



**HAL**  
open science

# Hands-on Techno Economic Assessment: HTS cable system

Andrea Musso, Loïc Quéval

► **To cite this version:**

Andrea Musso, Loïc Quéval. Hands-on Techno Economic Assessment: HTS cable system. École thématique. 3rd Training School of the Hi-SCALE COST Action 19108, Belgrade, Serbia. 2024. hal-04543739

**HAL Id: hal-04543739**

**<https://hal.science/hal-04543739>**

Submitted on 12 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Hands-on Techno Economic Assessment: HTS cable system

Andrea Musso<sup>3</sup>, Lo c Qu eval<sup>1,2</sup>

<sup>1</sup> University of Paris-Saclay, CentraleSup lec, CNRS, Group of electrical engineering - Paris, 91192, Gif-sur-Yvette, France

<sup>2</sup> Sorbonne University, CNRS, Group of electrical engineering - Paris, 75252, Paris, France

<sup>3</sup> Ricerca Sistema Energetico – RSE S.p.A., 20134 Milan, Italy



**Hi-SCALE**



**cost**  
EUROPEAN COOPERATION  
IN SCIENCE & TECHNOLOGY

# Content

- I. Case study
- II. TEA of conventional cable system
- III. TEA of HTS cable system
  1. Phase 1
  2. Phase 2
  3. Phase 3
  4. Phase 4
- IV. To go further

# I. Case study

# TEA on HTS cables → Line main features (case study)

Proposal: connect *Al Dhafra* photovoltaic plant with Abu Dhabi (e.g. its international airport).

Completed in 2023, *Al Dhafra* is the largest single-site solar PV power plant in the world (and the 3<sup>o</sup> in the world overall). More than 4 million PV modules involved



# TEA on HTS cables → Line main features (case study)

Proposal: connect *Al Dhafra* photovoltaic plant with Abu Dhabi (e.g. its international airport).

## ***Al Dhafra Solar Project:***

- **2 GW** produced.
- The plant is located about 30 km south of Abu Dhabi.
- The project includes 33/400 kV substations to connect the plant with 400 kV "conventional" overhead cables.
- **Could part of these conventional connections be replaced with a 33 kV HTS underground cable not requiring transformers and overhead cables into the highly urbanized area of Abu Dhabi?**



# TEA on HTS cables → Line main features (case study)

Proposal: connect *Al Dhafra* photovoltaic plant with Abu Dhabi (e.g. its international airport).

## ***Al Dhafra Solar Project:***

- **2 GW** produced.
- The plant is located about 30 km south of Abu Dhabi.
- The project includes 33/400 kV substations to connect the plant with 400 kV "conventional" overhead cables.
- **Could part of these conventional connections be replaced with a 33 kV HTS underground cable not requiring transformers and overhead cables into the highly urbanized area of Abu Dhabi?**



**Let's suppose we are going to substitute conventional cables for 1.5 GW, using HTS cables (2 HTS cables of 750 MW each).**



# TEA on HTS cables → Line main features (case study)

Technical model – Main features		
<i>Property</i>	<i>Symbol</i>	<i>Value</i>
Total power	$P_{tot}$	1.5 GW
Voltage rms	$V_{rms}$	33 kV
Load factor	$\cos\varphi$	0.95
Line length	$L_{line}$	32 km



## II. TEA of conventional cable system

# Hands-on !



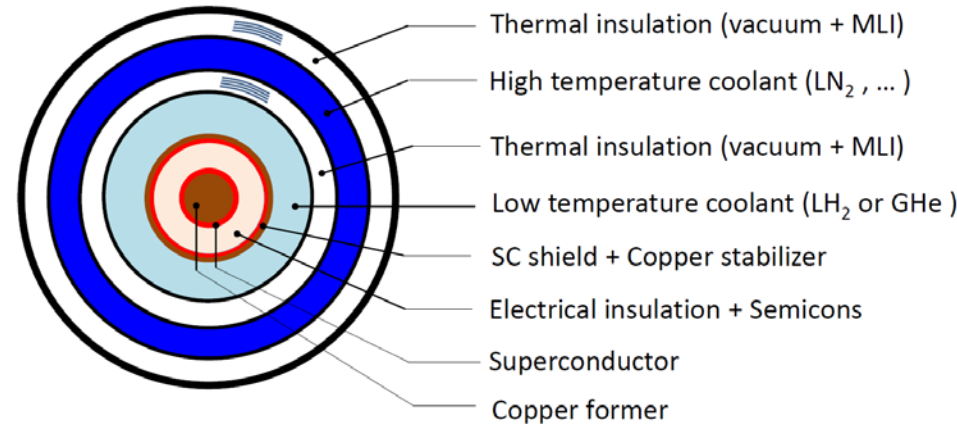
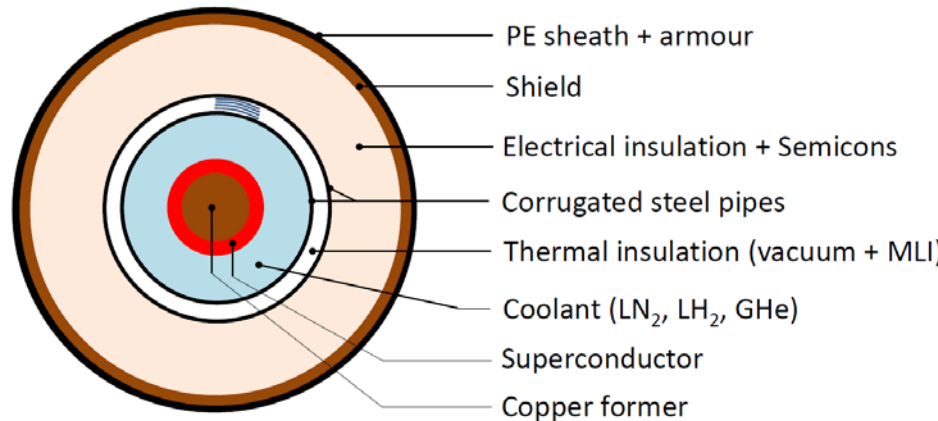
## III. TEA of HTS cable system

# Content

- ❑ Overview of HTS cable architectures
- ❑ The selected architecture
- ❑ HTS cable system components
- ❑ **Hands-on TEA for HTS cables**
  - The approach
  - Computing cable design
  - Computing losses
  - Computing constraints
  - **Computing the economic parameters**
  - Interpreting the results

# Overview of HTS cable architectures

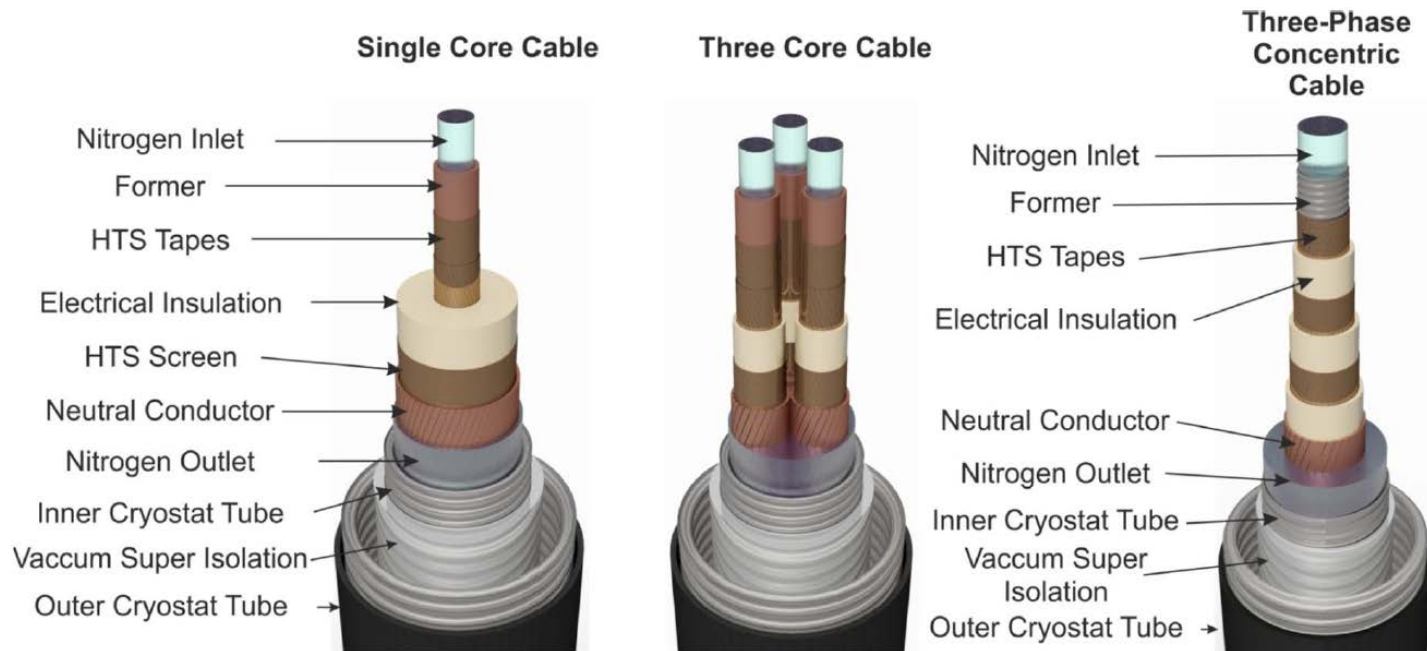
## Warm Dielectric (WD) vs Cold Dielectric (CD)



- ❑ The CD configuration makes it easier to access the cryostat, as it is electrically insulated from the conductive phases.
- ❑ Designing a CD cable is a complex task due to the number of components at cryogenic temperatures (terminations, joints, electrical insulation, etc.).
- ❑ Most superconducting cable prototypes proposed in the last years were designed using the CD configuration.

# Overview of HTS cable architectures

Single core vs 3-in-1 cores vs Concentric



- ❑ If the 3 phases of the concentric configuration are balanced, the magnetic field outside the phases can be greatly reduced without the need of a superconducting shield [3, 23]. The amount of superconductor needed is thus reduced.
- ❑ The concentric configuration is more compact and thus suited to be contained in the tunnels made for conventional lines, thus facilitating their retrofitting.

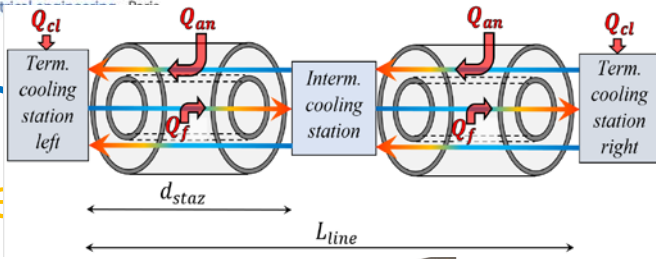
phases

cryogenic envelope

Source: Nexans

# Over architectures

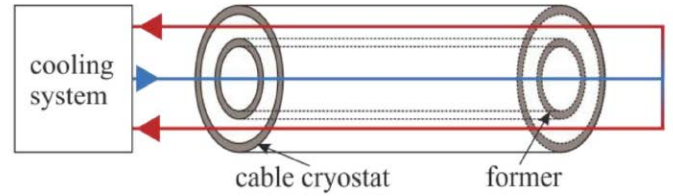
Single



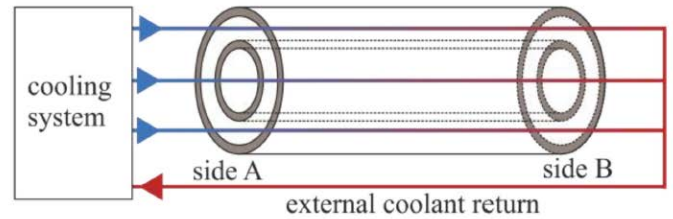
ds

- ❑ Managing 2 coolant flows introduces more complexity in cable manufacturing/design.
- ❑ Considering 2 flows improves the capability of uniformly cooling the superconductor.
- ❑ A forward and a return flows of coolant (*Both-sided cooling option*) do not require any external return → more compact system, but each cooling/pumping station has to manage 2 coolant flows in opposite directions.
- ❑ Potentially, the 2 different coolants could be involved (e.g. GHe in the inner channel and LN2 in the outer channel).

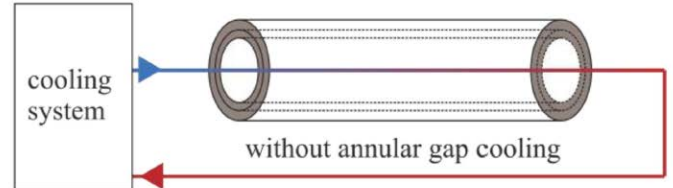
**Cooling option 1** single-sided cooling with internal coolant return flow



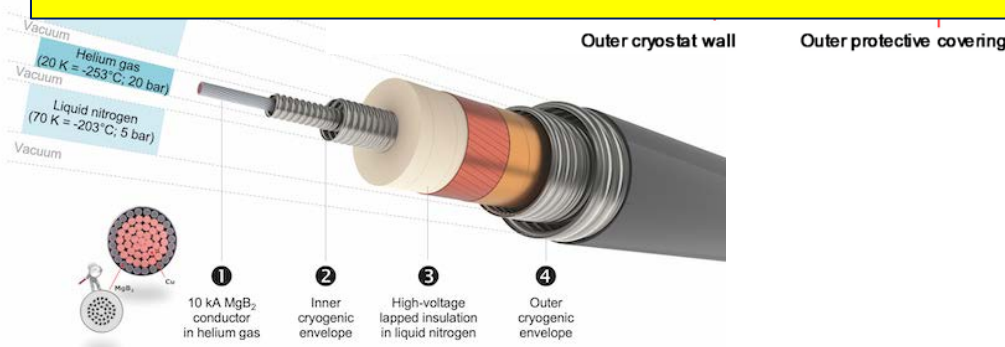
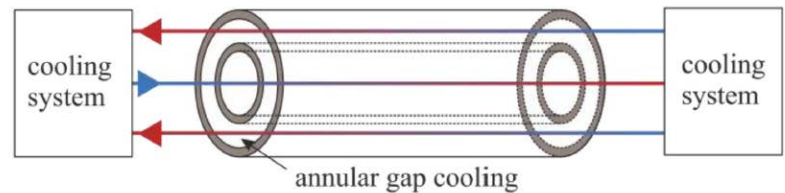
**Cooling option 2** single-sided cooling with external coolant return flow with annular gap cooling



**Cooling option 3** single-sided cooling with external coolant return flow without annular gap cooling



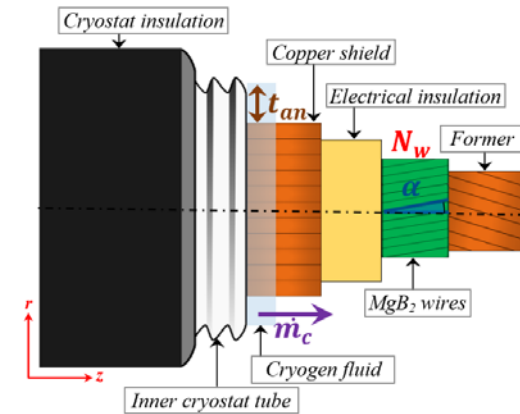
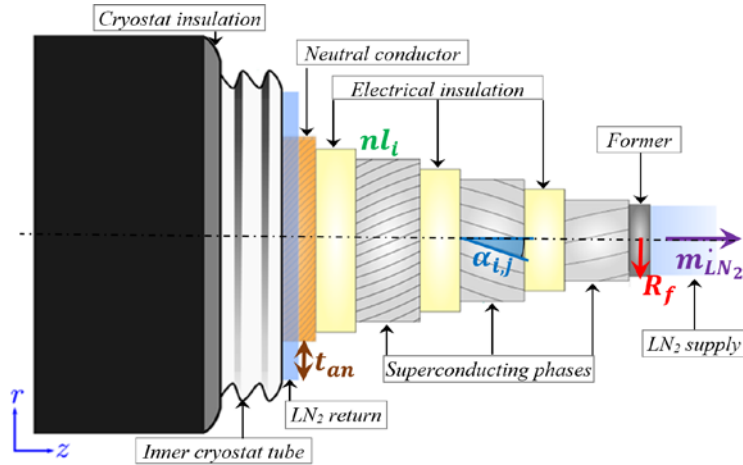
**Cooling option 4** both-sided cooling



HTS

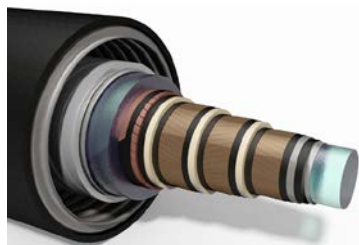
# Overview of HTS cable architectures

## HTS (AC) vs MgB<sub>2</sub> (DC)



$Q_{cl}$   $Q_{coun}$   $Q_{cryo}$   $n_{stat}$   $Q_{coun}$   $Q_{cryo}$   $Q_{cl}$

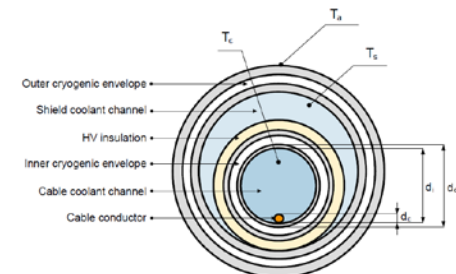
- ❑ MgB<sub>2</sub> manufacturing costs are relatively low compared to HTS tapes (10 – 15 times cheaper).
- ❑ MgB<sub>2</sub> wires are notoriously more subject to high AC losses, and thus their use is almost always limited to DC applications (DC cables).



Source: Metox



Source: Kiswire-KAT

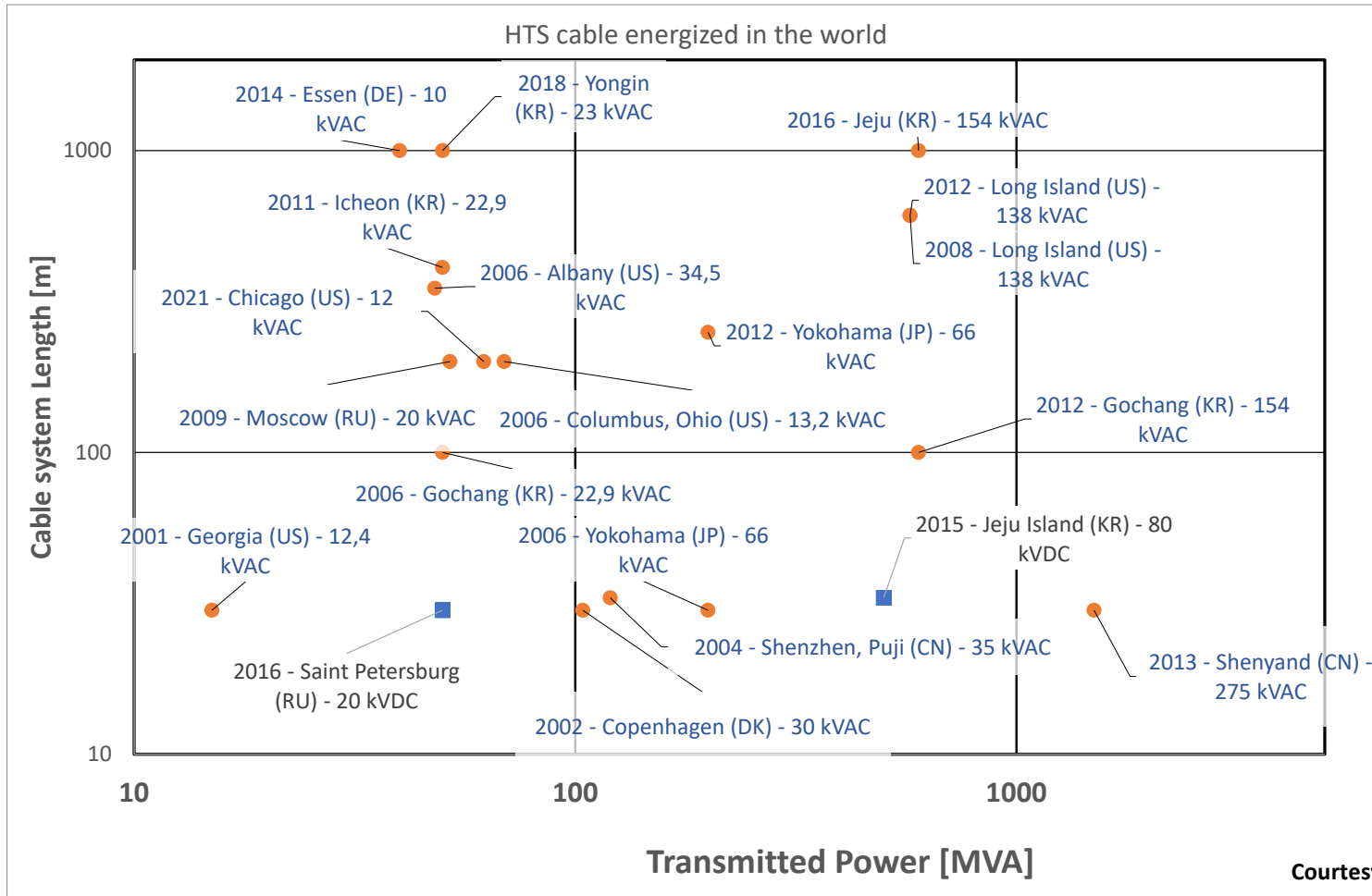




# Overview of HTS cable architectures

In the last 20 years, over 20 prototypes have been developed and installed around the world, with:

- ☐ 30 m < lengths < 1.5 km
- ☐ 10 MW < powers < 1 GW
- ☐ 10 kV < voltages < 275 kV

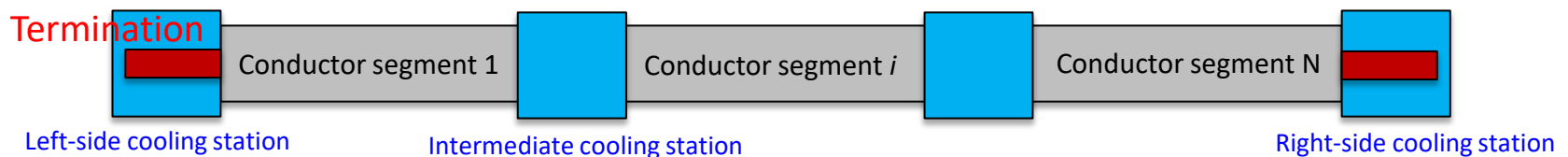


## Architecture selected

- CD configuration
- Coaxial configuration
- HTS AC cable
- Double-sided cooling option

Assumption → the cable is **modular**

- The configuration/geometry of each conductor segment included between adjacent cooling stations is the same.
- Even the thermodynamic properties of the coolants at the ends of each segment are the same (note that there are 2 counter-flows)



# Architecture selected



## Superconducting Cables

Prof. Dr.-Ing. Mathias Noe, Karlsruhe Institute of Technology

Institute for Technical Physics

EUCAS Short Course Power Applications, September 17th 2017, Geneva

KIT-ZENTRUM ENERGIE



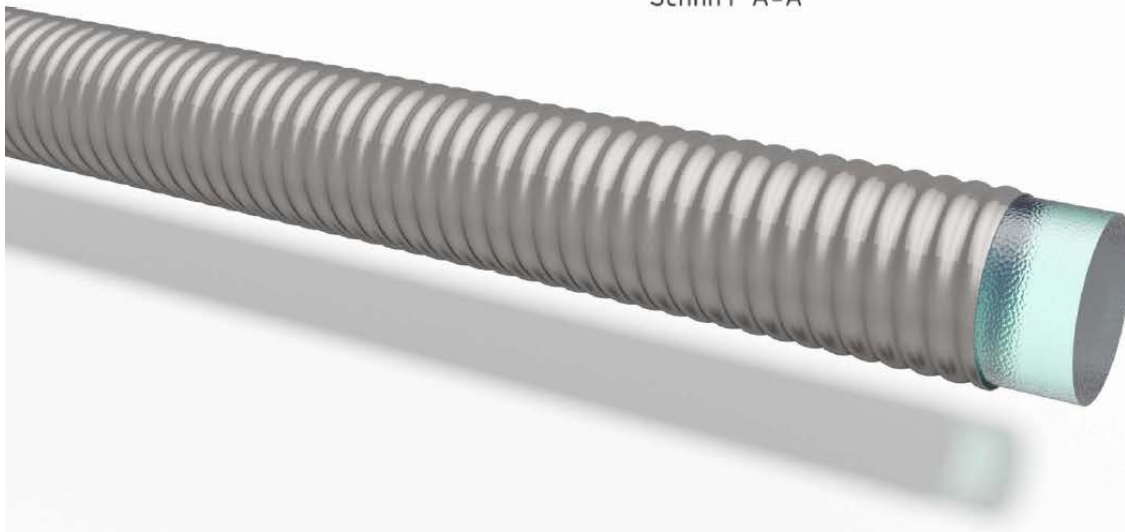
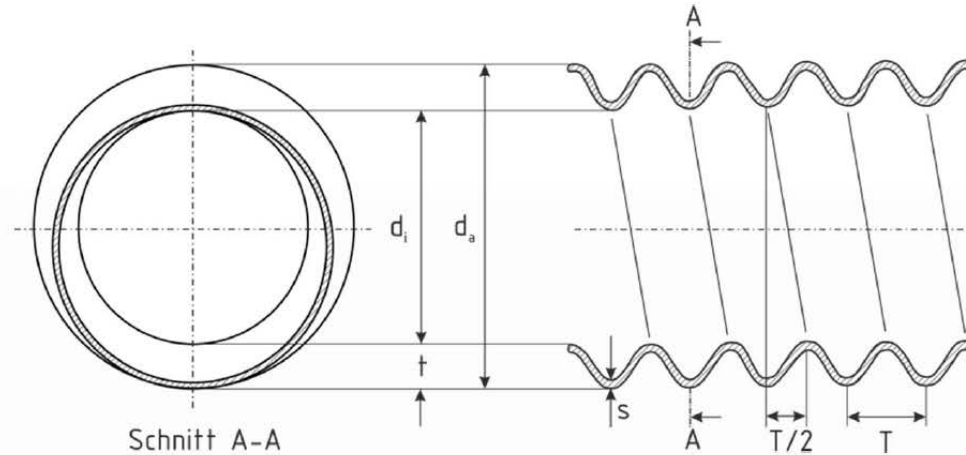
KIT – Die Forschungsuniversität in der Helmholtz Gemeinschaft

[www.kit.edu](http://www.kit.edu)

[4]

# Architecture selected

## General Setup - Former



# Architecture selected

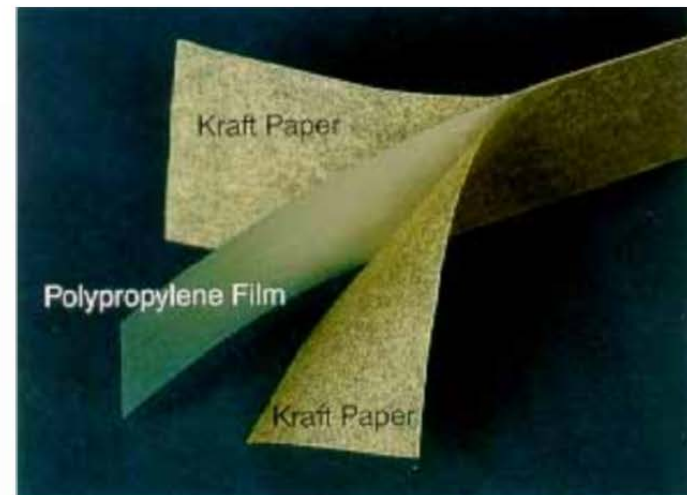
## General Setup – HTS Conductor



# Architecture selected

## General Setup – Dielectric Insulation

Polypropylene Laminated Paper (PPLP)



