Electric Power Systems Research 141 (2016) 381–391

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Efficiency of superconducting transmission lines: An analysis with respect to the load factor and capacity rating

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 5 February 2016
Accepted 5 July 2016
Available online 6 September 2016

Keywords:
Transmission line
Efficiency
Superconducting
Load factor
Sustainable grid
HVDC

ABSTRACT

Superconducting transmission lines (SCTL) are an innovative option for the future electricity grid and in particular for high-capacity HVDC power transmission. The promise of superconducting electric lines lies principally in their small size, with potential advantages in terms of efficiency, environmental impact and public acceptance. Furthermore, contrary to standard conductors, SCTL do not have any resistive losses, therefore the only remaining power loss is due to the cooling system that is needed to keep the superconductor at its cryogenic operating temperature. In order to obtain a realistic value for the SCTL efficiency, both the actual load factor and the capacity rating have to be taken into account. This paper analyzes the transmission efficiency characteristics for two long-distance SCTL designs developed at the IASS and at EPRI as a function of the load factor for capacities up to 10 GW, and in comparison with established transmission technologies. The focus of this study is the planned expansion of the HVDC transmission system in Germany, which is aimed at achieving the current CO_2 reduction goals by integrating an increased share of intermittent renewable energy (RE) into the grid. The results can be readily extended to other scenarios and can provide complementary information for decision processes directed at planning a sustainable future grid.

1. Introduction

A sustainable electric energy supply is one of the major tasks in the near future, especially in the context of increasing the renewable energy share to reduce greenhouse gas emissions and to meet the steadily growing global energy demand. Any innovative technology that can improve the efficiency of future electric grids will be a welcome and much needed addition to the established transmission- and distribution line options. Superconducting transmission lines (SCTL) have a number of advantages compared to standard technologies, in particular for high capacity HVDC power transmission. Besides their small size, the potential for an improved transmission efficiency is one of the key advantages. Additional benefits of SCTL are related to the easier acceptance by the public (small corridor width, underground, no electric fields) [1] and possibly economic advantages [2]. Due to the absence of electrical resistance, the only remaining loss for DC applications is the constant amount of power per unit length caused by the cooling system that is needed to keep the superconductor at its cryogenic operating temperature. The real efficiency of any transmission line, be it a standard technology or a SCTL, depends strongly on the load factor that in turn depends on the overall scenario the TL is embedded in and the boundary conditions thereof. The actual share of renewables in the electricity mix has a huge impact on the load factor, as for instance wind is an intrinsically intermittent energy source compared to hydro power where electric energy is generated using a water reservoir and the power output can be controlled to a certain degree. The complexity of the electric grid in which the HVDC high capacity TL is embedded plays a significant role too as it becomes more challenging to optimize the power flow for an overall minimization of energy losses between numerous centers of energy generation and demand in a meshed grid including the AC grid.

The aim of this paper is to give a more detailed insight into the efficiency of superconducting transmission lines in a real world application with respect to the load factor in a sustainable future electric transmission grid that integrates high shares of RE. A high-efficiency transmission line translates into low equivalent greenhouse gas emissions, which is one of the main reasons for switching to RE generation in order achieve the 2 °C goal.

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http://dx.doi.org/10.1016/j.epsr.2016.07.007

In the following, Germany and its planned HVDC transmission system are chosen as the case study for investigating the efficiency of superconducting lines. This should be merely seen as a convenient example due to the existing availability of concrete plans and detailed information [3,4]. Conclusions can be adapted to other regions or projects with similar load factor and capacity ratings.

The planned HVDC transmission corridors for the year 2025 are displayed in Fig. 1 for scenario B of the most recent German Grid Development Plan (GDP 2025 draft by the Federal Network Agency [3]). The time horizons for the GDPs are 10 and 20 years. The required level of power line route expansion was calculated to be 3200 km for HVDC corridors totaling a transmission capacity of 10 GW. This does not include the German share in the three DC interconnectors between Germany and Belgium, Denmark and Norway. Of particular interest for this paper are corridor A in the far west (and here the northern part A1) and corridor C (also called Südlink in Germany).

2. The load factor in the context of RE integration

Assuming a grid that integrates a high share of renewable energy generations for a future sustainable energy supply it will be hard to achieve a 100% load factor because:

1. The variation of the energy demand over the year and during the day.
2. The intermittent nature of RE – with an RES of the energy mix in Germany of already 25% (2014) and 80% by 2050 [5,6].
3. General considerations tend to match the capacity of transmission lines to the highest possible output of RE sources.

These factors lead to a limitation and reduction of the average load of transmission lines and in particular of HVDC high capacity transmission lines which are considered in this paper.

In contrast to SCTL, standard conductors have an electrical resistance and power losses show a quadratic dependence on the transport current for direct current (DC) applications $P_{\text{Loss}} \sim I^2$. Load factors of less than 100% of the maximum transmission line capacity therefore result in lower relative electric losses and higher efficiencies for standard conductors but in lower efficiencies for SCTL due to the fixed energy consumption of the cryogenic system.

A simulation of the load factors of the planned North-South HVDC TL in Germany was done by the Center for Energy Graz as part of a study on the required German grid extension commissioned by the Federal Network Agency [4]. The average load factors were investigated for various planned HVDC transmission corridors in Germany based on the GDP from 2012. The simulation assumes the forecasted installed RE and conventional generation capacities according to scenario B of the GDP 2012. These capacities are listed in Table 1 for the years 2024 and 2034 taken from the GDP (2014 2nd) and the year 2022 used by [4] (based on the GDP 2012 which has been updated with now slightly different numbers). The study included the forecasted power generation (mix) of adjacent countries and cross border electric energy exchange.

The average load factors are found to be between 54% (corridor C with 4 GW capacity as of GDP 2012) and 86% (corridor A1 with 2 GW capacity) for the year 2022 and to be between 21% (corridor C with 9.2 GW capacity) and 91% (corridor A1 with 6 GW capacity) for the year 2032. These results stem from the calculation B.NEP4K assuming all corridors A, B, C and D to be in place. Please note that the GDP 2014 2nd upgraded the capacity for corridor C to 6 GW in 2024. An improper connection to the AC grid at the southern end of HVDC corridor C is partly responsible for the low average load factor of that corridor. In any case, there are huge differences in the average load factor when comparing all corridors. The efficiency of a hypothetical superconducting TL would therefore vary tremendously depending on the corridor, as would the efficiency of standard conductors. Please note that corridor C actually consist of sub-corridors that have different start and end points where they connect to the AC grid but are located in geographical proximity. DC-AC converter and entry points will be located close to shutdown nuclear power plants to take advantage of existing AC grid infrastructure. Please also note that bulk energy HVDC transmission lines have been realized so far mainly by making point-to-point connections and using Line-Commutated-Converter (LCC) technology that does not allow to build a meshed DC-grid due to their black start inability. The planned HVDC corridors in Germany are in contrast based on Voltage-Source-Converter (VSC) technology that is more flexible and allows to build an HVDC-grid, similar to the existing AC grid, for instance to connect several wind farms to one transmission line or to simply make a 3-fold DC interconnection.

Table 1
Net generation capacities in Germany according to the baseline scenario B in 2022 (used for TU Graz simulations), 2024 and 2034.

