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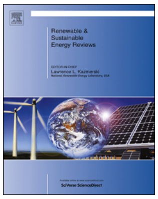
Renewable and Sustainable Energy Reviews 55 (2016) 59–72

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Superconducting transmission lines – Sustainable electric energy transfer with higher public acceptance?

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ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
18 June 2015
Accepted 21 October 2015
Available online 21 November 2015

Keywords:
Environmental impact
Superconducting transmission
Public acceptance
HVDC transmission
Future grid

ABSTRACT

Despite the extensive research and development investments into superconducting science and technology, both at the fundamental and at the applied levels, many benefits of superconducting transmission lines (SCTL) remain unknown to the public and decision makers at large. This paper aims at informing about the progress in this important research field. Superconducting transmission lines have a tremendous size advantage and lower total electrical losses for high capacity transmission plus a number of technological advantages compared to solutions based on standard conductors. This leads to a minimized environmental impact and enables an overall more sustainable transmission of electric energy. One of the direct benefits may be an increased public acceptance due to the low visual impact with a subsequent reduction of approval time. The access of remote renewable energy (RE) sources with high-capacity transmission is rendered possible with superior efficiency. That not only translates into further reducing CO_2 emissions in a global energy mix that is still primarily based on fossils, but can also facilitate the development of RE sources given for instance the strong local opposition against the construction of new transmission lines. The socio-economic aspects of superconducting transmission lines based on the novel magnesium diboride (MgB_2) superconductor and on high-temperature superconductors (HTS) are compared to state-of-the-art HVDC overhead lines and underground cables based on resistive conductors.

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http://dx.doi.org/10.1016/j.rser.2015.10.041
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1. Introduction

The objective of this paper is to outline the advantages of superconducting transmission lines with respect to public and social acceptance [1–3] and to show the status of existing and planned superconducting transmission lines, highlighting the positive sustainability characteristics of this technological option [4]. The path forward from industrial development to an utility application with obstacles and the future potential are also given. Thus the paper aims at giving interested stakeholders a more complete picture of superconducting transmission lines going beyond the technical aspects that constitute the focus of existing literature [5]. Only few of the recent reviews provide an insight into the social acceptance of superconducting transmission lines, for instance through detailed cost analyses [6]. This paper evaluates the benefits of superconducting transmission lines and subsequently gives a comparison to established standard transmission technologies, which increasingly cause public concern as a result of the electric grid expansion plans [7,8]. Experience shows that one of the main hindrances to a wider use of this technology is not the research and development (R&D) part, but simply economic reasoning and missing technology awareness.

The need to upgrade and expand the electric grid to meet the requirements imposed by the access and utilization of renewable energy sources, intermixed with a global growing energy demand, is increasingly challenged by environmental questions and the public community affected by these grid extension plans. This intensifies the urge to develop new sustainable technologies that can alleviate the multiple intricate problems arising from ecological, social and economic boundary conditions, in order to find suitable solutions for all involved stakeholders. Apart from the affected local communities, key stakeholders are the transmission and distribution system operators, transmission line manufacturers and potential investors.

Superconducting transmission lines are an innovative option to transfer electric energy and are now being tested and accepted by a growing number of operators and utilities as part of the electric distribution grid (for example, the AmpaCity project in Germany and the LIPA[1] project in the US will be discussed in detail in Section 2.2). This paper highlights the potential of SCTL to minimize the environmental and visual impact and thereby to increase the public acceptance of transmission lines compared to the case of standard HVDC overhead and underground lines. From a technical point of view, the higher transmission efficiency and the ability to use lower operating voltages while still preserving the total capacity are the dominant advantages. However, from the perspective of local residents and communities affected by new transmission line projects, the low visual impact due to the incredibly small size seems to be the main advantage. Moreover, estimated costs will be presented in Section 8.1 and hint that SCTL can be competitive with standard cables and even with overhead lines.

One of the showpiece examples for the dilemma explained above is the electric grid expansion as a consequence of the Energy Transition (Energiewende) in Germany. The grid expansion has been challenged for years by a strong opposition against the construction of new transmission lines, especially of new overhead lines. As an example, around 21,000 objections were recorded in the case of the Wahle-Mecklar overhead power line (380 kV, 190 km long) in Lower Saxony and Hesse [7], which amounts to about one complaint per 9 m of transmission line. Protesters and affected residents demand the use of underground cables despite the significantly higher costs. Furthermore, a new bill is now (Nov '15) debated by the ministry that states the preference of underground cables for the HVDC corridors in Germany. This is apparently triggered by the fact that the approval process of corridor C (Südlink) especially is hindered by public opposition. Another example in Europe is the France–Spain interconnection project that originated from an agreement signed in 1984 between France and Spain to transfer electricity to Spain. All projects considered until 2003 were abandoned due to multiple reasons including public opposition (for instance against the alteration of nature reserves and touristic areas). The project proposed in 2003 (now called INELFE[2]) still faced a lot of public opposition and concern [9]. Several NGOs were formed by local communities and governments ("Non à la THT"/"No to the extra high voltage", "Defensa de la Terra"). Finally, Spain and France had to ask for a European coordinator in 2006 to facilitate the implementation of the project. Of all non-commissioned transmission line projects in the ten-year-network-development-plan (TYNDP) 2010 at the time of publishing the TYNDP 2012, 34% was delayed and 3% was canceled [10,11]. The most frequent reason was public opposition by the local residents that led to the substitution of some OHL[3] sections with underground cables. The resulting average delay amounted to more than 2 years [11]

The concerns related to (overhead) transmission lines are connected to one or several of the following issues [12,13,1]:

- Visual impact
- Destruction or alteration of the natural landscape
- Possible impact on health
- Environmental impact
- Lower property value

This is mirrored in the obstacles identified for specific projects in the 2007 Priority Interconnection Plan (PIP) by the European Commission [14]. As pointed out by Buijs [15] most projects in the PIP encountered obstacles related to the NIMBY[4] phenomenon, i.e. people oppose projects that affect them directly and potentially have a negative impact on their lifestyle, despite actually having a positive attitude towards the general idea of for instance the "Energiewende" [16]. Out of 32 projects, 11 encountered obstacles related to electromagnetic fields (EMF), 9 related to environmental issues and 7 related to visual impact. Only the number of obstacles encountered due to the

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[1] Long Island Power Authority.

[2] Interconnexion électrique France Espagne.

[3] Overhead line.

[4] Not in my backyard.

Acronyms and nomenclature

AC	alternating current
BImSchV	Federal Emission Control Act Concerning Electromagnetic Fields
DC	direct current
EMF	electro-magnetic fields
GHe	gaseous helium
GIL	gas insulated line
HTS	high temperature superconductors
HV	high voltage
HVDC	high voltage direct current
LH2	liquid hydrogen
LN2	liquid nitrogen
LNG	liquefied natural gas
LTS	low temperature superconductors
MgB_2	magnesium-di-boride
MRI	magnet resonance imaging devices
NbTi	niobium titanium
NIMBY	not in my backyard
OHL	overhead line
E	polyethylene
RES	renewable energy share
ROW	right-of-way
SC	superconductors
SCTL	superconducting transmission line
SF_6	sulfur hexafluoride
TL	transmission line
TSO	transmission system operators
TYNDP	ten-year-network-development-plan
VSC	voltage source converter
XLPE	cross linked polyethylene
YBCO	yttrium–barium–copper-oxide
cm [39]	centimeter
g	gram
GW	gigawatt
GW h	gigawatt hours
Hz	hertz
K	kelvin
kA	kiloampere
kA m	kiloampere meter
km	kilometer
kV	kilovolt
kW h	kilowatt hours
m	meter
mm	millimeter
MW	megawatt
µT	microtesla

authorization procedure and legal framework (12) were higher. The explanation of public opposition purely by the NIMBY phenomenon may be outdated as the actual reasoning is overall more complex and multi-layered [17].

With respect to these contention points, superconducting direct current (DC) transmission lines are likely to generate a very different reaction due to their ability to carry more energy at a much smaller size, while at the same time being buried underground, and thus out of sight. This would substantially reduce the approval times. Also, the cost for right-of-way would be lowered due to the small size of SCTL.

