraulics and cooling
Cryostat
In order to increase the length of the cable hydraulic section, we assume a mainly rigid cryostat (with smooth hydraulic surfaces and with compensation bellows). Using [5, 8, 9], we derive the cryostat costs of 1.1 M€/km for the proposed HTS cable cooled with nitrogen, Fig. 2 and for MgB_2 cable [6] (cooled with hydrogen) we estimate the cryostat cost of 2.5 M€/km. The higher cryostat cost for MgB_2 as compared to the HTS cable are due to the lower operating temperature (16 K and 66.5 K respectively). To our opinion, namely reaching the cryostat cost below 2.5 M€/km at the heat inleak through the outer cryostat wall of below 0.4 W/m (currently at 5 W/m [6.3]) is a major challenge of MgB_2 cable.

Operating temperature and pressure
For the proposed cable we assume both HTS bipoles are placed in the same (inner) cryostat, are immersed in the same inner ("go") flow of sub-cooled nitrogen and operate at 65 to 67 K, while temperature in the outer ("return") flow changes from 67 to 77 K, see Figs. 2 and 3, right. The operating pressure changes from 15 to 5 bar in the "go" and "return" flows (along each hydraulic section). For MgB_2 cable cooled with LH_2 we assume the temperature of the inner flow of 15-16 K, the temperature range of the outer flow between 15 and 25 K, the pressure change in the inner and outer flows from 15 to 5 bar [6, 10].

Hydraulics
The hydraulic analysis of the HTS cable cooled with LN_2 was performed using a model of [10] adapted for nitrogen properties, accounting for the Joule-Thompson effect and allowing calculating e.g., the diameters of the inner and outer cryostats for given length of the cable hydraulic section, the operating temperatures and pressures. Example of the temperature and pressure distributions along the length of the HTS cable hydraulic section is shown in Fig. 3, right. The model in particular allows a direct comparison of the relevant properties of HTS cable cooled with LN_2 and MgB_2 cable cooled with LH_2. Our conclusion after performing such a comparison is that HTS cable cooled with LN_2 shows characteristics better or comparable to that of MgB_2 cable cooled with LH_2. Namely, the comparison of relevant (to superconducting cable with the same diameter) properties of LH_2 and LN_2 reveals the physical advantages of LN_2 cooling as compared to that with LH_2, which is in 2-3 times less cooling stations and in 30-70 times higher heat capacity of materials (e.g., 58, 30 times for copper, Hastelloy at 67 and 16 K respectively and hence much higher operational stability of superconductor against disturbances caused by the difference in operating temperature), while LH_2 cooling has one obvious advantage over LN_2 (caused by 11 times less density) in respect to the altitude changes (the latter is addressed below).

Cooling
Some liquid nitrogen cryocoolers can operate for at least 20 years (5 years between maintenance), such as TBF-1050 from Air Liquide with cold power of 120 kW at 65 K. One cooling station (for HTS cable from Table 1, Fig. 2) can consist of e.g., two units TBF-1050: to provide the cooling redundancy in the period of at least 40 years, we assume 6 cooling stations (three near each cable end) for each proposed 20 GW HTS cable. Though other cooling schemes are known, in order to directly compare YBCO and MgB_2 cables, we assume here the same cooling scheme as in [6.1]. In this case for YBCO cable cooled by nitrogen with $D_0 =$ 0.23, 0.33, 0.45 and 0.67 m, the cable length is four times and the distance between two cooling stations is two times of the length of hydraulic section, which is respectively: 125, 250, 500 and 1000 km (which allows for many of the links in Fig. 1 further reduction of the cable outer diameter D_0).
As clear from Fig. 4, in this case the cooling only comprises 2% of the HTS cable total material costs, which is sufficiently low. A similar assumption is made for MgB_2 cable cooled with LH_2 cryocoolers, which may be an underestimate, since LH_2 cooling is more complex.

Distance between two cooling stations
In the cooling scheme assumed above the distance between two cooling stations is double of the length of cable hydraulic section. When one station fails, the HTS cable goes out of service. Additional redundancy can be

