SCARLET

Superconducting CAbles foR sustainabLe Energy Transition

1.09.2022 – 28.02.2027

Call identifier: HORIZON-CL5-2021-D3-02

D1.1: Definition of use cases

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Submission date: 16/12/2022

Dissemination level		
PU	Public	
SEN	Sensitive, limited under the conditions of the Grant Agreement	X

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101075602

Document history

Issue date	Version	Changes made / Reason for this issue
06/12/2022	00	Initial version
15/12/2022	01	After partners review

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Glossary

DC = Direct Current

GW = GigaWatt

HTS = High Temperature Superconductors (superconductor materials with critical temperature above 30 K)

K = Kelvin

kA = KiloAmps

kV = kiloVolt

kVDC = kiloVolt Direct Current

LH2 = Liquid Hydrogen (around 20 K)

LN2 = Liquid Nitrogen (range of 67 to 80 K)

LNG = Liquid Natural Gas (mainly liquid methane)

MgB2 = Magnesium Diboride

MVDC = Medium Voltage Direct Current

PCCO = Point of Common Coupling Offshore (Junction between inter-array network and export network)

PCCT = Land power substation (to connect the wind park to the transmission grid through the export cable)

ReBCO = Rare earth Barium Copper Oxide (family of ceramics exhibiting superconductivity up to 90K). Rare earth = Yttrium (Y), gadolinium (Gd)…

SCTL = Superconducting transmission line

Tc = Critical temperature of superconductors

Top = Operational temperature (liquid nitrogen around 70 K for HTS and liquid hydrogen around 20 K for MgB2)

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EXECUTIVE SUMMARY

This deliverable aims at identifying the relevant use cases for HTS and MgB_2 superconducting cable systems up to 100 kVDC with powers of the order of 1 GW using the different technologies available.

Based on the main characteristics of onshore and offshore power links for renewable farm-to-grid or grid-to-grid connection, of cooling systems, and the constraints in terms of unit lengths for superconducting cable systems, a reduced set of cable layouts is proposed to address all types of power links.

The selected cable layouts, two for onshore and one for offshore, are defined by a unit length of cable (core and cryostat) linked to the distance between the cooling stations for a given range of cooling power at operational temperatures (close to 70 K for HTS and 20 K for MgB_2). Each cable layout requires specific types of accessories and ancillary services.

The converter architecture depends strongly on the power level (1 or 2 GW) in the existing configuration. For each power level, two possible cable system structures for HTS and two for MgB2 have been selected, with different properties in term of rated voltage, environmental impact, redundancies, expected cost and cable productions runs.

Depending on the performance criteria that are requested by customers, a selection is proposed with the most appropriate use cases to be studied in depth in terms of technical and economical assessments, as well as environmental impacts.

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1 INTRODUCTION

In the call text, it was stated that the voltage and power levels as well as lengths below should be considered:

- Up to ±100 kVDC, up to 1 GW power, superconducting cable system (HTS) up to 5 km, onshore.
- Up to ±100 kVDC, up to 1 GW power, superconducting cable system (HTS) up to 100 km, offshore.
- A superconducting transmission line (SCTL) based on MgB2 LH_2 cooled, for DC with a length up to 1 km and above, onshore. The voltage level and the cable section should be designed to have the maximum benefits in terms of insulation requirements and conductor section for a capacity transfer of 10 kA and above. For the project we have selected an operating voltage of 25 kVDC.

In this report, the scope of work has been extended to relevant levels of parameter values to address present and future markets for power links using HTS and MgB_2 superconducting cable systems and associated technologies.

For each technology, from cooling and superconducting cable to conversion, the key characteristics having an influence on the superconducting cable system will be highlighted to drive the choices of cable layouts in a first phase (chapter 2, 3, 4 and 5) and cable system structures in a second phase (chapter 6, 7 and 8). A more in-depth status will be proposed for the different technologies in the works carried out withinWP2 (HTS long cable design & manufacturing), WP3 (Offshore architectures), WP4 (MgB2 cable design & engineering) and WP5 (System protection).

A set of criteria is proposed to drive the final selection depending on customer needs (chapter 9).

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2 TYPE AND CHARACTERISTICS OF MVDC POWER LINKS

The project SCARLET aims at enabling a larger integration of renewable energy at different scales using superconducting cable systems at DC medium voltage.

Such cable systems can cost effectively connect the renewable generation site to the nearest grid:

- for offshore thanks to lower platform size (no transformer) and reduced footprint on the coast

- for onshore thanks to high ampacity without thermal impact.