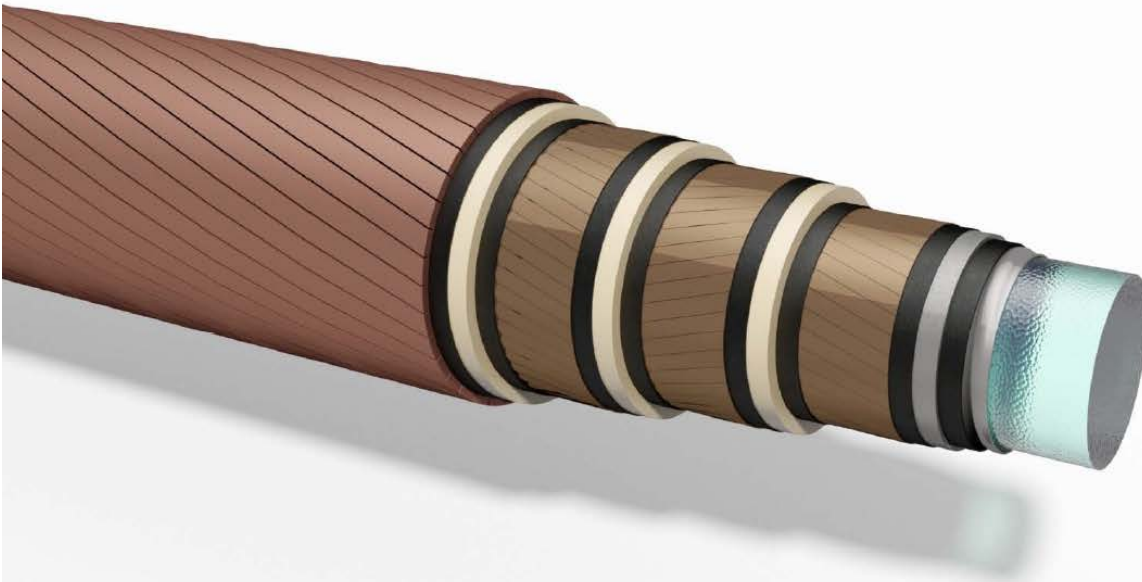
# Architecture selected

## General Setup – Three coaxial phases



# Architecture selected

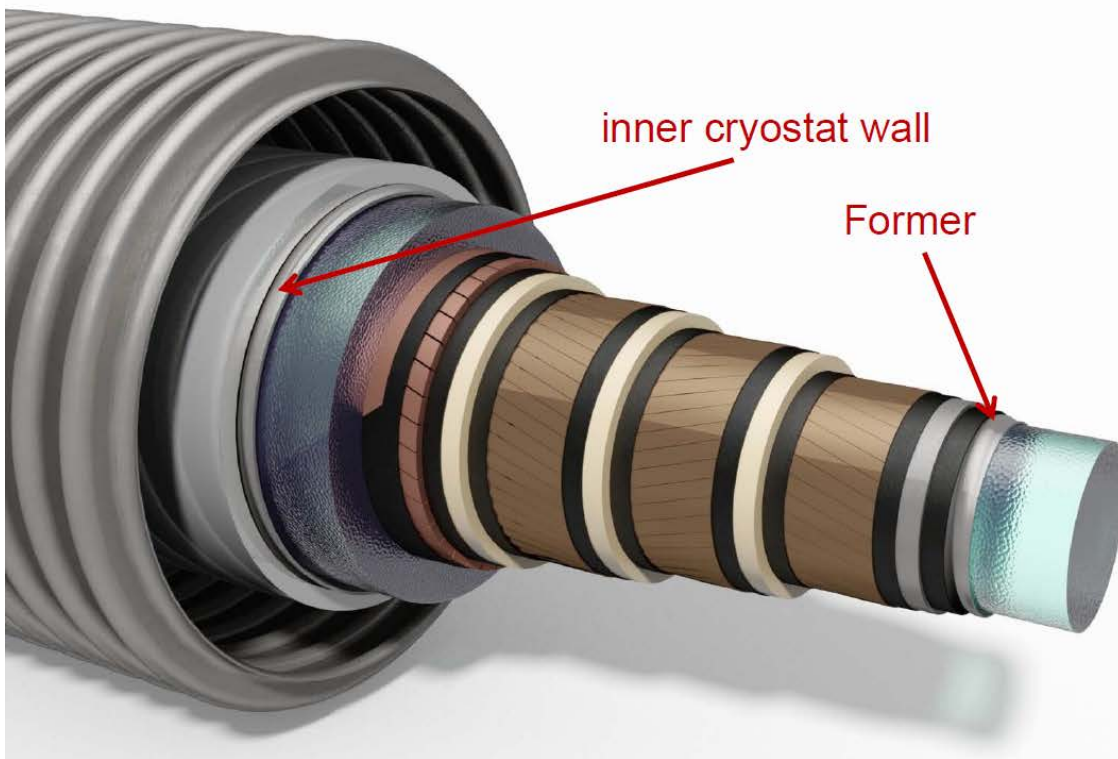
## General Setup – Copper Neutral Conductor





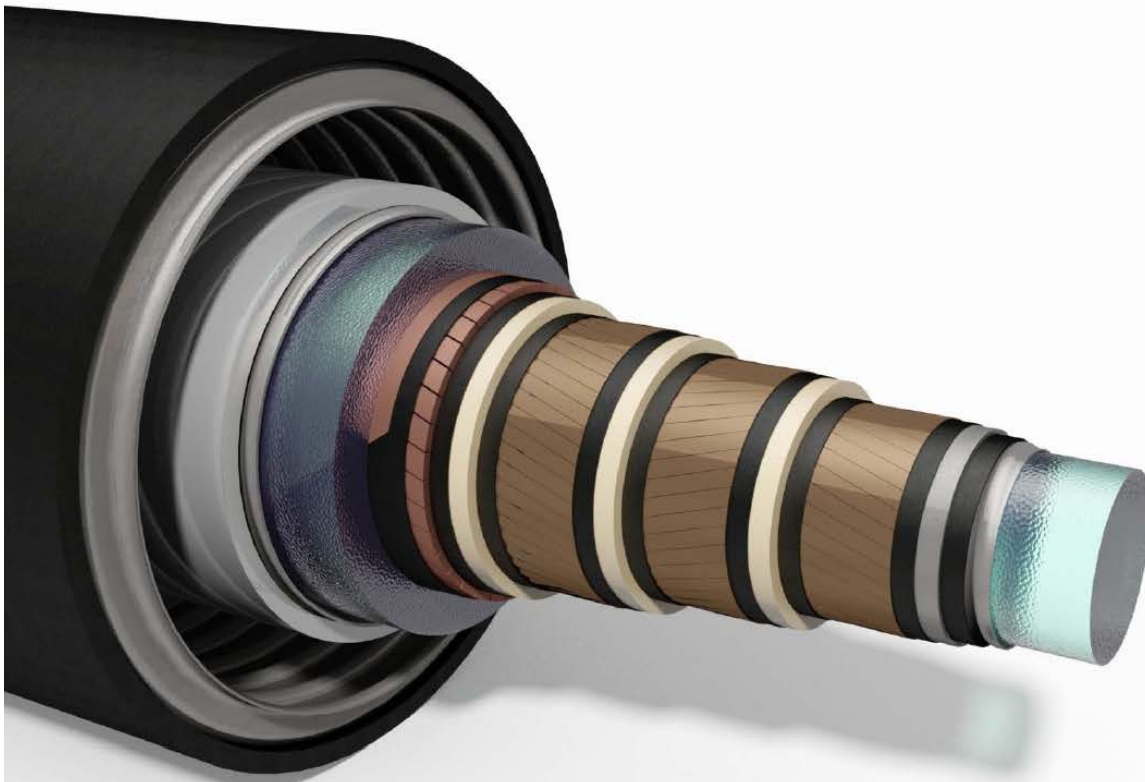
# Architecture selected

## General Setup – Cryostat

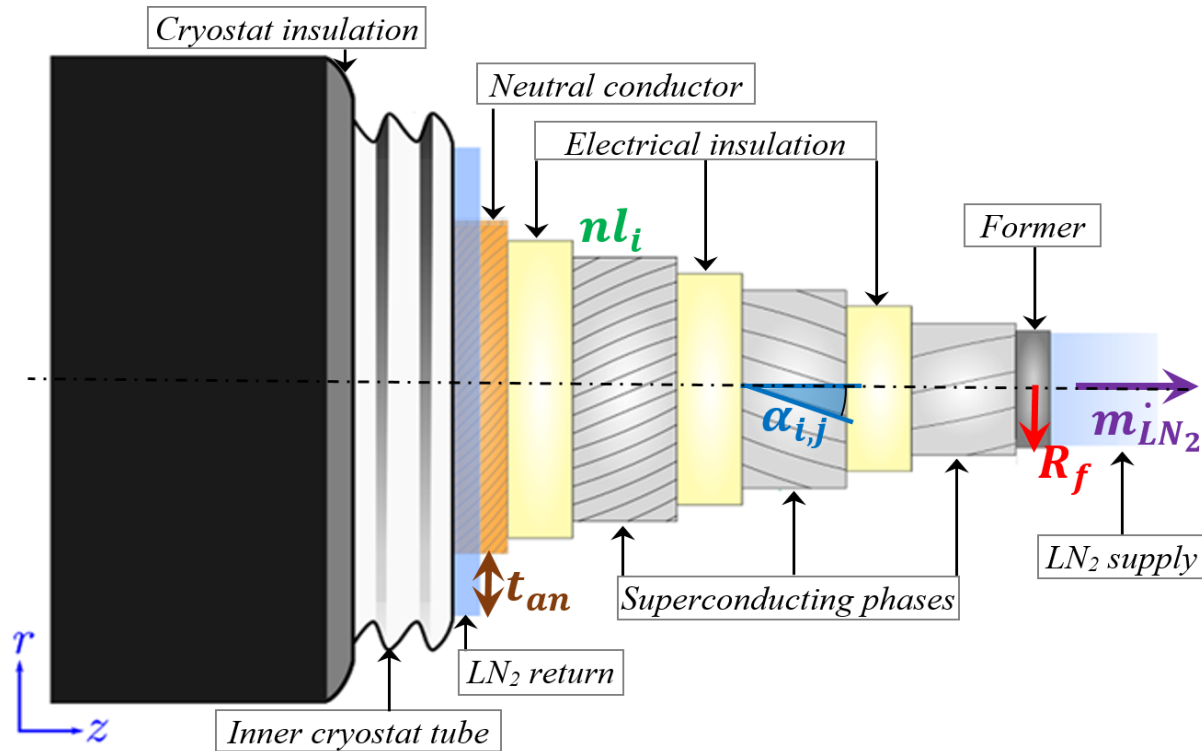


# Architecture selected

**General Setup – Outer Protection, extruded PE**



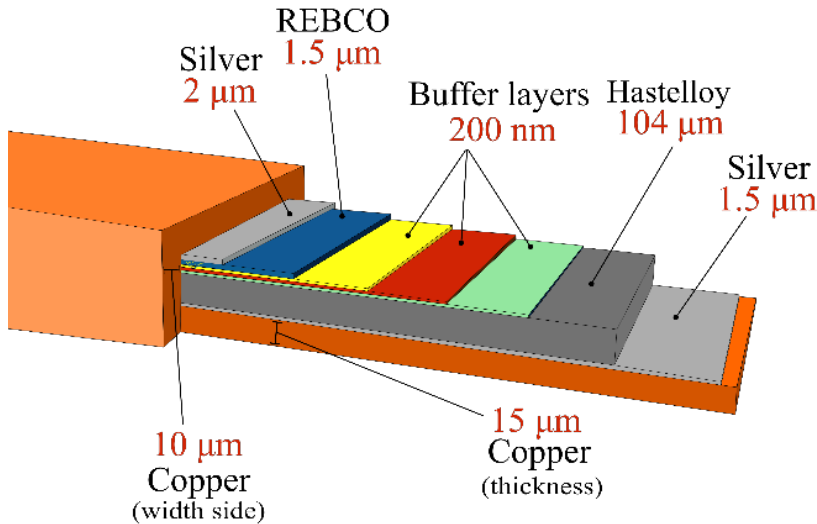
# HTS system components - conductor



[5]

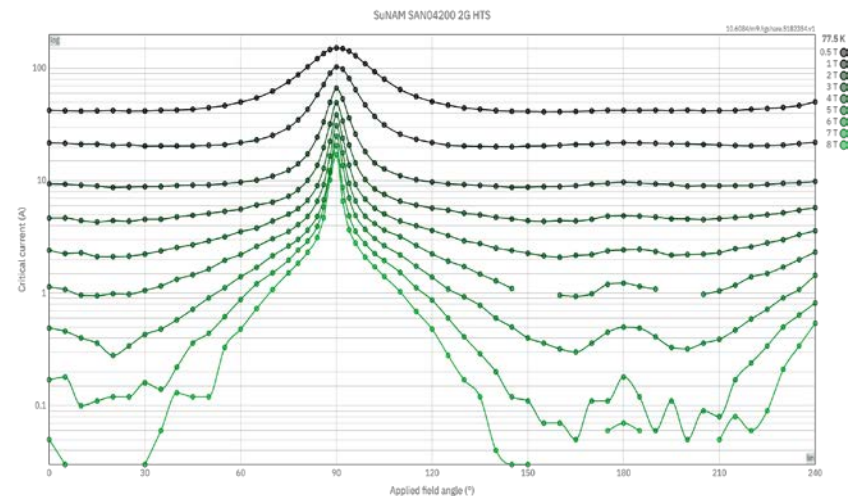
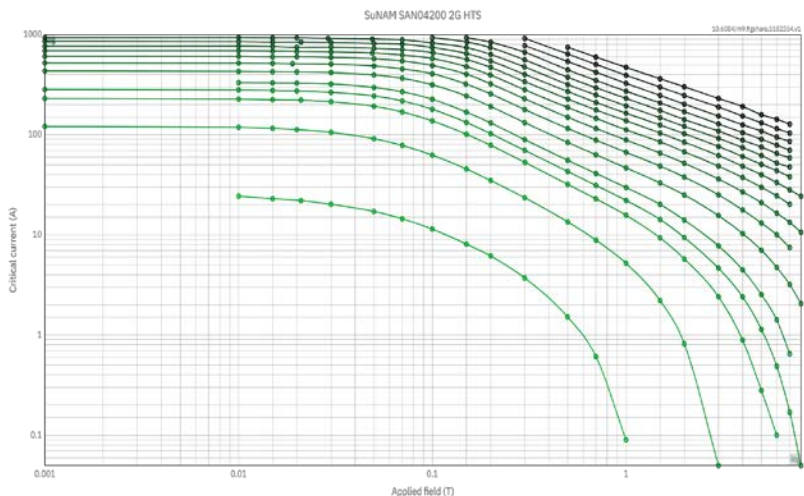
# HTS system components - conductor

## HTS tapes



Tape selected for this study: **SuNAM SCN04150 tape**

- Very high current carrying capacity with minimal losses.
- Very high cost compared to traditional conductors.
- Electrical properties strongly dependent on temperature/magnetic field.
- Mechanical properties makes their handling complex (not considered in today's study).



# HTS system components - conductor

## Cryogenic insulation (CD)

### ❑ DC cables

- Kraft paper → Dielectric strength = 25 ~ 50 kV/mm and  $\epsilon_r = 2 \sim 5$

### ❑ AC cables

- PolyPropylene Laminated Paper → Dielectric strength = 40 ~ 50 kV/mm and  $\epsilon_r = 2.2$



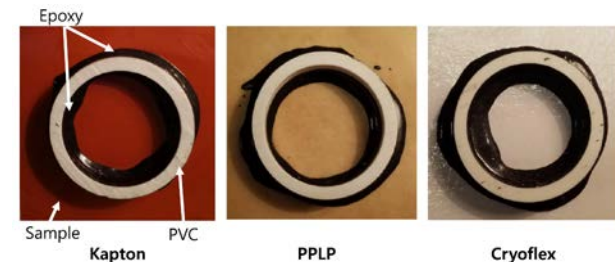
- ❑ LN2 under 5 ~ 10 bar → Dielectric strength 40 ~ 80 kV/mm (pressure dependant) and  $\epsilon_r = 1.4$ . Avoid bubbles: in GN2 the dielectric strength is only 2 ~ 3 kV/mm.

- ❑ Other dielectric materials have been considered in different publications: Kapton, XLPE, Cryoflex (by ULTERA), Tyvek/PE, Teflon.

Condition: LN <sub>2</sub> (T = 77 K)	PPLP	Tyvek/PE
$\epsilon_r$	1.90	1.73
$\tan\delta$	0.00058	0.00013

[3]

[2]

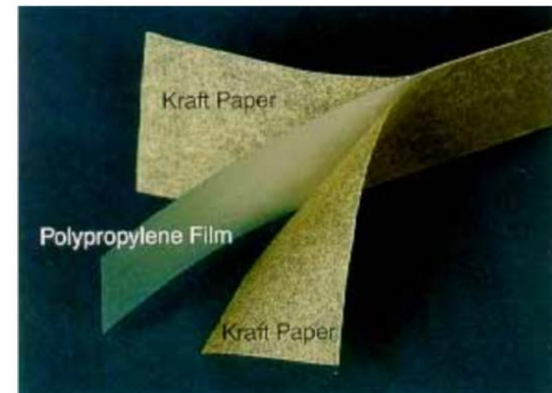
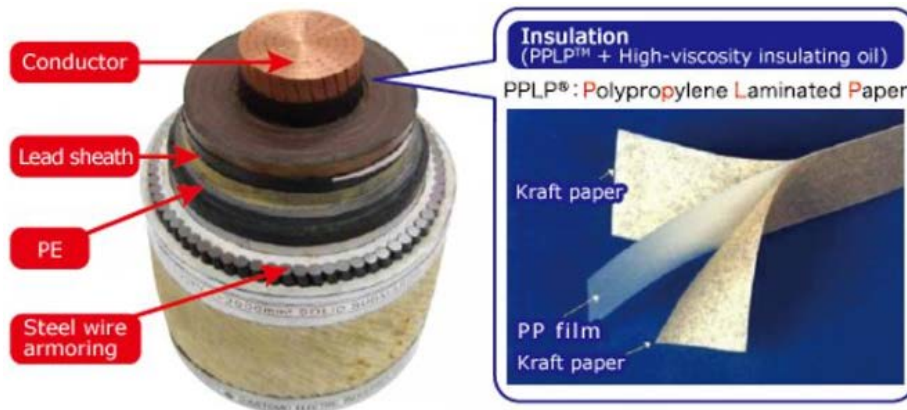


# HTS system components - conductor

## Cryogenic insulation (CD)

- ❑ **PolyPropylene Laminated Paper (PPLP)** has been widely used for HV power cables due to its excellent electrical and mechanical performances.
- ❑ Its use for power cable insulation can be traced back to 1970's, initially for HVAC cables but extended to HVDC cables and superconducting.

[1]



- ❑ Reliable hybrid insulation systems based on pressurized liquid nitrogen and polypropylene laminate paper (PPLP).

# HTS system components - conductor

## Cryostat

The cryostat contains the cable and (above all) the coolant, reducing the heat exchange with the outside.

It includes (inner to outer): **Inner cryogenic tube** → **Vacuum space** → **MLI** → **Outer cryostat** → **Jacket**

**Single envelope** vs **double envelope** (2 different fluids/temperatures) cryostat



Simple envelope

1. Corrugated inner tube
2. Low-loss spacer
3. Vacuum space
4. Multilayer superinsulation
5. Corrugated outer tube
6. PE jacket (optional)

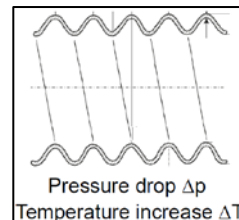
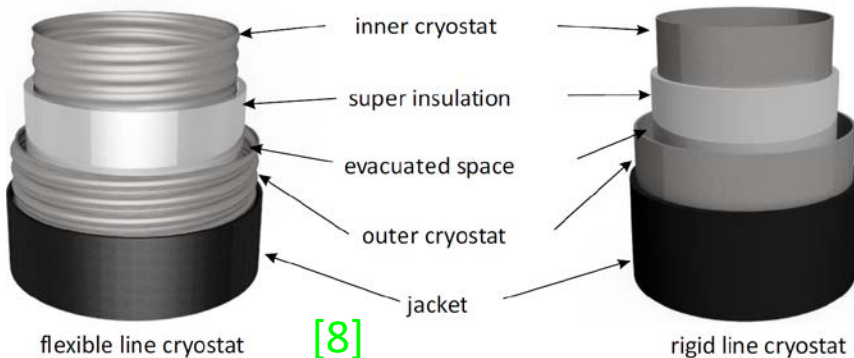


Double envelope with thermal shield for MgB<sub>2</sub>



Laying of the AC HTS cable into its flexible cryostat for the Ampacity project.

**Flexible** (easier to transport/laying) vs **rigid** (lower thermal losses) cryostat



[7]

# HTS system components - conductor

## Cryostat

The cryostat contains the cable and (above all) the coolant, reducing the heat exchange with the outside.

It includes (inner to outer): **Inner cryogenic tube** → **Vacuum space** → **MLI** → **Outer cryostat** → **Jacket**

**Single envelope** vs **double envelope** (2 different fluids/temperatures) cryostat



Simple envelope

1. Corrugated inner tube
2. Low-loss spacer
3. Vacuum space
4. Multilayer superinsulation
5. Corrugated outer tube
6. PE jacket (optional)

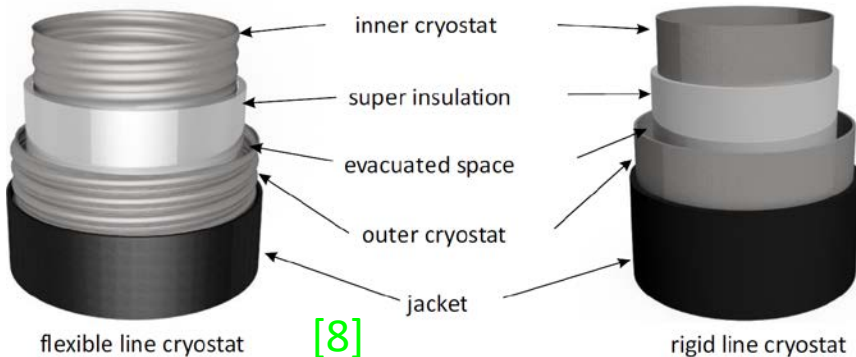


Double envelope with thermal shield for MgB<sub>2</sub>



HTS coaxial cable installation for the AEP Bixby project. The white cable on the drum is the superconductor and dielectric portion being fed into the black cryostat and outer jacket.

**Flexible** (easier to transport/laying) vs **rigid** (lower thermal losses) cryostat



flexible line cryostat

[8]

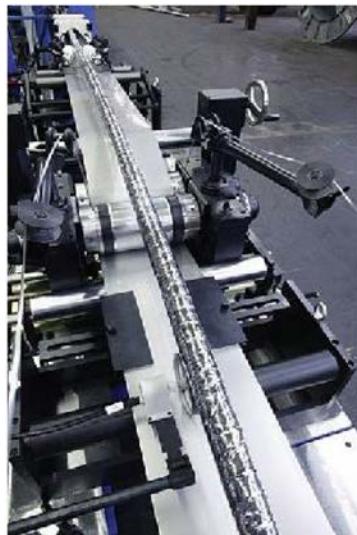
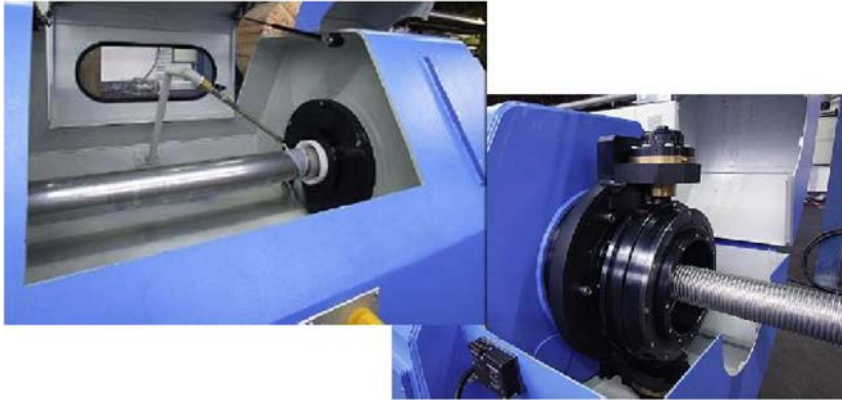
rigid line cryostat

[7]



# HTS system components - conductor Cryostat

*Corrugation of tubes (Flexibility)*



*Outer tube shaping and welding process*



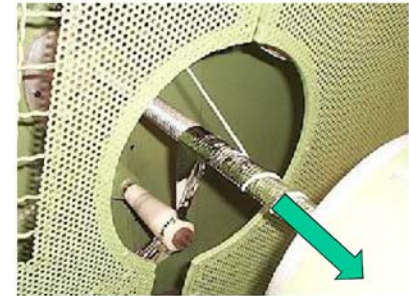
*Thermal insulation process*



Ultra-sonic  
cleaning



Super insulation laying



Spacer

**Nexans**

Introduction to superconducting power cable systems

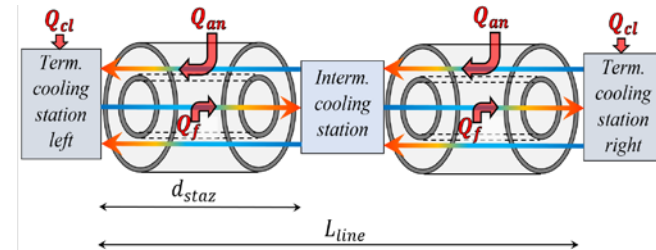
CE BRUZEK  
Nexans France

ESAS Summer school - 8-14 June 2016

# HTS system components – cooling system

Purpose of the cooling system:

- ❑ Ensure that the temperature of the HTS tapes is kept within the design limits by fluid cooling;
- ❑ Restore the temperature and pressure conditions of the coolants to their initial levels after their rise/drop occurring in each cable section (**avoid phase transition!**);
- ❑ Handle the coolants circulation at a given mass flow rate.

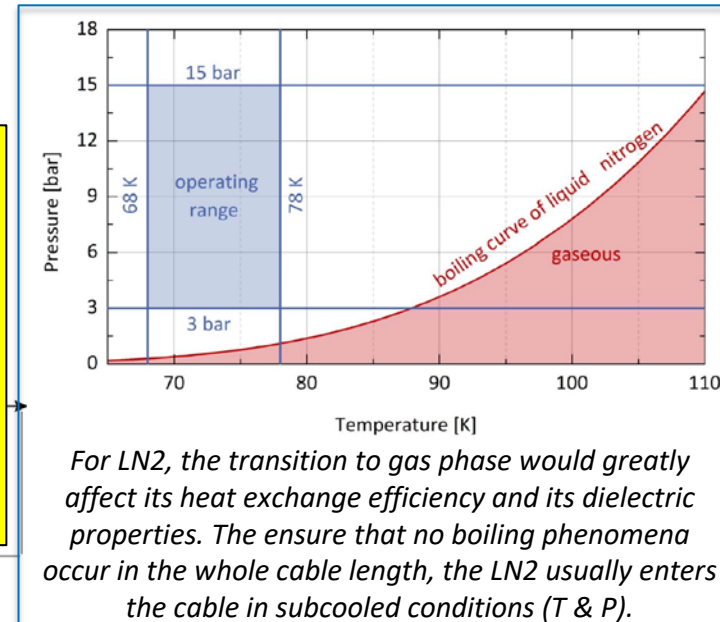


Typical cooling system for an HTS power cable system

- ❑ Cooling machines and pumps have their own efficiency.
- ❑ The ideal efficiency of cooling machines (Carnot) depends on the operating temperature. To extract the same amount of power but at lower temperatures, more electrical power is required.
- ❑ The real efficiency of cooling machines is significantly lower than the ideal one (7 ~ 10 times lower).