2. Superconducting transmission lines

2.1. Technology

Superconductors (SC) are materials that can conduct electric energy without losses below a certain critical temperature TC, i.e. they are non-resistive below TC. That distinguishes them from standard conductors like copper that are resistive and have power losses dissipated as heat. A cryogenic envelope is needed to keep the superconductor cooled below its critical temperature (see Fig. 1). State-of-the-art cryogenic envelopes allow less than 1 W of heat per meter length to enter the cryogenic system as heat influx from the environment. Since the second law of thermodynamics states that in a heat engine not all supplied heat can be used to do work, the mechanical power that is needed at room temperature in order to have the desired cooling power at the cryogenic temperature is much higher. The theoretically most efficient thermodynamic cycle is the Carnot process characterized by the Carnot factor, which defines the efficiency of the process and depends on both the cryogenic temperature and the higher temperature of the environment ($T = 300$ K). The Carnot factor is 3 for liquid nitrogen ($T = 77$ K) and 14 for liquid hydrogen ($T = 20$ K), meaning that the cooling efficiency is 4–5 times higher if using liquid nitrogen compared to liquid hydrogen. However, in a superconducting transmission line the electric losses due to cooling can be kept small for all considered coolants, as compared to the transferred power and to the losses of standard conductors.

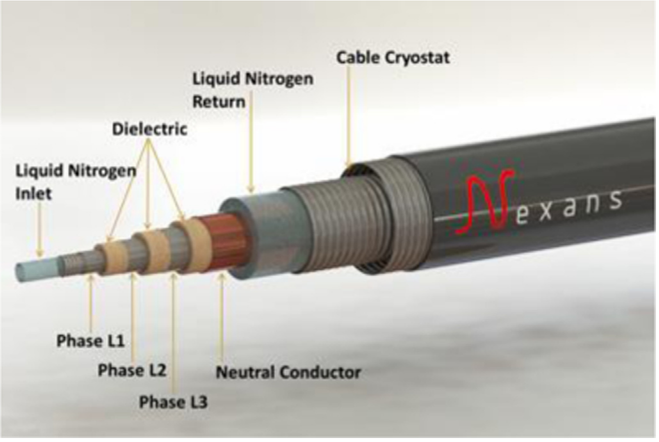

Fig. 1. Design of a high temperature superconducting (HTS) cable for AC operation with 3 phases cooled by liquid nitrogen (copyright Nexans).

The critical temperature of a SC varies in a wide range and there are basically two types of superconductors, low-temperature superconductors (LTS) like niobium titanium (NbTi, $T_C = 9.2$ K) and high-temperature superconductors (HTS) like yttrium-barium-copper-oxide (YBCO, $T_C = 93$ K). Most LTS need to be cooled by liquid helium ($T = 4.2$ K), while HTS can be cooled by liquid nitrogen ($T = 77$ K) allowing for a simpler design of the cryogenic envelope and opening the door for electric grid applications. With the discovery of superconductivity below $T = 39$ K in magnesium diboride (MgB_2) in 2001 [18], a promising new superconductor has come on the scene, that can be cooled by either gaseous helium or liquid hydrogen, is based on raw materials that are very abundant in nature and is therefore cheaper than any other competing superconductor.

In the more than 100 years since its discovery [19], superconductivity has been successfully applied to a significant number of large-scale particle-physics experiments, for instance

Table 1
Global superconducting cable projects that are planned to operate in the electric grid.

Project	Location	Length [m]	Capacity [MVA]	Schedule	Operator
LIPA	Long Island/USA	600	574 (138 kV AC, 2.4 kA)	In operation since 2008	LIPA
AmpaCity	Essen/Germany	1000	40 (10 kV AC, 2.3 kA)	Start of operation 01/2014	RWE
	Amsterdam/NL	6000	250 (50 kV AC)	Proposed	Alliander
St. Petersburg Project	St. Petersburg/Russia	2500	50 (20 kV DC, 2.5 kA)	Start of operation 2015	FGC UES[a]
Ishikari	Ishikari/Japan	2000	100 (±10 kV DC, 5 kA)	Start of construction spring 2014	City of Ishikari
	Icheon/Korea	100	154 (154 kV AC, 3.75 kA)	Operating since 11/2013	KEPCO[b]
	Jeju Island/Korea	1000	154 (154 kV AC, 3.75kA)	Operation 2015	KEPCO
	Jeju Island/Korea	500	500 (80kV DC)	Operation 2014	KEPCO
HYDRA	Westchester county/USA	170	96 (13.8 kV AC/4 kA)	Start of construction early 2014	ConEdison
	Yokohama/Japan	250	200 (66 kV AC, 5kA)	Operation stopped December 2013, continuation planned with new high-performance refrigerator 2015.	TEPCO[c]
	China	360	13 (1.3 kV DC, 10 kA)	Operation since 2011	IEE CAS[d]
REG[f]	Chicago/US	5 km	to be specified	Planning since 2014	ComEd[e]
Tres Amigas	New Mexico/US		750/5000	Postponed	Tres Amigas LLC

[a] Federal Grid Company United Energy System.
[b] Korea Electric Power Corporation.
[c] Tokyo Electric Power Company.
[d] Institute of Electrical Engineering, Chinese Academy of Sciences.
[e] Commonwealth Edison.
[f] Resilient Electric Grid

superconducting magnets, superconducting accelerator cavities and detectors used in accelerators at CERN, DESY, Brookhaven and Fermilab, as well as the fusion machine ITER. Additionally, superconductivity is today widely used in a number of commercial applications, for instance in NMR magnets, generators (wind turbines, hydro power plants, ship engines), transformers, wireless receivers in communication technology, inductive (metal) heating systems, magnetic levitation train (Maglev), fault current limiters, and superconducting magnetic energy storage (SMES).

One of the first proposed practical applications of superconductivity, envisaged for it already in 1915 by its discoverer Heike Kamerlingh-Onnes, is the transmission of electric power without losses. Apart from the lack of resistive losses, the very high current densities associated with superconductors allow for much smaller dimensions of the conductor and cable compared to the case of standard conductors.

The overall design of SCTL shares many similarities with natural gas pipelines, as far as carrying a highly pressurized medium and the need for refrigeration/compressor stations along the line. However, the dimensions are smaller (a few 10 cm compared to 140 cm diameter) and the maximum pressure is much lower (20 bar or less compared to 85 bar). There is no availability data for large-scale SCTL with cooling stations several tens of km apart because they have not been implemented so far. To give an impression of the reliability and availability of a large cryogenic system one can refer to the Large Hadron Collider (LHC) of CERN which has the longest and most complex cryogenic system in the world with a length of 27 km. The magnets operate at a temperature of 1.9 K, which is much more challenging than the cooling temperatures of 15 K or 70 K necessary for MgB_2 and HTS SCTL. 10,080 ton of liquid nitrogen and 136 ton of liquid helium are necessary to keep 36,000 ton of cold mass (magnets, equipment) at its nominal operating temperature. The system consists of about 60.000 inlets and outlets and has been running continuously from 2007 to 2013. It achieved a global availability of 94.8% for the year 2012 and an availability of 99.3% for each of the eight 3.3 km long cryogenic segments [20]. The non-availability time was caused by the cryogenic system (3.3%), by scientists conducting experiments/users (0.4%) and by other events (1.2%) triggered by single experiment events, IT or electricity supply by utilities. Thus, the cryogenic system of SCTL considered in this paper can have a much higher availability. Not only would the setup be much simpler for cooling only a bi-polar conductor, but the operating temperatures would be much higher and operation less demanding.

2.2. *State of the art – industrial development*

The idea of employing superconducting transmission lines to transfer GW of power over long distances has been around for decades [21] and is now making its way into real world grid applications [22–25] because SCTL offer benefits to TSOs that cannot be provided by standard solutions. At the moment we see the technology stage in between innovation (demonstration projects) and niche application (field projects) with high learning rates [26]. As for every commercially available product, a crucial point is the economic advantage for the operator and for the end user. The superconducting tapes and wires, i.e. the superconducting conductors itself, are more advanced in terms of technological development because they are increasingly used in a wide range of applications like magnet resonance imaging devices (MRI), electric generators or current leads for electric energy intensive industries like metal refining. Here, an accelerated cost reduction due to economy-of-scale reasons is likely. It is worth noting that the flexible cryogenic envelopes are already commercially available, they are used to transfer for instance liquefied natural gas (LNG).