Net capacity in GW	B-2022	B-2024	B-2034
Conventional			
Nuclear	0.0	0.0	0.0
Brown coal	18.6	15.4	11.3
Hard coal	25.1	25.8	18.4
Natural gas	31.3	28.2	37.5
Oil	2.9	1.8	1.1
Storage (incl. pump storage)	9.0	10.0	10.7
Others	2.3	3.7	2.7
Sum (conventional)	89.2	84.9	81.7
Renewables			
Hydro	4.7	4.7	5.0
Wind onshore	47.5	55.0	72.0
Wind offshore	13.0	12.7	25.3
Photovoltaics	54.0	56.0	59.5
Biomass	8.4	8.7	9.2
Other renewables	2.2	1.5	2.3
Sum RE	129.8	138.6	173.3
Sum total generation	219.0	223.5	255.0

3. Methods for calculation

3.1. Long-distance superconducting transmission line based on MgB_2 developed at IASS

Results shown are based on a bi-polar long-distance SCTL developed at the Institute for Advanced Sustainability Studies in Potsdam/Germany (IASS) which is based on the affordable superconducting material magnesium diboride (MgB_2) [7]. The underlying idea was to connect remote places of renewable energy generation by a highly efficient transmission technology. An MgB_2 based SCTL can have much lower costs than SCTL projects based on high-temperature superconductors (HTS) primarily due to lower production costs and can therefore facilitate an accelerated adoption of this promising technology. This MgB_2 SCTL was designed to have a capacity rating of 10 GW at a voltage and current rating of ±125 kV and 40 kA with cooling stations located every 300 km. It can either be cooled by liquid hydrogen or gaseous helium plus liquid nitrogen. This voltage is lower than that of state-of-the-art HVDC cables based on standard conductors (525 kV). Reducing the voltage level can lead to lower cost and simpler operation of relevant grid equipment. Superconductors have high current densities, meaning they have the ability to transfer a high current per cross section of the conductor. This allows for lower operating voltages leading to a simplified design with a smaller outer diameter, thus reducing the heat influx. Within a cooperation of CERN and the

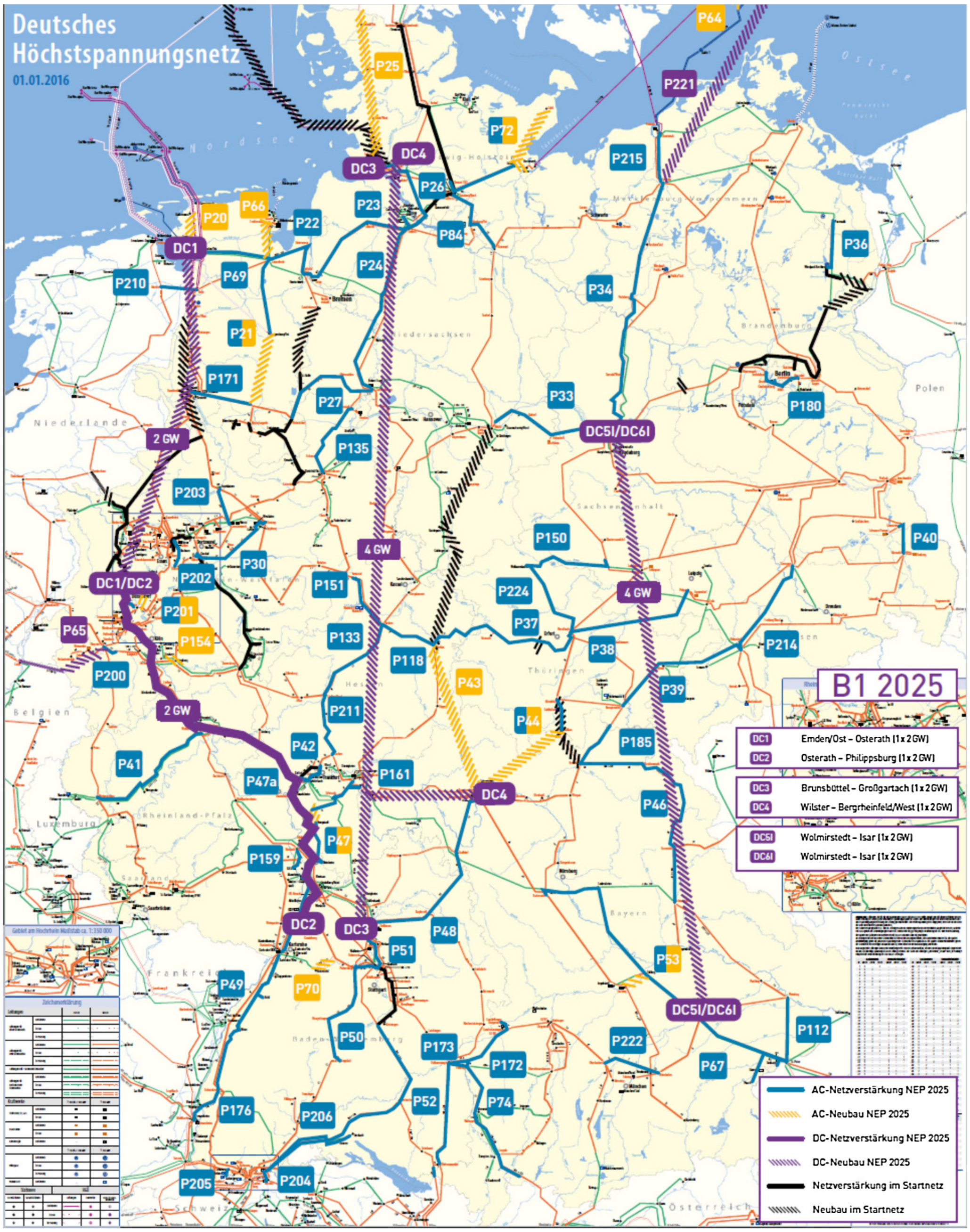

Fig. 1. Planned HVDC corridors – grid development plan Germany scenario B1 2025 [1]. DC1 and DC2 display the former corridor A, DC3 and DC4 display the former corridor C as used until GDP 2024.

Source: NEP 2025, Stand: February 2016, www.netzentwicklungsplan.de based on map "Deutsches Höchstspannungsnetz" from VDE.

IASS, a superconducting prototype cable based on MgB_2 was successfully tested in 2014 with a direct current rating of 20 kA. The total diameter of the cable setup and the cryogenic envelope was only 16 cm. The promise of this technology stimulated interest on the part of various industrial and transmission system operator (TSO) partners and led to the formation of a European consortium of industry, research centers and TSOs with the goal to design and test a high-voltage (200–320 kV) prototype MgB_2 cable to validate its operation under real grid conditions (BEST PATHS project as part of the 7th European Framework Program). This voltage level reflects the voltage of state-of-the-art standard underground cables, in particular the ±320 kV HVDC XLPE cables.

Up to now high-temperature superconductors have been the preferred choice for transmission purposes mainly due to the fact that liquid nitrogen (LN_2) can be used for cooling. Handling LN_2 is much easier than liquid helium (for low temperature SC) or liquid hydrogen (for MgB_2) and allows significant energy savings due to its higher operating temperature and therefore higher efficiency of the underlying thermodynamic cycle (Carnot). In this paper, we use a 5 GW HTS transmission design developed at the Electric Power Research Institute in the US [8] when comparisons are called for.