$T_{out}, P_{out}$

**Pump**



# HTS system components – cooling system

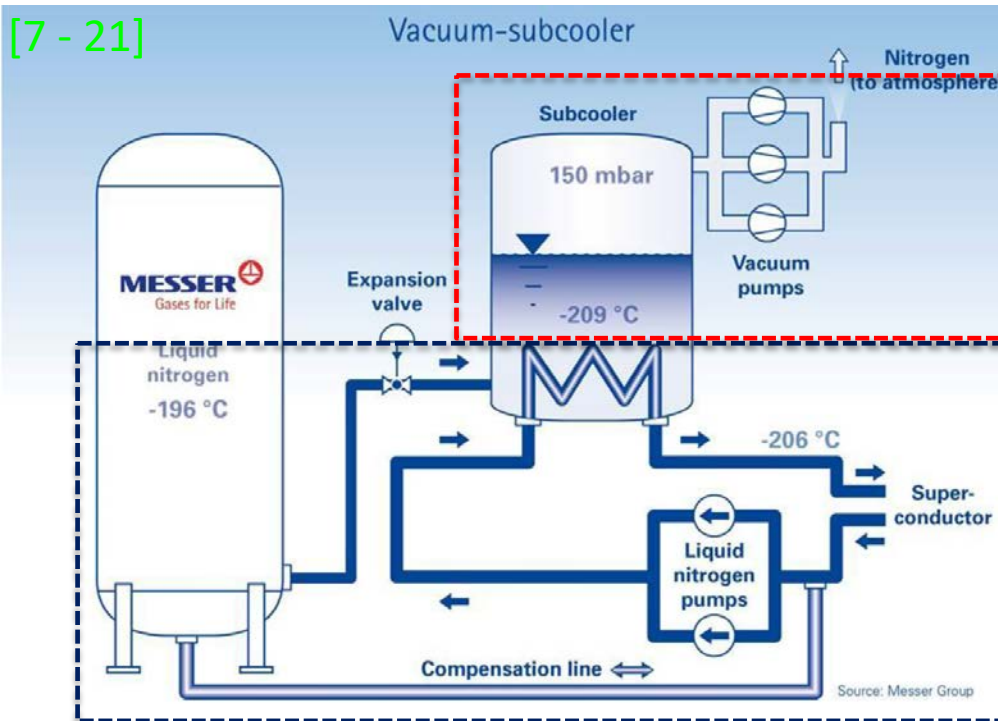
An HTS cable cooling system is a combination of two separate loops:

- ❑ One closed-loop consisting of LN2 circulated inside the cable cryostat and terminations to cool the cable system.
- ❑ One loop is part of the refrigerator itself (open or **closed**)



Turbo-Brayton machines: from 5kW to 30 kW at 70K and up to 5 kW at 20K

Gifford Mc-Mahon machines: up to 500W at 70K and 60W at 20K



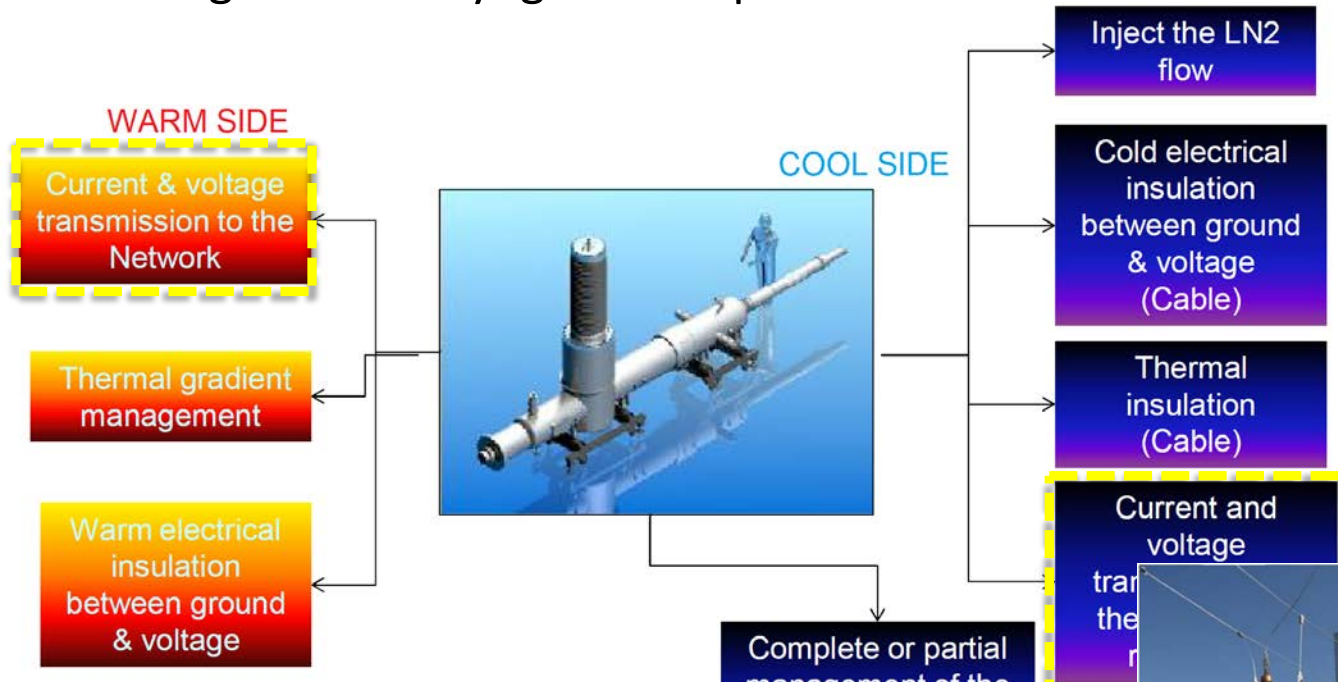
Cooling unit for the AmpaCity project

## Comparison among different cryogenic refrigeration technologies

	Reverse-Brayton	Turbo-Brayton	Stirling cryogenerator
Technology	Existing and proven technology	To be developed	Proven but old technology
Power consumption per cold watts	1 W <sub>cold</sub> /23.2 W <sub>electric</sub>	1 W <sub>cold</sub> /11.6 W <sub>electric</sub>	1 W <sub>cold</sub> /18.3 W <sub>electric</sub>
Carnot efficiency	~ 15%	>30%	~ 19%
Capital cost	High	High	Medium
Availability	High	Very high	High
Chilled water	Not required	Required	Required
Redundancy	Component level	System level	Component level
Maintenance	Medium (annual)	Low (several years)	High (6000 h)
Footprint	Medium	Small	Large

# HTS system components – terminations

HTS cable terminations are the links between the conventional power grid at  $T_{amb}$  and a superconducting cable at cryogenic temperature.



Rollers along the termination for Albany project

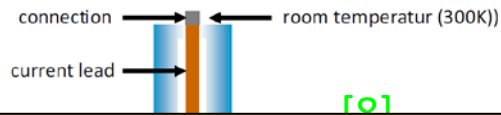
[7]

**Nexans**  
Introduction to superconducting power cable systems  
**CE BRUZEK**  
Nexans France  
ESAS Summer school – 8-14 June 2016

Once cooled, the core of a 1 km HTS cable contracts by about 3 m compared to its outer room-temperature jacket → movable terminations are adopted to handle such contraction.

# HTS system components – terminations

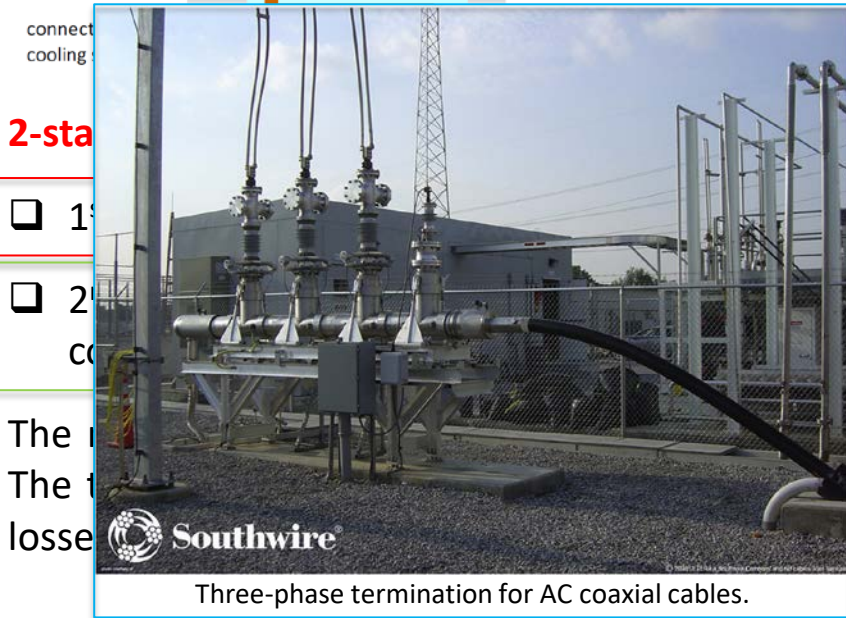
## 1-stage terminations:



[9]

The termination cryostat is very similar to a conventional horizontal cryogen storage tank (vacuum + MLI).

- For a single-core AC HTS cable configuration, each termination has its own cryostat (as the 3 phases).
- For a 3-in-1 or coaxial cable design all three terminations share one cryostat.



[7]

# III. TEA of HTS cable system

## Phase 1 – Goal and scope definition

# III. TEA of HTS cable system

## Phase 2 – Inventory analysis

# TEA on HTS cables → The approach

The cable system is addressed as an **economic model** and a **technical model**.

Different levels of detail can be applied.

*VERY broad*

**Economic model**

LCC (€ or €/km)

Little (optional) extra step:  
total CAPEX and OPEX (or OPEX<sub>year</sub>)



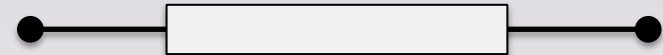
From manufacturer or literature, once the characteristics of the line are set (e.g. length, size, cable type).

$$LCC = CAPEX + \sum_{t=1}^{years} \frac{OPEX_{year}}{(1+r)^t}$$



**Technical model**

Basic data for the cable representation in an equivalent circuit of the grid (e.g. voltage level and power selected, AC or DC?, equivalent resistance...)





# TEA on HTS cables → The approach

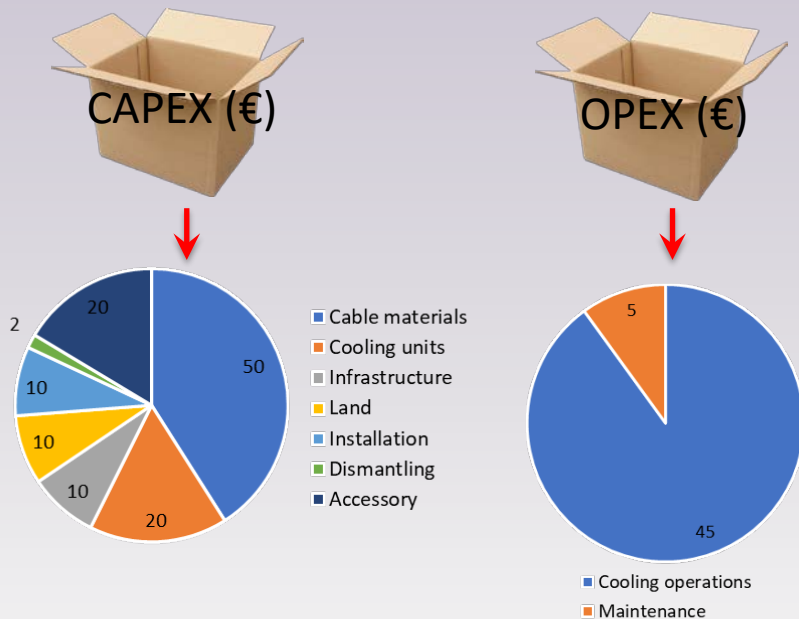
The cable system is addressed as an **economic model** and a **technical model**.

Different levels of detail can be applied.

*A little more specific*

## Economic model

Distinguish different CAPEX and OPEX terms



## Technical model

- Evaluate substituting one components with another (*e.g.* conductor, cooling station...) based on their technical properties and costs.
- Some terms may be available from the literature as parameterized functions depending on the line's features (*e.g.*, cooling costs based on cable power, land costs contingent upon the installation site...).

The terms are in € or €/km, from manufacturer or literature.

# TEA on HTS cables → The approach

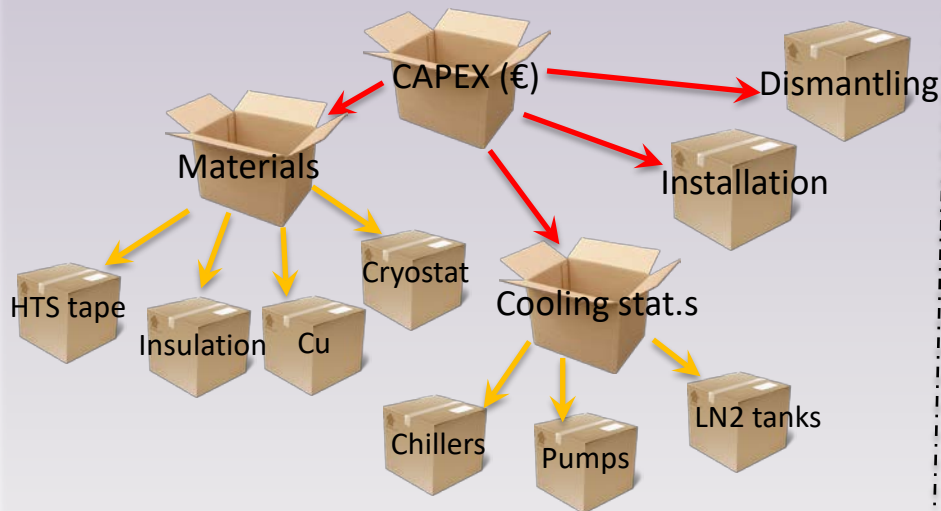
The cable system is addressed as an **economic model** and a **technical model**.

Different levels of detail can be applied.

*Thoroughly detailed*

## Economic model

The single CAPEX and OPEX terms are expanded (not necessarily all of them)



Some cost terms are "simply" parameterized to the main cable features, others are based on the cable design (in combination with the technical model).



## Technical model

For each term to expand, it is required to know:

- Properties of the materials/components involved;
- Relationships between the properties and the line features to compute the necessary quantities (simplifying assumptions are generally applied);
- Eventual operating constraints establishing the limits for each material/component quantity.

*e.g.* HTS tapes)

- HTS tape properties →  $I_c(T, |B|, \vartheta)$ , geometry...
- Quantity → cable length, cable current...

- Constraints →  $\begin{cases} [I_{tape}/I_c]_{min}^{max} \\ \text{Geometrical (cable layers dimensions, twist angle...)} \\ \text{Economic (reduce AC losses to reduce OPEX ...)} \end{cases}$

## TEA on HTS cables → The approach

The cable system is addressed as an **economic model** and a **technical model**.

Different levels of detail can be applied.



When should we stop going further in detailing (term by term)?

- When specific data, such as costs and properties of sub-components, are no longer accessible.
- When we recognize that a greater detail would not produce a significant change in the results.
- When we assess that the effort or calculation time are no longer comparable with our aims. For instance: are we grid managers seeking to evaluate multiple cable technologies for broad applications? Or are we manufacturers aiming to optimize costs for a particular case study involving a specific cable architecture?

# TEA on HTS cables → The workflow

## Inventory analysis phase

1) Collect INPUT Data:

- Select the case study
- Have the equations for economic and technical models available
- Select the constraints

2) Set some (or all) parameters of the cable design  
(e.g.  $R_{former}$ ,  $n_{stat}$ ,  $m_{LN2}$ ,  $t_{annulus}$ ,  $n_{l_i}$ ,  $\alpha_{i,j}$ )

## Cable design phase

3) Compute the cable design in cascade

4) Compute the cable system losses

3-bis) Alternatively, the full design complying with the constraints, as well as the losses, are provided to you without calculations.

5) Verify if the cable design complies with the constraints

no

Change the parameters originally selected

yes

6) Compute CAPEX, OPEX and LCC

## Calculation of indicators phase

Interpreting the results

Interested to parametric analyzes?

yes

## Interpretation phase

Phase 3

# TEA on HTS cables → The workflow in our Excel file

## Inventory analysis phase

Look at the Excel sheet called:  
**1-Goal and scope definition**

Use the Excel sheet called:  
**2-Inventory analysis-HTS**

## Cable design phase

Calculate cable design, losses and constraints using the Excel sheet called:  
**3.0-HTS Cable design**

Use the Excel sheet called:  
**3-Calculation of indicators-HTS**

## Calculation of indicators phase

## Interpretation phase

Use the Excel sheet called:  
**4-Interpretation**

Interested to  
parametric analyzes?

yes

Change the  
parameters originally  
selected

P  
h  
a  
s  
e  
  
3

# TEA on HTS cables → Input data

## What we need to know to start the study:

### ➤ Line main features

- Voltage level and power to be transferred
- Line length
- Cable architecture (DC or AC? Coaxial? Cold dielectric?)

### ➤ A clear idea of the terms composing CAPEX and OPEX

- Materials/sub-components properties (technical and economic)

### ➤ What are the constraints

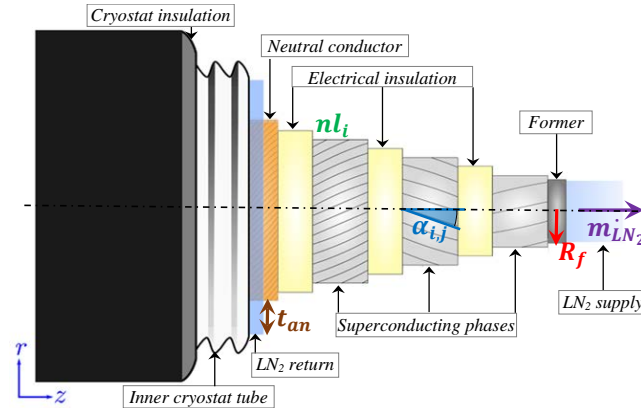
# TEA on HTS cables → Where to find information

**Industrial Consultant**

**Literature**

**Specialists**

# TEA on HTS cables → Line main features (case study)



**Technical model – Main features**

Property	Symbol	Value
Total power	$P_{tot}$	1.5 GW
Cable power	$P$	750 MW
N° of HTS cables running in parallel	$n_{cables}$	2
Voltage rms	$V_{rms}$	33 kV
Load factor	$\cos\varphi$	0.95
rms value of the total AC current in each phase	$I_{rms}$	$I_{rms} = \frac{P}{\sqrt{3} V_{rms} \cos\varphi} = 13.81 \text{ kA}$
Line length	$L_{line}$	32 km



# TEA on HTS cables → Line main features (case study)

The case study is set in the **Inventory analysis – HTS** sheet of our Excel file.

Transmission link between solar plant and substation

Phase 2: Inventory analysis

## HTS system MAIN FEATURES

Technical parameter	Symbol	HTS system	Units	Comment
Line length	$L_{line}$	3.20E+04	m	
Power delivered by each cable	$P$	7.50E+08	W	Maximum Power for 1 cable = 750 MW
Voltage level rms of each cable	$V_{rms}$	3.30E+04	V	Phase-to-phase voltage
Load factor	$cos\varphi$	0.95		
Mean ambient temperature in the installation site	$T_a$	303.15	K	30° C
Frequency	$f$	50	Hz	

## HTS tapes

Technical parameter	Symbol	HTS system	Units	Comment
Tape width	$w_{HTS}$	4.00E-03	m	
Mean HTS temperature in the cable, for all phases (tentative)	$T_{HTS}$	70.1	K	
Critical current of the tape at 77 K and s.f.	$I_{c\_HTS\_77K}$	293.7	A	
Safety value of $I_{tape}/I_{c\_HTS}$ not to be passed	$safety_{HTS}$	0.8		80%
N° of HTS layers in phase 1	$n_{l\_1}$	2		
N° of HTS layers in phase 2	$n_{l\_2}$	1		
N° of HTS layers in phase 3	$n_{l\_3}$	1		
Inner radius of HTS layer 1 - phase 1	$R_{HTS\_1\_1}$	3.39E-02	m	
Inner radius of HTS layer 2 - phase 1	$R_{HTS\_2\_1}$	3.41E-02	m	
Inner radius of HTS layer 1 - phase 2	$R_{HTS\_1\_2}$	4.86E-02	m	
Inner radius of HTS layer 1 - phase 3	$R_{HTS\_1\_3}$	6.24E-02	m	
Twist angle of HTS layer 1 - phase 1	$\alpha_{1\_1}$	11	°	
Twist angle of HTS layer 2 - phase 1	$\alpha_{2\_1}$	15	°	
Twist angle of HTS layer 1 - phase 2	$\alpha_{1\_2}$	-13	°	
Twist angle of HTS layer 1 - phase 3	$\alpha_{1\_3}$	-14	°	

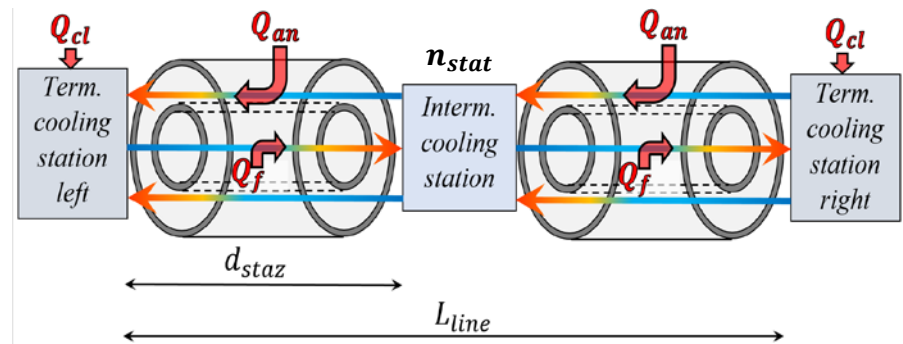
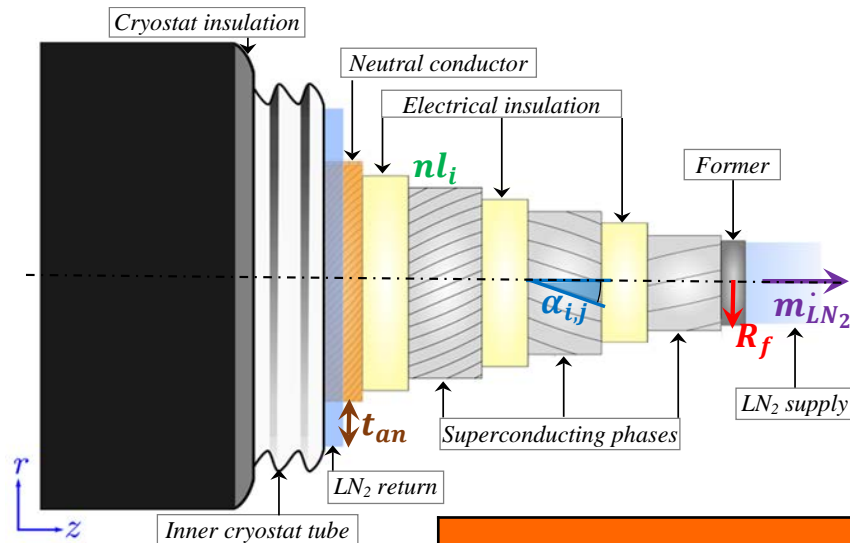
1-Goal and scope definition | 2-Inventory analysis-Benchmark | **2-Inventory analysis-HTS** | 3.0-HTS Cable design | 3-Calculation of indicators-HTS | 4-Int ...

# III. TEA of HTS cable system

## Phase 3 – Calculation of indicators

# Set some cable design parameters

# TEA on HTS cables → Set some cable design parameters



Technical model		
Property	Symbol	Value
Former radius (inner)	$R_{former}$	30 mm
LN2 mass flow rate	$\dot{m}_{LN2}$	2.15 kg/s
Twist angle for each layer of phase 1	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
Twist angle for each layer of phase 2	$\alpha_{1,2}$	-13°
Twist angle for each layer of phase 3	$\alpha_{1,3}$	-14°
N° of HTS layers for phase 1	$n_{l_1}$	2
N° of HTS layers for phase 2	$n_{l_2}$	1
N° of HTS layers for phase 3	$n_{l_3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

# TEA on HTS cables → Set some cable design parameters

The parameters set are colored in red in the **Inventory analysis - HTS** sheet of our Excel file.

Transmission link between solar plant and substation  
Phase 2: Inventory analysis

HTS system MAIN FEATURES				
Technical parameter	Symbol	HTS system	Units	Comment
Line length	$L_{line}$	3.20E+04	m	
Power delivered by each cable	$P$	7.50E+08	W	Maximum Power for 1 cable = 750 MW
Voltage level rms of each cable	$V_{rms}$	3.30E+04	V	Phase-to-phase voltage
Load factor	$cos\varphi$	0.95		
Mean ambient temperature in the installation site	$T_a$	303.15	K	30° C
Frequency	$f$	50	Hz	

HTS tapes				
Technical parameter	Symbol	HTS system	Units	Comment
Tape width	$w_{HTS}$	4.00E-03	m	
Mean HTS temperature in the cable, for all phases (tentative)	$T_{HTS}$	70.1	K	
Critical current of the tape at 77 K and s.f.	$I_{c\_HTS\_77K}$	293.7	A	
Safety value of $I_{tape}/I_{c\_HTS}$ not to be passed	$safety_{HTS}$	0.8		80%
N° of HTS layers in phase 1	$n_{l\_1}$	2		
N° of HTS layers in phase 2	$n_{l\_2}$	1		
N° of HTS layers in phase 3	$n_{l\_3}$	1		
Inner radius of HTS layer 1 - phase 1	$R_{HTS\_1\_1}$	3.39E-02	m	
Inner radius of HTS layer 2 - phase 1	$R_{HTS\_2\_1}$	3.41E-02	m	
Inner radius of HTS layer 1 - phase 2	$R_{HTS\_1\_2}$	4.86E-02	m	
Inner radius of HTS layer 1 - phase 3	$R_{HTS\_1\_3}$	6.24E-02	m	
Twist angle of HTS layer 1 - phase 1	$\alpha_{1\_1}$	11	°	
Twist angle of HTS layer 2 - phase 1	$\alpha_{2\_1}$	15	°	
Twist angle of HTS layer 1 - phase 2	$\alpha_{1\_2}$	3	°	
Twist angle of HTS layer 1 - phase 3	$\alpha_{1\_3}$	-14	°	

# The full cable design is provided

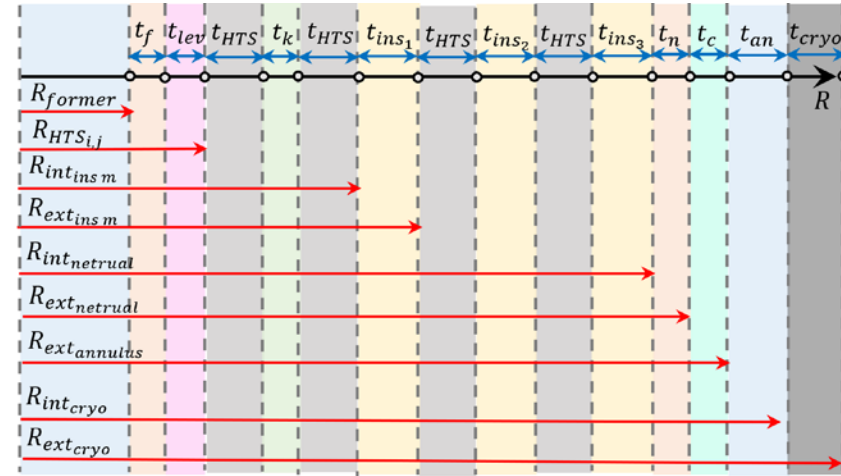
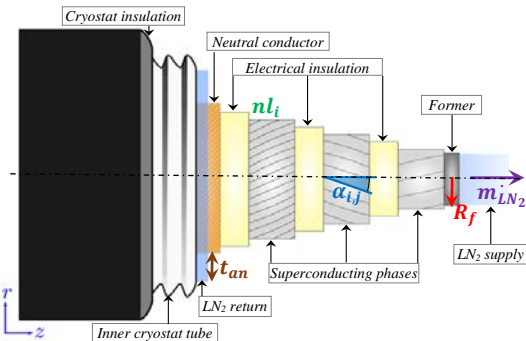
# TEA on HTS cables → Cable design for the case study

If you are lucky enough, you can find the whole design of your device at the operating conditions you selected from manufacturer' or literature' data.