As of now, many demonstrators and proof-of-principle superconducting cables have been commissioned by utility companies worldwide or are already in operation and fully integrated in the electric grid, as listed in Table 1. The average length of these superconducting cables is a few hundred meters and capacities are fairly low, but nonetheless these SCTL offer intrinsic advantages like the ability to tailor the voltage level, especially to lower it. The AmpaCity HTS cable [27,22] connecting two power substations in the city center of Essen holds the record with 1 km length (Spring 2014), but will be soon surpassed by the St. Petersburg cable with 2.5 km length [24,28]. In the case of AmpaCity, the responsible utility company RWE was convinced by an economic study that showed that a SC cable is one of the two cheapest options to upgrade the existing grid. In particular, by employing a SC cable, one can take advantage of its high current density to operate at a lower voltage (10 kV) and one can thus eliminate the aging 110-10 kV AC transformers.

Fig. 2. TEPCO/Sumitomo 66 kV AC HTS test station at Asahi substation in Yokohama/Japan: left image shows the cable with a joint, right image shows the 66 kV AC end stations responsible for the transition from standard conductor to superconductor and from room to cryogenic temperature (2014).

Another prominent example is the LIPA project [29], a 600 m superconducting power cable operating in the grid at 138 kV and 2400 Ampere since 2008 and based on HTS material. It was commissioned by the Long Island Power Authority (LIPA) that was established in 1998 as the primary electric service provider for Long Island. Expecting a significant increase in energy demand until 2020, LIPA made substantial investments in system upgrades and improvements, thereby acknowledging the promise of the superconducting technology.

LIPA recognized superconducting power lines as a possible solution to various needs and related problems [23]:

a. Right-of-way (ROW) congestion: superconducting cables provide increased power transfer capability within existing ROWs
b. Public acceptance: permission problems for overhead lines
c. Potential cost savings: cheaper than upgrading to 345 kV overhead transmission systems

Despite the increasing number of demonstrator projects, the awareness or acceptance as a mature technology among decision and policymakers is small. According to the TYNDP 2012 (page 206) superconducting transmission lines are still seen as a technology that is in the research stage, i.e. the lowest development stage, with no practical application yet [11]. However, as described earlier, the LIPA cable has been operating in the grid since 2008 with a nominal capacity of 574 MW (reduced to ~150 MW by bottlenecks created by the standard technology grid) and the AmpaCity in Essen has shown reliable operation since early 2014. If successful in the longer term, it can lead to retrofitting 30 km of standard technology transmission lines in Essen. These projects can be rated as being in large-scale testing phase (stage 2 following the TYNDP 2012). Stage 1 technologies are mature and have already proven their general reliable applicability within the existing meshed grid.

As a last example of reliable operation, Fig. 2 shows the HTS test facility of TEPCO in Yokohama [30]. During two years of operation within the Asahi substation of an HTS cable built by Sumitomo Electric Industries (SEI), no faults were reported. The installation, including the refrigeration system, was remotely monitored from TEPCO in Tokyo with no service man at the station. TEPCO has shown continued interest in superconducting transmission lines because the coastal area of Japan especially around Tokyo is very densely populated. Due to the small size of SCTL, existing ROW could be used, rendering new transmission corridors unnecessary and/or making system upgrades possible.

2.3. Main obstacles for widespread utilization

From a technological point of view, SCTL have a higher complexity than standard transmission lines. The fact that during operation they rely on a fluid at cryogenic temperatures can be seen as a disadvantage. The cryogen cannot be allowed to transition into the gas phase and because the cooling system is powered by electric energy, it needs an absolutely reliable power source. The electric energy could be tapped from the TL itself and backed up by on-site RE sources in combination with energy storage devices in remote areas. Here it is worth pointing out that the natural gas pipeline system has a very similar setup and has a proven record of operating reliably over many decades. The complex large-scale cryogenic system of the LHC[5] at CERN, that achieved availabilities above 99% per year, can also be taken for comparison [31]. In terms of maintenance, no significant degradation of the superconducting cable is expected compared to standard cables.

However, for longer-distance field installation, the cryogenic envelope and cooling system and the joints connecting the various cable segments represent the main technical and engineering challenges. This stems from the need for a good high-voltage electric insulation combined with the need of perfect thermal insulation when creating a temperature bridge from room to cryogenic temperatures. The design of the superconducting cable itself also requires substantial engineering for optimum performance (especially for AC operation due to the fast switching magnetic field). But these challenges have been already addressed and solutions only need to be adapted to the specific transmission line project. Few official technical guidelines and specification codes for operation exist, although recently there have been increased efforts in this direction.

From an economic point of view, the projected capital cost of superconducting transmission lines and the necessity of economic competitiveness play a vital role in the utilization and further application of SCTL in the electric grid. No grid operator will install an SCTL if the benefits do not outweigh the disadvantages when it comes down to projected costs. The high cost of the HTS tapes very surely hindered the utilization of SCTL on a larger scale up to now. With an increased factory output and new cost-saving production technologies these costs can be reduced, likely to 50$/kA m for HTS tapes in the near future. Until HTS reaches economic competitiveness, MgB_2 based SCTL will see increased interest,

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[5] Large Hadron Collider.

development and application. From the perspective of an industrial company, the development of superconducting power line technology involves substantial financial investments and can therefore be considered rather risky, given the small niche application market at the moment. Also, the investments that were already made in R&D of "standard" transmission line options have to be first amortized.

Also, the awareness of the regulatory bodies with regard to SCTL is quite low, hence a lot of dissemination work is needed in the future, as outlined in the next section.

2.4. Future potential and path forward

As already mentioned, SCTL have a much higher capacity per size/width ratio than any other transmission line option. That makes them the first choice if limited space meets high-capacity transmission needs, for instance in ROW-impacted areas, like urban areas or densely populated areas in general. If SCTL are economically competitive compared to standard transmission lines (TL), they can potentially replace vast fractions of the existing medium- and high-voltage grid (as in the AmpaCity project). Theoretically, the complete high-voltage grid could be changed into a superconducting low- to medium-voltage grid, making high-voltage up and down transformers unnecessary with a direct power plant to city connection at the turbine output voltage (10–30 kV).

SCTL are inherently predestined to transfer large amounts of electric energy due to the absence of losses except for the cooling losses. The higher the capacity, the more attractive is a SCTL with respect to energy efficiency (please see chapter 9) [32]. The underlying reason is that the design and size of a SCTL do not change much when increasing the capacity, due to the high current density of superconductors. The cost/capacity ratio is smaller for higher capacities, especially for cheaper superconductors like MgB_2 because the costs for the cryogenic envelope and trenching are practically fixed and only the additional SC material has to be paid for. However, low-capacity SCTL can still be economically competitive and be used to overcome disadvantages of existing grids. For instance low-voltage SCTL can be used to remove high-voltage lines and transformers. A technical advantage of the SCTL is that the capacity is not reduced in hot climates compared to standard TL. For the transport of tens of GW over distances of several 1000 km, standard solutions are not suitable yet because their electric losses and voltage drops will be too high [33]. Here, SCTL may be the only viable option.

In the next years, it will be very important to continue to show economic competitiveness with standard options and demonstrate reliability under real grid operating conditions. To have a significant impact on the energy efficiency and sustainability of the electric grid, projects with longer length of superconducting lines need to be pursued. Moreover, it is mandatory to have codes and standards for operation and safety issued by official international bodies.

Beyond these steps, the visibility of this technology to key stakeholders (TSOs, DSOs, regulatory bodies) needs to be increased by strong information and dissemination activities.