A detailed technical description of SCTL in general and the MgB_2 SCTL in particular is published elsewhere [7,8]. However it is meaningful to give a brief technical insight for general understanding. Firstly, a superconductor has no resistive losses in DC applications (in AC applications, SC exhibit losses which very much depend on the design and geometry of the cable/conductor), and secondly, it has an extremely high current density resulting in a fairly

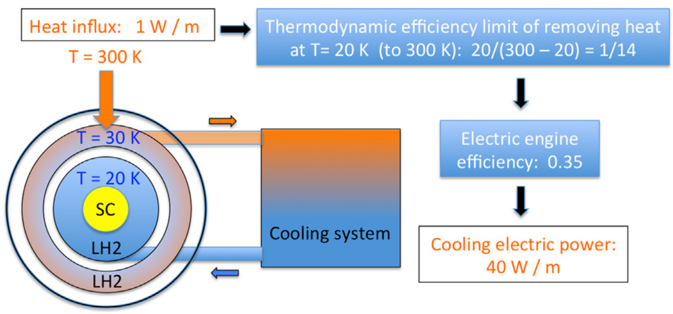

Fig. 2. Simplified energy consumption and efficiency scheme of a superconducting (SC) transmission line cooled by liquid hydrogen (LH_2).

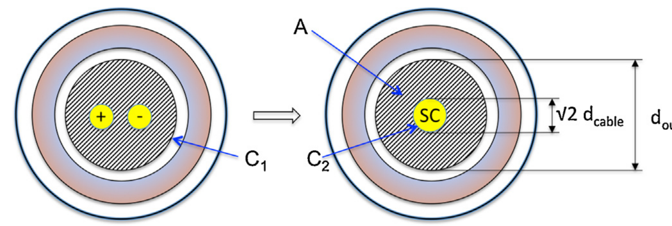

Fig. 3. Scheme used for the calculation of the outer diameter of the inner tube holding the superconducting cable. For simplicity, it is assumed that the two superconducting poles of the MgB_2 SCTL design act like one cable with equal cross section. The hatched area is the enclosed fluid area *A*.

small superconductor size compared to the outer diameter of the complete (cryogenic) system. Doubling the nominal current of a SCTL will thus not lead to a doubling of the outer diameter. The heat influx and therefore the electric power consumption to keep the cryogen at its operating temperature is proportional to the outer diameter of the cooling system and mainly determined by the necessary hydraulic diameters that fulfill the mass flow and heat transport requirements. Besides the operating temperature the distance between cooling stations and the type of cryogen also play a major role here. Lower operating temperatures lead to a lower efficiency of the underlying thermodynamic cycle (Carnot) of the refrigeration system with subsequent higher electric power losses for cooling, as sketched in Fig. 2.

The operating temperature for magnesium diboride (MgB_2) is 15–20 K. This material was only recently discovered to be superconducting in 2001 [9] but is very promising due to its simple manufacturing process and low costs compared to HTS. Ultra-high voltages can lead to an increased outer diameter larger than required by the hydraulic diameters of the coolant transferring tubes due to the necessary electric insulation of the cable. But only for extreme voltage/current combinations can the necessary electric insulation have a substantial influence on the outer diameter. SCTL can therefore have extremely high power efficiencies and are an incredibly interesting choice for a more efficient and sustainable grid, especially for long-distance and high capacity transmission of renewable energy from remote sources or high capacity transmission in densely populated areas. Though this paper only discusses HVDC applications, it is worth mentioning that SCTL can also be operated in AC mode. However, electric losses will then occur in the superconductor caused by the oscillating electro-magnetic field that greatly depends on the design of the cable.

3.2. Electric losses of SCTL in DC mode are independent of their capacity rating

One of the central assumptions in this paper is that the cooling power losses of SCTL are constant and independent from the capacity. For medium- and long-distance power transmission and voltage ratings of 20–150 kV, the outer diameter and therefore the electric power consumption are to a certain extent independent of the capacity. This aspect distinguishes SCTL from standard conductor transmission lines. These experience resistive losses and multiple transmission systems have to be combined to reach the desired capacity. This includes cables that have to be added to make up for a decreased ampacity due to a temperature increase of the conductor triggered for instance by higher local soil temperatures. To verify the prior assumption, calculations for 4 different combinations of voltage and current values were carried out (constant voltage of 30 kV and 125 kV respectively, and constant current of 40 kA and 100 kA respectively). The aim is to find the resulting outer diameter of the MgB_2 based SCTL which then is proportional to the heat influx and the power losses due to cooling. Parameters are the superconducting cable cross section which is proportional to the current rating and the width of the necessary electric insulation layer. The reference is the bi-polar MgB_2 SCTL design developed at IASS to transfer 10 GW of power [7]. The breakdown voltage per length of cryogens is approx. 1000 kV/cm in DC mode [10] and the coolant maybe used for electric insulation, what is assumed here. The hydraulic diameter d_H is the same for every capacity – outer diameter pair to ensure consistent fluid dynamic properties. It can be calculated by multiplying the enclosed fluid area *A* with 4 and dividing by the wetted outer perimeter $C = C_1 + C_2$ (Fig. 3) leading to

$$d_H = \frac{4A}{C} = \frac{\pi(d_{out}^2 - 2d_{cable}^2)}{\pi(d_{out} + \sqrt{2}d_{cable})} = d_{out} - \sqrt{2}d_{cable} \quad (1)$$

and

$$d_{out} = d_H + \sqrt{2}d_{cable} \quad (2)$$

Because the superconducting cable diameter based on MgB_2 (without electric insulation but with copper for thermal stabilization) is only 2–3 cm for 40 kA ampacity (with 2 cables in bi-polar operation) and the design value for the most inner tube diameter is 17 cm, it is evident that the outer diameter does not change significantly for different capacities for constant voltages. In this case, the constant voltage scenario at 125 kV results in the same diameter as the constant current scenario at 40 kA.

All tube diameters carrying cryogenic fluids were chosen to allow for proper hydrodynamic characteristics like high enough mass flow able to carry the heat influx, a low pressure drop and small temperature increase between cooling stations. The necessary electric insulation can in principle be provided by the cryogen for both constant current scenarios because the inner tube diameter is large enough that the necessary distance for proper electric insulation is fulfilled. This is a visionary concept that would require the conductor to be exactly centered in the inner cryogenic tube. The outer diameter is therefore constant for the assumed 40 kA and 100 kA constant current scenarios. Even considering standard electric insulation using paper (soaked with the cryogen) and assuming a voltage breakdown safety factor of 20 leading to 2 × 1 cm added diameter per extra 50 kV (1 cm/MV voltage breakdown distance) results only in a small increase of heat influx due to the larger outer diameter.