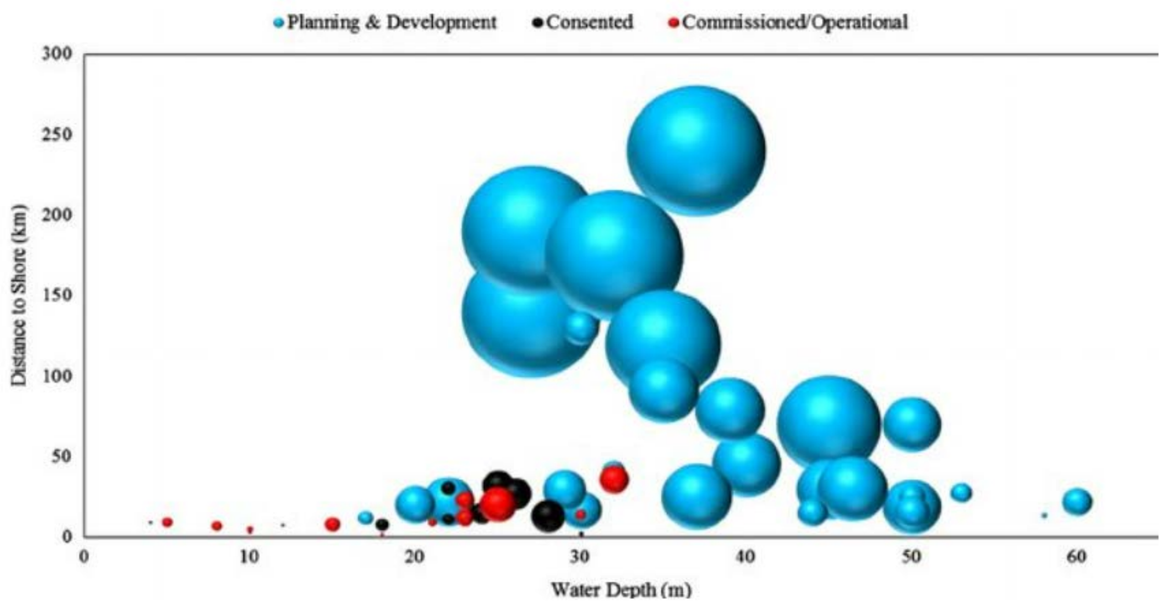

Figure 1: Distance to shore and water depth of current and future offshore wind projects [1]

At larger grid scale to manage intermittency of an energy mix based on renewable, the grids of different countries should be interconnected and able to transmit a large amount of power.

Finally, large end users inside the cities, industrial areas with intensive electricity needs or crossing of protected areas or natural obstacles can find a solution in MVDC power links based on superconductors.

Table 1: Type and Characteristics of MVDC power links

Type of link	Description	Characteristics	
		Onshore	Offshore
R2G = Renewable to Grid	**Wind** **Solar**	1 to 20 km	10 to 250 km

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G2G = Grid to Grid interconnection	**Between countries** **Grids reinforcement or stabilization (FACTS)**	1 to 20 km	10 to 250 km
		Congested areas (cities, industry intensive...) **Protected areas** **Natural obstacles**	**Seabed mounted or floating**

3 CABLE SYSTEMS LENGTHS

3.1 Limitations coming from production

Depending on the type of market, cable plants can be equipped with drum pay off and take up (onshore) or turn tables (offshore).

Typical drum capacity can vary from 500 m to 2 km depending on cable outer diameter (cryogenic envelope) and linear weight. This value will be represented by the acronym **LoD** standing for “**Length on a Drum**” in the rest of the document.

For plants producing offshore cables, turn tables are mandatory and can reach up to 10 000 tons. Usually, the turn table in the factory has a capacity in the same range as the turn table on the installation ship.

3.2 Limitations coming from transport

- For onshore projects
    - Two types of transport are possible, by road or along river or channel.
    - Drums are suitable for all type of transports. Small turn tables on trucks or barge can be considered if the project is easily accessible and close to the sea, a river or a channel.

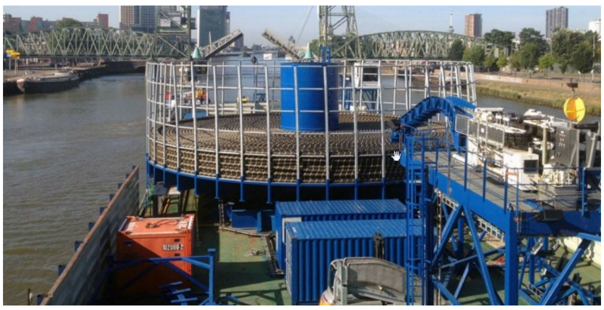

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Figure 2: Transport of cable drums and turn tables on truck and barge

- For offshore projects
  - o Large turn tables are installed on the installation ship with various possible dimension.
  - o As an example, for a cable with 30 kg/m, one length of 300 km can be loaded in a 10 000-tons turn table (or carrousel).