# TEA on HTS cables → Cable design for the case study

Technical model – Main Features		
Property	Symbol	Value
Cable power	$P$	1 GW
Voltage rms	$V_{rms}$	25 kV
Load factor	$\cos\varphi$	0.95
Line length	$L_{line}$	32 km

Technical model – Set design parameters		
Property	Symbol	Value
Former radius	$R_{former}$	30 mm
LN2 mass flow rate	$\dot{m}_{LN2}$	2.15 kg/s
Twist angle for each layer of each phase	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
	$\alpha_{1,2}$	-13°
	$\alpha_{1,3}$	-14°
N° of HTS layers for each phase	$n_{l_1}$	2
	$n_{l_2}$	1
	$n_{l_3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

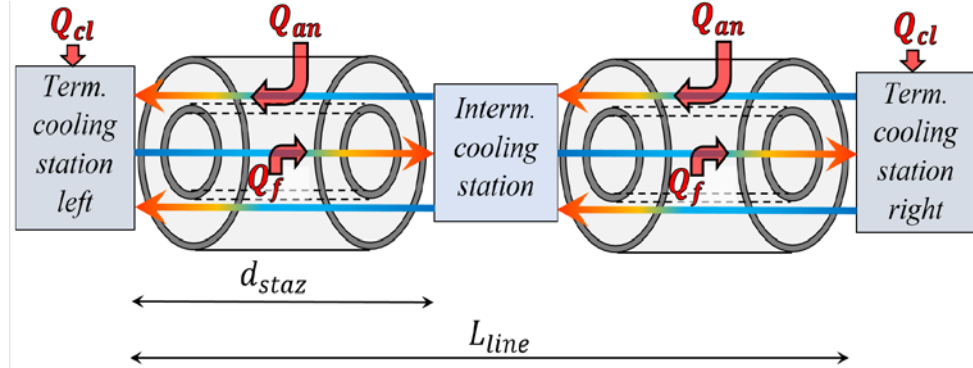


Technical model – Remaining design parameters		
Property	Symbol	Value
Radius of the HTS layers of phase 1 (inner)	$R_{HTS_{1,1}}, R_{HTS_{2,1}}$	33.9 mm , 34.1 mm
Radius of the HTS layers of phase 1 (inner)	$R_{HTS_{1,2}}$	48.6 mm
Radius of the HTS layers of phase 1 (inner)	$R_{HTS_{1,3}}$	62.4 mm
N° of HTS tapes in the layers of phase 1	$Tapes_{1,1}, Tapes_{2,1}$	52 , 52
N° of HTS tapes in the layers of phase 2	$Tapes_{1,2}$	74
N° of HTS tapes in the layers of phase 3	$Tapes_{1,3}$	95
Inner radius of the 3 insulating layers	$R_{int_{ins_1}}, R_{int_{ins_2}}, R_{int_{ins_3}}$	34.3 mm , 48.8 mm, 62.5 mm
Outer radius of the 3 insulating layers	$R_{ext_{ins_1}}, R_{ext_{ins_2}}, R_{ext_{ins_3}}$	48.6 mm, 62.4 mm , 75.8 mm
Inner radius of the copper neutral layer	$R_{int_{neutral}}$	75.8 mm
Outer radius of the copper neutral layer	$R_{ext_{neutral}}$	77.8 mm
Inner radius of the annular gap for LN2	$R_{int_{annulus}}$	78.6 mm
Outer radius of the annular gap for LN2	$R_{ext_{annulus}}$	106.0 mm
Inner radius of the cryostat	$R_{int_{cryo}}$	106.0 mm
Outer radius of the cryostat	$R_{ext_{cryo}}$	137.8 mm



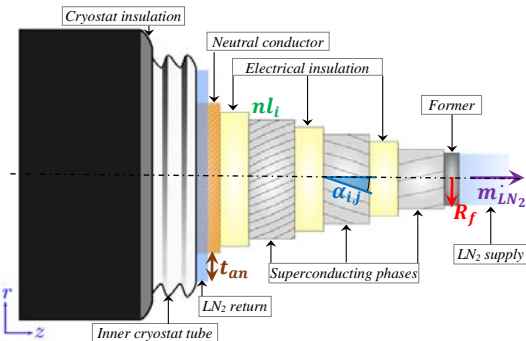
# TEA on HTS cables → Losses and cooling stations for the case study

Technical model – Main Features		
Property	Symbol	Value
Cable power	$P$	1 GW
Voltage rms	$V_{rms}$	25 kV
Load factor	$\cos\varphi$	0.95
Line length	$L_{line}$	32 km



Technical model – Set design parameters		
Property	Symbol	Value
Former radius	$R_{former}$	30 mm
LN2 mass flow rate	$\dot{m}_{LN2}$	2.15 kg/s
Twist angle for each layer of each phase	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
	$\alpha_{1,2}$	-13°
	$\alpha_{1,3}$	-14°
N° of HTS layers for each phase	$n_{l1}$	2
	$n_{l2}$	1
	$n_{l3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

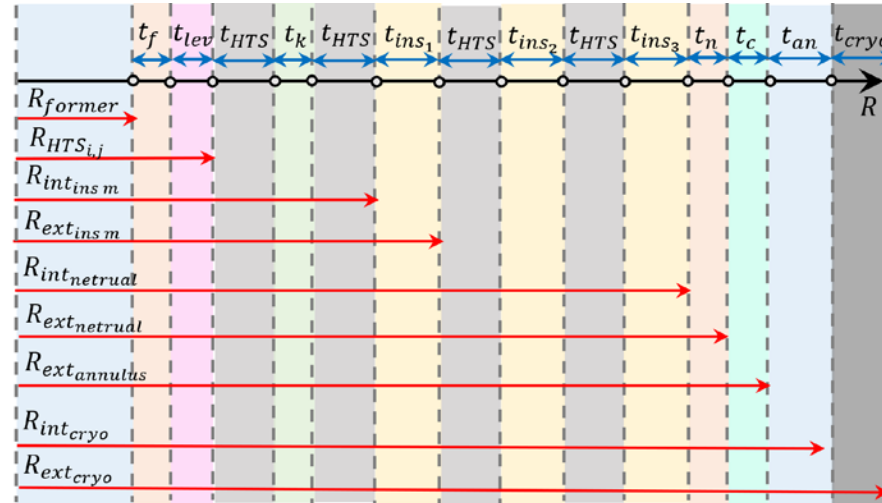
Technical model – Losses and fluid dynamics parameters		
Property	Symbol	Value
Total AC losses by HTS tapes in the cable	$LOSS_{AC\ HTS}$	423.2 kW
Total losses by the insulating layers in the cable	$LOSS_{ins}$	98.0 kW
Total heat inputs from the cryostat in the cable	$LOSS_{cryo}$	71.6 kW
Total eddy currents losses in the cable	$LOSS_{eddy}$	31.2 kW
Total losses by cable terminations	$LOSS_{term}$	5.3 kW
Thermal inputs into the LN2 in the former in a single cable segment	$Q_f$	38.7
Thermal inputs into the LN2 in the annular gap in a single cable segment	$Q_{an}$	50.6
Losses by terminations in a single side of the cable	$Q_{cl}$	2.6
Temperature rise in the LN2 in the former in a single cable segment	$\Delta T_{former}$	3.5 K
Temperature rise in the LN2 in the annular gap in a single cable segment	$\Delta T_{annulus}$	4.6 K
Pressure drop in the LN2 in the former in a single cable segment	$\Delta P_{former}$	3.1 bar
Pressure drop in the LN2 in the annular gap in a single cable segment	$\Delta P_{annulus}$	4.6 bar
Mean HTS temperature in a single cable segment	$T_{HTS}$	70 K



# Compute the cable design in cascade



# TEA on HTS cables → Compute the cable design in cascade



Technical model		
Property	Symbol	Value
Former thickness	$R_{former}$	30 mm
Thickness of the former	$t_f$	2 mm
Thickness of the levelling layer between former and innermost HTS layer	$t_{lev}$	1.9 mm
Thickness of HTS tapes	$t_{HTS}$	0.15 mm
Thickness of layer between HTS layers of the same phase	$t_k$	0.05 mm
Thickness of insulating layers	$t_{ins_1}, t_{ins_2}, t_{ins_3}$	See next slides
Thickness of copper neutral layer	$t_n$	3 mm
Thickness of core fixture layer between netruatl and annular gap	$t_c$	0.8 mm
Thickness of the annular gap	$t_{annulus}$	27.8 mm
Cryostat wall thickness	$t_{cryo}$	31.8 mm

[8]

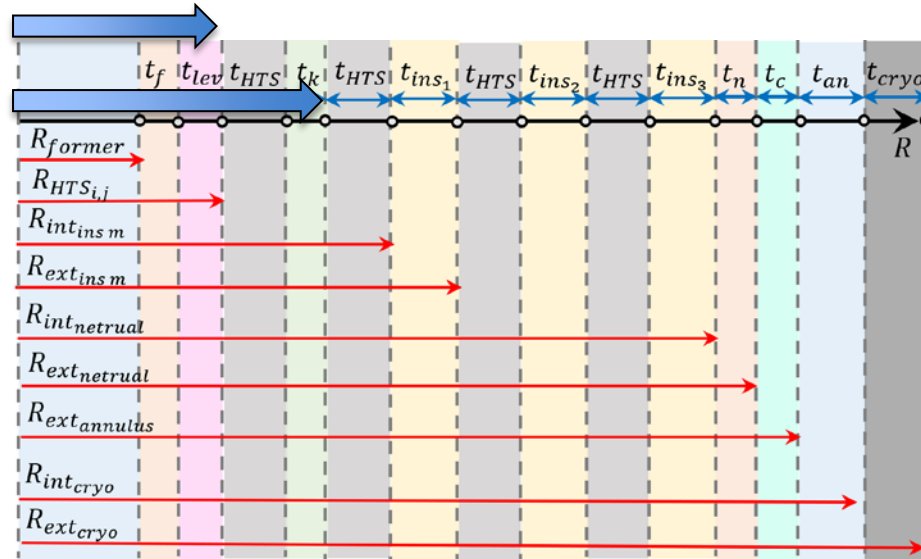
[6]

[5]

[6]

[5]

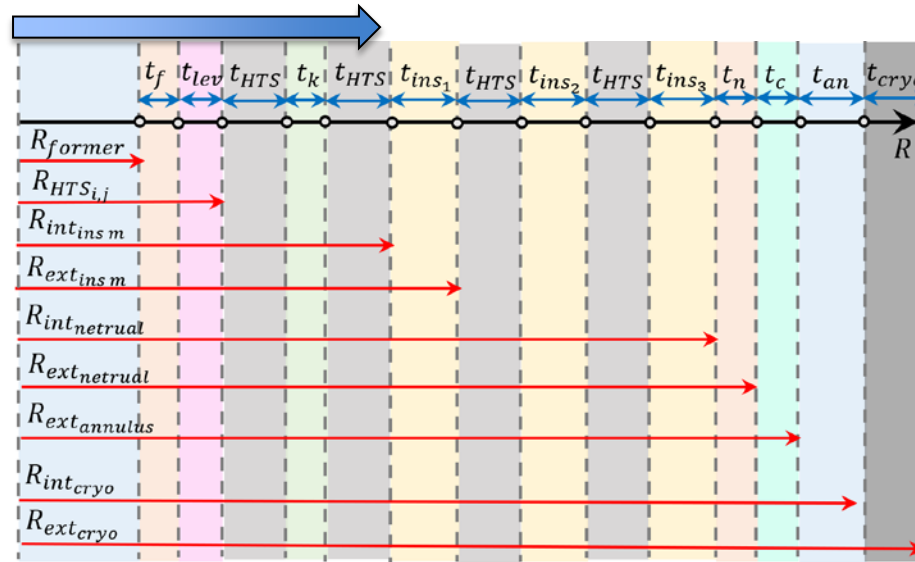
# TEA on HTS cables → Compute the cable design in cascade



$$R_{HTS_{1,1}} = R_{former} + t_f + t_{lev}$$

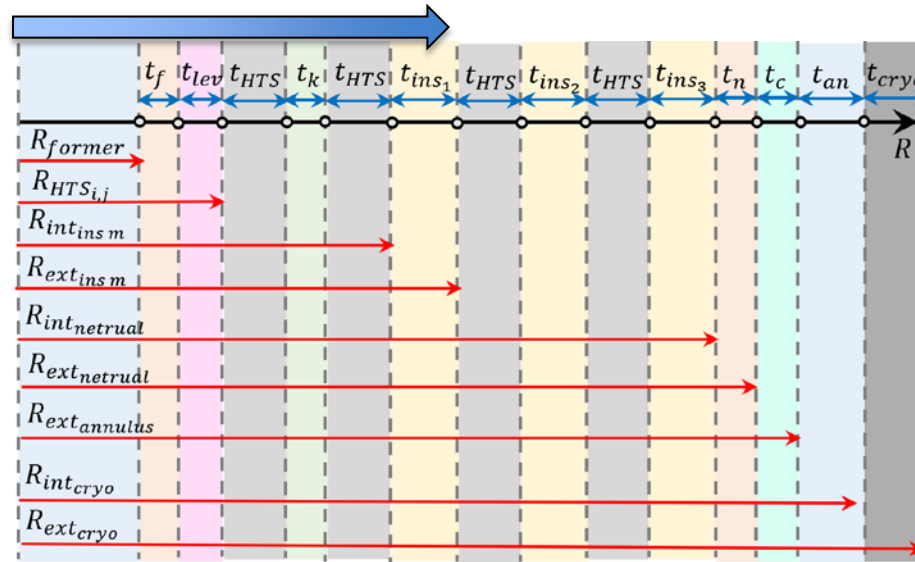
$$R_{HTS_{k,1}} = [t_{HTS}(n_{l_1} - 1)] + [t_k(n_{l_1} - 1)]$$

# TEA on HTS cables → Compute the cable design in cascade



$$R_{int_{ins\_1}} = R_{HTS_{1\_1}} + (t_{HTS} n_{l_1}) + [t_k (n_{l_1} - 1)]$$

# TEA on HTS cables → Compute the cable design in cascade



[9 - 13]

Technical model	
Symbol	Value
$k_{1im}$	1.32
$k_{2im}$	1
$k_{3im}$	1
$V_{im}$	150 kV
$E_{im}$	76 MV/m
$k_{1AC}$	1.59
$k_{2AC}$	1
$k_{3AC}$	1.45
$V_{AC}$	$2.5 (\sqrt{2}V_{rms})/\sqrt{3}$
$E_{AC}$	52 MV/m

$$R_{ext_{ins_1}} = R_{int_{ins_1}} + \max(t_{ins_{im_1}}, t_{ins_{AC_1}})$$

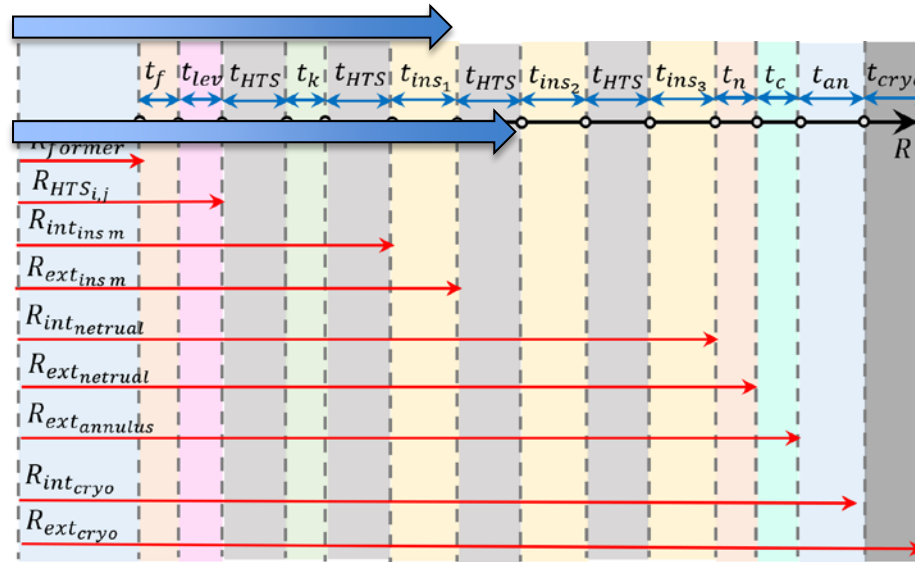
withstand voltage  
under lighting impulse

$$t_{ins_{im_1}} = R_{int_{ins_1}} \left[ \exp \left( \frac{k_{1im} k_{2im} k_{3im} V_{im}}{R_{int_{ins_1}} E_{im}} \right) - 1 \right]$$

withstand voltage  
under the operating  
frequency

$$t_{ins_{AC_1}} = R_{int_{ins_1}} \left[ \exp \left( \frac{k_{1AC} k_{2AC} k_{3AC} V_{AC}}{R_{int_{ins_1}} E_{AC}} \right) - 1 \right]$$

# TEA on HTS cables → Compute the cable design in cascade

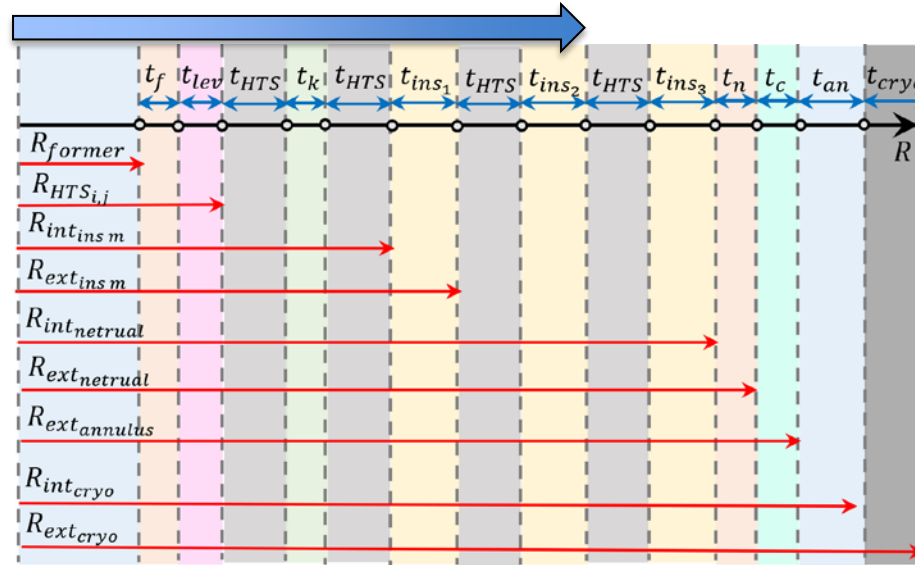


$$R_{HTS_2} = R_{ext_{ins_1}}$$

$$R_{int_{ins_2}} = R_{HTS_2} + (t_{HTS} n_{l_2}) + [t_k (n_{l_2} - 1)]$$



# TEA on HTS cables → Compute the cable design in cascade



[9 - 13]

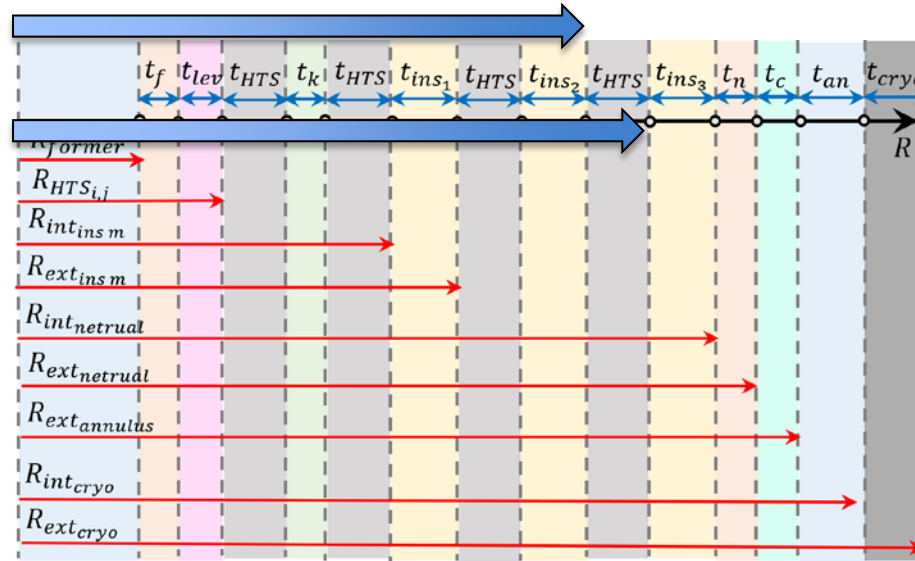
Technical model	
Symbol	Value
$k_{1im}$	1.32
$k_{2im}$	1
$k_{3im}$	1
$V_{im}$	150 kV
$E_{im}$	76 MV/m
$k_{1AC}$	1.59
$k_{2AC}$	1
$k_{3AC}$	1.45
$V_{AC}$	$2.5 (\sqrt{2}V_{rms})/\sqrt{3}$
$E_{AC}$	52 MV/m

$$R_{extins_2} = R_{intins_2} + \max(t_{insim_2}, t_{insAC_2})$$

$$t_{insim_2} = R_{intins_2} \left[ \exp \left( \frac{k_{1im} k_{2im} k_{3im} V_{im}}{R_{intins_2} E_{im}} \right) - 1 \right]$$

$$t_{insAC_2} = R_{intins_2} \left[ \exp \left( \frac{k_{1AC} k_{2AC} k_{3AC} V_{AC}}{R_{intins_2} E_{AC}} \right) - 1 \right]$$

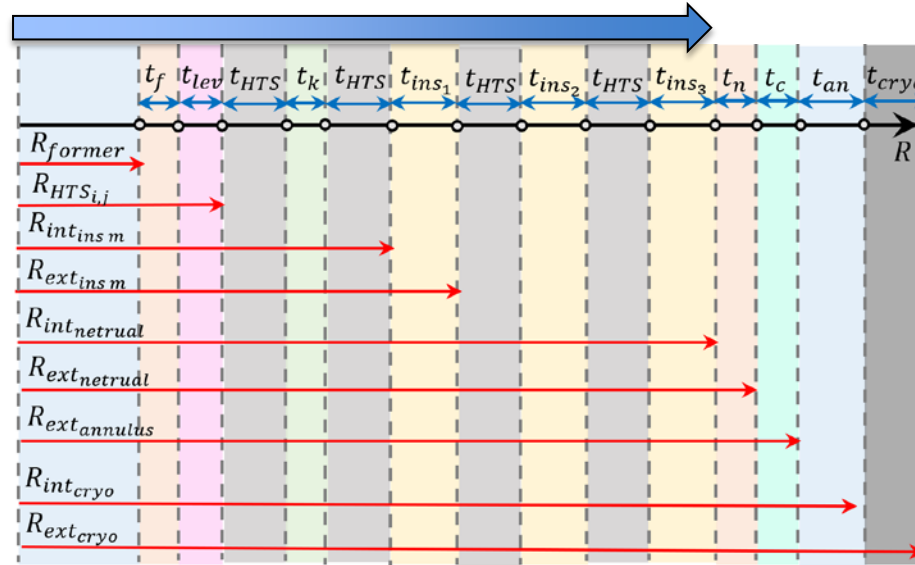
# TEA on HTS cables → Compute the cable design in cascade



$$R_{HTS_3} = R_{ext_{ins_2}}$$

$$R_{int_{ins_3}} = R_{HTS_3} + (t_{HTS} n_{l_3}) + [t_k (n_{l_3} - 1)]$$

# TEA on HTS cables → Compute the cable design in cascade



[9 - 13]

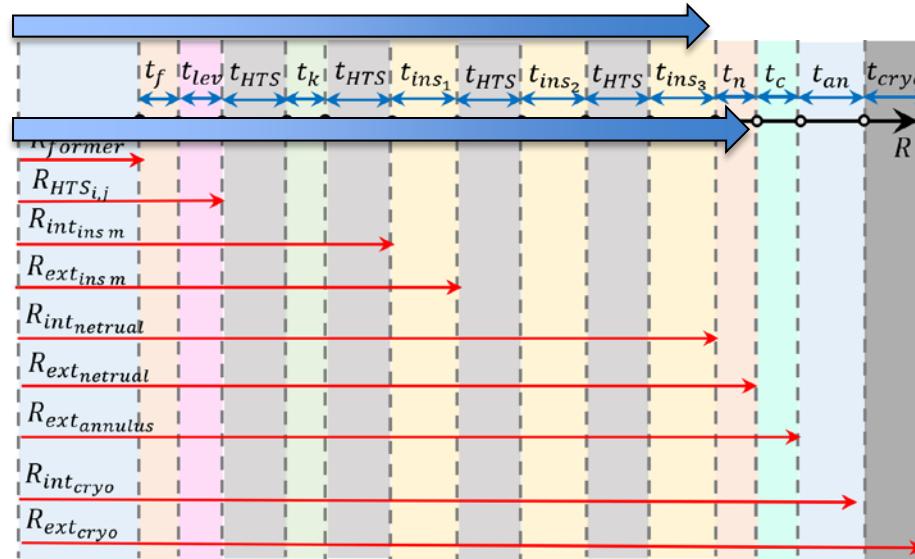
Technical model	
Symbol	Value
$k_{1im}$	1.32
$k_{2im}$	1
$k_{3im}$	1
$V_{im}$	150 kV
$E_{im}$	76 MV/m
$k_{1AC}$	1.59
$k_{2AC}$	1
$k_{3AC}$	1.45
$V_{AC}$	$2.5 (\sqrt{2}V_{rms})/\sqrt{3}$
$E_{AC}$	52 MV/m

$$R_{extins_3} = R_{intins_3} + \max(t_{insim_3}, t_{insAC_3})$$

$$t_{insim_3} = R_{intins_3} \left[ \exp \left( \frac{k_{1im} k_{2im} k_{3im} V_{im}}{R_{intins_3} E_{im}} \right) - 1 \right]$$

$$t_{insAC_3} = R_{intins_3} \left[ \exp \left( \frac{k_{1AC} k_{2AC} k_{3AC} V_{AC}}{R_{intins_3} E_{AC}} \right) - 1 \right]$$