As seen in Fig. 4, the constant voltage scenarios show a slight positive slope because the diameter of the inner tube has to increase with increasing capacity, i.e. increasing current and therefore increasing superconducting cable diameter. If the diameter of the inner tube changes, all diameters of the outer tubes will subsequently increase. The slope is very moderate because the current density of superconductors is extremely high. This is mirrored into the small change of the outer diameter. Consequently a constant total outer diameter and heat influx are assumed in this paper for all considerations because the emphasis is put on medium- and

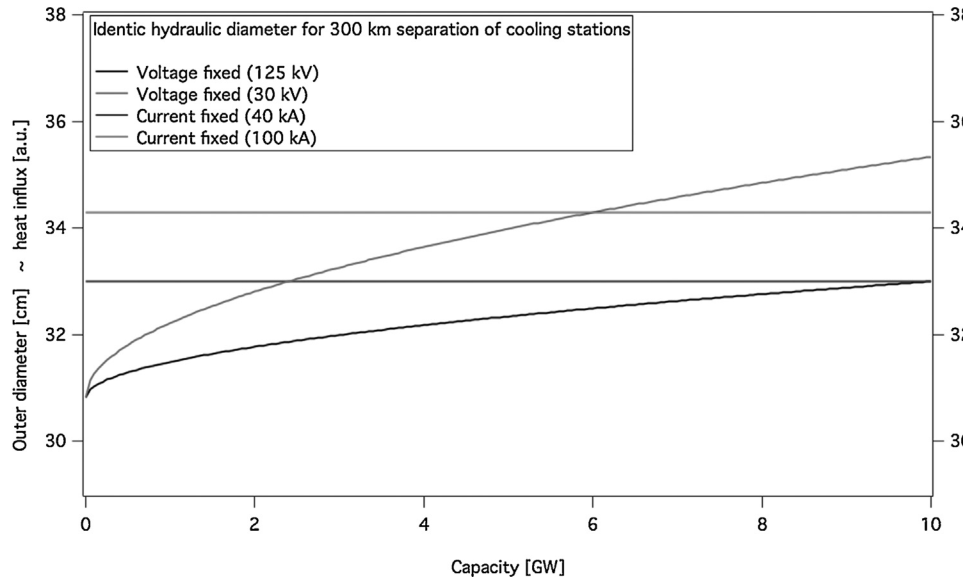

Fig. 4. Total outer diameter and heat influx in arbitrary units are displayed for different fixed voltage and current ratings dependent on capacity for an MgB_2 SCTL design cooled by liquid hydrogen developed at IASS. A fixed voltage means that the current rating is chosen to meet the capacity rating hence the small increase of the diameter with capacity. The hydraulic diameters are the same for every example.

long-distance TLs. The outer diameter is 32 cm for the MgB_2 based SCTL cooled by LH_2 for instance, due to hydrodynamic and thermodynamic boundary conditions like heat transfer and pressure drop along the line. Because the heat influx is assumed to be constant, the power losses caused by cooling are assumed to be constant too.

3.3. Power losses of standard transmission options

The technology of choice for future grid applications depends on the specific project. Besides investment and operating costs, the transmission efficiency, public acceptance issues and the environmental impact are most relevant. In this regard, SCTL are competing with standard technologies like ±320 kV HVDC XLPE underground cables and ±500/800 kV HVDC overhead lines (OHL) as those are the solution preferred by TSOs for high capacity long- and medium distance transfer of electric energy up to now. Efficiency numbers for these technologies were supplied by ABB/Switzerland and by the French Electricity Transmission Network (RTE). The mentioned cables have losses of 6.5% per 1000 km at full load [11] and a double bi-polar system of ±500 kV HVDC OHL experiences losses of 3.35%/1000 km if transferring 4 GW [12]. For different capacities, the electric losses of standard TL options, especially for OHL, can change abruptly because each system has a fixed capacity rating. Depending on the chosen capacity, a system can be at its transmission limit with subsequent maximum losses if the load reaches maximum capacity, or it can have lower losses if the maximum load is smaller than the capacity rating. For instance, two ±500 kV OHL systems that are able to transfer a maximum of 6 GW total power have much lower resistive losses if only 4 GW need to be transferred. However, the second OHL necessary for transporting the last GW comes with extra costs and right-of-way width.

3.4. Converter losses

The electric losses of converters are not included in the efficiency calculations because the capacity rating is the same for every transmission option. VSC converters are built using IGBT modules with current ratings of 400–900 A and output voltages of approximately 2 kV, much below the required grid voltage. A certain number of modules have to be stacked and wired to match the grid voltage and capacity [13]. The number of these modules will therefore be the same for all HVDC transmission line options and thus the losses are assumed to be the same (~1% of the converted power for modular multilevel VSC).

3.5. Calculation of load factor dependent efficiency

The efficiency ε of SCTL in DC mode is calculated by dividing the power losses P_{Loss} – which are only caused by cooling – by the power transferred P_{Trans}, i.e. by the capacity rating CR times the load factor LF:

$$\varepsilon = \frac{P_{\text{Loss}}}{P_{\text{Trans}}} = \frac{P_{\text{Loss}}}{\text{CR} \cdot \text{LF}} \quad (3)$$

As mentioned earlier it was assumed that the power losses of SCTL are independent from the capacity rating and that no extra losses occur in addition to cooling losses because the superconducting cable is operated in DC mode. This was verified by calculations based on the IASS long-distance SCTL design.

3.6. Impact of the environment on the efficiency

The soil temperature influences the electric losses of buried standard conductors as well as the electric losses for cooling a superconducting transmission line. Whereas for standard conductors in DC applications this is described by the linear temperature coefficient α (3.9×10^{-3} for Cu at 20 °C) and an according increase in resistance R and power losses $P = I^2R$ with increased temperature of the conductor $R = R_{20\,^\circ\text{C}}\,(1 + \alpha(T - 20\,^\circ\text{C}))$, the situation is more complicated for SCTL. Highly reflective thin layers and stacks of aluminized Mylar foil separated by fiberglass or polyester are inserted in the vacuum to further reduce the heat influx by the dominant radiation losses according to the Stefan-Boltzmann law. The total heat influx q entering a cryogenic system can be described by an empirical formula [14,15]

$$q_{(n)} = \frac{(T_2^2 - T_1^2)a}{2n} + \frac{(T_2^4 - T_1^4)b}{n}, \quad [\text{W/m}^2] \quad (4)$$

with $a = 4.025 \times 10^{-4}\,\text{W/m}^2\,\text{K}^2$ and $b = 2.349 \times 10^{-9}\,\text{W/m}^2\,\text{K}^4$ 60 layers of Mylar and cryogen temperatures of $T = 20\,\text{K}$ (LH_2) respectively 65 K (LN_2) were assumed for the efficiency calculations done for the MgB_2 transmission lines. A (soil) temperature increase of

10 K from 300 K to 310 K would therefore lead to an 11% increase in heat influx for either LH_2 or LN_2, causing increased power losses due to cooling. An increase in soil temperature leads to a limited maximum operating current to prevent a thermal runaway and overheating of the conductor, as described by the Neher–McGrath formula [16]. The maximum ampacity is greatly influenced by the soil moisture that is much smaller in hot climates and also directly affected by the heat that is produced due to the resistive underground cable conductor. For hotter climates the result is a need for an increased number of standard cables with a wider separation that translates into increased capital costs and wider transmission corridors. Also, the total ampacity is limited by the weakest point along the line, i.e. the lowest local ampacity due to, for instance, other local heat sources. As an example, the number of cables is doubled and the trench width tripled for a 5 GW capacity HVDC underground transmission line located in North Africa, as compared to the North of France [11]. This is not the case for superconducting TLs and constitutes one of their intrinsic advantages. Especially in hot climates where the sun irradiance is high and solar power installations are most efficient can SCTL be utilized for electric power transmission (for instance in Southwest US, Mexico, Arabian Peninsula, most parts of Africa, Andes plateau, Australia, India).