Table 2: Size and capacity of turn tables

	Outside Diameter	Load Capacity	Height
Carousel 1000	8m	1000 mT	up to 8 m
Carousel 1500	16 m	1500 mT	up to 8 m
Carousel 2000	18 m	2000 mT	up to 8 m
Carousel 7000	28m	7000 mT	up to 8 m
Carousel 8000	32m	8000 mT	up to 8 m

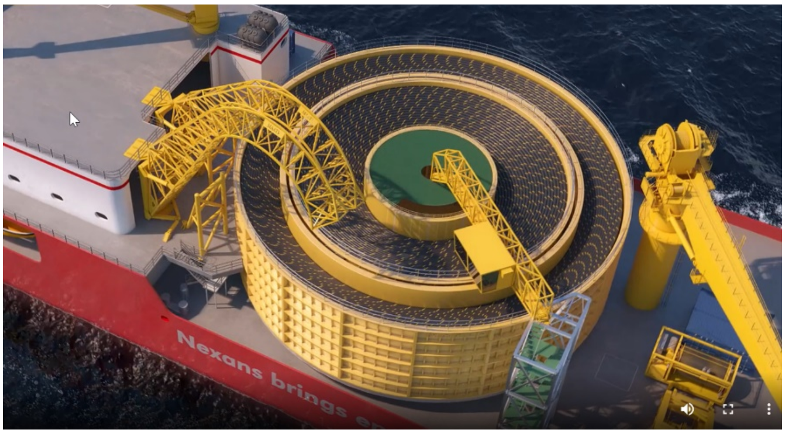

Figure 3: 10 000 tons turn table on the laying ship NEXANS CLV Aurora

3.3 Limitations coming from installation

Onshore superconducting cables are pulled in the same way as conventional HV cables but has a lower linear weight.

The maximum length that has ever been pulled is 3 km for conventional cables. This limitation is

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mainly linked to the friction force during pulling that can overcome the elastic deformation of the cable structure. However, 3 km cable lengths are not easy to transport on the road, eventually with small transportable turn tables from a barge.

The more practical value corresponds to a drum capacity that can be transport on road. However, the cable unit lengths can be prolongated with joints.

For offshore applications, the installation capacity is equal to the size of the turn table onboard the laying ship.

3.4 Limitation coming from design and exploitation

Length is limited by the pressure drop and the maximum pressure in the cryostats as well as the maximum temperature to keep a margin to the boil-off of the cryogenic fluid acting as dielectric.

This length is called "**Max THL**" for the maximum thermohydraulic length that can be cooled with a single cooling station at one end.

Max THL depends mainly on the characteristics of cable core, cable cryostat and existence of return lines.

3.5 Conclusion on length limitation

In this paragraph we introduce important acronyms that will be used throughout the work packages of SCARLET:

- **LoD** = max length that can be loaded on a drum (weight or volume constraints)
- **Max THL** = maximum thermohydraulic length that can be cooled with a cooling station at one end. The Max THL will be evaluated for each combination of cable core, cable cryostat with or without return line selected for the use cases in WP2, WP3 and WP4.

Note that both values are depending on the cable design.

<u>Offshore systems:</u>

The conclusion for offshore systems is that the production, transport or installation are not a limit. The design allowing the exploitation is the only limit for the unit length.

However, the use of intermediate cooling station(s) and offshore joint(s) allows to increase the length of the link to any value provided that the installations and supply of offshore cooling stations are feasible.

<u>Onshore cable systems:</u>

As for offshore systems, it is possible to install intermediate cooling stations and specific joints that allow to extend the length of the link to any value provided that the installation and the supply of intermediate cooling stations are feasible.

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4 COOLING SYSTEMS

For HTS, the cooling machines power range for cryogenic applications shows a large gap between 1 and 100 kW@Top.

In the range below 1 kW, we can find various spatial and medical applications. The food industry is using directly liquid nitrogen delivered by truck.

In the range of 10 to 100 kW@Top, the development of LNG applications has led to very mature and robust machines. The LNG tankers are now equipped with liquefaction units to reliquefy the vapor of natural gas.

For the project we shall consider mature technologies with low maintenance requirements existing at 1 kW with the pulse tube (see Figure 4) and at 100 kW with the Turbo Brayton (see Figure 5, Table 3 and Figure 6).

Note that the same cooling machines can be operated within a wide range of temperatures including 20 K, corresponding to liquid hydrogen, and 80 K, corresponding to liquid nitrogen.