# TEA on HTS cables → Compute the cable design in cascade



$$R_{int_{neutral}} = R_{ext_{ins_3}}$$

$$R_{ext_{neutral}} = R_{int_{neutral}} + t_n$$

# TEA on HTS cables → Compute the cable design in cascade



$$R_{int_{annulus}} = R_{ext_{neutral}} + t_c$$

$$R_{int_{annulus}} = R_{int_{annulus}} + t_{annulus}$$

# TEA on HTS cables → Compute the cable design in cascade

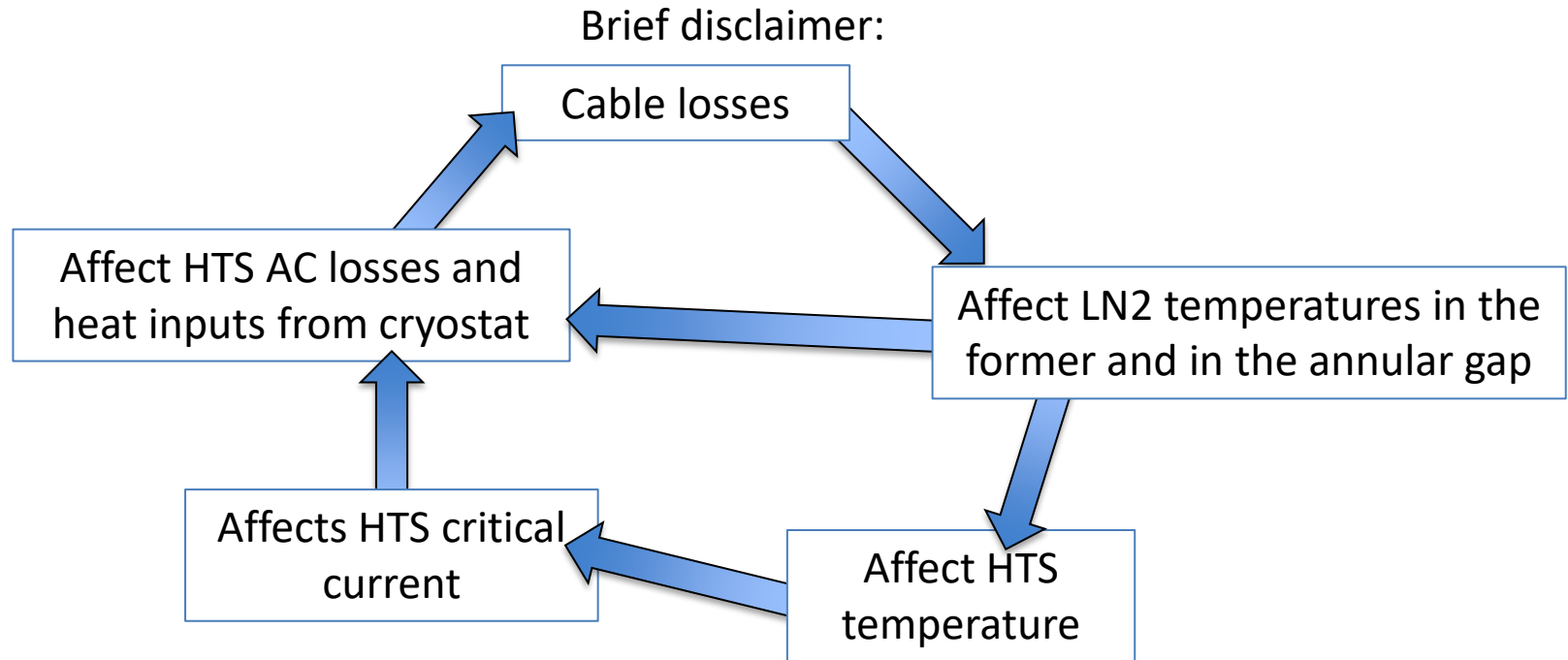


$$R_{int_{cryo}} = R_{ext_{annulus}}$$

$$R_{ext_{cryo}} = R_{int_{cryo}} + t_{cryo}$$

# Compute losses

# TEA on HTS cables → Compute the cable system losses

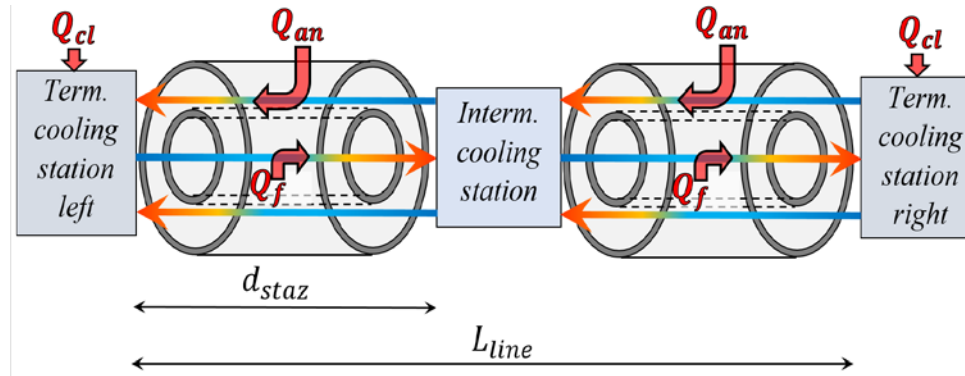


This loop can be solved numerically via a constrained minimization operation (losses, cable cost).  
 In this analysis, we set a tentative value of the mean temperature of HTS ( $T_{HTS}$ ) and the mean temperature of the LN2 in the annular gap ( $T_{annulus}$ ).  
 Then, we could adjust them once we get the results.

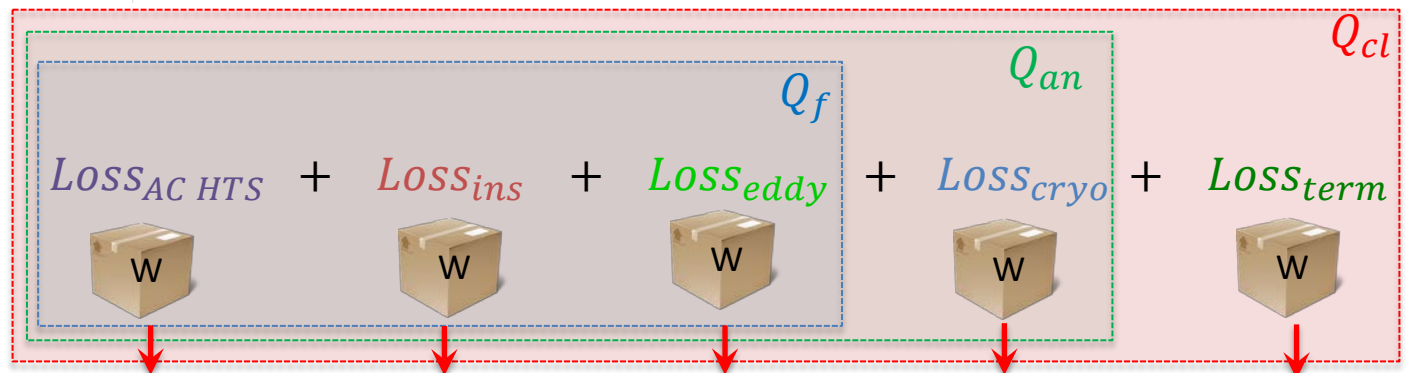
Technical model – Tentative temperatures	
$T_{HTS}$	70.1 K
$T_{annulus}$	70.4 K



# TEA on HTS cables $\rightarrow$ Losses



Losses =



**cable design**  
(HTS length,  
 $I_{tape}/I_c$ ) + tape  
properties ( $I_c(T)$ )

Line main  
features (cable  
length, voltage) +  
**cable design**  
(insulation  
dimensions)

Line main  
features (cable  
current) + normal  
conductors  
properties model  
(W/kA)

Line main features  
(cable length) + **cable  
design** (cryostat  
dimensions,  $T_{LN2}$ ) +  
cryostat properties ( $\lambda$ )

Line main  
features (cable  
current) +  
terminations  
properties (W/kA)

Each term will be detailed in the next slides...

# TEA on HTS cables $\rightarrow$ Losses $\rightarrow$ $LOSS_{AC\ HTS}$

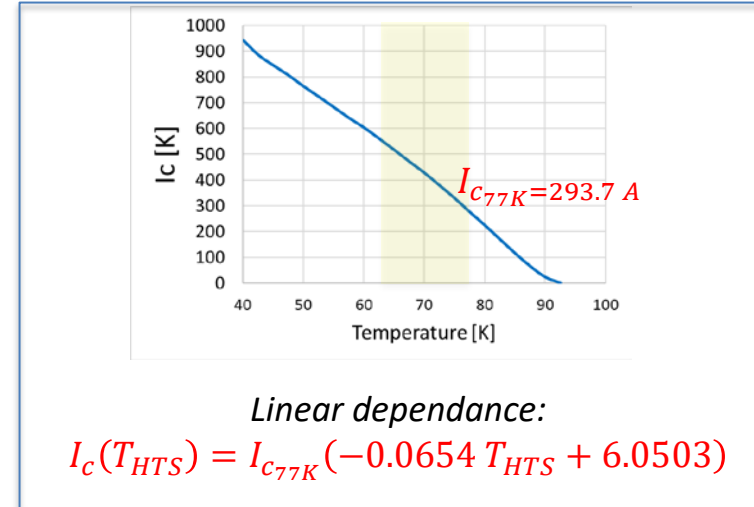
$$Losses = \boxed{LOSS_{AC\ HTS}} + LOSS_{ins} + LOSS_{eddy} + LOSS_{cryo} + LOSS_{term}$$

$$LOSS_{AC\ HTS} = \sum_i^3 \left[ \sum_j^{nl_i} Tapes_{i,j} \frac{L_{line}}{|\cos(\alpha_{i,j})|} \frac{\mu_0 f}{\pi} I_c^2(T_{HTS}) \xi_{i,j} \right] \quad [14]$$

$$\xi_{i,j} = (1 - F_{i,j}) \ln(1 - F_{i,j}) + (1 + F_{i,j}) \ln(1 + F_{i,j}) - F_{i,j}^2$$

$$F_{i,j} = \frac{I_{M_{i,j}}}{I_c(T)} = \frac{\sqrt{2} I_{rms_{i,j}}}{Tapes_{i,j} I_c(T_{HTS})}$$

$$Tapes_{i,j} = \text{round} \left( \frac{2\pi R_{HTS_{i,j}} |\cos(\alpha_{i,j})|}{w_{HTS}} \right)$$



Technical model		
Property	Symbol	Value
AC current frequency	$f$	50 Hz
N° of intermediate cooling stations	$n_{stat}$	5
N° of HTS layers for each layer	$nl_i$	2, 1, 1
Twist angle for each HTS layer/phase	$\alpha_{i,j}$	11°, 15°, -13°, -14°
rms value of the AC current in each layer of phase 1	$I_{rms_{1,1}}, I_{rms_{2,1}}$	6.9 kA , 6.9 kA
rms value of the AC current in each layer of phase 2	$I_{rms_{1,2}}$	13. 81 kA
rms value of the AC current in each layer of phase 3	$I_{rms_{1,3}}$	13. 81 kA
HTS tape critical depending on its mean temperature	$I_c(T_{HTS})$	
Line length	$L_{line}$	32 km
Tape width	$w_{HTS}$	4 mm

Reference material :  
SuNAM SCN04 4mm tape

[15]

# TEA on HTS cables $\rightarrow$ Losses $\rightarrow$ $LOSS_{ins}$

$$Losses = LOSS_{AC\ HTS} + \boxed{LOSS_{ins}} + LOSS_{eddy} + LOSS_{cryo} + LOSS_{term}$$

$$LOSS_{ins} = \sum_w^3 [2 \pi f L_{line} \tan \delta_{ins} Capac_w V_{rms}^2]$$

$$Capac_w = \frac{2 \pi \varepsilon_{ins} \varepsilon_0}{\ln \left( \frac{R_{ext_{ins\ w}}}{R_{int_{ins\ w}}} \right)}$$

[16, 17, 18]

Reference material : PPLP

Technical model		
Property	Symbol	Value
AC current frequency	$f$	50 Hz
N° of intermediate cooling stations	$n_{stat}$	5
Loss tangent of insulation	$\tan \delta_{ins}$	6e-4
Permittivity of insulation	$\varepsilon_{ins}$	2.21
Voltage level of the cable	$V_{rms}$	33 kV
Inner radius for each insulating layer	$R_{int_{ins_1}}, R_{int_{ins_2}}, R_{int_{ins_3}}$	34.3 mm , 48.8 mm, 62.5 mm
Outer radius for each insulating layer	$R_{ext_{ins_1}}, R_{ext_{ins_2}}, R_{ext_{ins_3}}$	48.6 mm, 62.4 mm , 75.8 mm
Line length	$L_{line}$	32 km

# TEA on HTS cables $\rightarrow$ Losses $\rightarrow$ $LOSS_{cryo}$

$$Losses = LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy} + \boxed{LOSS_{cryo}} + LOSS_{term}$$

$$LOSS_{cryo} = L_{line} \frac{2\pi \lambda [T_a - T_{annulus}]}{\ln(R_{ext\ cryo}/R_{int\ cryo})}$$

Technical model		
Property	Symbol	Value
N° of intermediate cooling stations	$n_{stat}$	5
Effective thermal conductivity of the cryostat	$\lambda$	0.4 mW/(m K)
Ambient temperature (outside the cable)	$T_a$	300 K
$T_{LN2}$ in the annulus (mean - tentative)	$T_{annulus}$	70.4 K
Inner radius of the cryostat	$R_{int\ cryo}$	106.0 mm
Outer radius of the cryostat	$R_{ext\ cryo}$	137.8 mm
Cryostat wall thickness	$t_{cryo}$	3.18 cm
Line length	$L_{line}$	32 km

[19]

# TEA on HTS cables $\rightarrow$ Losses $\rightarrow$ $LOSS_{eddy}$ , $LOSS_{term}$

$$Losses = LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy} + LOSS_{cryo} + LOSS_{term}$$

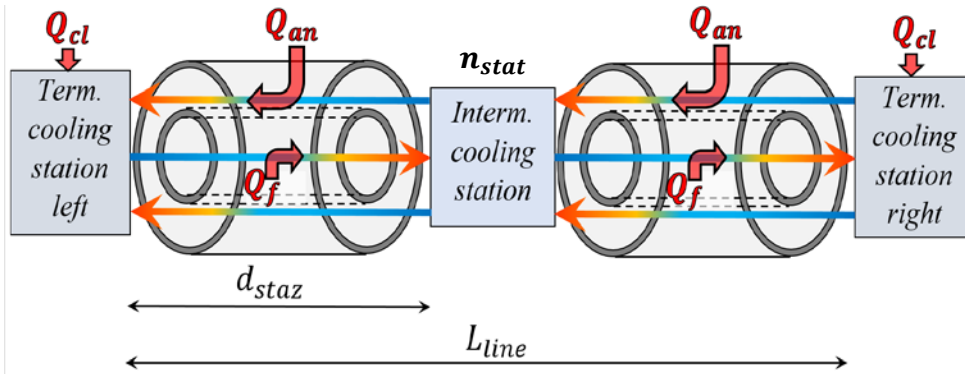
$$\left\{ \begin{array}{l} LOSS_{eddy} = L_{line} Q_{eddy} I_{max} \\ LOSS_{term} = n_{term} Q_{term} I_{max} \end{array} \right.$$

Technical model		
Property	Symbol	Value
Eddy current loss per unit of length and unit of current	$Q_{eddy}$	50 mW/(kA*m)
Amplitude of the AC current in each phase	$I_{max}$	19.53 kA
N° of terminations (both ends)	$n_{term}$	6
Loss for each termination per unit of current	$Q_{term}$	45 W/kA
Line length	$L_{line}$	32 km

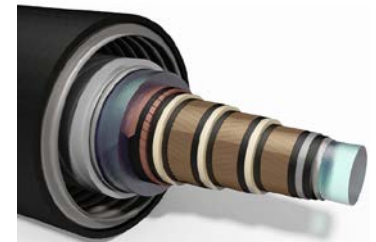
[7]

# Verify constraints

# TEA on HTS cables $\rightarrow$ Losses



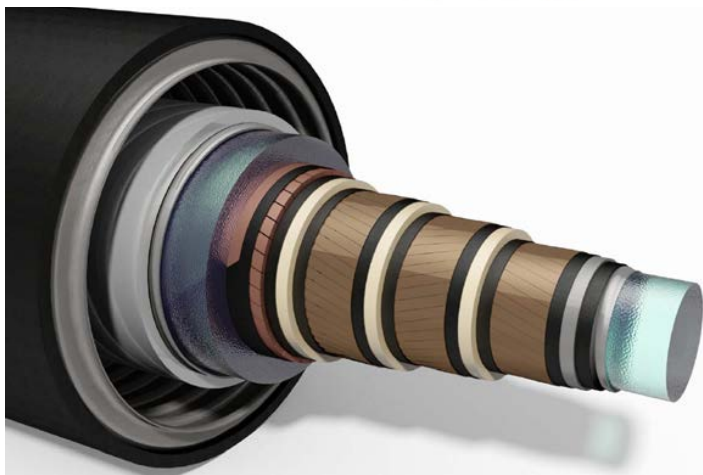
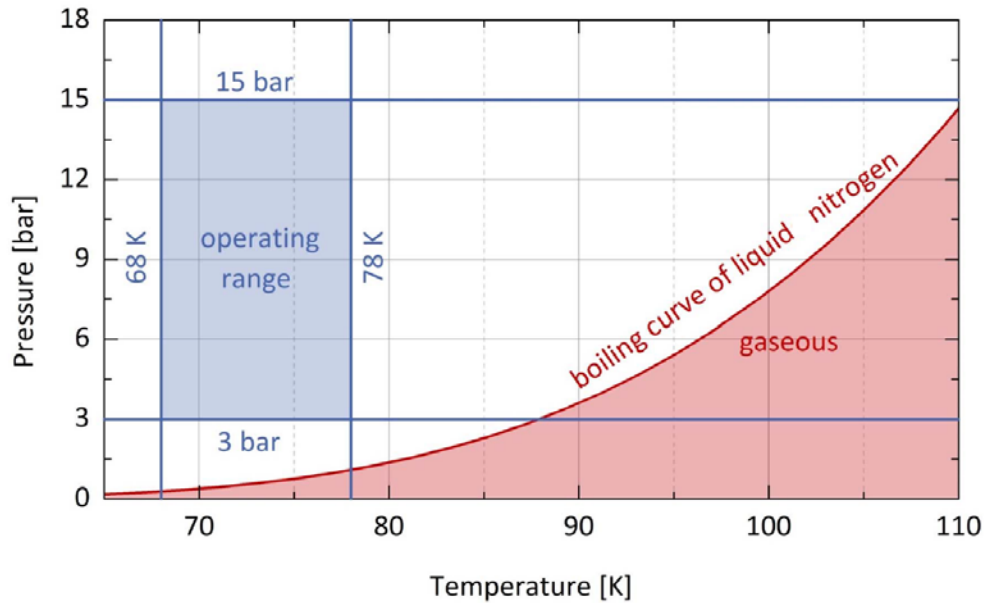
Note: the losses are conveniently divided based on which fluid will be affected into a cable segment (LN2 in the former or LN2 in the annular gap).



$$\left\{ \begin{aligned} Q_f &= \left( \frac{LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy}}{2} \right) \left( \frac{1}{n_{stat} + 1} \right) \\ Q_{an} &= \left( \frac{LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy}}{2} + LOSS_{cryo} \right) \left( \frac{1}{n_{stat} + 1} \right) \\ Q_{cl} &= \frac{LOSS_{term}}{2} \end{aligned} \right.$$

$\left\{ \begin{aligned} \text{intermediate station} &\rightarrow Q_f + Q_{an} \\ \text{left termination station} &\rightarrow Q_{an} + Q_{cl} \\ \text{right termination station} &\rightarrow Q_f + Q_{cl} \end{aligned} \right.$

# TEA on HTS cables → Constraints → $\Delta T_{LN2}$ and $\Delta P_{LN2}$



$$\left\{ \begin{array}{l} \Delta T_{former} \leq \Delta T_{LN2_{max}} \\ \Delta T_{annulus} \leq \Delta T_{LN2_{max}} \\ \Delta P_{former} \leq \Delta P_{LN2_{max}} \\ \Delta P_{annulus} \leq \Delta P_{LN2_{max}} \end{array} \right.$$

Technical model		
Property	Symbol	Value
Inlet temperature	$T_{0LN2}$	68 K
Maximum temperature rise	$\Delta T_{LN2_{max}}$	10 K
Inlet pressure	$P_{0LN2}$	3 bar
Maximum pressure drop	$\Delta P_{LN2_{max}}$	12 bar

[5]



# TEA on HTS cables $\rightarrow$ Constraints $\rightarrow \Delta T_{LN2}$ and $\Delta P_{LN2}$

$$\left\{ \begin{array}{l} \Delta T_{former} \leq \Delta T_{LN2max} \Rightarrow \Delta T_{former} = d_{stat} \left( \frac{v_{LN2former}^2 f_{LN2former}}{4 R_{former} c_{pLN2}} \right) + \frac{Q_f}{2 \dot{m}_{LN2} c_{pLN2}} \\ \Delta T_{annulus} \leq \Delta T_{LN2max} \Rightarrow \Delta T_{annulus} = d_{stat} \left( \frac{v_{LN2annulus}^2 f_{LN2annulus}}{4 t_{annulus} c_{pLN2}} \right) + \frac{Q_{an}}{2 \dot{m}_{LN2} c_{pLN2}} \end{array} \right.$$

$$\left\{ \begin{array}{l} \Delta P_{former} \leq \Delta P_{LN2max} \Rightarrow \Delta P_{former} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2former}^2 f_{LN2former}}{4 R_{former}} \right) + (g \rho_{LN2} \Delta h) \\ \Delta P_{annulus} \leq \Delta P_{LN2max} \Rightarrow \Delta P_{annulus} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2annulus}^2 f_{LN2annulus}}{4 t_{annulus}} \right) + (g \rho_{LN2} \Delta h) \end{array} \right.$$

$$\left\{ \begin{array}{l} f_{LN2former} = \left\{ -1.8 \ln \left[ \left( \frac{\varepsilon_{former}}{7.4 R_{former}} \right)^{1.11} + \left( \frac{6.9}{Re_{former}} \right)^{1.11} \right] \right\}^{-2} \\ Re_{former} = \frac{2 R_{former} v_{LN2former} \rho_{LN2}}{\mu_{LN2}} \\ v_{LN2former} = \frac{\dot{m}_{LN2}}{\rho_{LN2} \pi R_{former}^2} \end{array} \right.$$

$$\left\{ \begin{array}{l} f_{LN2annulus} = \left\{ -1.8 \ln \left[ \left( \frac{\varepsilon_{annulus}}{7.4 t_{annulus}} \right)^{1.11} + \left( \frac{6.9}{Re_{annulus}} \right)^{1.11} \right] \right\}^{-2} \\ v_{LN2annulus} = \frac{\dot{m}_{LN2}}{\rho_{LN2} \pi t_{annulus}^2} \end{array} \right.$$

Friction with the ducts walls causes both:

- heating of the fluid ☹️
- pressure drop ☹️

# TEA on HTS cables → Constraints → $\Delta T_{LN2}$ and $\Delta P_{LN2}$

$$\Delta T_{former} \leq \Delta T_{LN2_{max}} \Rightarrow \Delta T_{former} = d_{stat} \left( \frac{v_{LN2_{former}}^2 f_{LN2_{former}}}{4 t_{annulus}} \right) + \frac{Q_f}{m_{LN2} \dot{c} p_{LN2}}$$

**[8] Technical model**

Property	Symbol	Value
LN2 dynamic viscosity	$\mu_{LN2}$	25.08 $\mu Pa \cdot s$
LN2 density	$\rho_{LN2}$	839 $kg/m^3$
LN2 heat capacity	$c p_{LN2}$	2662 $J/kg \cdot K$
roughness of the pipe	$\varepsilon$	1.4 mm
Height difference between the two cable ends	$\Delta h$	1 m

$$\Delta T_{annulus} \leq \Delta T_{LN2_{max}} \Rightarrow \Delta T_{annulus} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2_{annulus}}^2 f_{LN2_{annulus}}}{4 t_{annulus}} \right) + (g \rho_{LN2} \Delta h)$$

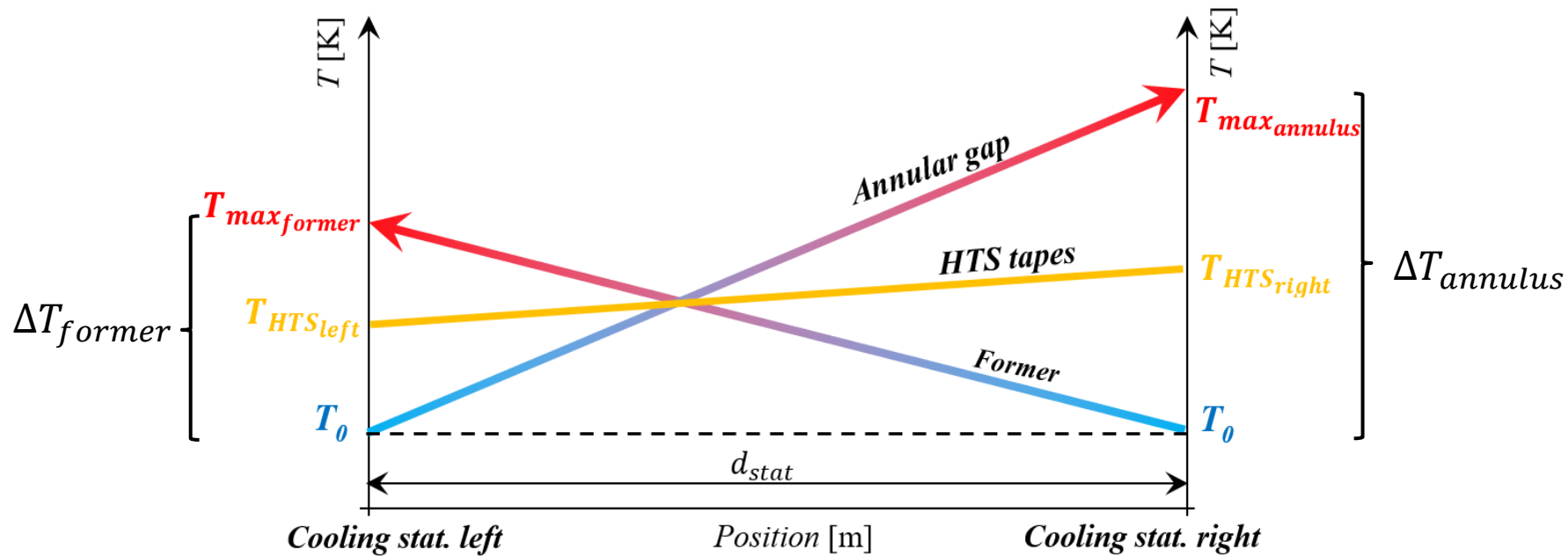
$$\Delta P_{former} \leq \Delta P_{LN2_{max}} \Rightarrow \Delta P_{former} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2_{annulus}}^2 f_{LN2_{annulus}}}{4 t_{annulus}} \right) + (g \rho_{LN2} \Delta h)$$

$$\Delta P_{annulus} \leq \Delta P_{LN2_{max}} \Rightarrow \Delta P_{annulus} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2_{annulus}}^2 f_{LN2_{annulus}}}{4 t_{annulus}} \right) + (g \rho_{LN2} \Delta h)$$

- ❑ The number of cooling stations must prevent  $\Delta T_{LN2}$  and  $\Delta P_{LN2}$  from exceeding the maximum limits set.
- ❑ This does not mean that it is always economically convenient to use the minimum number of stations (spacing them as much as possible).
- ❑ Designing the cable system to have more cooling stations than the minimum can allow working with higher pressure and temperature margins → it **could** be more cost-effective!

# TEA on HTS cables $\rightarrow$ Constraints $\rightarrow \Delta T_{LN2}$ and $\Delta P_{LN2}$

We can verify whether the hypotheses on  $T_{HTS}$  and  $T_{annulus}$  were acceptable.



Relevant simplifying assumption:

the temperature of all HTS layers/phases is constant for each cable cross-section.

Otherwise, we should use 3D models to estimate the real distribution.