4. Results

4.1. The impact of load factor and capacity rating on the efficiency of SCTL

The electric losses and the efficiencies of superconducting and standard transmission line options will be discussed for different scenarios, capacities and load factors. First, a TL with 4 GW capacity and 810 km length is assumed based on the parameters of the Südlink/HVDC corridor C of the grid extension plan in Germany. Second, a TL with 10 GW capacity and 3000 km length is assumed simulating a long-distance TL. Third, the capacity and load dependent efficiencies are given for two SCTL options based on HTS cooled by liquid nitrogen and MgB_2 cooled by liquid hydrogen for capacities up to 10 GW. The MgB_2 based SCTL option using liquid nitrogen plus gaseous helium as coolants has very similar electric losses as the HTS option due to employing the same coolant for the outermost tube and results are therefore not displayed. The electric losses for MgB_2 based superconducting transmission lines are 29.7 MW and 9.5 MW for a length of 810 km (Table 2), using liquid hydrogen or gaseous helium + liquid nitrogen as cryogen. These values stem from the long-distance SCTL design developed at IASS.

The electric loss for the high temperature superconductor (HTS) transmission line is 7.3 MW for 810 km (Table 2) and was taken from a design developed at the Electric Power Research Institute (EPRI) with an operating voltage of ±100 kV [8]. For a 4 GW capacity TL, the electric power losses of ±500 kV HVDC OHL and ±320 kV HVDC XLPE cables are much higher at 100% load compared to all superconducting options (Table 2, Fig. 5). Power losses of standard cables are for instance 31× higher than for an HTS based SCTL. When operated at 50% load, the losses of standard overhead lines are already lower than the losses of hydrogen cooled MgB_2 TLs and are smaller than every considered SCTL option at 25% load for 4 GW capacity. As a consequence SCTL are especially suited for high capacity TLs with high average load factors such as corridor A1 of the German grid development plan, and are not so appropriate from an energetic efficiency point of view for TLs with a low average load factor like corridor C (year 2032). Base load transmission with a constant energy transfer at high load factors seems to be one of the most reasonable applications for SCTL. The HVDC transmission corridor A1 in Germany can be taken as an example, especially if one considers the likely public acceptance advantage of SCTL compared to standard transmission line technologies in the densely populated state of North-Rhine-Westphalia. SCTL would really excel in efficiency for long-distance transmission over several 1000 km of bulk electric energy on the order of 10 GW, for instance generated by hydro or geothermal power plants. Long-distance transmission lines with capacities up to 6 GW based on standard technologies are for instance already operating in China and South America. Fig. 5 graphically displays the electric transmission losses versus load assuming the length and capacity rating of the Südlink HVDC corridor in Germany, which are 810 km and 4 GW respectively for the year 2022. This corridor is envisioned to have a capacity of 10 GW in 2034 (50 Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, 2014). This value is lower than calculated in the grid development plan prepared in 2013 that mentions 12 GW for corridor C for the year 2032.

The transmission line losses per transferred energy unit would then be lower for SCTL because the losses are fixed. This still holds true if one assumes two separate 5 GW SCTL to fulfill $(n-1)$ requirements. HTS based SCTL using only liquid nitrogen as coolant have much lower losses than any other option down to 29% load, where standard ±500 kV OHL become more efficient. Please remember that this was calculated for 2 OHL systems transferring 4 GW total power, hence the relatively low electric losses for the OHL. The MgB_2 based SCTL reach parity at 32% (LN_2 + GHe) and 37% (LH_2). For the specific case of corridor C in 2022 with a simulated load of 54% (Energie Zentrum Graz, 2012) the liquid hydrogen cooled MgB_2 SCTL has similar losses as the standard ±500 kV HVDC OHL and half the losses of standard ±320 kV cables. The losses as a function of capacity and load are displayed in Fig. 6 for a liquid hydrogen cooled MgB_2 based SCTL and in Fig. 7 for a liquid nitrogen cooled HTS based SCTL.

It is evident that superconducting transmission lines have an efficiency disadvantage at low loads and small capacities. The relative loss function is: Loss [%] = $C/(\text{load} \times \text{capacity})$ with C representing the fixed cooling losses (36.7 MW for LH_2/MgB_2 and 9 MW for LN_2/HTS). The red edge of the contour plots marks the 6% loss/1000 km line, that separates the load–capacity combinations with a non-acceptable efficiency (non-colored). The limit was taken from the losses of ±320 kV standard cables at 100% load. Even considering the size advantage and a potential increase of the public acceptance, SCTL should not be considered as an option for those load–capacity combinations due to unacceptably high electric power losses. The black line in the contour plots shows when the losses of standard ±320 kV cables equal the total electric power losses of a liquid hydrogen cooled MgB_2 based SCTL (Fig. 6) and a liquid nitrogen cooled HTS based SCTL (Fig. 7). From an energetic efficiency point of view, SCTL should be preferred above that black line because an increased load factor means increased losses for standard cables (±320 kV) but not for SCTL. For comparison, the TLs for corridors A1 and C of the German HVDC grid with their corresponding capacity rating and simulated load factor in the year 2032 are marked in the contour plots. Whereas corridor A1 favors both superconducting transmission lines over standard ±320 kV HVDC cables to gain a higher efficiency, there is no clear winner for corridor C due to its considerably low load factor of 21%. The minimum capacities to have electric losses not higher than 6%/1000 km, a loss number that stems from standard underground cables and should not be exceeded due to sustainability and efficiency reasons, are listed in Table 3.

These numbers are based on the long- and medium distance designs developed at IASS for MgB_2 with refrigeration stations located every 300 km and at EPRI for HTS with refrigeration stations located every 20 km. Power losses due to cooling will change for other separation distances due to changing outer diameters and also due to changed efficiencies of cooling machines with different

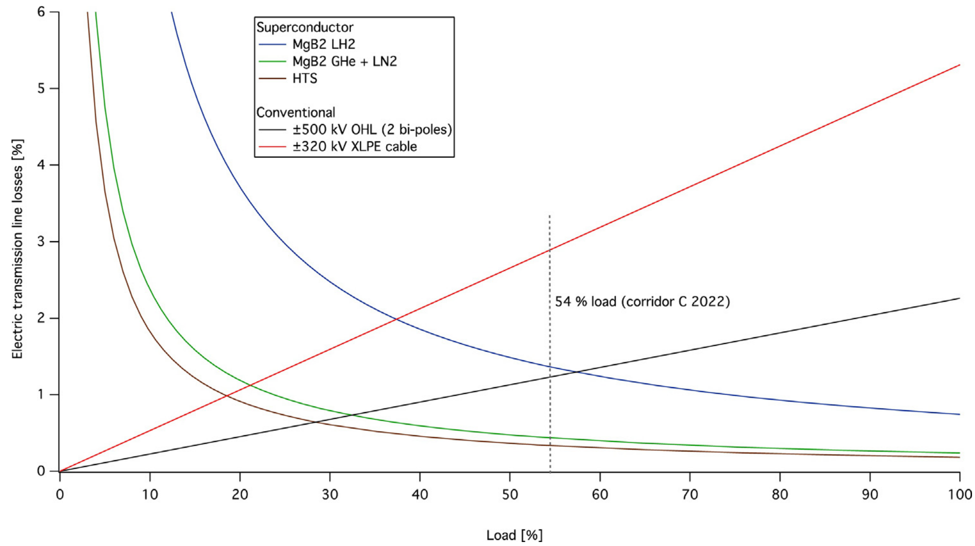

Fig. 5. Relative electric losses of HVDC transmission line options for 4 GW and 810 km not including converter losses (Corridor C/Südlink).