Figure 4: Example of pulse tube cryocooler delivering a cooling power of 1450 W@77K

Figure 5: Turbo Brayton cryocooler delivering a cooling power of 50 kW@77K

Table 3: Typical characteristics of a set of Turbo Brayton cryocoolers (all existing in offshore version)

	TBF-175	TBF-350	TBF-1050
Cooling power at 77K	16,5 kW	50,8 kW	152,4 kW
Electrical consumption	195 kW	390 kW	1170 kW
Weight	15 t	17 t	42 t
Dimensions (Lxwxh)	9,5x1,7x3 m	11x1,7x3 m	13x4,5x4 m

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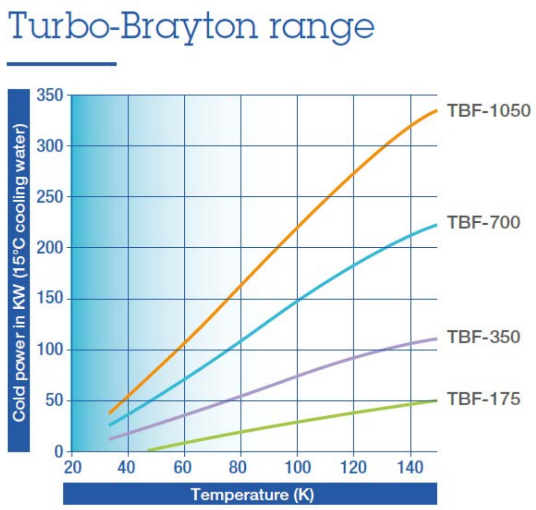

Figure 6: Cold power available as a function of cold temperature for Turbo Brayton cryocooler (source: Air liquid website)

Within this project for MgB_2 cables, the operating range 18 to 22 K requires a flow of liquid hydrogen or helium gas as a substitute. The cryo-refrigerator is the only option available with up to 300 W@20K or Turbo Brayton > 500 W@20K. Liquefaction units for LH_2 are under development. Note that to reduce the losses at 20 K on long length cable systems, a thermal shield that reduces the inlet by a factor of 4-5 based on a counter-cryostat with a flow of liquid nitrogen or gaseous H_2 can be used.

The efficiency of a cooling machine depends on the operating temperature and the delivered power. The temperature coefficient can be calculated considering an ideal Carnot cycle. This ideal coefficient has to be corrected by the efficiency of the heat exchange for practical applications. It is dependent on the size of the machine – the smaller the machine the lower the efficiency. For the cable project, we will need approximately 1.5 to 2 kW for 1 km. In this range of power, the efficiency is approximately 10% of the value for the ideal Carnot cycle.

This optimization will be specifically discussed in the case studies within in WP2 for onshore HTS cable, WP3 for offshore HTS cable and WP4 for MgB_2 in LH_2.

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5 CABLE SYSTEM LAYOUT

Taking the input of chapters 3 and 4 into account, we can propose three cable system layouts (see Table 4) – whether it is HTS or MgB_2 technology – to be compared from technical and economical point of views.

Table 4: Superconducting cable systems layouts:

Ref	Adressable Type of links	Length	Unit Length	Accessories	Ancillary equipment
OnA	Onshore R2G, G2G	N x Max THL	Max THL (max unit length)	2 terminations N-1 joints with flow separation Standard joints within the unit length	Cooling station at each end of unit length (range of up to 100 kW@Top)
OnB	Onshore R2G, G2G	N x LoD	LoD (min unit length)	2 terminations N-1 joints with flow separation	N or N+1 small compact cooling stations (range of 1 kW@Top), at each joint pit and both ends
OffA	Offshore R2G, G2G	N x Max THL	Max THL	2 terminations N-1 joints with flow separation on intermediate platform	N-1 intermediate platform Cooling station onshore and on intermediate platforms (range of up to 100 kW@Top)

A key accessory to be developed is the joint with cooling flow separation between inlet and outlet with 2 couplings to connect cooling/pumping station(s).

From a cooling management point of view the cases OnA and OffA are very similar.

The two onshore cases correspond to two extremes in terms of choice of the management of cooling along the cable system length. In the case of OnB, the reduction of cooling distance by using small, distributed cooling systems will allow to reduce the temperature and pressure gradient in each section, allowing to downsize the cable cryostat (and the overall losses) and to use less superconducting tapes as the range of temperature would be lower.

6 CONVERTER ARCHITECTURES

The choice between symmetrical and asymmetrical (ground used for current transport) cable systems is dependent on the power transmitted.