$T_{annulus}$       2       $T_{HTSright}$

# TEA on HTS cables → Constraints → $I_{HTS}/I_c$

The maximum current flowing in each tape have to stay below a safety margin of the  $I_c$ .  
This has to be valid for all layers in all phases.

$$\left[ \begin{array}{l} \frac{\sqrt{2} I_{rms}}{Tapes_{i,j}} / I_c \left( \max \left[ T_{HTS_{left}}, T_{HTS_{right}} \right] \right) \leq safety_{HTS} \\ Tapes_{i,j} = \text{round} \left( \frac{2\pi R_{HTS_{i,j}} |\cos(\alpha_{i,j})|}{W_{HTS}} \right) \end{array} \right.$$

Technical model		
Property	Symbol	Value
Twist angle for each layer/phase	$\alpha_{i,j}$	11°, 15°, -13°, -14°
rms value of the total AC current in each phase	$I_{rms}$	13.81 kA
HTS tape critical current depending on its max temperature	$I_c \left( \max \left[ T_{HTS_{left}}, T_{HTS_{right}} \right] \right)$	424 A
Safety marging for the $I_{HTS}/I_c$ ratio	$safety_{HTS}$	80%
Tape width	$W_{HTS}$	4 mm

# TEA on HTS cables → Constraints

In this section of the sheet **Calculation of indicators – HTS** you can verify if the computed values comply with the constraints that you have selected.

VERIFY CONSTRAINTS AND CHECK QUALITY OF TENTATIVE TEMP.S				
Temperature rise in the LN2 flowing in the former	$\Delta T_{LN2\_former}$	3.5	K	
Temperature rise in the LN2 flowing in the annular gap	$\Delta T_{LN2\_annulus}$	4.6	K	
<b>Maximum temperature rise allowed for the LN2 in both ducts</b>	<b><math>\Delta T_{LN2\_max}</math></b>	<b>10.0</b>	<b>K</b>	
Pressure drop in the LN2 flowing in the annular gap [bar]	$\Delta P_{LN2\_annulus}$	3.1	bar	
Pressure drop in the LN2 flowing in the annular gap [bar]	$\Delta P_{LN2\_annulus}$	4.6	bar	
<b>Maximum pressure drop allowed for the LN2 in both ducts</b>	<b><math>\Delta P_{LN2\_max}</math></b>	<b>12.0</b>	<b>bar</b>	
Mean LN2 temperature in the annular gap (TENTATIVE)	$T_{annulus}$	70.4	K	
<b>Mean LN2 temperature in the annular gap (COMPUTED)</b>	<b><math>T_{annulus}</math></b>	<b>70.3</b>	<b>K</b>	
Mean HTS temperature in the cable (TENTATIVE)	$T_{HTS}$	70.1	K	
<b>Mean HTS temperature in the cable (COMPUTED)</b>	<b><math>T_{HTS}</math></b>	<b>70.0</b>	<b>K</b>	
Critical current of HTS tapes at maximum temperature	$I_{c\_HTS\_T\_HTS\_max}$	426.5	A	
Ratio between $I_{max}$ in HTS tapes and their $I_c$ in layer 1 - phase 1	$I_{max\_1\_1}/I_{c\_HTS\_T\_HTS\_max}$	0.440		$I_{max}$
Ratio between $I_{max}$ in HTS tapes and their $I_c$ in layer 2 - phase 1	$I_{max\_2\_1}/I_{c\_HTS\_T\_HTS\_max}$	0.440		$I_{max}$
Ratio between $I_{max}$ in HTS tapes and their $I_c$ in layer 1 - phase 2	$I_{max\_1\_2}/I_{c\_HTS\_T\_HTS\_max}$	0.619		$I_{max}$
Ratio between $I_{max}$ in HTS tapes and their $I_c$ in layer 1 - phase 3	$I_{max\_1\_3}/I_{c\_HTS\_T\_HTS\_max}$	0.482		$I_{max}$
Safety value of $I_{tape}/I_{c\_HTS}$ not to be passed	$safety_{HTS}$	0.80		

Variable	Symbol	HTS system	Units
-Goal and scope definition	2-Inventory analysis-Benchmark	2-Inventory analysis-HTS	3.0-HTS Cable design

3-**Calculation of indicators-HTS** 4-Int ... (+)

# Compute CAPEX and OPEX

## TEA on HTS cables → CAPEX and OPEX for conventional power cables



### CAPEX

- Conductor
- Terminations and joints
- Installation and civil
- Land
- Dismantling
- Management, regulation, commissioning, studies, consents...

### OPEX


- Conductor resistive losses  
↓  
energy loss along the line
- Maintenance

## TEA on HTS cables → CAPEX and OPEX for HTS system costs

### CAPEX

- Conductor components (HTS, insulation, Cu...)
- Cabling
- Vacuum system
- Cooling stations
- Cryogenic fluid
- Land
- Dismantling
- Terminations
- Cryostat
- Civil eng., Management, Commissioning, Studies...

### OPEX

- Heat inputs along the line  
  
energy to operate the cooling stations
- Maintenance



# LCC

$$LCC = \sum_{t=1}^L \frac{CAPEX_t + OPEX_t}{(1+r)^t}$$

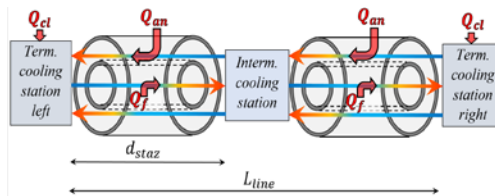
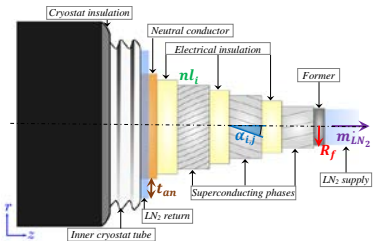
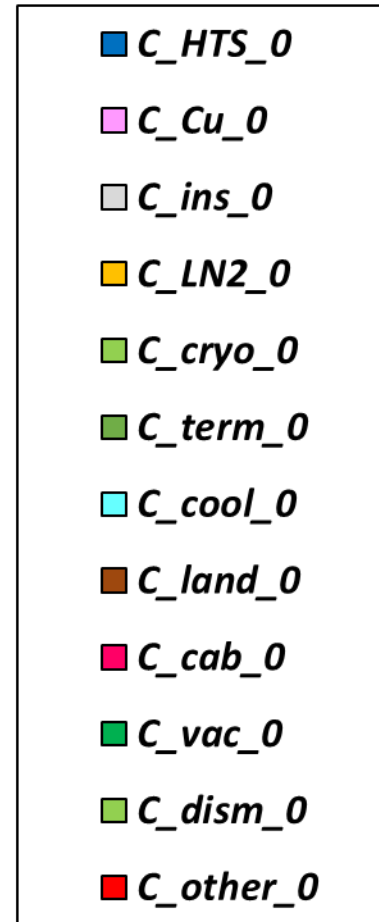
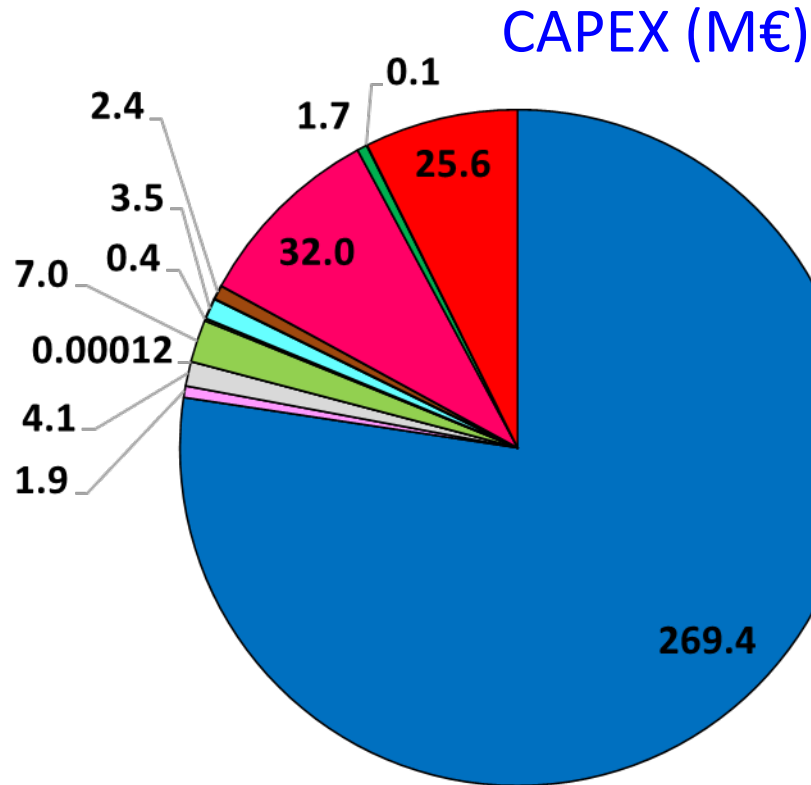
## TEA on HTS cables → Costs for the case study

Again, by searching appropriate databases (... and being lucky), the economic data you need may already be available, without doing any calculations.

# TEA on HTS cables → Costs for the case study

Technical model – Main Features		
Property	Symbol	Value
Cable power	$P$	1 GW
Voltage rms	$V_{rms}$	25 kV
Load factor	$\cos\varphi$	0.95
Line length	$L_{line}$	32 km

Technical model – Set design parameters		
Property	Symbol	Value
Former radius	$R_{former}$	30 mm
LN2 mass flow rate	$\dot{m}_{LN2}$	2.15 kg/s
Twist angle for each layer of each phase	$\alpha_{1,1}, \alpha_{2,1}$ $\alpha_{1,2}$ $\alpha_{1,3}$	11°, 15° -13° -14°
N° of HTS layers for each phase	$n_{l_1}$ $n_{l_2}$ $n_{l_3}$	2 1 1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

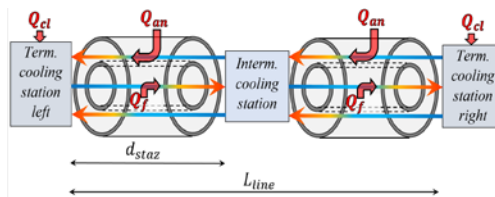
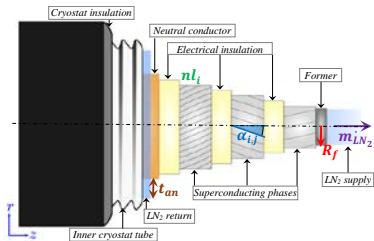
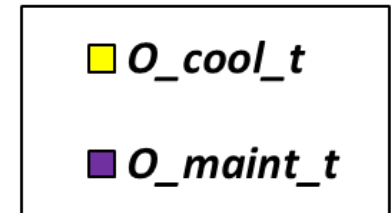
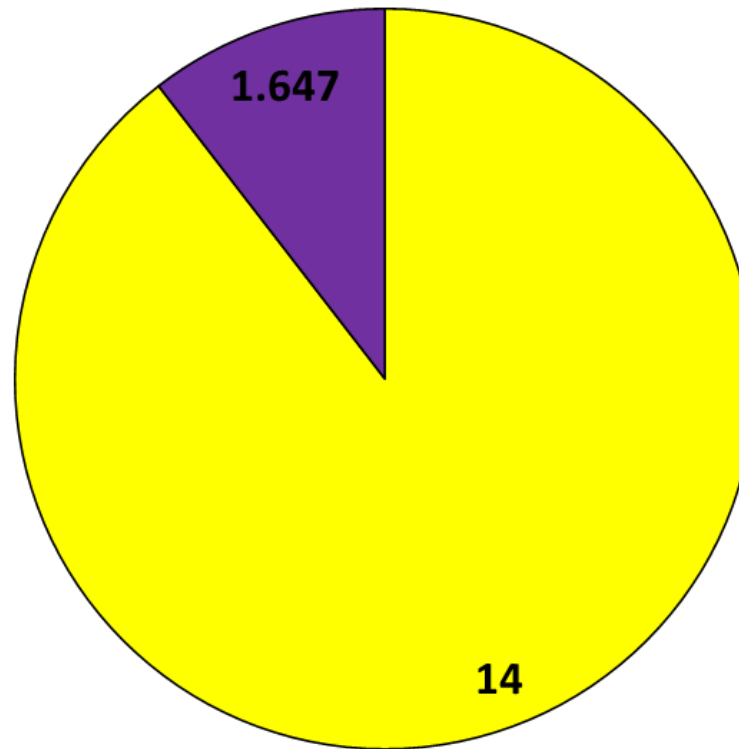


# TEA on HTS cables → Costs for the case study

Technical model – Main Features		
Property	Symbol	Value
Cable power	$P$	1 GW
Voltage rms	$V_{rms}$	25 kV
Load factor	$\cos\varphi$	0.95
Line length	$L_{line}$	32 km

Technical model – Set design parameters		
Property	Symbol	Value
Former radius	$R_{former}$	30 mm
LN2 mass flow rate	$\dot{m}_{LN2}$	2.15 kg/s
Twist angle for each layer of each phase	$\alpha_{1,1}, \alpha_{2,1}$ $\alpha_{1,2}$ $\alpha_{1,3}$	11°, 15° -13° -14°
N° of HTS layers for each phase	$n_{l_1}$ $n_{l_2}$ $n_{l_3}$	2 1 1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

OPEX (M€)

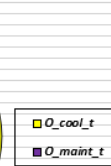
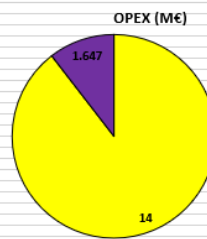
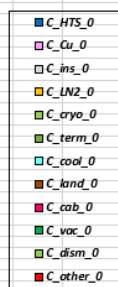
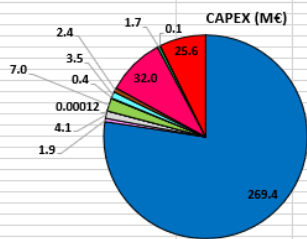


# TEA on HTS cables → Costs for the case study

...however, in this lecture we will provide the equations to calculate the costs ourselves, so you can have more control on the outputs at different conditions and a better understanding.

We will do this in the sheet **Calculation of indicators – HTS** of our Excel file.

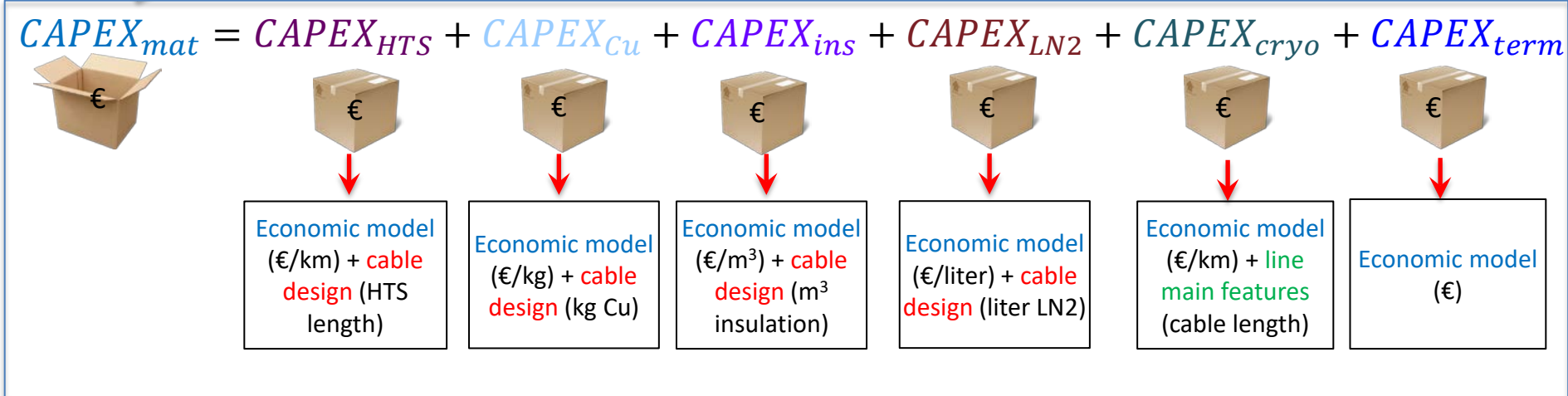
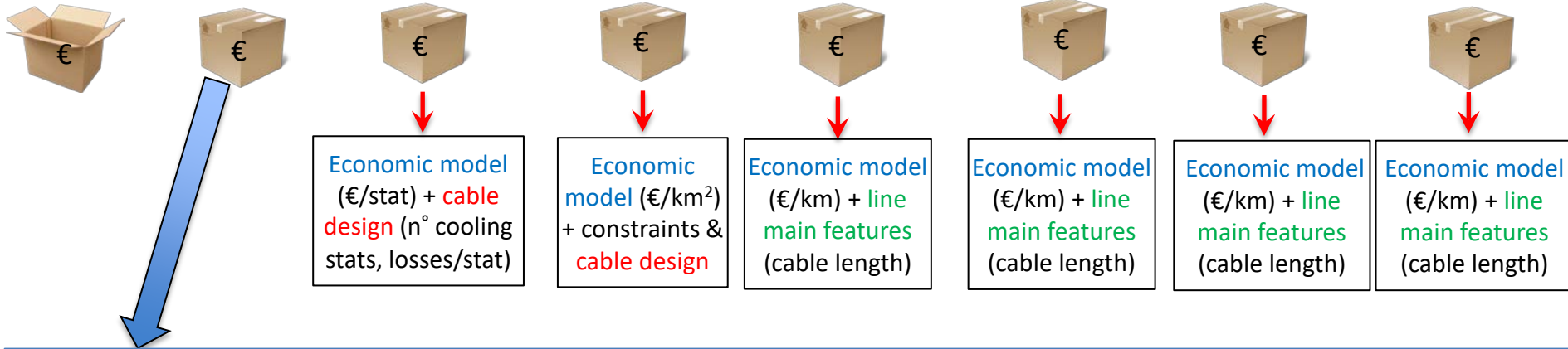
Variable	Symbol	ITS system	Units	Economic model	Comment
<b>MATERIALS</b>					
HTS tape CAPEX	$C_{HTS\_0}$	269.4	MI	$C_{HTS\_0} \cdot C_{HTS\_VL\_HTS\_t+L\_HTS\_0} + L\_HTS\_0$	
Copper CAPEX	$C_{Cu\_0}$	1.9	MI	$C_{Cu\_0} \cdot C_{Cu\_t} \cdot C_{Cu\_t} \cdot C_{Cu\_t}$	
Insulation CAPEX	$C_{ins\_0}$	4.1	MI	$C_{ins\_0} \cdot C_{ins\_t} \cdot C_{ins\_t} \cdot C_{ins\_t}$	
LN2 CAPEX	$C_{LN2\_0}$	0.00012	MI	$C_{LN2\_0} \cdot C_{LN2\_t} \cdot C_{LN2\_t} \cdot C_{LN2\_t}$	
Cryostat CAPEX	$C_{cryo\_0}$	7.0	MI	$C_{cryo\_0} \cdot C_{cryo\_t} \cdot C_{cryo\_t}$	
Terminator CAPEX	$C_{term\_0}$	0.4	MI	$C_{term\_0}$	
<b>COOLING STATIONS</b>					
Cooling station CAPEX	$C_{cool\_t}$	3.5	MI	$C_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t}$	
Yearly cooling station OPEX	$O_{cool\_t}$	14.1	MI/year	$O_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t}$	
Total cooling station OPEX discounted at t=0	$O_{cool\_t}$	14.1	MI	$O_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t} \cdot C_{cool\_t}$	
<b>LAND</b>					
Land CAPEX	$C_{land\_0}$	2.4	MI	$C_{land\_0} \cdot C_{land\_t} \cdot C_{land\_t}$	
<b>CABLING</b>					
Cabling CAPEX	$C_{cab\_0}$	32.0	MI	$C_{cab\_0} \cdot C_{cab\_t} \cdot C_{cab\_t}$	
<b>VACUUM SYSTEM</b>					
Vacuum system CAPEX	$C_{vac\_0}$	1.7	MI	$C_{vac\_0} \cdot C_{vac\_t} \cdot C_{vac\_t}$	
<b>DISMANTLING</b>					
Dismantling CAPEX	$C_{dism\_0}$	0.1	MI	$C_{dism\_0} \cdot C_{dism\_t} \cdot C_{dism\_t}$	
<b>OTHER COSTS</b>					
Other costs CAPEX	$C_{other\_0}$	25.6	MI	$C_{other\_0} \cdot C_{other\_t} \cdot C_{other\_t}$	
<b>MAINTENANCE</b>					
Yearly maintenance OPEX	$O_{maint\_t}$	1.6	MI/year	$O_{maint\_t} \cdot C_{maint\_t} \cdot C_{maint\_t}$	
Total maintenance OPEX discounted at t=0	$O_{maint\_t}$	1.6	MI	$O_{maint\_t} \cdot C_{maint\_t} \cdot C_{maint\_t}$	
<b>TOTAL</b>					
Capital expenditure (increased at t=0)	$CAPEX\_t$	348.2	MI	$CAPEX\_t \cdot C_{HTS\_0} + C_{Cu\_0} + C_{ins\_0} + C_{LN2\_0} + C_{cryo\_0} + C_{term\_0} + C_{cool\_t} + C_{land\_0} + C_{cab\_0} + C_{vac\_0} + C_{dism\_0} + C_{other\_0}$	
Yearly operational expenditure	$OPEX\_t$	18.7	MI/year	$OPEX\_t \cdot C_{cool\_t} + O_{maint\_t}$	
Total operational expenditure discounted at t=0	$OPEX\_t$	18.7	MI	$OPEX\_t \cdot C_{cool\_t} + O_{maint\_t}$	
Life cycle cost (t=0, r=0.05)	$LCC(t=0, r=0.05)$	365.9	MI	$CAPEX\_t + OPEX\_t$	



Year	$O_{cool\_t}$	$O_{maint\_t}$	Units
1	0.5	0.091	MI
2	0.7	0.087	MI
3	0.7	0.083	MI
4	0.7	0.079	MI
5	0.6	0.075	MI
6	0.6	0.072	MI
7	0.6	0.068	MI
8	0.6	0.065	MI
9	0.5	0.062	MI
10	0.5	0.059	MI
11	0.5	0.056	MI
12	0.5	0.053	MI
13	0.4	0.051	MI
14	0.4	0.048	MI
15	0.4	0.045	MI
16	0.4	0.041	MI
17	0.4	0.042	MI
18	0.3	0.040	MI
19	0.3	0.038	MI
20	0.3	0.036	MI
21	0.3	0.034	MI
22	0.3	0.032	MI
23	0.3	0.031	MI
24	0.3	0.030	MI
25	0.2	0.028	MI
26	0.2	0.027	MI
27	0.2	0.026	MI
28	0.2	0.024	MI
29	0.2	0.023	MI
30	0.2	0.022	MI
31	0.2	0.021	MI
32	0.2	0.020	MI
33	0.2	0.019	MI
34	0.2	0.018	MI
35	0.1	0.017	MI
36	0.1	0.017	MI

# TEA on HTS cables → CAPEX

$$CAPEX = CAPEX_{mat} + CAPEX_{cool} + CAPEX_{land} + CAPEX_{cab} + CAPEX_{vac} + CAPEX_{dism} + CAPEX_{other}$$



Each term will be detailed in the next slides...

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ $CAPEX_{mat}$ $\rightarrow$ $CAPEX_{HTS}$

$$CAPEX_{mat} = \boxed{CAPEX_{HTS}} + CAPEX_{Cu} + CAPEX_{ins} + CAPEX_{LN2} + CAPEX_{cryo} + CAPEX_{term}$$

$$CAPEX_{HTS} = n_{cables} c_{HTS} \sum_i^3 \sum_j^{nl_i} Tapes_{i,j} \frac{L_{line}}{|\cos(\alpha_{i,j})|}$$

$$Tapes_{i,j} = \text{round} \left( \frac{2\pi R_{HTS_{i,j}} |\cos(\alpha_{i,j})|}{W_{HTS}} \right)$$

## Economic model

Property	Symbol	Value
HTS tape cost per unit length	$c_{HTS}$	30 €/m

Reference material : SuNAM SCN04 4mm tape

## Technical model

Property	Symbol	Value
Tape width	$W_{HTS}$	4 mm
HTS layers radius in phase 1	$R_{HTS_{1,1}}$ $R_{HTS_{2,1}}$	33.9 mm 34.1 mm
HTS layer radius in phase 2	$R_{HTS_{1,2}}$	48.6 mm
HTS layer radius in phase 3	$R_{HTS_{1,3}}$	62.4 mm
Twist angle for each layer/phase	$\alpha_{i,j}$	11°, 15°, -13°, -14°
Line length	$L_{line}$	32 km

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ $CAPEX_{mat}$ $\rightarrow$ $CAPEX_{Cu}$

$$CAPEX_{mat} = CAPEX_{HTS} + CAPEX_{Cu} + CAPEX_{ins} + CAPEX_{LN2} + CAPEX_{cryo} + CAPEX_{term}$$

$$\left\{ \begin{aligned} CAPEX_{Cu} &= n_{cables} c_{Cu} \rho_{Cu} Volume_{Cu} \\ Volume_{Cu} &= L_{line} \pi (R_{ext_{neutral}}^2 - R_{int_{neutral}}^2) \end{aligned} \right.$$

## Economic model

Property	Symbol	Value
Copper cost per unit of weight	$c_{Cu}$	7 €/kg

## Technical model

Property	Symbol	Value
Copper density	$\rho_{Cu}$	8850 kg/m <sup>3</sup>
Inner radius of Cu neutral	$R_{int_{neutral}}$	75.8 mm
Outer radius of Cu neutral	$R_{ext_{neutral}}$	77.8 mm
Line length	$L_{line}$	32 km



# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ CAPEX<sub>mat</sub> $\rightarrow$ CAPEX<sub>ins</sub>

$$CAPEX_{mat} = CAPEX_{HTS} + CAPEX_{Cu} + CAPEX_{ins} + CAPEX_{LN2} + CAPEX_{cryo} + CAPEX_{term}$$

$$CAPEX_{ins} = n_{cables} c_{ins} \rho_{ins} Volume_{ins}$$

$$Volume_{ins} = L_{line} \pi \sum_w^3 (R_{ext_{ins}w}^2 - R_{int_{ins}w}^2)$$

## Economic model

Property	Symbol	Value
Insulation cost per unit of weight	$c_{ins}$	10 €/kg

[20]

Reference material : PPLP

## Technical model

Property	Symbol	Value
Insulation density	$\rho_{ins}$	0.9 ton/m <sup>3</sup>
Inner radius for each insulating layer	$R_{int_{ins}1}$ $R_{int_{ins}2}$ $R_{int_{ins}3}$	34.3 mm 48.8 mm 62.5 mm
Outer radius for each insulating layer	$R_{ext_{ins}1}$ $R_{ext_{ins}2}$ $R_{ext_{ins}3}$	48.6 mm 62.4 mm 75.8 mm
Line length	$L_{line}$	32 km

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ CAPEX<sub>mat</sub> $\rightarrow$ CAPEX<sub>LN2</sub>

$$CAPEX_{mat} = CAPEX_{HTS} + CAPEX_{Cu} + CAPEX_{ins} + CAPEX_{LN2} + CAPEX_{cryo} + CAPEX_{term}$$

$$\left\{ \begin{aligned} CAPEX_{LN2} &= n_{cables} c_{LN2} \left( \frac{kg}{l} \right)_{LN2} Volume_{LN2} \\ Volume_{LN2} &= L_{line} \pi \left( R_{ext_{annulus}}^2 - R_{int_{annulus}}^2 + R_{former}^2 \right) \end{aligned} \right.$$

Economic model		
Property	Symbol	Value
LN2 cost per liter	$c_{LN2}$	0.16 €/liter

Technical model		
Property	Symbol	Value
Kg on liter ratio for LN2	$\left( \frac{kg}{l} \right)_{LN2}$	1.235 kg/liter
Inner radius of the annular gap	$R_{int_{annulus}}$	78.6 mm
Outer radius of the annular gap	$R_{ext_{annulus}}$	106.0 mm
Former radius (inner)	$R_{former}$	30 mm
Line length	$L_{line}$	32 km