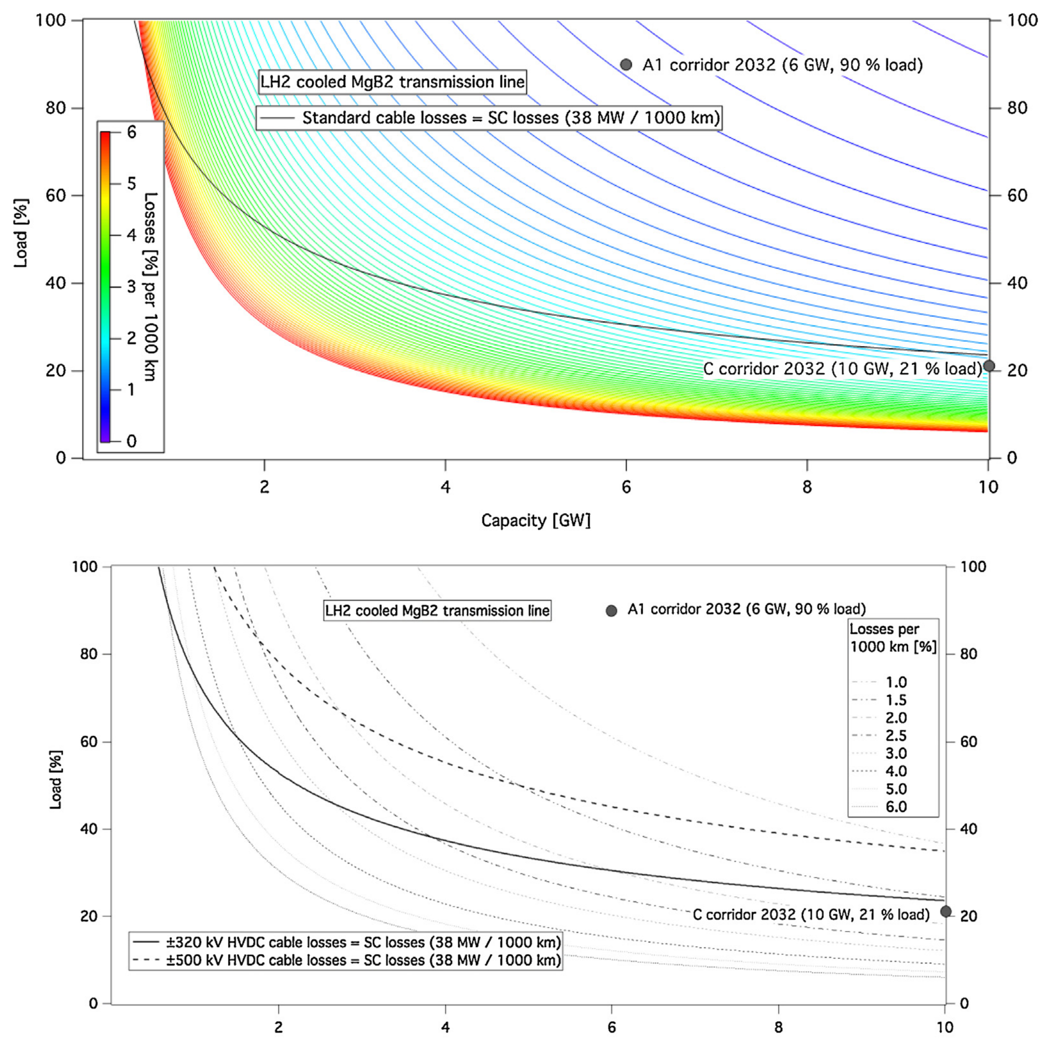

Fig. 6. The colored contour plot shows the percentile electric power losses for a specific load and capacity of a LH_2 cooled superconducting transmission line (MgB_2). The black line displays equal total losses compared to standard ±320 kV XLPE cables – it marks the 38 MW loss/1000 km line. Above that line, the superconducting cable (LH_2) has lower total losses compared to ±320 kV XLPE TLs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Electric losses of transmission line options for 4 GW and 810 km.

Electrical losses [load] – 4 GW, 810 km	MgB_2 LH_2	MgB_2 GHe + LN_2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Load: 100%					
Power losses [MW]	29.7	9.5	7.3	92.6	223.4
Power losses [%] of load	0.72	0.23	0.18	2.23	5.24
Load: 50%					
Power losses [MW]	29.7	9.5	7.3	23.2	55.9
Power losses [%] of load	1.44	0.46	0.36	1.12	2.62
Load: 25%					
Power losses [MW]	29.7	9.5	7.3	5.8	14.0
Power losses [%] of load	2.88	0.92	0.71	0.56	1.31