- Up to 1 GW converters are available in symmetrical monopole (no transport of current by the ground) architectures that considerably simplifies the layout both on the AC and the DC sides

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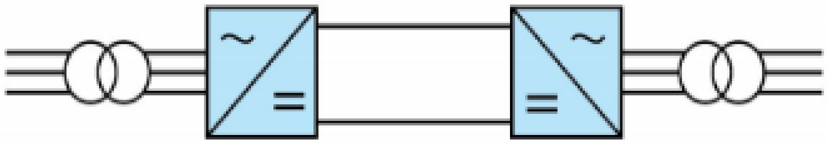

Figure 7: AC/DC converter – 1 GW symmetric monopole architecture

- Considering 2 GW would lead to a bipolar architecture

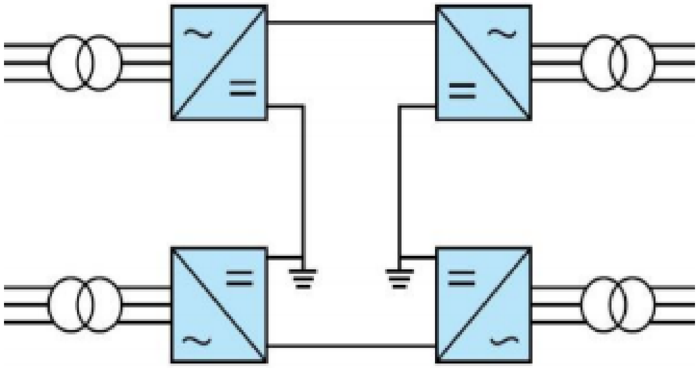

Figure 8: AC/DC converter – 2 GW asymmetric monopoles or bipolar architecture

- Another 2 GW Architecture is technically possible with 2 independent asymmetric monopoles allowing to push the return current in the screen. With conventional cables it is not preferred as it is costly and difficult to add a large cross section screen on the cable. With superconducting cables, however, the screen takes much less space. This architecture allows for having no external magnetic fields.

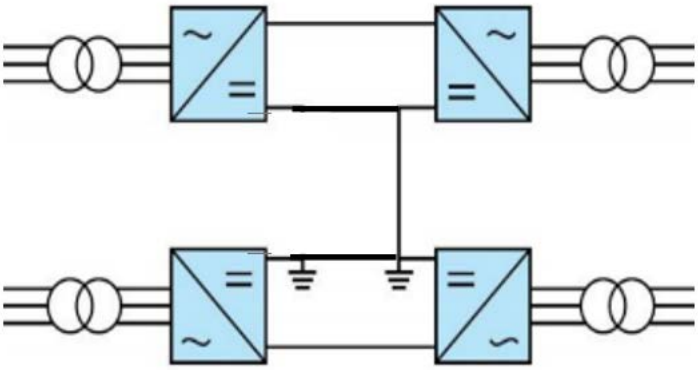

Figure 9: AC/DC converter – 2 GW - 2 independent asymmetric monopoles

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7 CABLE SYSTEM STRUCTURE

7.1 Number of superconducting poles per cable

The superconducting cable comprises a MV cable core inside a flexible cryostat.

Depending on the converter architecture described in chapter 6, three types of cable cores can be used to transmit DC power:

- 1 pole (*symmetric monopole architecture for converter*):
  - to transmit rated current at rated voltage
  - one dielectric sized for rated voltage

Figure 10. HTS cables with 1 pole each

- 2 asymmetric poles (*bipolar architecture for converter*):
  - 1st pole to transmit rated current at rated voltage
  - one dielectric sized for rated voltage
  - 2nd pole for the return of the rated current at 0 volt (neutral conductor)

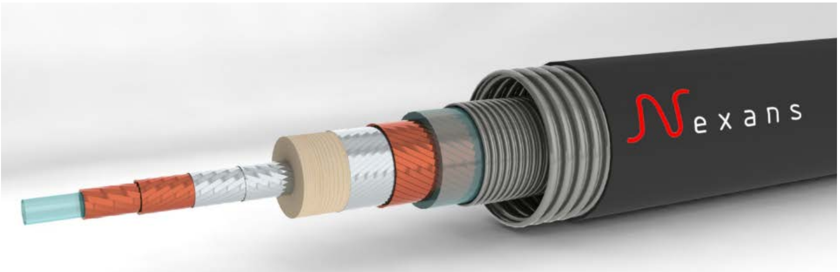
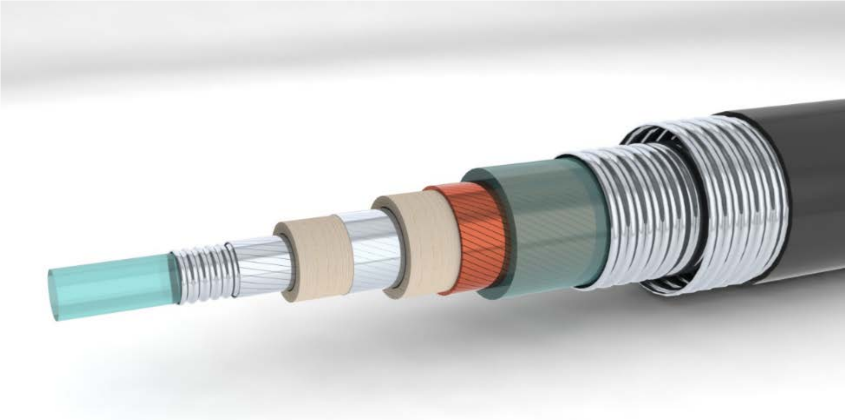