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ $CAPEX_{mat}$ $\rightarrow$ $CAPEX_{cryo}$ , $CAPEX_{term}$

$$CAPEX_{mat} = CAPEX_{HTS} + CAPEX_{Cu} + CAPEX_{ins} + CAPEX_{LN2} + CAPEX_{cryo} + CAPEX_{term}$$

$$\left\{ \begin{array}{l} CAPEX_{cryo} = n_{cables} c_{cryo} L_{line} \\ n_{cables} CAPEX_{term} \end{array} \right.$$

## Economic model

Property	Symbol	Value
Cryostat cost per unit length	$c_{cryo}$	220 k€/km
Terminations cost for a single cable	$CAPEX_{term}$	400 k€

## Technical model

Property	Symbol	Value
Line length	$L_{line}$	32 km

# TEA on HTS cables → CAPEX → $CAPEX_{cool}$

$$CAPEX = CAPEX_{mat} + CAPEX_{cool} + CAPEX_{land} + CAPEX_{cab} + CAPEX_{vac} + CAPEX_{dism} + CAPEX_{other}$$

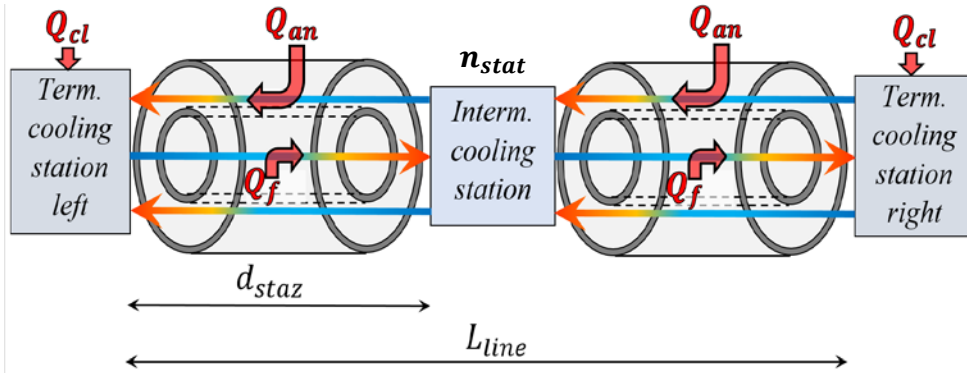
$$CAPEX_{cool} = n_{cables} \sum_k^{n_{stat}+2} \left\{ C_{cool_{fixed}} + [(c_{cryocooler} Q_{c_k}) \beta_Q] \beta_r \right\}$$

$$Q_{c_k} = \begin{cases} Q_f + Q_{an} & \text{if } k = \text{intermediate stat.} \\ Q_{an} + Q_{cl} & \text{if } k = \text{left termination stat.} \\ Q_f + Q_{cl} & \text{if } k = \text{right termination stat.} \end{cases}$$

Economic model		
Property	Symbol	Value
Fixed costs for each cooling station besides the device cost (installation, maintenance, disposal...)	$C_{cool_{fixed}}$	500 k€/km
Cryocoolers cost per unit of power	$c_{cryocooler}$	25 €/W
Mark-up to consider possible heat peaks	$\beta_Q$	1.1
Mark-up for the devices where no parametric cost function has been found (circulation pumps, LN <sub>2</sub> tank...)	$\beta_r$	1.1

Technical model		
Property	Symbol	Value
N° of intermediate cooling stations	$n_{stat}$	5
Heat to be extracted from LN2 by $k^{th}$ cryocoolers	$Q_{c_k}$	Cable design
Hydraulic power delivered by the $k^{th}$ pumps to LN2	$Q_{p_k}$	Cable design

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ $CAPEX_{cool}$ $\rightarrow$ Losses



Note: the losses are conveniently divided based on which fluid will be affected into a cable segment (LN2 in the former or LN2 in the annular gap).

$$\left\{ \begin{aligned} Q_f &= \left( \frac{LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy}}{2} \right) \left( \frac{1}{n_{stat} + 1} \right) \\ Q_{an} &= \left( \frac{LOSS_{AC\ HTS} + LOSS_{ins} + LOSS_{eddy}}{2} + LOSS_{cryo} \right) \left( \frac{1}{n_{stat} + 1} \right) \\ Q_{cl} &= \frac{LOSS_{term}}{2} \end{aligned} \right.$$

$\left\{ \begin{aligned} \text{intermediate station} &\rightarrow Q_f + Q_{an} \\ \text{left termination station} &\rightarrow Q_{an} + Q_{cl} \\ \text{right termination station} &\rightarrow Q_f + Q_{cl} \end{aligned} \right.$

# TEA on HTS cables $\rightarrow$ CAPEX $\rightarrow$ $CAPEX_{land}$

$$CAPEX = CAPEX_{mat} + CAPEX_{cool} + CAPEX_{land} + CAPEX_{cab} + CAPEX_{vac} + CAPEX_{dism} + CAPEX_{other}$$

$$CAPEX_{land} = n_{cables} c_{land} L_{line} (2 R_{Blimit})$$

## Economic model

Property	Symbol	Value
Land cost per unit of surface	$c_{land}$	20 €/km <sup>2</sup>

## Technical model

Property	Symbol	Value
Radial distance from the cable where the magnetic field is still greater than the limit (6 $\mu$ T)	$R_{Blimit}$	0.3 m
Line length	$L_{line}$	32 km

# TEA on HTS cables → CAPEX → $CAPEX_{cab}, CAPEX_{vac}, CAPEX_{dism}, CAPEX_{other}$

$$CAPEX = CAPEX_{mat} + CAPEX_{cool} + CAPEX_{land} + CAPEX_{cab} + CAPEX_{vac} + CAPEX_{dism} + CAPEX_{other}$$

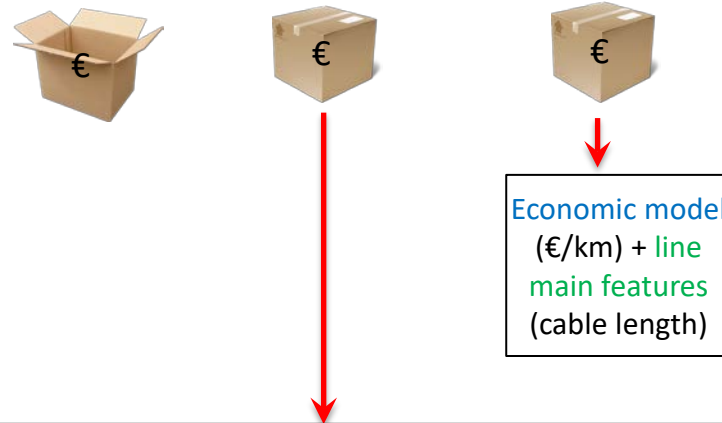
$$\left\{ \begin{array}{l} CAPEX_{cab} = n_{cables} c_{cab} L_{line} \\ CAPEX_{vac} = n_{cables} c_{vac} L_{line} \\ CAPEX_{dism} = n_{cables} c_{dism} L_{line} \frac{1}{(1+r)^{years}} \\ CAPEX_{other} = n_{cables} c_{other} L_{line} \end{array} \right.$$

Economic model		
Property	Symbol	Value
Cabling cost per unit of length	$c_{cab}$	1 M€/km
Vacuum system cost per unit of length	$c_{vac}$ [21]	52 k€/km
Dismantling cost per unit of length	$c_{dism}$ [22]	20 k€/km
Other costs (commissioning, installation, civil eng., regulation, accessories) per unit of length	$c_{other}$	800 k€/km

Technical model		
Property	Symbol	Value
Annual interest ratio	$r$	5%
Total n° of years of operations	$years$	40
Line length	$L_{line}$	32 km

# TEA on HTS cables → OPEX (total)

$$OPEX = OPEX_{cool} + OPEX_{maintenance}$$



**Economic model (energy cost)**

+

**Technical model:**

- loss calculation
- estimate of  $\Delta T_{LN2}$ ,  $\Delta P_{LN2}$  in each cable segment

Each term will be detailed in the next slides...



# TEA on HTS cables → OPEX → $OPEX_{cool}$

$$OPEX = OPEX_{cool} + OPEX_{maintenance}$$

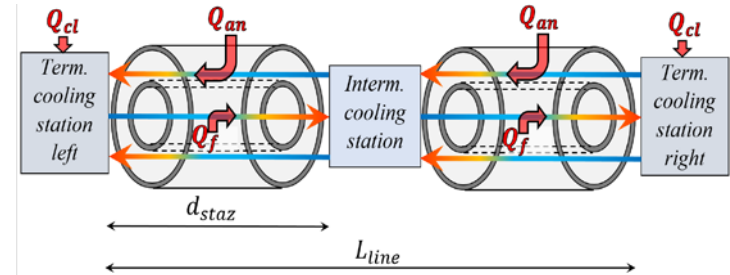
$$OPEX_{cool} = n_{cables} \sum_k^{n_{stat}+2} \left\{ \sum_{t=1}^{years} c_{kWh} h_y \left[ \left( \frac{Q_{ck}}{\eta_{cry}} \frac{(T_a - T_0)}{T_0} \right) + \frac{Q_{pk}}{\eta_p} \right] \frac{1}{(1+r)^t} \right\}$$

Economic model		
Property	Symbol	Value
Actual energy cost	$C_{kWh}$	0.015 €/kWh

Technical model		
Property	Symbol	Value
N° of intermediate cooling stations	$n_{stat}$	5
Hours of operation in a year	$h_y$	8760
Total n° of years of operations	$years$	40
Annual interest ratio	$r$	5%
Ambient temperature (outside the cable)	$T_a$	300 K
$T_{LN2}$ at the beginning of each cable section (both in the former and in the annulus)	$T_0$	68 K
Heat to be extracted from LN2 by the cryocoolers of intermediate cooling stations	$Q_f + Q_{an}$	89.3 kW
Heat to be extracted from LN2 by the cryocoolers of left side cooling station	$Q_{an} + Q_{cl}$	53.3 kW
Heat to be extracted from LN2 by the cryocoolers of right side cooling station	$Q_f + Q_{cl}$	41.3 kW
Hydraulic power delivered by the pumps of intermediate cooling stations to LN2	$m_{LN2} \frac{\Delta P_f + \Delta P_{an}}{\rho_{LN2}}$	2 kW
Hydraulic power delivered by the pumps of left side cooling stations to LN2	$\frac{m_{LN2} \Delta P_{an}}{\rho_{LN2}}$	1.2 kW
Hydraulic power delivered by the pumps of right side cooling stations to LN2	$\frac{m_{LN2} \Delta P_f}{\rho_{LN2}}$	0.8
Cryocoolers efficiency	$\eta_{cry}$	10%
Pumps efficiency	$\eta_p$	70%

# TEA on HTS cables $\rightarrow$ OPEX $\rightarrow$ $OPEX_{cool}$ $\rightarrow$ Losses & $\Delta P$

$$OPEX_{cool} = \sum_k^{n_{stat}+2} \left\{ \sum_{t=1}^{years} c_{kWh} h_y \left[ \left( \frac{Q_{ck}}{\eta_{cry}} (T_a - T_{ann}) \right) + \frac{Q_{pk}}{\eta_p} \right] \frac{1}{(1+r)^t} \right\}$$



$$Q_{ck} = \begin{cases} Q_f + Q_{an} & \text{if } k = \text{intermediate stat.} \\ Q_{an} + Q_{cl} & \text{if } k = \text{left termination stat.} \\ Q_f + Q_{cl} & \text{if } k = \text{right termination stat.} \end{cases}$$



Losses to be managed by each cooling /pumping station.

$$Q_{pk} = \begin{cases} m_{LN2} \frac{\Delta P_f + \Delta P_{an}}{\rho_{LN2}} & \text{if } k = \text{intermediate stat.} \\ \frac{m_{LN2} \Delta P_{an}}{\rho_{LN2}} & \text{if } k = \text{left termination stat.} \\ \frac{m_{LN2} \Delta P_f}{\rho_{LN2}} & \text{if } k = \text{right termination stat.} \end{cases}$$



Hydraulic power to be managed by each cooling/pumping station to restore LN2 pressure.

Note: these losses and these  $\Delta P$  are computed in single cable segments between 2 adjacent cooling stations.

Technical model		
Property	Symbol	Value
LN2 mass flow rate	$m_{LN2}$	2.15 kg/s
LN2 density	$\rho_{LN2}$	839 kg/m <sup>3</sup>

# TEA on HTS cables → OPEX → *OPEX*<sub>maintenance</sub>

$$OPEX = OPEX_{cool} + OPEX_{maintenance}$$

$$OPEX_{maintenance} = n_{cables} \sum_{t=1}^{years} \frac{L_{line} C_{maint}}{(1+r)^t}$$

## Economic model

Property	Symbol	Value
Maintenance cost per unit of length per year	$C_{maint}$	3 k€/km/year

[8]

## Technical model

Property	Symbol	Value
Total n° of years of operations	$years$	40
Annual interest ratio	$r$	5%
Line length	$L_{line}$	32 km

# III. TEA of HTS cable system

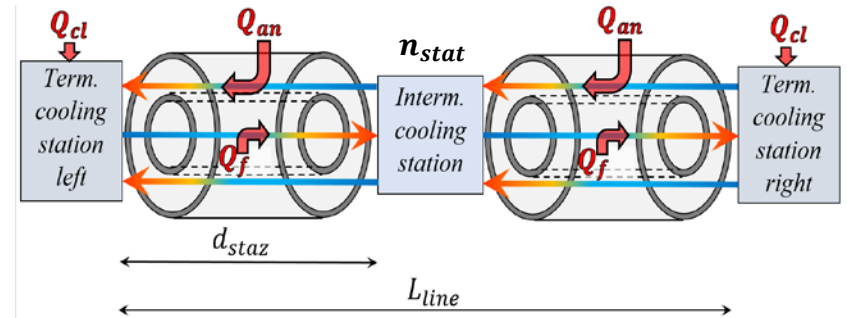
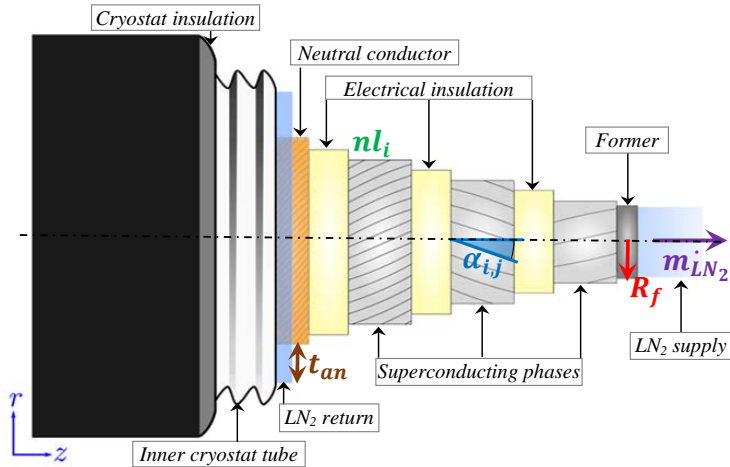
## Phase 4 – Interpretation



## IV. To go further...

# Cable optimization modelling

You will have noticed that by modifying the **input design parameters** of our Excel file, the constraints imposed may no longer be respected. Furthermore, even if we could change those values freely, it is not immediately clear how these affect costs.



Technical model – Main features

Property	Symbol	Value
Cable power	$P$	750 MW
Voltage rms	$V_{rms}$	33 kV L-L RMS
Load factor	$\cos\varphi$	0.95
rms value of the total AC current in each phase	$I_{rms}$	$I_{rms} = \frac{P}{\sqrt{3} V_{rms} \cos\varphi} = 13.81 \text{ kA}$
Line length	$L_{line}$	32 km

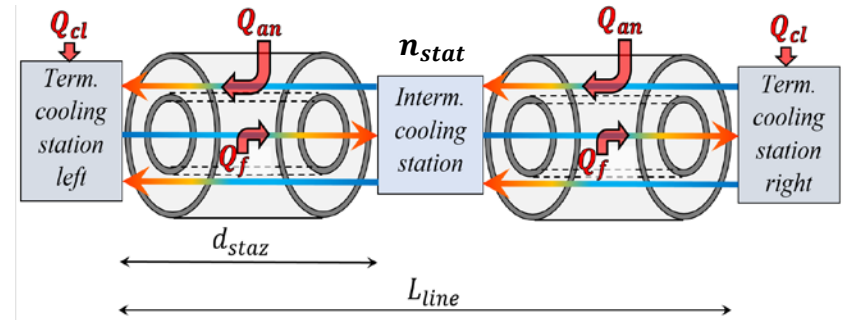
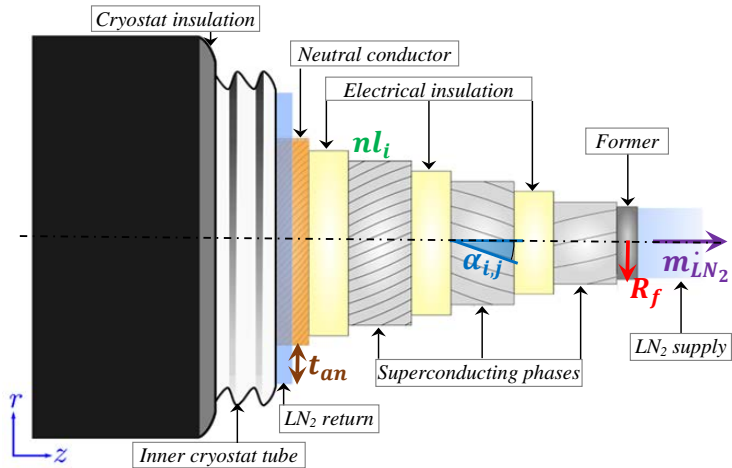
Technical model

Property	Symbol	Value
Former radius (inner)	$R_{former}$	30 mm
LN2 mass flow rate	$m_{LN2}$	2.15 kg/s
Twist angle for each layer of phase 1	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
Twist angle for each layer of phase 2	$\alpha_{1,2}$	-13°
Twist angle for each layer of phase 3	$\alpha_{1,3}$	-14°
N° of HTS layers for phase 1	$n_{l_1}$	2
N° of HTS layers for phase 2	$n_{l_2}$	1
N° of HTS layers for phase 3	$n_{l_3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

# Cable optimization modelling

Indeed, we cannot perform a fine optimization of the cable design with our Excel.

The “suggested” input parameters that we have used are the outputs coming from another optimization tool, computed for a specific combination of operating parameters.



Technical model – Main features

Property	Symbol	Value
Cable power	$P$	750 MW
Voltage rms	$V_{rms}$	33 kV L-L RMS
Load factor	$\cos\varphi$	0.95
rms value of the total AC current in each phase	$I_{rms}$	$I_{rms} = \frac{P}{\sqrt{3} V_{rms} \cos\varphi} = 13.81 \text{ kA}$
Line length	$L_{line}$	32 km

Technical model

Property	Symbol	Value
Former radius (inner)	$R_{former}$	30 mm
LN2 mass flow rate	$m_{LN2}$	2.15 kg/s
Twist angle for each layer of phase 1	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
Twist angle for each layer of phase 2	$\alpha_{1,2}$	-13°
Twist angle for each layer of phase 3	$\alpha_{1,3}$	-14°
N° of HTS layers for phase 1	$n_{l_1}$	2
N° of HTS layers for phase 2	$n_{l_2}$	1
N° of HTS layers for phase 3	$n_{l_3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{staz}$	5



# Cable optimization modelling

We would like to have a tool that automatically computes the combination of design parameters optimized for a given criteria (e.g., minimum cost while complying with constraints).

The one developed by RSE is presented here, but there are numerous options available, and everyone can create their own



**What matters most is to grasp the approach!**

Technical model – Main features

Property	Symbol	Value
Cable power	$P$	750 MW
Voltage rms	$V_{rms}$	33 kV L-L RMS
Load factor	$\cos\varphi$	0.95
rms value of the total AC current in each phase	$I_{rms}$	$I_{rms} = \frac{P}{\sqrt{3} V_{rms} \cos\varphi} = 13.81 \text{ kA}$
Line length	$L_{line}$	32 km

Technical model

Property	Symbol	Value
Former radius (inner)	$R_{former}$	30 mm
LN2 mass flow rate	$m_{LN2}$	2.15 kg/s
Twist angle for each layer of phase 1	$\alpha_{1,1}, \alpha_{2,1}$	11°, 15°
Twist angle for each layer of phase 2	$\alpha_{1,2}$	-13°
Twist angle for each layer of phase 3	$\alpha_{1,3}$	-14°
N° of HTS layers for phase 1	$n_{l_1}$	2
N° of HTS layers for phase 2	$n_{l_2}$	1
N° of HTS layers for phase 3	$n_{l_3}$	1
Thickness of the annular gap	$t_{annulus}$	27.8 mm
N° of intermediate cooling stations	$n_{stat}$	5

# Cable optimization modelling

**OSCaR: a tool for techno-economic assessment of superconducting power cables** [1, 2]

Optimization tool for **S**uperconducting **C**able **R**esearch

- ❑ **Scope of the tool:** determine the optimized cable design according to the operating parameters selected by the user (e.g. active power, voltage level, line length).
- ❑ A **constrained minimization problem** for a multi-variable function (the **cable system cost**) is solved using a **genetic algorithm** in MATLAB.
- ❑ The first version of the code refers to the so-called **coaxial configuration** of AC HTS cables. The cooling configuration adopted is the so-called **both-sided cooling option**, with 2 counter-flows of liquid nitrogen.
- ❑ **Multiple constraints are imposed** (e.g. currents balancing between phases and layers, maximum current in the tapes, coolant temperature and pressure).

Activity carried out in collaboration with the University of Bologna



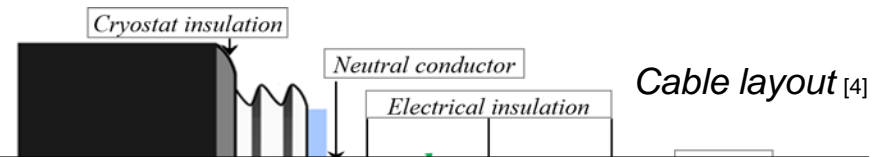
HTS coaxial AC cable [3]

[1] A. Musso et al., IEEE Trans. On Appl. Supercond., vol. 32, no. 9, p. 4803516, 2022.  
 [2] A. Musso et al., IEEE Trans. On Appl. Supercond., vol. 33, no. 5, p. 5401105, 2023.  
 [3] M. Noe, EUCAS Short Course, 2017.

# Cable optimization modelling

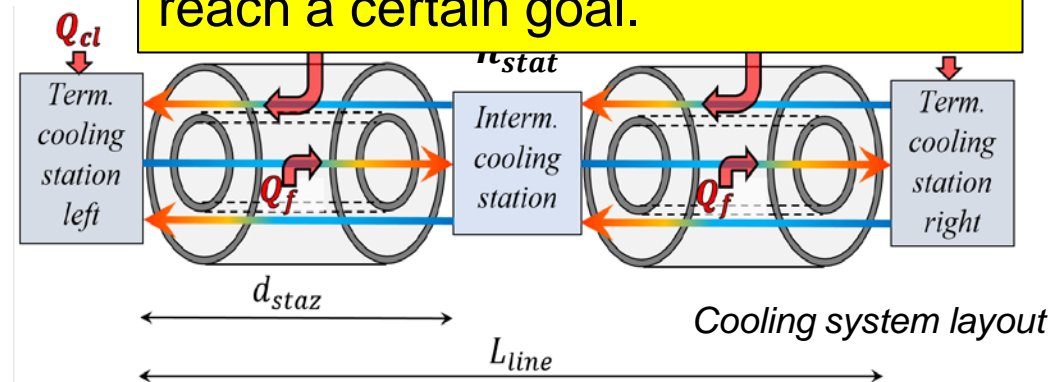
## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

- ❑ The capital and operating cost indexes and the heat inputs calculations are parameterized to the cable design features.
- ❑ The optimized cable parameters considered are:
  - the n° of layers per phase ( $n_{l_i}$ );
  - the winding angle in each layer ( $\alpha_{i,j}$ );
  - the former radius ( $R_f$ );
  - the annular gap thickness ( $t_{an}$ );
  - the LN<sub>2</sub> mass flow rate ( $m_{LN2}$ );
  - the n° of cooling stations ( $n_{stat}$ ).



The same technical and economic models that we set in our Excel file are implemented in the code.

What changes is the numerical approach to the problem, making the PC do numerous iterations to reach a certain goal.

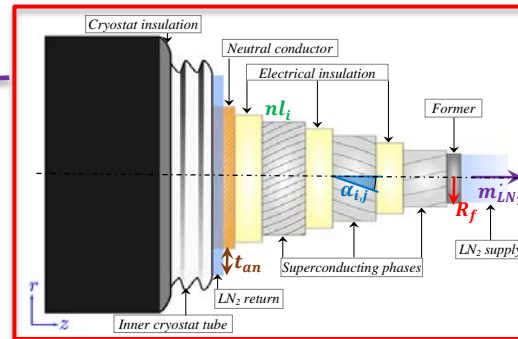


[4] W. T. B. de Sousa et al., Supercond. Sci. Technol, vol. 34, 2021.

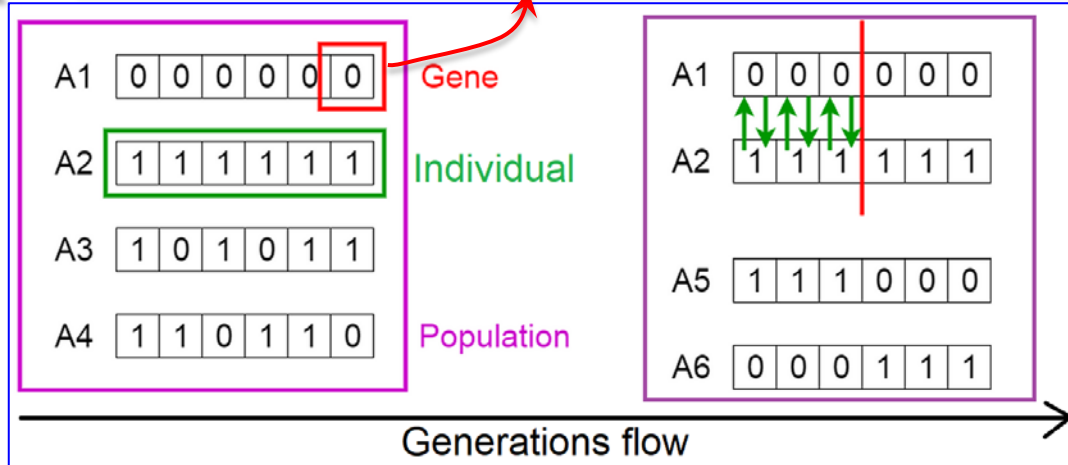
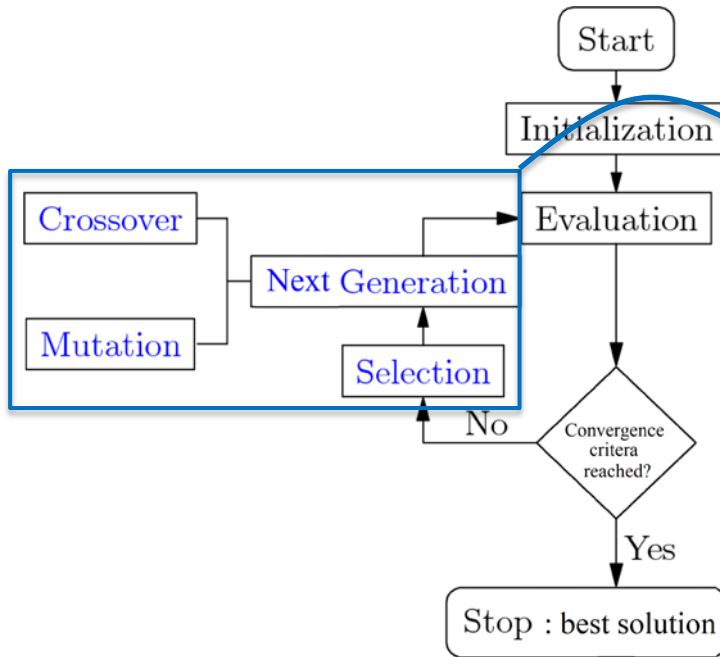
# Cable optimization modelling

## OSCaR: a tool for techno-economic assessment of superconducting power cables

The cable system cost is the function to be minimized (we want to most economically convenient cable). The “genes”/”design parameters” have been parametrized to this cost, in the same way we have done in our Excel file.