Most of these points are addressed by a newly started collaborative project on novel energy transmission applications within the European Commission's 7th research framework, which was funded with EUR 63 million. The project acronym BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering AC corridors and multi-Terminal HVDC Systems" and was chosen to reflect the variety of the five demonstrators involved. Thus, one of the five constituent demonstrators is a superconducting high-power transmission line based on the novel MgB_2 technology pioneered in an experimental collaboration between CERN and the IASS. Headed by the leading cable manufacturer Nexans and bringing together transmission operators, industrial manufacturers and research organizations, this project envisages the development of a monopole cable system operating in helium gas in the range 5–10 kA/200–320 kV, which corresponds to a transmitted power of 1–3.2 GW. The current international practices will be taken into consideration by using the recommendations issued by the International Council on Large Electric Systems (CIGRÉ). The research and demonstration activities will be accompanied by a comprehensive dissemination package.

3. Advantages of superconducting transmission lines

SCTL share the advantages of underground cables compared to overhead lines:

1. Very low visual impact on the landscape due to their underground location.
2. Generation of lower electromagnetic fields that could affect the surrounding area.
3. Smaller environmental footprint than overhead lines (except for wetlands).
4. Minimization of land use and property acquisition, leaving the value of local real estate unchanged.
5. No affection by most natural weather phenomena such as wind, fog, snow and ice.
6. No emission of noise.

In addition to these advantages buried cables have in general, SC cables comprise several other advantages compared to standard HVDC underground cables. The following points highlight the advantages of superconducting power lines compared to the most modern underground standard HVDC cables (± 320 kV XLPE HVDC):

1. A size advantage (a few 10 cm width of only one needed SC cable compared to a 17 m wide trench consisting of 24 cables for 10 GW capacity for a standard HVDC ± 320 kV cable installation - not including 2.5 m safety area on both sides).
2. Much smaller land use potentially as low as 10% of standard HVDC cable installations depending on the capacity, area (urban or land) and regulations.
3. Appealing option for long-distance and high-capacity electric energy transport if underground cables are required because standard conductor cables have high losses (> 6%/1000 km at 100% load for ± 320 kV XLPE HVDC).
4. Adjusting the nominal current to meet the desired or existing operating voltage, especially that of medium and low voltage grids. Thus eliminating transformers results in less occupied space and less components in the grid chain that are prone to technical failures.
5. Much better option for hot climates because of the vacuum-isolated cryogenic envelope that prevents heat from entering the system and therefore stabilizes the temperature of the SC conductor. The capacity of standard HVDC cables is reduced by higher soil temperatures (the resistivity of Cu and Aluminum increases with higher temperatures and so do the power losses).
6. Do not heat the surrounding soil (does not alter soil humidity).
7. Option for a hybrid transmission line, transferring not only electrical energy but also hydrogen, the fuel with the highest energy density per weight (Please note that the efficiency of the hydrogen liquefaction process is rather low and that it takes 40% of the chemical energy of hydrogen to liquefy it from 300 K to 20 K).

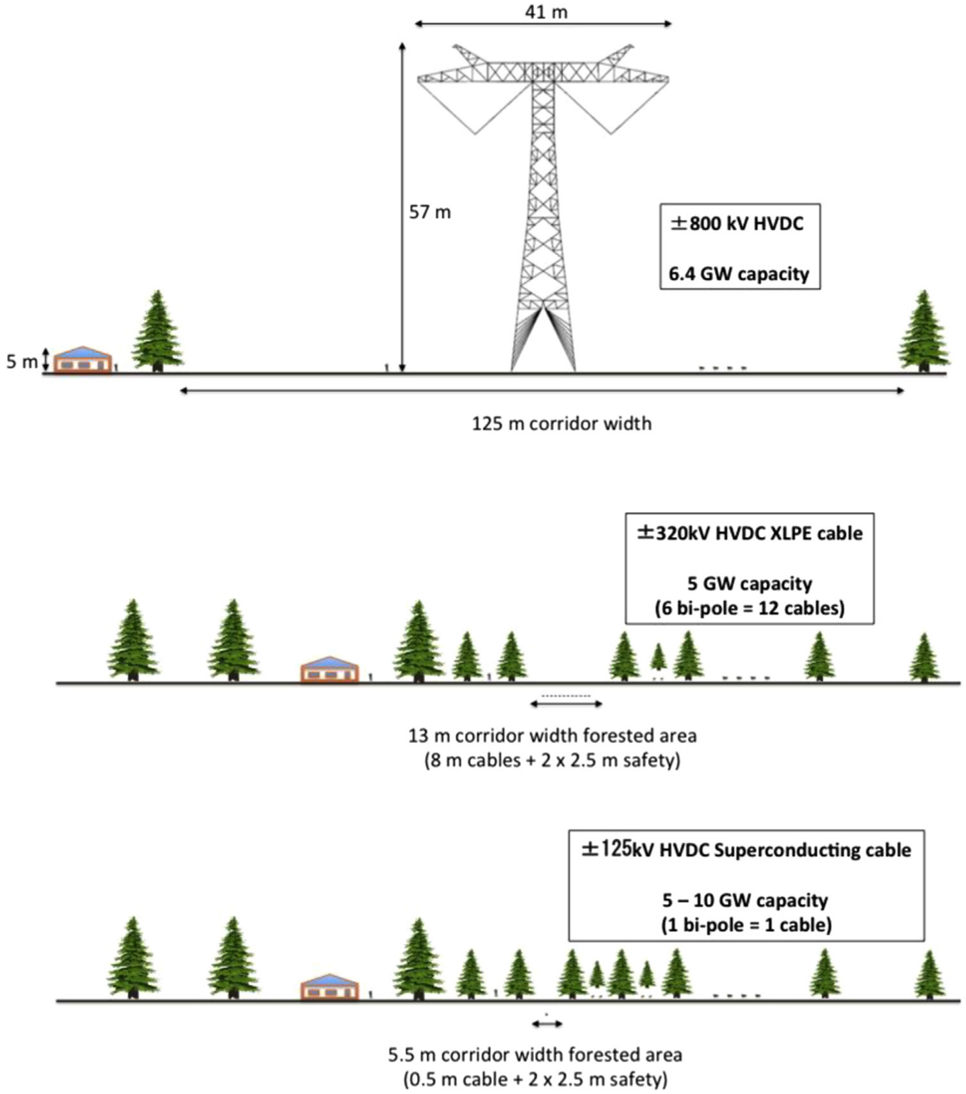

Fig. 3. Possible layouts to fulfill HVDC 5 GW power transmission requirements with ROW in forested areas and associated costs. The size proportions are meant to be realistic. A capacity of 5 GW was chosen with respect to the planned North–South HVDC transmission lines in Germany. The ROWs for 10 GW and 3000 km length are 245 m (±800 kV), 22 m (±320 kV underground cable) and 5.5 m (superconducting line).

8. Much easier use of existing right-of-ways (ROW) to transfer GWs of power
9. Can potentially be operated in AC with much smaller losses than standard HVDC cables. No cost-intensive AC–DC converter would be needed.
10. The cryogenic system can store energy by cooling to lower operating temperatures at times of high renewable energy input.

It is apparent, that the advantages of SCTL address many public concerns. Especially the size advantage can potentially decrease the public opposition against new transmission lines. The technological advantages of SCTL are evident and TSOs can profit from installing and operating SCTLs (potentially reduced delays, technological advantages) creating a win-win situation with affected communities.

4. Methods

The characteristics of superconducting transmission lines used for comparison with standard technologies in this paper stem from a long-distance SCTL design that was developed at the Institute for Advanced Sustainability Studies e.V. (IASS) in Potsdam [34]. The important numbers highlighted in this paper which are relevant to public and social acceptance, i.e. size, cost, EM-fields and efficiency are based upon this design and were derived according to standard thermo- and fluid dynamic and electrostatic theories resulting in a design that fulfills the requirements for efficient long-distant electric energy transfer. The cryogen pressure dictates the stainless steel wall thickness (cost factor) and the distance between cooling stations plus the necessary mass flow (to remove the heat) determines the hydraulic and finally the outer diameter (size, cost factor) which subsequently determines the heat influx and the transmission efficiency. Please be referred to the existing literature for a complete technical description [6,34] as this is beyond the scope of this paper.