Figure 11. HTS cable with 2 asymmetric poles (+ /0 or - /0)

- 2 symmetric poles (*symmetric monopole architecture for converter*):
  - 1st pole to transmit rated current at rated voltage
  - 1st dielectric sized for 2 times the rated voltage
  - 2nd pole for the return of the rated current at opposite voltage compared to the 1st pole
  - 2nd dielectric sized for the rated voltage



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- **Figure 12. HTS cable with 2 symmetric poles beneath a copper screen (neutral) (+ / - /0)**

Pros and cons of the three types are listed in Table 5.

Table 5: Benefits and drawbacks of the 3 types of DC HTS cable cores

Type of DC superconducting cable core	Benefits	Drawback
1 pole	• Compact • Uses less than half of superconductors compared to the 2 other types	• Magnetic field outside the cable • Requires 2 cables to transmit full power • No redundancy or degraded mode to transmit part of the energy
2 asymmetric poles	• No magnetic field outside the cable • Still possible to transmit 50% of the power if one cable fails	• Requires twice the amount of superconductors compared to the 1 pole type • Requires 2 cables to transmit full power
2 symmetric poles	• No magnetic field outside the cable • Requires only 1 cable (less cable cryostat length)	• Requires twice the amount of superconductors compared to the 1 pole type • No redundancy or degraded mode to transmit part of the energy • Larger core diameter and production cost due to the 2 dielectric layers • Requires a return line for cooling fluid

For each type, the layers composition is detailed in Table 6.

Table 6: Composition of DC HTS cable cores

Composition	1 pole	2 asymmetric poles	2 symmetric poles
Former	A stranded copper conductor or a tube (corrugated tube for example)		
SuperPole 1	One or several superconducting layers made of tapes/wires wound on a cylindric support		
Dielectric 1	Lapped dielectric made of insulation material that will be impregnated by a cooling fluid during cool down		

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SuperPole 2	None	One or several superconducting layers made of tapes/wires wound on a cylindric support	
Dielectric 2	None	None	Lapped dielectric made of insulation material that will be impregnated by a cooling fluid during cool down
Screen	One or several layers made of stranded copper tapes		

7.2 Number of cables per link

Depending on the converter architecture and the type of DC cable core, the link should comprise a certain number of cables.

For powers up to 1 GW, the symmetric monopole architecture is preferred (see chapter 6). Two options are possible:

- Two cables with 1 pole type 50 kVDC 10 KA HTS/25 kVDC 20 kA MgB_2 cables

Figure 13: A 1 GW power link based on two HTS DC cables with 1 pole (cable 1: 10 kA@+50kV and cable 2: -10 kA@-50kV)

- One cable with 2 symmetric poles type 50 kVDC 10 kA HTS/25 kVDC 20 kA MgB_2 cable

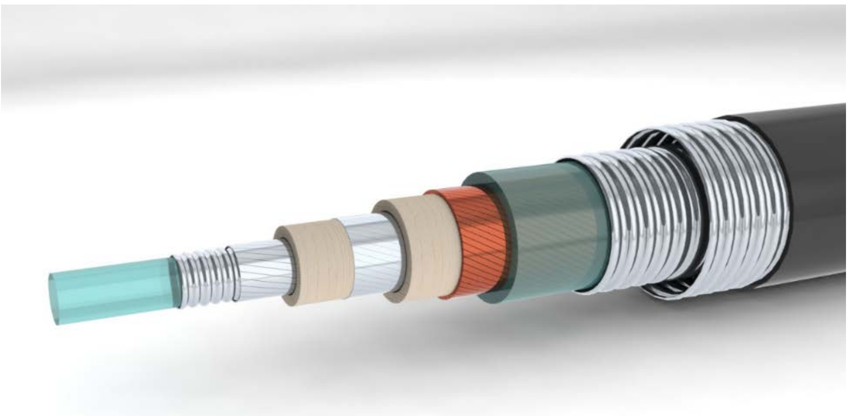

Figure 14. A 1 GW power link comprising one HTS cable with 2 symmetric poles. Here a cooling fluid return line is needed but not represented. Pole 1 = 10 kA@+50 kV and Pole 2 = -10 kA@-50 kV)