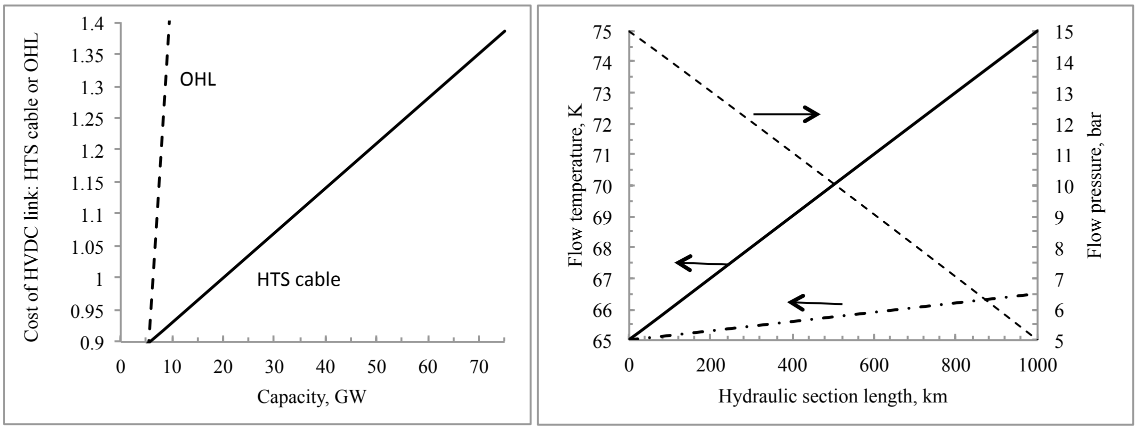

Figure 3. Left – estimated costs versus the power capacity of the proposed HTS cable (the solid line) and of the OHL (the dashed line), both scaled by the cost of the 20 GW HTS cable; Right - temperature and pressure distribution along the length of a 20 GW HTS cable hydraulic section (for D_0=0.67 m; the solid and dash-dotted lines are temperatures of the outer and inner flows respectively; the dashed line is the pressure in each of the flows; depending on the assumptions, actual cable length is 2-4 times of the hydraulic length)

provided assuming the distance between two cooling stations is equal to the length of the hydraulic section. In this case more than two cooling stations along the cable length can be assumed and when any intermediate cooling station fails, two adjacent cooling stations are still able to keep the HTS cable cold indefinitely. Additional cooling stations will not distract the electrical insulation, since both HTS poles are cooled from the outside. This way the cable outer diameter and hence the cost can be reduced, larger altitude changes along the cable route can be accommodated (see more details below), etc.

Effect of altitude and other challenges

The above estimates are made assuming the zero altitude change. In the selected range of operating parameters for HTS cable, each ±100 m of altitude change adds about ±8.5 bar of pressure. To meet this challenge, thickness of the cryostat walls can be changed respectively. For larger altitude change e.g., ±2 km, other options are available, e.g., a local cooling of HTS cable core with LH_2 (similar to that proposed for MgB_2 cable [6]) or helium can be employed. This options is not considered here in detail, since for 1000 km long links this is just one of the many challenges to be addressed (that make final design more complex and costly as compared to the concept, regardless of the option).

Perhaps equally important to extend the following statement for HVDC cables (formulated in [15] for AC cables): “since reliability, power capacity, maturity, availability, failure rates, maintenance, time of repair, connection length, and life expectancy of HTS cables in respect to OHL are to be demonstrated, until then“ it is an option to use HTS cables in parallel to OHL. This approach (of a hybrid link) allows a smooth introduction of HTS HVDC cables without compromising the grid reliability, which also gives time to address the above challenges, something of value in projects such as Suedlink.

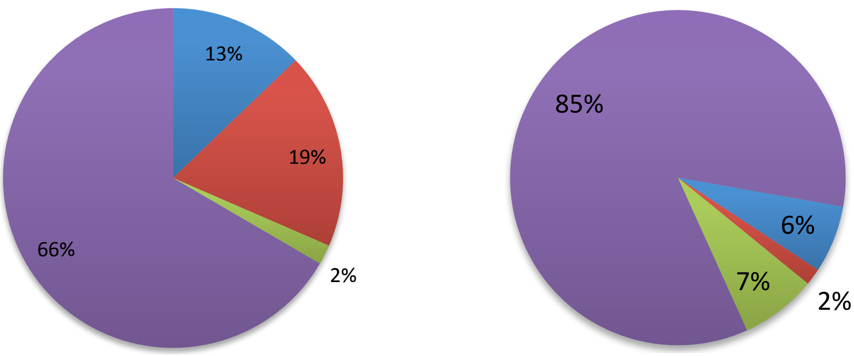

Figure 4. Estimated breakdown of the material costs for the (left) proposed 20 GW HTS HVDC cable: 66, 19, 13 and 2% are respectively the cost of: cryostat, electrical insulation, conductors and cooling (% of the total material cost, which is 1.64 M€/km in this case); (right) 10 GW MgB_2 cable as proposed in [6] and estimated in this paper: 85, 2, 6 and 7% are respectively the cost of: cryostat, electrical insulation, conductors and cooling (% of the total cost, which is 2.95 M€/km in this case)

Fire hazard

During normal operation HTS cable hardly interacts with environment (except at the cooling stations). In extreme situation (e.g., when damaged by accidental digging or by lightning strike) there is no fire hazard. A spill of liquid nitrogen is not excluded, but it can be terminated within reasonable time (using sensors and pumps). When spilled to ground, liquid nitrogen (very cold) behaves very much like a hot water, furthermore it is not flammable (in fact it has a fire damping capacity) and it evaporates quickly leaving no trace. At the lowest points along the HTS cable route a pit may be needed to temporarily absorb the spilled nitrogen. In contrast to that, both MgB_2 itself and liquid hydrogen are flammable and special handling is a must.