Based on the superconducting material MgB_2, it can either be cooled by liquid hydrogen or gaseous helium plus liquid nitrogen with cooling stations located every 300 km in the first design phase. The design can easily be adapted to other separations. In a cooperation between CERN and the IASS Potsdam a superconducting prototype cable based on MgB_2 was successfully tested in 2014 with a direct current rating of 20 kA [35]. The test configuration consisted of 2 × 20 m long MgB_2 cables that were immersed in helium gas to maintain the required temperature (20 K). The total diameter of the cable setup and the cryogenic envelope was only 16 cm. This success caused various interests on the industrial and transmission system operator (TSO) side and led to the formation of a European consortia of industry, research centers and TSOs with the goal to design and test a high-voltage (± 320 kV) prototype MgB_2 cable to validate its operation in a real grid (BEST PATHS project as part of the 7th European framework programme).

For completeness, a ± 100 kV DC long-distance SCTL design developed by EPRI based on high temperature superconductors (HTS) is used for comparison [6]. The standard technologies taken for comparison are the ± 320 kV HVDC XLPE cable as a direct competitor – as it is also buried underground – and ± 500/800 kV HVDC overhead lines (OHL) as it is the preferred technology by TSOs for high capacity long distance transfer of electric energy up to now.

Please be referred to the existing literature for a complete technical description of superconducting transmission lines [6,34] as this is beyond the scope of this paper.

5. Visual impact of high-capacity transmission lines – a chance for superconducting power lines?

The main objection point of communities who oppose the construction of new transmission lines is the visual impact. Whereas smaller electric powers could be transferred by using standard underground cables (either AC or DC) and that way reduce the visual impact, the transmission of electric power in the range of several GW will leave a substantial corridor width if established transmission technologies are employed. In urban areas it is practically impossible to install new multi-GW transmission lines using standard technologies. Examples for such urban areas can be the Ruhr district in Western Germany as a consequence of new North–South HVDC corridors to be build and the coastal lowlands of Japan where existing ROWs have to be used to increase the transmission capacity.

5.1. Overhead line HVDC

A single pylon of a ± 800 kV 6.4 GW HVDC power line has a height of 50–90 m and the width of the corridor was estimated to be ~125 m adapting similar calculations from 380 kV AC corridors and regulations in Germany. Two HVDC lines capable of transferring 10 GW (max. 12.8 W) have a width of 245 m. Towers for ± 500 kV HVDC TLs have similar dimensions and require much broader ROWs due to the lower capacity which scales with the square of the voltage. The visual impact is humongous: A 50 m high construction can be seen from ~25 km if standing at sea level (using the earth curvature). That means that a HVDC overhead TL construction is potentially compromising the landscape of 50 km^2 per every km length. However, state-of-the-art HVDC power lines did show quite a technological development during the last years and are practically the first choice for long-distance electrical energy transfer at the moment until new advantageous technologies – as SCTL show reliable operation. The right-of way of ± 800 kV HVDC overhead lines (OHL) is compared to standard ± 320 kV HVDC underground cables and superconducting cables in Fig. 3.

Despite SCTL have much smaller dimensions than standard cables they still require a ROW of several meter width because of additional unforested zones added as protection measurements against tree roots. ROW for SCTL can be much smaller in urban settings.

5.2. Standard HVDC underground cable

A single XLPE cable has a current rating of 1.760 A and is thus capable of transferring 563 MW at 320 kV. The conductor diameter with an area of 2500 mm^2 is an industrial limit and a substantial increase of ampacity for a single cable in the near future is unlikely. These types of cables were used for the France–Spain interconnector (INELFE project). Other cables with higher voltages using oil-impregnated paper for electric insulation are not considered in this discussion. Recently, the development of a 525 kV XLPE HVDC cable with a capacity rating of 2.6 GW per bi-polar system was presented by ABB.

To transfer 5 GW of electric power over a distance of 700 km six bi-polar systems (12 single cables) are required assuming a location in northern France. The trench width for 6 bi-poles is 8 m. To transfer 5 GW in northern Africa 8 bi-poles are necessary and the separation between cables has to be much higher resulting in a trench width of 19 m [36]. To transfer 10 GW over 3000 km the total trench width would be 22 m and much wider in northern Africa (> 30 m).

Cables heat up the surrounding soil and thus reduce the capacity of other cables in a system because the soil temperature is increased.

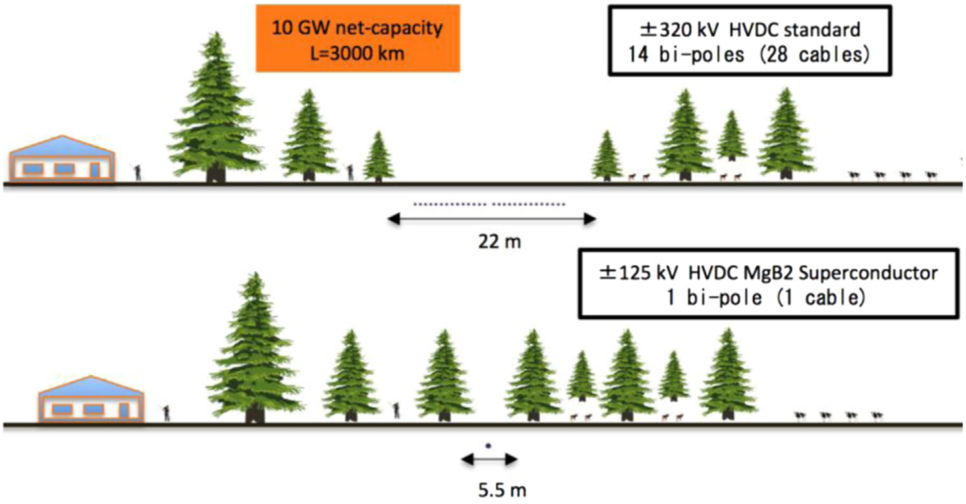

Fig. 4. Possible layouts to fulfill HVDC 10 GW power transmission requirements with ROW in forested areas and associated costs using underground cables. The size proportions are meant to be realistic. The ROW for a ± 800 kV OHL with 10 GW capacity and 3000 km length is 245 m (not shown).

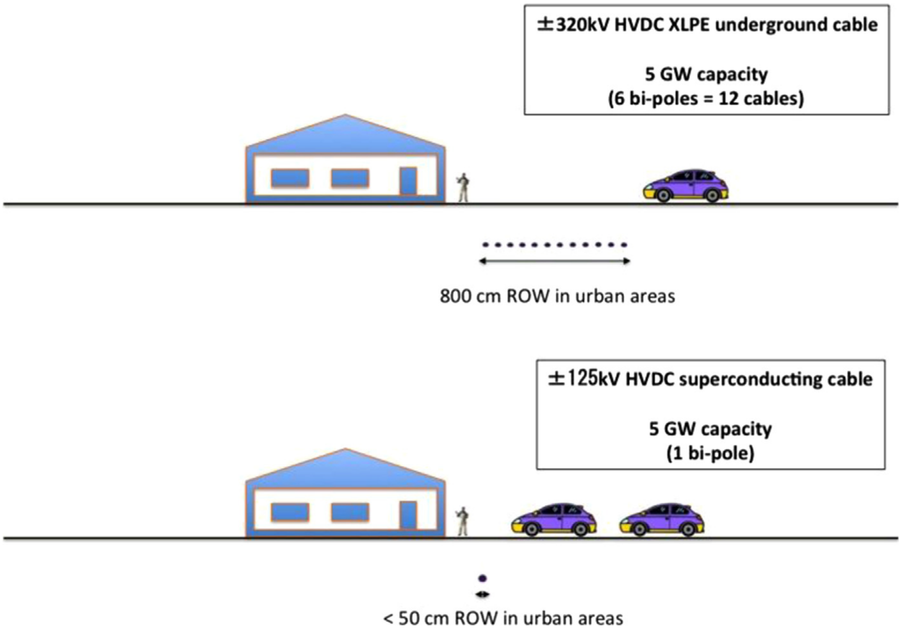

Fig. 5. ROW in urban areas for 5 GW underground transmission systems.