For powers of 2 GW, two types of power links are possible, and the preferred architectures are bipolar or with 2 independent asymmetric poles (see chapter 6):

- Two HTS cables with 1 pole type at 100 kVDC 10 kA/50 kVDC 20 kA MgB_2, by connecting the two converters to the same middle point but not to the cable screen

Figure 15. A 2 GW Power link based on two 1 pole HTS DC cables

(Cable 1: 10 kA@+100 kV and cable 2: -10 kA@-100 kV)

- Two HTS cables with 2 asymmetric poles type 100 kVDC 10 kA HTS/50 kVDC 20 kA MgB_2, by connecting 0 poles of independent asymmetric converters together on both cable sides through the cable screen.

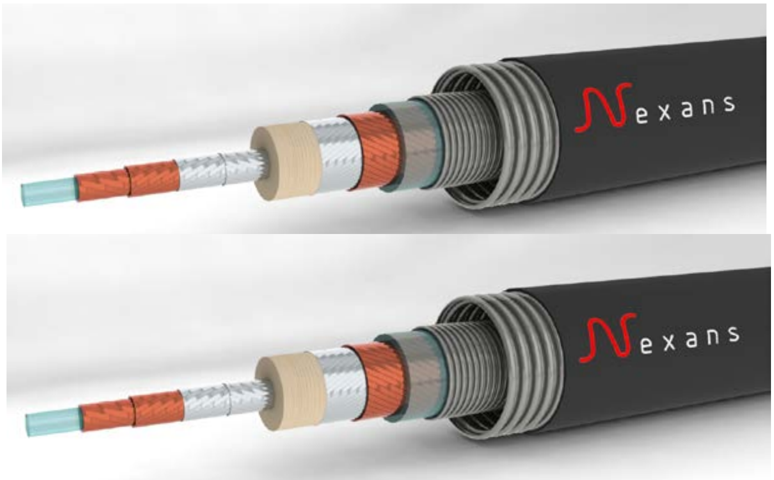

Figure 16. A 2 GW Power link based on 2 asymmetric poles HTS DC cables

(Cable 1: 10 kA@+100 kV / -10 kA@0 V and cable 2: -10 kA@-100 kV / +10 kA@0 V)

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8 LIST OF POTENTIAL USES CASES

From the information presented in chapters 6 and 7, two power levels can be addressed with cable structure with or without a second pole.

The study of the different configurations of power links up to 100 kVDC leads to 8 different structures (4 HTS and 4 MgB_2) of superconducting cables carrying powers of 1 and 2 GW (see Table 7).

Table 7: List of superconducting cable system structures for power link carrying 1 and 2 GW

Ref	Cable(s) structure (diel = dielectric)	Number of super-poles	Minimum number of cables per link	SuperPole 1 Voltage [kVDC]	SuperPole 2 Voltage [kVDC]	Current [kADC]	Archit. Convert.	Transmitted Power [GW]
70K_1	Former / HTS 10kA / diel 50 kV / Copper	1	2	+ 50 and - 50	NA	10	Monopol Sym	1
70K_2	Former / HTS 10kA / diel 100kV / HTS 10kA / diel 50kV / Copper	2	1	50	-50	10	Monopol Sym	1
70K_3	Former / HTS 10kA / diel 100 kV / Copper	1	2	100	NA	10	Bipolar (0/100)	2
70K_4	Former / HTS 10kA / diel 100 kV / HTS 10kA / Copper	1	2	100	0	10	2 ind Asym Monopol (0/100)	2
20K_1	Copper / MgB2 20kA /diel 25 kV / Copper	1	2	+ 25 and - 25	NA	20	Monopol sym	1
20K_2	Copper / MgB2 20kA / diel 50 kV / MgB2 20kA / diel 25 kV / Copper	2	1	25	-25	20	Monopol sym	1
20K_3	Copper / MgB2 20kA /diel 50 kV /Copper	1	2	50	NA	20	Bipolar	2
20K_4	Copper / MgB2 20kA /diel 50 kV / MgB2 20 kA /Copper	1	2	50	0	20	2 ind Asym Monopol	2

Note that the cable structures corresponding to HTS 10 kA@50 kV with HTS screen and to MgB2 20 kA@25 kV with MgB2 screen have not been selected as it is not possible to inject currents in the

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superconducting screens at 1 GW with a monopole symmetric converter.

The 8 cable structures can be practically used in the 3 cable system layouts of **Table** 4: Superconducting cable systems layouts.