5. Conclusions

1. Our study confirms that future transmission of electricity over large distances is economically and environmentally the most effective using HVDC technology with HTS cables. Namely, we expect that HTS cables cooled with LN_2 will be better than other alternatives selected and compared in this paper (including conventional overhead lines, conventional cables, elpipes and MgB_2 cables cooled with liquid hydrogen).
2. Proposed here concept of HTS cable cooled with liquid nitrogen shows potential for cost-competitive, high capacity, underground or offshore, long length (with acceptable distance between cooling stations) transmission interconnector. Moreover, the concept addresses existing need in a sound HTS cable design adequate for this application. As a result, better solution is now possible for a 20-75 GW 250-2000 km-long, N-2 redundant HVDC link that can become a backbone of the future overlay HVDC grid of year 2050.
3. Main challenge for the proposed HTS cable cooled with liquid nitrogen is in reduction of the HTS (YBCO) tape price down to 15 €/kAm, this challenge is addressed and it is not of scientific, but of investment nature. To our opinion, for the MgB_2 cable cooled with liquid hydrogen, the main challenges are in demonstrating the cryostat cost below 2.5 M€/km at the heat inleak of below 0.4 W/m through the outer cryostat wall and in handling high currents, such as rated current of 80 kA and even higher short circuit current.

6. Acknowledgement

This research is funded internally and therefore this paper (particularly the proposed concept of HTS HVDC cable) is property of HTS-powercables.nl B.V., all rights reserved.

7. References

[1] A. Oudalov, M. Reza, “Externality implication on bulk energy transport”, ABB, 2007; McCelley, “A survey of transmission technologies for planning long distance bulk transmission overlay in US”, Electrical Power and Energy Systems 54 (2014) 559–568; “High voltage DC transmission”, CIGRE 2001, p. 21, Table 2; “Electricity transmission costing study”, an independent report from Parsons and Brinckerhoff, April 2012

[2] Desertec power: Getting connected, final report 2014; “Roadmap to the supergrid technologies”, FOSG report 2014; www.e-highway2050.eu/e-highway2050

[3] R. Faulkner, “Hybridizing HVDC transmission with non-local energy storage and large dispatchable loads for load leveling”, 2011

[4] M. Stemmle, e.a., “Superconducting HVDC power cables for voltage source converter systems”, CIGRE, 2012, B1-302

[5] Hazenzahl, e.a., “Program on technology innovation: a superconducting DC cable”, EPRI, 2009

[6] H. Thomas, A. Chervyakov and A. Marian, “Some socio-economic aspects of long-distance energy transport by superconducting power lines with a focus on MgB_2”, 2012 at: www.w2agz.com/Presentations/2012/11-29%20IASS%20Potsdam/Talks/; C. Rubbia, “The future of large power electric transmission”, SC workshop, May 2011; www.bestpaths-project.eu; V. S .Vysotsky, e.a. “New 30 m flexible hybrid energy transfer line with liquid hydrogen and superconducting MgB2 cable-development and test results”, 2015

[7] “The new 525 kV extruded HVDC cable system”, ABB white paper, Aug 2014

[8] A. Poncet, and V. Parma, “Series-produced helium II cryostats for the LHC magnets: technical choices, industrialization, costs” 2008, Adv. In Cryog. Engineering, AIP Conf. Proceedings 985

[9] M. Gouge, “Flexible cryostats for superconducting cables: reliability and lifetime issues”, DOE 2006 Development workshop

[10] L. Trevisani, e.a., “Long distance renewable-energy-sources power transmission using hydrogen-cooled MgB_2 superconducting line”, Cryogenics, 2007, v.47, pp. 113-120; A. Sasaki, e.a., “LN_2 circulation in cryopipes of superconducting power transmission line”, Cryogenics, 2011, 51, pp. 471-476

[11] V. Matias e.a., “Reactive Co-Evaporation of YBCO as a Low-Cost Process for Fabricating Coated Conductors”, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009; V. Matias, R.H. Hammond, “YBCO superconductor wire based on IBAD-textured templates and RCE of YBCO: process economics”, Physics Procedia 36 (2012) pp 1440-1444

[12] A. P. Malozemoff, “Second-generation high-temperature superconductor wires for the electric power grid”, Annu. Rev. Mater. Res. 2012, 42: 373-397

[13] D. C. van der Laan, e.a., “High-current dc power transmission in flexible ReBCO coated conductor cables”, Superconductor Science and Technology, 25 (2012).

[14] M. Callavik, e.a., “The hybrid HVDC breaker”, ABB, 2012

[15] R. Zuijderduin, e.a., “Strengthening of the future electricity grid of the Netherlands by integration of HTS transmission cables”, 2014, Journal of Physics, Conf. Series 507, 032009