5.3. Superconducting transmission line (cable/underground)

The ROW corridors of superconducting transmission lines are determined not only by the size of the cable system but also by the existing regulations for medium- and high-voltage cable installations. That includes an operation of the cable according to effective regulations concerning limits of the electro-magnetic stray field (Federal Emission Control Act Concerning Electromagnetic Fields/26. BImSchV in Germany). The ROW in forested areas is wider than in un-forested and urban areas because a protective zone (2.5 m on each side in Germany) is mandatory to prevent tree roots from damaging the cable unless the cable is installed in another protective tube (Fig. 4).

The exact ROW of a superconducting multi-GW transmission line in urban settings can only be estimated at the moment because respective regulations and norms for such high capacity TL cables may not be based on existing regulations. Therefore only the pure size and width of the cable system in urban settings is compared (Fig. 5).

The magnetic field of a DC bi-polar SC TL with a coaxial design is zero as long as the opposing currents (bi-polar TL) are equal. It may not be possible to ensure this for all times and a magnetic field can remain in that case for short periods. This depends on the cable design, how the cable is operated as part of the grid and the safety handling of cable failures. However, the ROW of a multi-GW SCTL has potentially the width of less than 50 cm in un-forested urban areas.

6. Technical aspects of superconducting transmission lines relevant for local communities

6.1. Electro-magnetic (EM) fields

EM fields are a major concern for local residents affected by transmission lines and hence a major objection point in grid planning. DC power lines have favorable magnetic field characteristics compared to AC power lines because inherently they do not have an oscillating magnetic field but a static field. The magnetic field is proportional to the current transferred in the conductor and inversely proportional to the distance from the conductor. It can be minimized by choosing a proper layout for the cable system design. For instance, a coaxial design of a bi-polar cable leads to zero magnetic fields assuming both (oppositely directed) currents are equally high. Such a design is not available for high capacity standard conductor HVDC cables at the moment because the dissipated heat cannot be removed properly from the inner conductor of such (coaxial) design. Contrary to that, superconductors do not experience any resistivity and therefore do not dissipate heat. There are no electrical fields outside a DC cable due to the shielding of the conductor.

Because the current density of SC is much higher than that of standard conductors, the current carried by a SC cable can be much higher. This would result in equally stronger magnetic fields of a single line (mono-pole) because the magnetic field is proportional to the transferred current (compare 1.7 kA for a standard HVDC cable with potentially 40 kA or more for SC). However, if bi-polar designs are used, what will be the case also due to contingency reasons, the single magnetic fields of both poles partially or totally cancel each other out. Fig. 6 displays the magnetic field of a bi-polar SCTL with a nominal current rating of 40 kA per pole as it was developed at IASS for long-distance electric energy transport. This calculation shows that high currents of superconducting transmission lines do not pose a threat. The pole centers are separated by 6 cm, and the cable is buried 1.5 m underground. The resulting magnetic field is 210 μT at surface level and 54 μT 1 m above surface right above the cable. This calculation does not include the superposition with the Earth magnetic field (50 μT) – the total magnetic field depends on the orientation of the cable. That is lower than the limit for static magnetic fields of 500 μT of the revised Federal Emission Control Act in Germany (26. BImSchV – signed into law in 8/2013) that for the first time includes limits for DC lines. It is worth mentioning that the new amendment of the 26th BImschV bans new AC low frequency (50 Hz) overhead power lines in new corridors spanning residential housing for voltages of 220 kV and more. For AC low-frequency magnetic fields, the maximum magnetic flux allowed in Germany is 200 μT for 50 Hz.

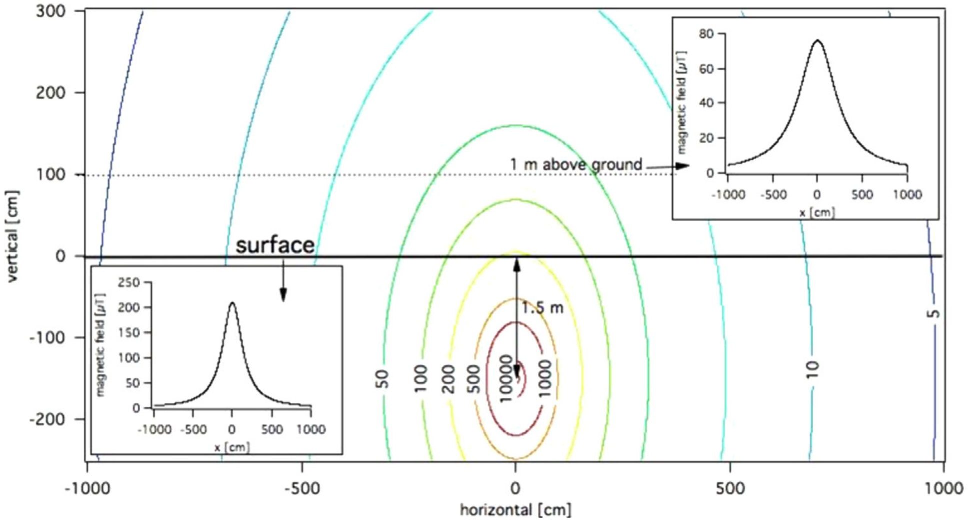

Fig. 6. Stray magnetic field of a 40 kA bi-polar transmission line as proposed from the IASS. The poles are separated by 6 cm. The overall magnetic field generated by both poles is much lower than the magnetic field of a single pole due to opposite direction of current flow and hence partial cancellation of magnetic fields. A coaxial design of the conductor would theoretically result in a non-existing magnetic field as long as both opposing currents are equal. The calculation does not include any soil with high iron content or magnetic shielding (SC can act as a magnetic shield for static fields).

6.2. No heat dissipation into the soil

Besides a lower visual impact due to their extremely small size and potentially no electro-magnetic fields due to their coaxial cable design that is not applicable for standard HVDC cables superconducting transmission lines have more advantages. Dissipated heat from standard HVDC underground cables into the surrounding soil results in a temperature rise and moisture migration. Less moisture of the soil results in a higher heat resistivity of the soil and leads to higher temperatures of the conductor itself that in turn dissipates even more heat. This circle can ultimately lead to a thermal runaway and a cable breakdown, the temperature limit of soil next to a standard HVDC XLPE cable is 55 °C in summer [36]. The consequences of heated soil have not been investigated in detail so far but an impact on local fauna is to expect. A maximum temperature increase of 5 K at 50 cm below soil surface has been recommended by the German Ministry for Environment. The most relevant negative impact of cables is on wetlands. The use of overhead lines is recommended here and for the case of drinking water resources. Irreversible damage of local hydrology can often be prevented by proper soil management during the construction. Superconducting cables only exchange a minimum amount of heat with the environment due to their almost perfect vacuum insulation and therefore do not alter the soil except for trenching. Only one trench is necessary for 10 GW capacity transmission for SCTL. An example is the installation of the AmpaCity superconducting cable in the city center of Essen/Germany buried underneath a road.

6.3. Potential health hazards

To get an idea how vulnerable an underground SCTL potentially is leakage and accident statistics of gas pipelines can be used for comparison. The 5-year moving average failure frequency in 2010, which represents the 5-year incident frequency from 2006–2010, equals 0.16 per 1000 km per year [37,38,10]. That would mean that for a 1000 km long North-South HVDC transmission line in Germany 1 leakage appears over a period of 6 years. Most leakages are caused by external interference (48.4%) like excavation or ramming damage, 16.7% by construction defects/material failure, 16.1% by corrosion, 7.4% by soil movements like landslides, 4.8% by accidently connecting high pressure to low pressure or even water pipes and 6.7% by maintenance, lightning, design errors and others (2006–2010). The released gas ignited in 4.5% of these accidents from 1970–2010. It is worth mentioning that the failure frequency due to corrosion is only 0.01 per 1000 km per year for polyethylene (PE) coated gas pipelines. Flexible cryogenic transfer lines for liquid gas (for instance Cryoflex from Nexans) have a PE-coating. With respect to superconducting lines gas pipelines have only one cylinder, i.e. only one wall between the gas and the environment and provide therefore less safety in case of an accident. It is very unlikely that coolant can enter the environment due to an internal failure of the SCTL during a lifetime of 30–40 years.