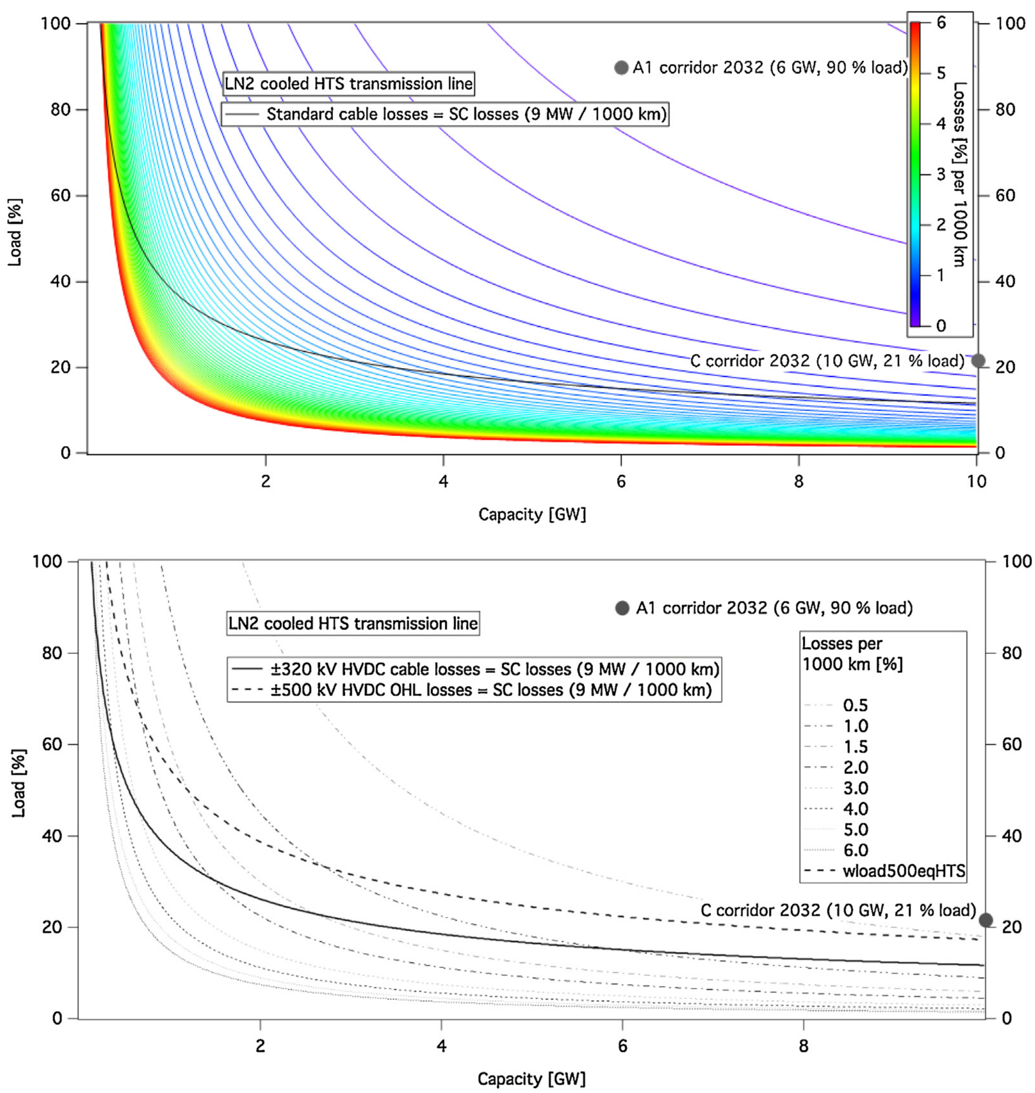

Fig. 7. The colored contour plot shows the percentile losses for a specific load and capacity of a LN_2 cooled superconducting transmission line (HTS). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

power ratings. The above-mentioned minimum capacities would therefore have been to be reevaluated. A realistic load factor of 50% leads to minimum capacities of 1.2 GW for the LH_2 cooled SCTL and 300 MW for LN_2 cooled SCTL. Below these capacities, a reasonably efficient operation of SCTL is not possible for the designs discussed here. To have electric losses equal to those of standard cables the capacities have to be even higher with 550 MW (EPRI LN_2) and 2.2 GW (IASS LH_2) at a 50% load factor.

Table 3
Minimum capacity ratings for SCTL options for different load factors to have maximum losses of 6%/1000 km and to equal losses of ±320 kV HVDC standard cables.

	100% load factor, max. 6% losses	50% load factor, max. 6% losses	50% load factor, max. ±320 kV cable losses
LH_2 MgB_2 SCTL	610 MW	1220 MW	2200 MW
LN_2 HTS SCTL	150 MW	300 MW	550 MW

Table 4
Power losses and efficiency of HVDC options and associated costs assuming a 810 km long transmission line with a net capacity of 4 GW and 50% load (corridor C 2022/Südlink). AC-DC converter losses and costs are not included.

Electrical losses and associated costs	MgB_2 LH_2	MgB_2 GHe + LN_2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Power losses [MW]	29.7	9.5	7.3	23.4	56.6
Transmission line loss [MWh/y]	261,063	83,066	64,079	206,114	497,457
Total losses (losses/input) [%]	1.46	0.47	0.36	1.13	2.66
% of electricity demand in GER (555 TWh/y)	0.047	0.015	0.012	0.037	0.090
Transmission loss costs @ 82$/MWh [M$/y]	21	7	5	17	41
Present value 40 y. period [M$]	322	102	79	254	614

Table 5
Power losses and efficiency of HVDC options and associated costs assuming a 3000 km long transmission line with a net capacity of 10 GW and 100% load. AC-DC converter losses and costs are not included.

Electrical losses and associated costs	MgB_2 LH_2	MgB_2 GHe + LN_2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Power losses [MW]	110.0	35.0	27.0	939.3	2470.3
Transmission line loss [MWh/y]	966,900	307,650	237,330	8,256,477	21,713,526
Total losses (losses/input) [%]	1.08	0.35	0.27	8.39	19.72
% of electricity demand in GER (555 TWh/y)	0.174	0.055	0.043	1.488	3.912
Transmission loss costs @ 82$/MWh [M$/y]	79	25	19	677	1781
Present value 40 y. period [M$]	1193	380	293	10,187	26,790

4.2. Overall energetic and monetary impact

The relevance with respect to the total electric energy consumption in Germany as well as the monetary impact of electric losses are listed in Table 4 for the discussed corridor C of the German grid with 4 GW capacity assuming a 50% load factor and in Table 5 for a hypothetical 10 GW transmission line at 100% load factor as developed at the Institute of Advanced Sustainability Studies in Potsdam. All SCTL have an efficiency advantage compared to standard ±320 kV HVDC cables even at a 50% load factor with total energy losses of 13% for liquid nitrogen cooled SCTL to 52% for liquid hydrogen cooled SCTL. The results also show that SCTL with 4 GW capacity at a 50% load factor are competitive in terms of efficiency with HVDC OHLs, not only compared to ±500 kV but also compared to ±800 kV HVDC OHL which have been employed in China for bulk electric energy transmission. The amount of electric losses compared to the electricity demand in Germany is practically insignificant for all options for a single TL at 50% load factor. However, considering that the total installed HVDC North-South capacity in Germany in 2032 is on the order of 25 GW and the average load factor may be higher, a solution using only standard HVDC cables could lead to electric losses reaching 1% of the electric energy demand in Germany.

The costs associated with the electric losses over a 40 year lifetime are 614 M$ for standard cables and 79 (HTS) to 322 M$ (MgB_2 LH_2) for SCTL (Tables 4 and 5). Converter losses are not included. Capital costs for a 4 GW, 810 km length TL have been estimated to be 1.4 B$ (± 125 kV MgB_2 LH_2), 2.6 B$ (±125 kV MgB_2 He + LN_2), 5 B$ (±100 kV HTS), 1.6 B$ (±500 kV HVDC OHL) and 4.2 B$ (±320 kV HVDC XLPE cable) [1,2]. It is not surprising that the losses of standard transmission lines and especially ±320 kV XLPE cables are quite enormous at 100% load and for a 3000 km long TL. A TL with those parameters reaches a remarkable 4% of the annual electricity demand of Germany. Please note that in order to deliver a net power of 10 GW, the input power has to be higher to make up for the losses occurring along the length of 3000 km, which also means an increase of the nominal AC-DC converter capacity at the entry point with subsequent higher converter losses and costs. Present value loss costs for a 40-year lifetime add up to about 66% of the capital cost for a 3000 km length, 10 GW capacity TL based on ±320 kV XLPE cables (45 B$ without converter cost) [1,2]. Costs will also increase because the capacity of the TL itself has to be higher. This is not directly relevant for SCTL as the conducting material has no electric losses itself in DC operation and at such high capacity ratings, the losses due to cooling are almost negligible if tapped straight from the TL.

4.3. Impact on CO_2 emissions

The EU Commission's CO_2 emission reduction targets are to achieve a cut by 40% until the year 2030 based on the policy framework for climate and energy. Germany's goal is to reduce CO_2 emissions by 80% until 2050. Very recently the US announced the goal to cut emissions by 26–28% until 2025 and China to achieve a stop and peak of emissions until 2030. No matter whether this can be achieved or not, it is clear that a substantial fraction of electric energy will still be generated worldwide using fossil energy sources also in the year 2050. Globally, there is a substantial potential for new high-capacity long-distance transmission lines. The power losses of transmission lines can be linked to CO_2 emissions because losses of electrical energy need to be compensated by an increase of the generated electric energy unless one assumes that a hypothetical SCTL would transfer 100% of RE with an excess of RE available for cooling. The renewable energy share (RES) of the electricity mix in Germany was 23% at the end of 2012. The average emission of CO_2 per generated kWh was 563 g in 2010 [17]. The CO_2 emissions of superconducting transmission lines are compared to standard overhead and underground transmission lines in Table 6 for the example of corridor C of the German grid development plan (Südlink) assuming a load factor of 50%.