9 CRITERIA AND SELECTION OF USE CASES FOR THE PROJECT

9.1 Criteria

We have 24 potential use cases after a first selection based on

- a reduced number of elementary cable layout (2 onshore and 1 offshore, see Table 4) that allows us to treat all types of links
- the adequate combination of converter architectures and cable system structures (see Table 7)

The following criteria are proposed to differentiate the different cable system structures:

- level of power reachable
- rated voltage
- presence of electromagnetic fields (EMF) near the cable
- existence of redundancy or degraded mode
- number of cables needed
- return line
- quantity of superconductor
- cable production runs (runs through the stranding or lapping lines)

For HTS we got the following table:

Table 8: Differentiation matrix for HTS cable structure

Ref	Power	Rated voltage	EMF	Redund.	Nb cable	Return line	Qty HTS	Cable runs
70K_1	1	50 kV	yes	0	2	0	m	-
70K_2	1	50 kV	no	0	1	1	m	+++
70K_3	2	100 kV	yes	0	2	0	m	+
70K_4	2	100 kV	no	50%	2	0	2 x m	++

For MgB2 we got the following table:

Table 9: Differentiation matrix for MgB2 cable structure

Ref	Power	Rated voltage	EMF	Redund.	Nb cable	Return line	Qty MgB2	Cable runs
20K_1	1	25 kV	yes	0	2	0	m	-
20K_2	1	25 kV	no	0	1	1	m	+++
20K_3	2	50 kV	yes	0	2	0	m	+
20K_4	2	50 kV	no	50%	2	0	2 x m	++

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9.2 Analysis

The increase in power requires an increase in voltage based on the rules for building converters.

The only cases that offer partial redundancies are the cases K_4 that allow to keep 1 GW out of 2 GW in case of loss of one of the cables.

The lowest consumption of superconducting tape per GW transmitted are the cases K_3, especially interesting for HTS.

The cases K_1 and K_2 are very similar in terms of power rating and only a more detailed study could tell which one has the lower thermal losses and pressure drop. The only major difference is that K_2 has a coaxial configuration that allows for the suppression of any electromagnetic field. The price to pay is a more complex cable manufacturing process, resulting in higher lead times due to an increased number of runs through the machines.

Depending on customer priority regarding the power level, redundancy, cost, or presence of electromagnetic fields, the following cable system options are available.

Table 10: Choice of superconducting cable structure cases considering power, redundancy, EMF, expected cost and lead time

Power	Redundancy	EMF	Cost	Cabling runs	Preferred case
1 GW	0	-	-	+++	70K_2 and 20K_2
1 GW	0	+	-	-	70K_1 and 20K_1
2 GW	50%	-	++	++	70K_4 and 20K_4
2 GW	0	+	+	+	70K_3
2 GW	50%	-	++	+++	2 x K_2
2 GW	50%	+	++	-	2 x K_1

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101075602

10 CONCLUSION

This report is a synthesis of all technologies associated to MVDC superconducting cable systems with the target to guide the selection of relevant uses cases for the different types of links: renewables-to-grid connections links: renewable connection as well as grid-to-grid connections.

Similar structures and layouts of cable systems can be used for both types of links, and to address the specific needs in term of overall length and environment.

Two key values have been introduced:

- **LoD** = maximum length than can be loaded on a drum (weight or volume constraints)
- **Max THL** = maximum thermohydraulic length that can be cooled with a cooling station at one end. The Max THL will be evaluated for each combination of cable core, cable cryostat with or without return line selected for the use cases in WP2, WP3 and WP4.

Two onshore layouts have been proposed: one with distributed small cooling units at every joint bay with very optimized cable cryostat and cable core, and one with a cooling station every maximum unit length possible (Max THL).

For offshore systems, the cable layout consists of a repetition of modules of Max THL unit lengths cooled independently from an intermediate platform.

The cable structures are mainly driven by the converter architecture that imposes the voltage for a given power range r and the possibility to have return current in a second pole in the cable.

The final choice of an adequate cable system structure is very dependent on the customer requirements. If the presence of magnetic fields outside the cable is a constraint, the K2 and K4 cases are possible with cable structures having 2 poles respectively at 1and 2 GW.

If redundancy is required, the full power should be 2 GW, either with a bipolar converter architecture of 2 GW and the K_4 structure with 2 poles cable structure, or with 2 x 1 GW symmetric monopole converters and 4 x 1 pole cables (K_1) or coaxial 2 x 2 poles (K_2).

At this stage it is very difficult to predict the acceptable level of magnetic field, the power level as well as the need for redundancy, therefore further evaluations need to be done in the relevant WPs. Furthermore, the advisory group should be consulted to eventually reduce the number of cable structures to be studied in depth.

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