The coolants helium, hydrogen and nitrogen are not toxic and have no direct health impact except that they can potentially replace oxygen in air and lead to suffocation or cryogenic combustions caused by splashing liquid coolants in the case of a major leak. This is however very unlikely because the outer coolant cylinder is embraced by another cylinder that holds the outer vacuum space between environment and cryogenic envelope. Any leaks will immediately lead to higher vacuum pressures and should give enough time to take measures. Contrary to that gas-insulated lines (GIL) employ sulfur hexafluoride (SF_6) to electrically insulate the conductor of standard underground HV lines. SF_6 is extremely toxic and potential gas leaks are a danger to health and life.

Hydrogen pipes are routinely operated in industry and hydrogen liquefaction is state of the art. For instance is the German industrial gas supplier Linde operating a 80 km long hydrogen gas pipeline network since 1994 and producing 33,000 l of liquid hydrogen (LH2) per hour in Leuna/Germany [39].

Leaks in the cryogenic system of a superconducting transmission line using hydrogen as the coolant can potentially lead to explosions if hydrogen is released into the atmosphere and mixes with oxygen. However, natural gas pipelines share similar concerns and are widely accepted. Hypothetically, released hydrogen, nitrogen or helium will not contaminate the environment as oil and gas does. If hydrogen mixes with air, only mixtures that contain 4–75.6% hydrogen are explosive when lightened. For comparison, explosive gasoline mixtures are formed if they do contain 1–11% gasoline vapor and explosive propane mixtures if they do contain 2.1–9.5% propane. These gases create explosive mixtures with air at much lower concentrations than hydrogen but leaking air into a hydrogen reservoir creates an explosive gas mixture at 24.4% air content already. Also, air is solid at liquid hydrogen temperatures and special care has to be taken to prevent solid air–liquid hydrogen mixtures, which are highly explosive. The minimum energy required to ignite hydrogen gas mixtures is 0.019 mJ, that is 1/10 of the energy required to ignite propane [40]. However, hydrogen gas mixtures cannot ignite without an energy influx, i.e. they cannot self-ignite.

7. Sustainability relevance for the environment

7.1. CO_2 emissions

Superconducting transmission lines can potentially have much lower power losses than standard options, especially than standard cables. These power losses of transmission lines can be linked to CO_2 emissions because losses in transferred electrical energy need to be compensated by an increase of the generated electric energy. It would have therefore not a local but a national impact and also be relevant for policy makers. In the case of Germany between 5% and 6% are lost during transmission from generation to consumption due to losses in power lines and transformers. Though a big portion of losses (about 50% in Germany) are accumulated in the low-voltage level grid primarily due to its long length, losses in the transmission and regional distribution grids cannot be neglected in aspects of energy efficiency. The renewable energy share (RES) of the electricity mix in Germany was 33% in the first half of 2015. The average emission of CO_2 per generated kW h was 562 g in 2012 and a similar number was forecasted for 2014. The CO_2 emissions of superconducting transmission lines are compared to standard overhead and underground transmission lines in Tables 2 and 3.

The CO_2 emissions are proportional to the power losses and can therefore be lower for superconducting transmission lines compared to standard transmission lines depending on the cryogenic system used, the capacity and the load factor. Especially if liquid nitrogen is used to separate the cryogenic system from the environment, losses can be significantly lower for SCTL than for standard lines. However, reduced load factors as mentioned above will alter this advantage to a certain degree. A MgB_2 based SCTL of 4 GW capacity cooled with liquid hydrogen experiences half the losses as ±320 kV XLPE standard cables at 50% load. The annual CO_2 emissions due to electrical losses of both underground TL variants with 810 km length and 4 GW net capacity (North-South HVDC corridors in Germany without converter losses) would be equal to about 3.4% and 6.5% of the CO_2 emissions of a standard coal power plant with an electric energy generation of 4300 GW h/year and 1000 g of CO_2 emitted per kW h generated. This further changes in favor of the SCTLs with increasing capacity and load factor due to the fixed amount of energy needed for cooling. As an example, the CO_2 emissions for 3000 km long, TLs with 10 GW net-capacity are listed in Table 3. The emissions associated with the electric losses for standard cables would be equivalent to the emissions of almost 3 coal power plants!

7.2. Efficiency of SCTL with respect to renewable energy transfer

It is evident that SCTL have the potential to reduce the electric transmission losses compared to standard transmission options, especially underground cables what is also mirrored in potentially lower CO_2 emissions associated with the electric losses. However, this has to be evaluated for the specific project individually and depends not only on the actual design of the cryogenic envelope but on the actual load because the electric losses for superconducting transmission lines are constant whereas the electric losses of standard conductors in DC mode are proportional to the load squared ($load^2$).

Table 2
CO_2 emissions associated with power losses of transmission lines (4 GW, 810 km length) assuming the RES of 2012 in Germany. Electricity mix 2012 (562 g/kW h). Load: 50%. Coal power plant: 4300 GW h/year with 1000 g of CO_2 emitted per kW h generated.

CO_2 equivalent emission of losses	MgB_2 LH2	MgB_2 GHe + LN2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Electricity mix 2012 (562 g/kW h)					
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 3
CO_2 emissions associated with power losses of transmission lines (10 GW, 3000 km length) –load: 100%, otherwise same assumptions as in Table 2.

CO_2 equivalent emission of losses	MgB_2 LH2	MgB_2 GHe + LN2	HTS cable	±500 kV HVDC OHL	±320 kV HVDC cable
Electricity mix 2012 (562 g/kW h)					
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 CO2 equivalent emission [%]	12.6	4.0	3.1	107.9	283.8

Two facts make it hard to achieve 100% load:

1. The load varies over the year, over the day.
2. The fluctuating nature of renewable energy generation – with an RES of the energy mix in Germany of already 33% (2015) and 80% by 2050.

Very sophisticated energy management systems in combination with massive energy storage capabilities can overcome the differences of supply and demand and achieve high load factors. Intelligent grids can increase the load factor of superconducting transmission lines and reduce at the same time the load of standard transmission lines by redirecting the current flow. Excess energy could also be stored by cooling the cryogen to lower temperatures and a warm-up to regular operating temperatures at times of low load with no use of electric energy. Neglecting the fact that SCTL are not ready to be utilized, i.e. actually constructed, for long-distance transmission projects probably for the next 10 years, calculations show that SCTL can have favorable efficiencies for the planned North–South HVDC corridors in Germany assuming realistic load factors of 30–80% depending on the corridor [41] and the officially specified capacities of 2–12 GW per corridor in the grid development plan scenario B for 2023 and 2032 [32].

8. Cost

8.1. Capital cost of SCTL in comparison to standard technologies

As no large-scale installations of several 10 or 100 km length have been built yet (2015) and costs depend on the specific design and terrain, costs can only be estimated for superconducting

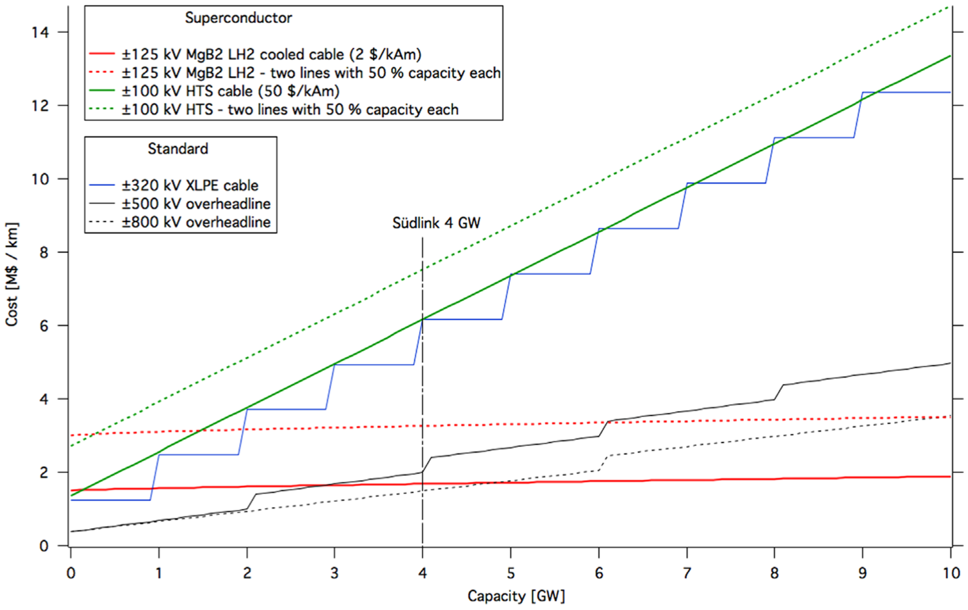

Fig. 7. Indicative capital cost per capacity and length for HVDC options. The cost of two redundant SCTL systems is shown with respect to the $(n-1)$ criterion and possible redundancy requirements. The step like appearance of standard transmission lines stems from fixed costs like towers, trenching, installation or cables systems (± 320 kV XLPE) needed to accommodate increased capacity. For SCTL increased capacity is accommodated for by adding more superconducting material without changing the design and thus only small further additional costs in case of MgB_2 appear. Refs.:[42,43,6,44,45].