For instance would standard cables experience losses equivalent to 6.5% of the CO_2 emitted by a typical steam-cycle coal power plant (4300 GWh/year). Consistent with the electric losses, the emissions are lowest for liquid nitrogen cooled SCTL (0.8–1.1% coal power plant CO_2 emission equivalent). The efficiency drastically changes in favor of the SCTLs with increasing capacity and load factor due to the fixed amount of energy needed for cooling SCTL. As an example, the CO_2 emissions for a 3000 km long transmission line with a 10 GW net-capacity at 100% load are listed in Table 7.

The emissions associated with the electric losses for standard cables would be equivalent to almost 3 coal power plants! HVDC overhead lines would also be responsible for the emission of 30× the amount of CO_2 nitrogen cooled SCTL indirectly emit. The German electric grid (AC) experiences total electric losses of 5–6% for transmission and voltage conversion when bringing electric energy from source to load. The low voltage level is responsible for the largest fraction of these losses, followed by the medium-voltage

Table 6
CO_2 emissions associated with power losses of transmission lines (4 GW, 810 km length) assuming the RES of 2012 in Germany – load: 50%.

CO_2 equivalent emission of losses	MgB_2 LH_2	MgB_2 GHe + LN_2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Electricity mix 2012 (563 g/kWh)					
Per year [t]	146,717	46,683	36,012	115,836	279,571
For 40 years [t]	5,868,696	1,867,312	1,440,498	4,633,439	11,182,826
Coal power plant CO_2 equivalent emission [%]	3.4	1.1	0.8	2.7	6.5

Table 7
CO_2 emissions associated with power losses of transmission lines (10 GW, 3000 km length) – load: 100%.

CO_2 equivalent emission of losses	MgB_2 LH_2	MgB_2 GHe + LN_2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Electricity mix 2012 (563 g/kWh)					
Per year [t]	543,398	172,899	133,379	4,640,140	12,203,002
For 40 years [t]	21,735,912	6,915,972	5,335,178	185,605,613	488,120,066
Coal power plant CO_2 equivalent emission [%]	12.6	4.0	3.1	107.9	283.8

distribution grid and the high/ultra-high voltage transmission grid. That is primarily related to the total length. The capacity of low voltage transmission lines may be too low for SCTL to be more efficient than standard technologies, but the use of SCTL can offer advantages to local distribution grids in terms of efficiency. Considering the length of planned HVDC corridors in Germany and elsewhere, the use of SCTL can lead to reduced CO_2 emissions for these applications. Ultimately, one can think of a combined transmission and distribution grid completely utilizing SCTL at only one voltage level all the way from generation (10–30 kV turbine/generator output voltage) to the distribution centers. Thus one would get rid of up-and-down transformer stations and save associated electric losses (0.3–1.1%, municipal utilities Munich and Berlin).

4.4. Using SCTL to store excess RE

As mentioned in the beginning, simply connecting intermittent renewable energy sources at high efficiencies using SCTL will require a sophisticated energy management system to achieve a high average load factor. In this respect, the cryogenic system of SCTLs could store excess energy during times of high RE generation by cooling the cryogen to lower temperatures and warm-up to regular operating temperatures at times of low load with no use of electric energy. As cooling at cryogenic temperatures is required anyway for operation, the efficiency of this type of storage would be relatively high in this specific case. The power and capacity would be small though – like 7–30 MW for the described 800 km long SCTL as would be the storage capacity (a few MWh per Kelvin for LH_2 @ 17 K/17 bar) – please compare with Table 2 – however much less in pure urban short length applications due to the smaller necessary diameter and lower cryogen mass. The short length Long Island Power Authority (LIPA) SCTL based on HTS cooling system has a power of 6 kW @ 70 K in comparison. This possible storage in the cryogenic system is in line with the physical characteristics of a superconductor to exhibit a clearly increased current density at lower temperatures, which translates into a higher capacity of the SCTL. Excessive RE could also be stored as hydrogen in SCTL as a coolant by means of electrolysis and liquefaction and transferred this way. The liquefaction process however is very inefficient and the mass flow of the cryogen low.

5. Summary

The efficiency advantage of superconducting transmission lines is often highlighted in relevant debates. However, the electric losses of SCTL are per se not lower than for standard transmission technologies and a careful evaluation of every transmission line case has to be made. As a basic rule, the higher the capacity and the higher the average load factor, the higher the efficiency for SCTL. The full energy efficiency advantages of SCTL can be best exploited if this technology is used to connect power plants with a constant energy output with constant load centers, in order to obtain a high load factor or simply to provide the minimum base load. From an energy efficiency point of view, connecting remote geothermal and hydro power plants with capacities of several GW or even tens of GW may be one of the top applications for SCTL in the future electricity grid due to their high capacity factors (70% for geothermal and 50% for hydro [18]) as long as other more intermittent RE sources like wind and solar are not backed by adequate storage capacity. Energy storage could also be realized by reducing the operating temperature through an increase of the refrigeration power at times of high load, and vice versa by letting the cryogen warm up at times of low load. In the meantime, SCTL will be utilized on much smaller scale in local and regional grids not for an efficiency advantage but for public acceptance and reduced space requirement reasons. Standard technologies can have equal or even higher efficiencies for low average load factors. Recently, “standard” HVDC XLPE cables were developed with voltage ratings of ±525 kV compared to the former limit of ±325 kV and hence corresponding lower electric losses (or higher capacities). In this respect, SCTL can have a technological edge as they could be operated at significantly lower voltages with the same capacity. An example is the Ampacity project in Essen by RWE that recently announced the failure-free operation since start of operation in early 2014. Finally, SCTL have the potential to reduce CO_2 emissions, but in order to obtain a realistic number for the efficiency of SCTL, the characteristics of the adjacent grid, especially the load factor, have to be included.

Acknowledgements

This work was funded by the German Federal Ministry of Education and Research (BMBF) and the state of Brandenburg/Germany.

Appendix. Acronyms and nomenclature

AC	alternating current
cm	centimeter
DC	direct current
GHe	gaseous helium
GW	gigawatt
GWh	gigawatt hours
HTS	high temperature superconductors
HV	high voltage
HVDC	high voltage direct current
IGBT	insulated gate bi-polar transistor
K	Kelvin
kA	kiloampere

km	kilometer
kV	kilovolt
kWh	kilowatt hours
LCC	line commutated converter
LH_2	liquid hydrogen
LN_2	liquid nitrogen
LTS	low temperature superconductors
m	meter
MgB_2	magnesium-di-boride
MLI	multilayer insulation
MW	megawatt
OHL	overhead line
q	heat influx
RE	renewable energy
RES	renewable energy share
ROW	right-of-way
SC	superconductors
SCTL	superconducting transmission line
T	temperature
TL	transmission line
TSO	transmission system operator
VSC	voltage source converter
W	watt
XLPE	cross linked polyethylene

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