transmission lines. The cost for operation and maintenance were assumed to be 1% per year of the initial capital cost following standard economic calculations. There may be no or less degradation of the (super)-conductor itself for SCTL contrary to standard conductors. Furthermore, HVDC installations need AC–DC converter (and DC–AC) and the costs for converter can make up for a substantial part of the costs, especially for short high-capacity power lines. For instance, two 65 km long HVDC superconducting TLs each with 2 GW capacity, as needed in Northwestern Germany, would have estimated total capital costs of 1980M€ (HTS – today costs) and the costs for the converter alone would be 1620M€ (82%). That means that the technology used to transmit electric energy may not have a substantial financial impact for HVDC applications depending on length and capacity and therefore the type of transmission line can be chosen that meets other than financial requirements best, i.e. has the smallest ecologic footprint etc. In any case, cost of superconducting transmission lines can be cost competitive with standard technologies, for instance with ± 500 and ± 800 kV HVDC overhead lines and ± 320 kV HVDC XLPE cables. The cost per capacity and length of HVDC transmission options are displayed in Fig. 7.

The cost calculation was made for two designs developed at IASS using MgB_2 as the superconducting material and cooled by liquid hydrogen and liquid nitrogen/gaseous helium. The cost for trenching and installation are included in the total cost but not the converter cost for easier comparison. The fulfillment of the $(n-1)$ principle was not investigated but the cost of two SCTL systems each with 50% capacity is shown for comparison. The cost for the single MgB_2 transmission line is given for a one tube, bi-polar design with two separate cables inside the cryogenic tube.

Two ± 500 kV HVDC transmission lines systems are assumed to be needed to transfer 4 GW, this is in accordance with the current planning status of Südlink – the corridor C of the German Grid Development Plan 2013 (Netzentwicklungsplan) with 4 GW capacity and 810 km length [46]. Südlink is needed to mainly transfer wind energy from the North to the South of Germany and operation is projected to start until 2023. At the moment Südlink is planned to be build with ± 500 kV, not with ± 800 kV. Reasons can be of technical nature – voltage limitation of the voltage source converter (VSC) technology or voltage mismatches of OHL and standard cables – or simply the effort to prevent even stronger public opposition due to the higher voltage.

MgB_2 based SCTL become cheaper compared to standard solutions with increasing capacity because the conductor itself accounts only for a small fraction of the total cost which are dominated by the cost of the cryogenic system that is practically cost-independent of the capacity for longer length. For capacities of more than 2 GW even a redundant design with 2 separate lines is competitive with standard cables. Competitiveness with OHL is reached between 3 and 6 GW depending on the actual electric design.

8.2. Right-of-way associated cost

When transmission line installations are constructed on or cross private property and public land usually a one-time compensation fee has to be paid by the transmission system operator (TSO). These cost can make up for a substantial fraction of the total cost. In northern Germany, compensation payments to municipalities and land owners for limited future planning options and lowered property value due to new 380 kV AC OHL are being discussed and negotiated right now and add up to about 75k€/km [47,48]. That includes 5000€ per tower erected and 20% of market property value payments of spanned area to land owners besides 40,000€/km payments to municipalities. This value is much higher in urban areas where OHL may cause the loss of building land for owners because regulations prohibit the construction of housing structures underneath OHL. The dimensions of 380 kV AC towers are comparable with towers for ± 800 kV HVDC lines and ROW costs should be comparable. Two ± 800 kV HVDC lines are necessary to transfer 10 GW and have a combined span width of 80 m and thus ROW costs of 150k€. That would represent 5% of the construction cost (4M$/km) for the transmission line itself excluding costs for AC–DC converter. Including the converter, the fraction of total costs for ROW payments can be much lower.

SCTL would have less impact on property value and would result in lower ROW associated cost. However, the cost advantage due to lower ROW payments seems to play a bigger role only in urban areas.

Delayed approval and operation can cause indirect costs induced by ROW issues. In a study initiated by the German Federal Ministry for the Environment the cost for a 1-year delay of operating two 65 km long transmission lines with approx. 2 GW maximum capacity each in 2020 in Northwestern Germany to transfer wind energy southwards was calculated to be 120M€ [42]. The BMU study is comparing a pure OHL and partly (~10%) cabled transmission lines, all AC operated. As a result, costs are comparable if costs due to a 1-year delay are included assuming shorter approval times for partly cabled TLs. The amount of energy which could not be transferred due to the delay in the ZIP code 2 area (NW Germany) is 7300 GW h, the total installed wind power in that area will be 20 GW in 2020 [49]. Potentially, the deployment of new technologies can alleviate the opposition against new transmission lines to such an extent that the approval time will be reduced by several years. In that case even technologies with a multiple cost factor compared to the standard solution (OHL) can achieve benefits in this way that make them more cost effective [15].

9. Summary and outlook

Superconducting transmission lines are an innovative and promising transmission option that can be one of the many components needed to achieve a more sustainable transmission and distribution of electric energy. The manifold advantages of SCTL like a potentially much higher efficiency and small size requirements can have a direct positive impact on the environment and would likely increase the public acceptance. The access and utilization of renewable energy sources can indirectly be facilitated by faster approval procedures. SCTL have a much lower visual impact on landscape than standard OHL and also require much less space than standard cables for high capacity transmission. They can alleviate the ROW problematic and lead to an increased public acceptance. Underground transmission lines with several GW of power could be realized using existing right-of-ways like highways, train tracks or standard cable conducts in cities. For small capacities the size advantage of SCTL is less evident but a technological advantage can still exist, especially for transmission system operators. For instance can the operating voltage be tailored by adjusting the operating current with still keeping the same small size what allows to reduce the amount of transformer equipment and free space. Superconducting transmission lines based on MgB_2 can potentially be cost competitive without taking savings from reduced ROW requirements into account. Cost of SCTL will also decrease in time due to cheaper production processes of the superconductor itself and if the demand and output is higher (both, HTS and MgB_2). Standard transmission lines have gone through this process already long time ago and cost reductions are not expected. The losses and related costs depend on the actual load factor and the capacity. In general, high capacities and high load factors work in favor of SCTL. The size of superconductors makes it possible to minimize the outside magnetic field by choosing a proper layout for the cable system design. A coaxial design of a bi-polar cable leads to zero magnetic fields if both opposing current are equal. Heat dissipation of resistive conductors deny this design option for high capacity standard HVDC cables. For long distance and high capacity transmission SCTLs can be the best choice of all transmission options. However, the global output of superconducting wires and tapes would not be enough to supply one multi-GW and 1000 km long transmission line at the moment but can once SCTLs are accepted as a mature and cost competitive technology and output is increased to meet demand. Reduced CO_2 emissions are another sustainability asset and can further increase the acceptance of SCTL. It is very important to inform about the progress in the area of superconducting power transmission. This is all the more necessary since on-going events in Europe as well as other regions show that it is crucial to engage the local communities in the early stages of the planning process. It is crucial to further invest in and foster the development of superconducting transmission lines in order that they become a commercially available option for the future electric grid as an alternative to standard technologies with a number of advantages.

Acknowledgment

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

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