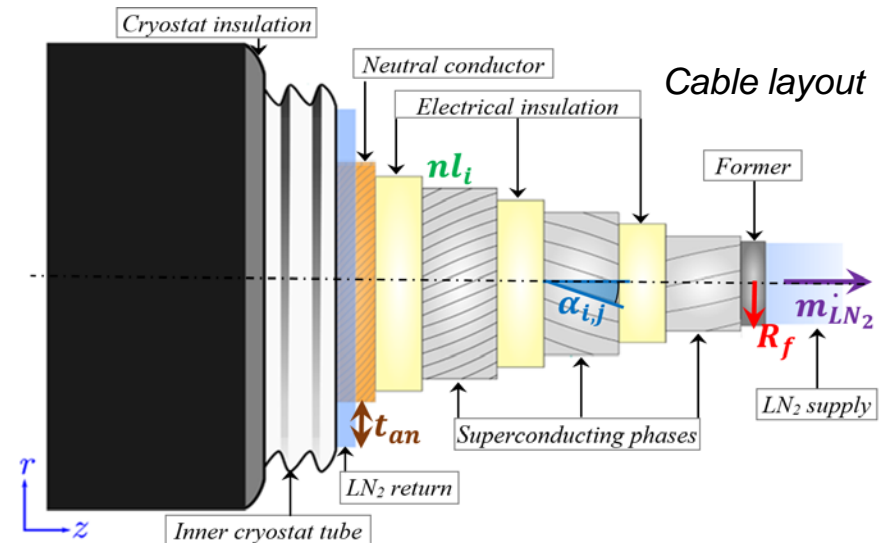
The “genes” of each individual are the variables of our fitting function (the cable system cost).



# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

- ❑ The capital and operating cost indexes and the heat inputs calculations are parameterized to the cable design features.
- ❑ The optimized cable parameters considered are:
  - the n° of layers per phase ( $n_{l_i}$ );
  - the winding angle in each layer ( $\alpha_{i,j}$ );
  - the former radius ( $R_f$ );
  - the annular gap thickness ( $t_{an}$ );
  - the LN<sub>2</sub> mass flow rate ( $\dot{m}_{LN_2}$ );
  - the n° of cooling stations ( $n_{stat}$ ).



The algorithm selects only the individuals who comply with the imposed constraints. Furthermore, we can "facilitate" its task by suggesting upper and lower boundaries for each variable (e.g. include the radius of the former between a certain minimum and maximum values) and/or a sensible initial solution.

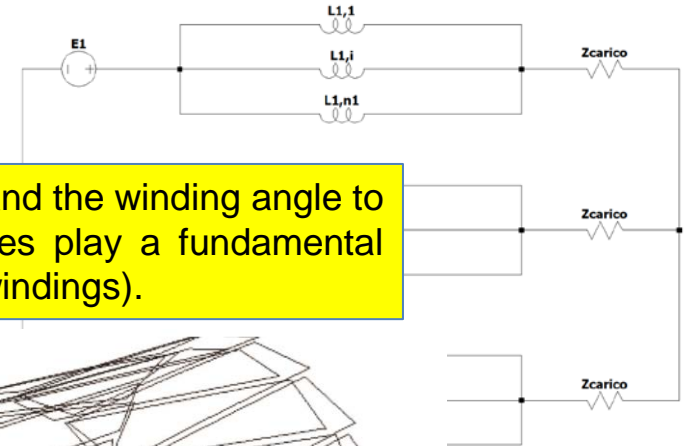
# Cable optimization modelling

## OSCaR: a tool for techno-economic assessment of superconducting power cables

The main **constraints** applied regards:

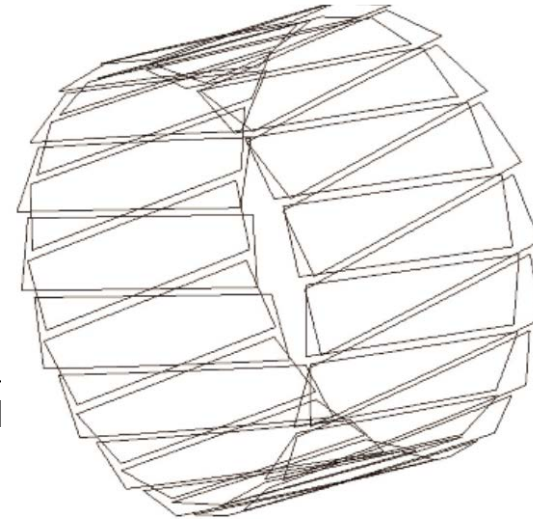
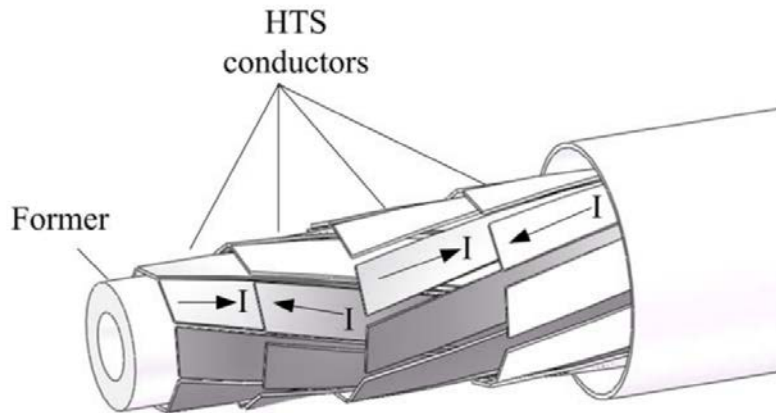
- the **currents balancing** between phases and layers;

You can tune the radius of each layer (if allowed) and the winding angle to obtain a balance of their inductances (inductances play a fundamental role in the current distribution in superconducting windings).

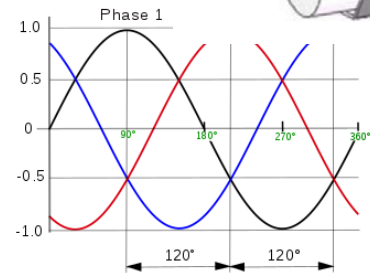


$$\begin{cases} \underline{E}_1 = \frac{V_{rms}}{\sqrt{3}} = \sum_{j=1}^{3 \text{ n}^\circ \text{ layers } p} \\ \underline{E}_2 = \frac{V_{rms}}{\sqrt{3}} e^{-j\frac{2}{3}\pi} \\ \underline{E}_3 = \frac{V_{rms}}{\sqrt{3}} e^{j\frac{2}{3}\pi} \end{cases}$$

$$\sum_j^{3 \text{ n}^\circ \text{ layers } pha} \sum_h$$



$$\frac{r_{i,k}}{r_{j,h}} \tan(\alpha_{i,k}) \tan(\alpha_{j,h}) e^{j\varphi}$$



maximum tolerance is imposed on their phase shift.

- if some phases are composed of more than 1 layer, "it makes sense" that the current is distributed uniformly between them → a maximum tolerance is imposed on the difference between the modules of the layers currents.

e system → a modules and on

# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

The main **constraints** applied regards:

- ❑ the **currents balancing** between phases and layers;
- ❑ the **maximum current** in the HTS tapes;

The same we applied in our Excel file.

$$\left\{ \begin{array}{l} \frac{\sqrt{2} I_{rms}}{Tapes_{i,j}} / I_c \left( \max [T_{HTS_{left}}, T_{HTS_{right}}] \right) \leq safety_{HTS} \\ Tapes_{i,j} = \text{round} \left( \frac{2\pi R_{HTS_{i,j}} |\cos(\alpha_{i,j})|}{w_{HTS}} \right) \end{array} \right.$$

# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

The main **constraints** applied regards:

- ❑ the **currents balancing** between phases and layers;
- ❑ the **maximum current** in the HTS tapes;
- ❑ the **coolant temperature and pressure**;

We may apply the same equations as in our Excel file.

$$\Delta T_{former} \leq \Delta T_{LN2max} \Rightarrow \Delta T_{former} = d_{stat} \left( \frac{v_{LN2former}^2 f_{LN2former}}{4 R_{former} c_{pLN2}} \right) + \frac{Q_f}{2 m_{LN2} c_{pLN2}}$$

$$\Delta T_{annulus} \leq \Delta T_{LN2max} \Rightarrow \Delta T_{annulus} = d_{stat} \left( \frac{v_{LN2annulus}^2 f_{LN2annulus}}{4 t_{annulus} c_{pLN2}} \right) + \frac{Q_{an}}{2 m_{LN2} c_{pLN2}}$$

$$\Delta P_{former} \leq \Delta P_{LN2max} \Rightarrow \Delta P_{former} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2former}^2 f_{LN2former}}{4 R_{former}} \right) + (g \rho_{LN2} \Delta h)$$

$$\Delta P_{annulus} \leq \Delta P_{LN2max} \Rightarrow \Delta P_{annulus} = \left( d_{stat} \frac{\rho_{LN2} v_{LN2annulus}^2 f_{LN2annulus}}{4 t_{annulus}} \right) + (g \rho_{LN2} \Delta h)$$



# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

The main **constraints** applied regards:

- ❑ the **currents balancing** between phases and layers;
- ❑ the **maximum current** in the HTS tapes;
- ❑ the **coolant temperature and pressure**;

Or we may consider more complex fluid-dynamics models.

$$\begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial \rho}{\partial x} \end{bmatrix} = [Q_{\delta T \delta \rho}(\rho, T)]^{-1} \begin{bmatrix} - \int_0^{d_{stat}} [Q_{f/an}(T)] a_c dx - \frac{\dot{m}_c \tau_c P_c}{a_c^2 \rho} \\ \dot{m}_c g \sin \beta + \frac{\dot{m}_c \tau_c P_c}{a_c^2 \rho} \end{bmatrix}$$

$$[Q_{\delta T \delta \rho}(\rho, T)]^{-1} = \frac{1}{\Delta Q_{\delta T \delta \rho}(\rho, T)} \begin{bmatrix} G_{\delta \rho}(\rho, T) & -H_{\delta \rho}(\rho, T) \\ -G_{\delta T}(\rho, T) & H_{\delta T}(\rho, T) \end{bmatrix}$$

$$\Delta Q_{\delta T \delta \rho}(\rho, T) = H_{\delta T}(\rho, T)G_{\delta \rho}(\rho, T) - G_{\delta T}(\rho, T)H_{\delta \rho}(\rho, T)$$

$$H_{\delta T} = \frac{\dot{m}_c}{a_c \rho} \left( \frac{\partial P}{\partial T} - \rho \frac{\partial h}{\partial T} \right) ; \quad H_{\delta \rho} = \frac{\dot{m}_c}{a_c \rho} \left( \frac{\partial P}{\partial \rho} - \rho \frac{\partial h}{\partial \rho} \right)$$

$$G_{\delta T} = -\frac{\dot{m}_c}{a_c \rho} \frac{\partial P}{\partial T} ; \quad G_{\delta \rho} = \frac{\dot{m}_c}{a_c \rho} \left( \frac{\dot{m}_c^2}{\rho^2} - \frac{\partial P}{\partial \rho} \right)$$

System of non-linear differential equations obtained from the equations of energy and momentum conservation and the continuity equation, considering stationary conditions, and applying a 1-dimensional (the cable length x) approximation.

The system needs to be solved numerically. It is more accurate as it mathematically models all the thermodynamic and thermo-physic properties of the cryogenic fluid considered.

Double these equations for the LN2 in the former and in the annular gap

[6] G. Angeli et al., IEEE Trans. Appl. Supercond., vol. 27, no. 4, 2017, p. 5600406.

# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

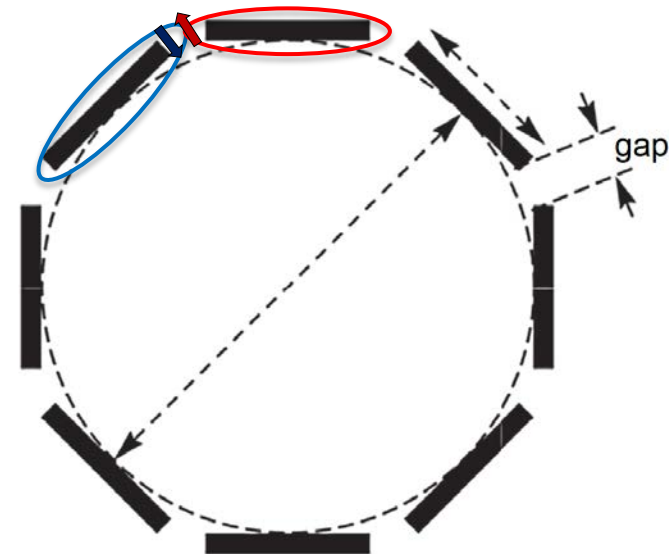
The main **constraints** applied regards:

- ❑ the **currents balancing** between phases and layers;
- ❑ the **maximum current** in the HTS tapes;
- ❑ the **coolant temperature and pressure**;
- ❑ the **distance between adjacent tapes** in each layer;
- ❑ the **line voltage drop**.

To ensure that the loads connected to the cable can operate at a voltage level close to their design value, the voltage drop across  $L_{line}$  has to be lower than a certain maximum percentage of the design voltage  $V_{rms}$ , imposed by the user and generally dependent on grid regulations.

$$\frac{\omega \left| [M] \cdot [I_{i,j}] \right|}{V_{rms}} \leq 4\% \quad \begin{cases} \text{for } i = 1, 2, 3 \\ \text{for } j = 1, \dots, nl_i - 1 \end{cases}$$

If the tapes are too far apart (gap > 3  $w_{HTS}$ ), their applied transverse magnetic fields do not cancel out and this impacts both their critical current and AC losses.

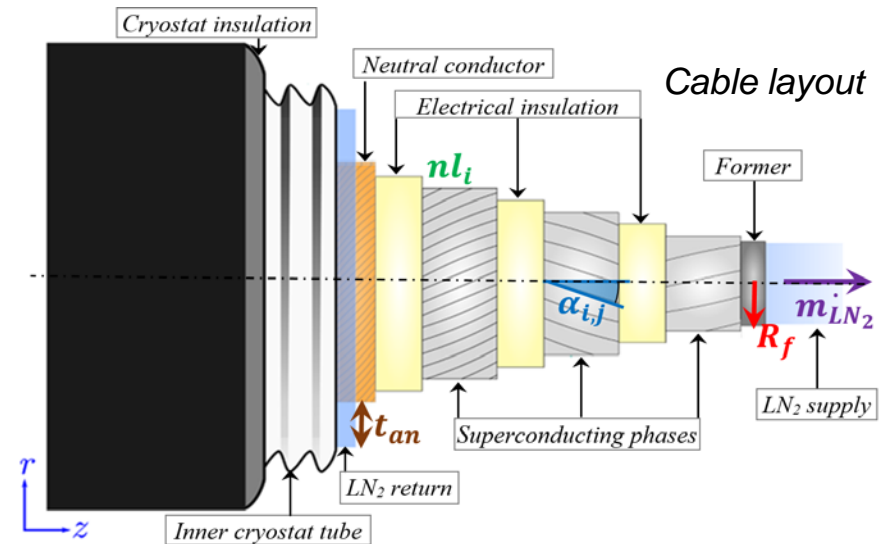


# Cable optimization modelling

## OSCaR: a tool for techno-economic assessment of superconducting power cables

The main **constraints** applied regards:

- ❑ the **currents balancing** between phases and layers;
- ❑ the **maximum current** in the HTS tapes;
- ❑ the **coolant temperature and pressure**;
- ❑ the **distance between adjacent tapes** in each layer;
- ❑ the **line voltage drop**.



The user can select the **operating conditions**:

- ❑ the **active power** to be transferred through the line ( $P$ );
- ❑ the **voltage level**, in the medium voltage range ( $V_{rms}$ );
- ❑ the **line length** ( $L_{line}$ );
- ❑ the **load factor** ( $\cos\phi$ );



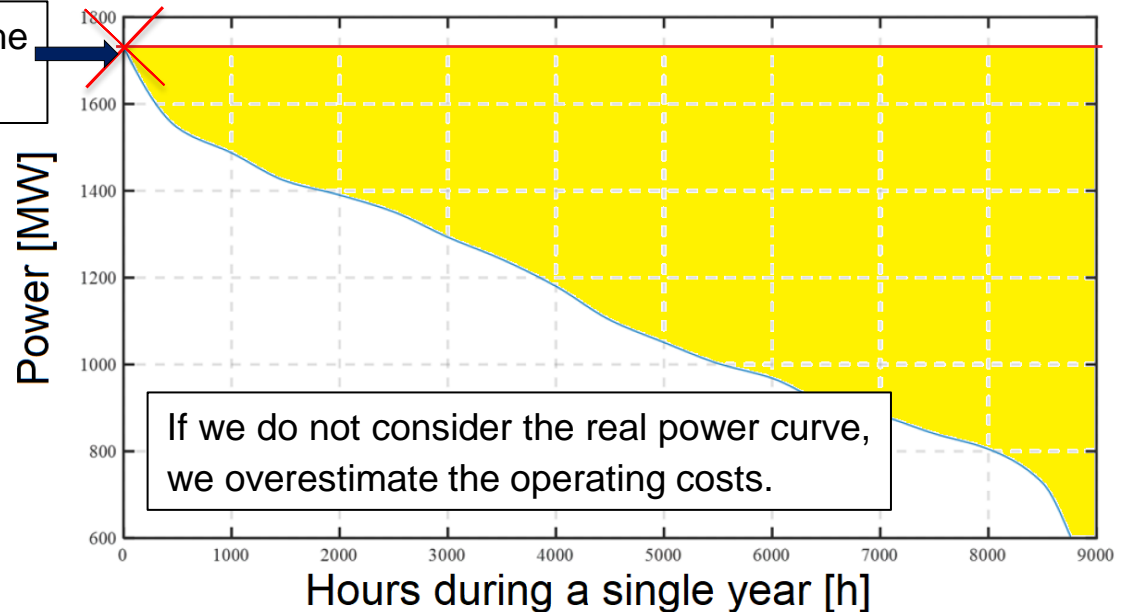
Technical model – Main features		
Property	Symbol	Value
Cable power	$P$	?
Voltage rms	$V_{rms}$	?
Load factor	$\cos\phi$	?
Line length	$L_{line}$	?

# Cable optimization modelling

## *OSCaR: a tool for techno-economic assessment of superconducting power cables*

The main objective is to size the cable design for the maximum power it can reach.

- the number of layers;
- the **maximum current** in the HTS;
- the **coolant temperature and pressure** in each layer;
- the **distance between adjacent layers** in each layer;
- the **line voltage drop**.



The user can select the **operating conditions**:

- the **active power** to be transferred through the line ( $P$ );
- the **voltage level**, in the medium voltage range ( $V_{rms}$ );
- the **line length** ( $L_{line}$ );
- the **load factor** ( $\cos\phi$ );

A cable might not always carry the maximum current/power all year round.

# Cable optimization modelling

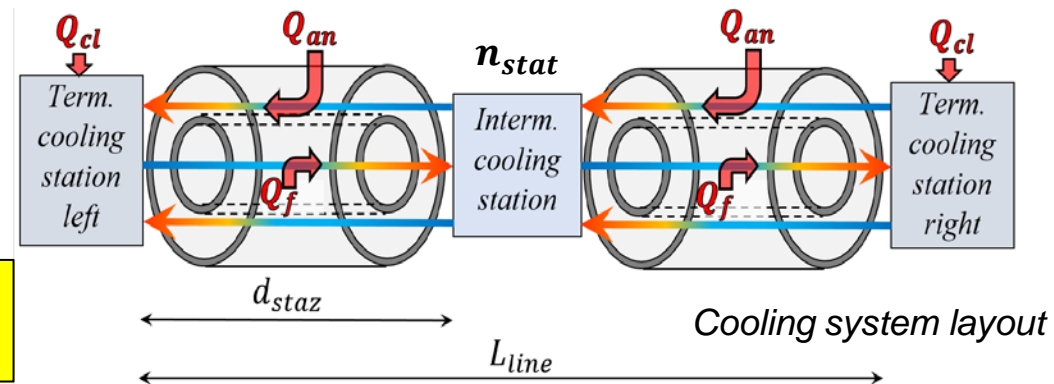
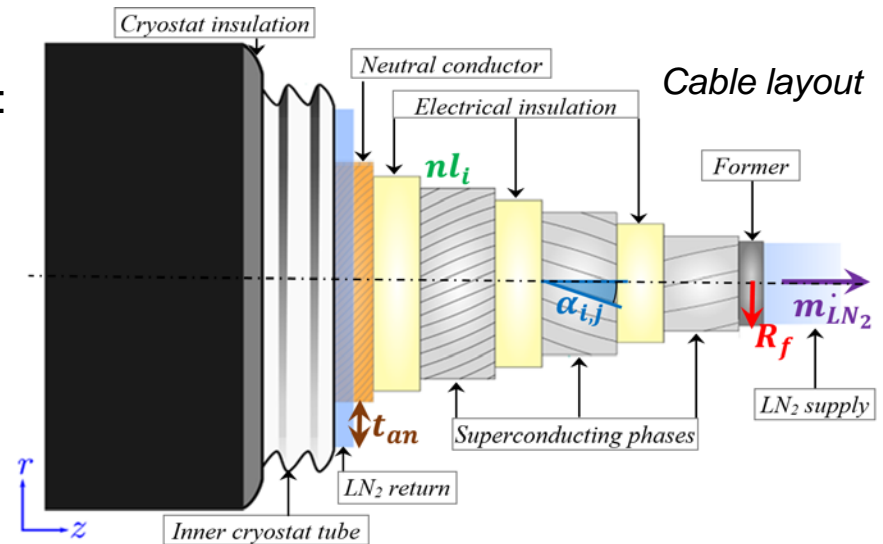
## OSCaR: a tool for techno-economic assessment of superconducting power cables

In the end, for each combination of operating parameters selected by the user, the tool returns:

- ❑ The cost of the cable system (which has to be minimized), with details of the single cost indexes.
- ❑ The optimized design parameters corresponding to that cable cost.
- ❑ All the other cable design parameters calculated in cascade from the optimized parameters.
- ❑ A quantification of compliance with the various constraints



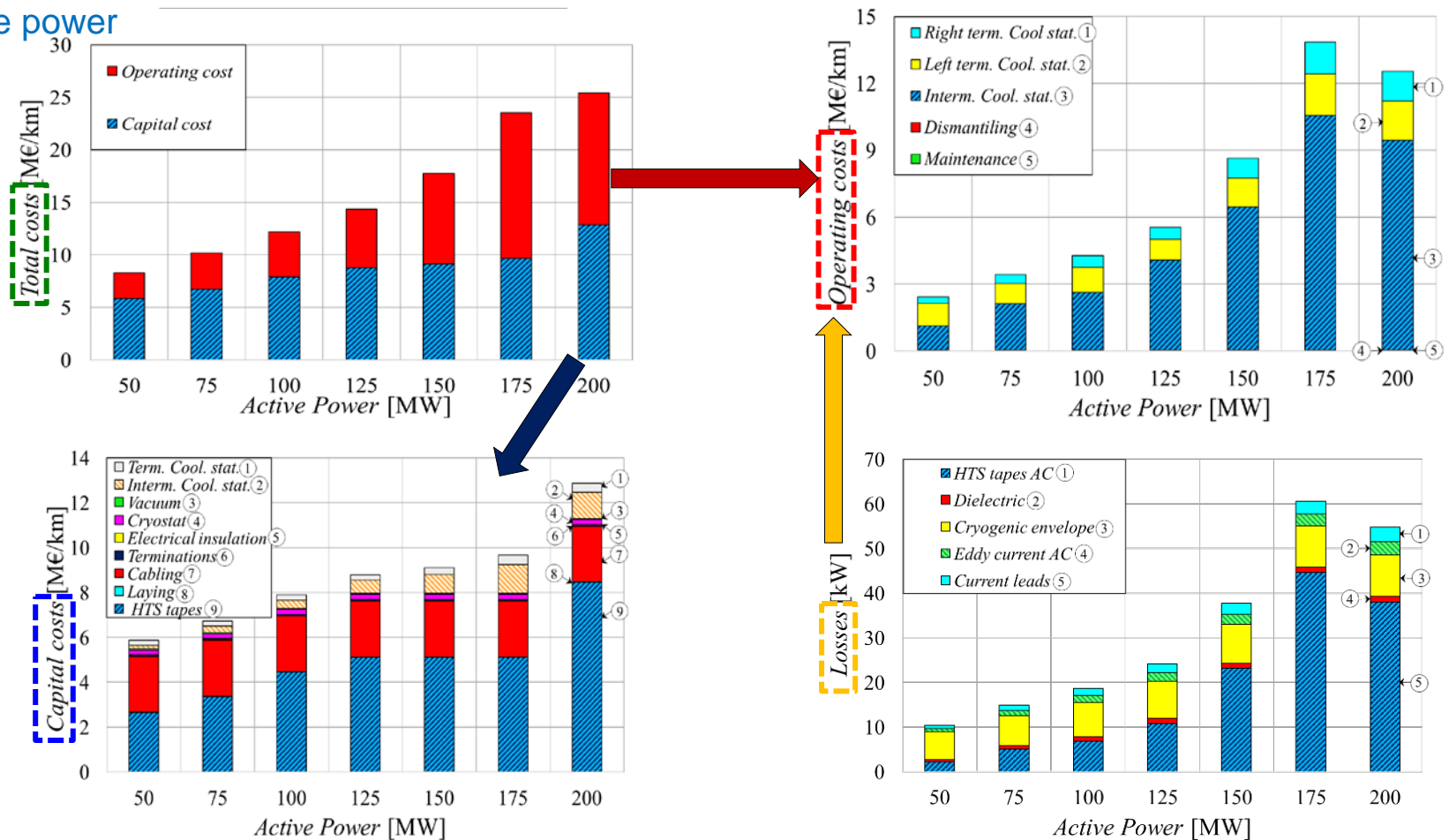
This "automated" approach is well suited to perform various parametric analyses.



# OSCaR: examples of parametric analyses

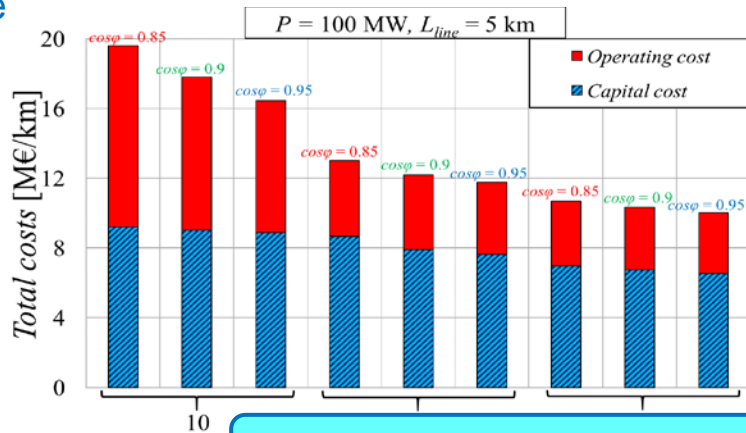
CASE STUDY : Line length = 5 km ;  $V_{rms} = 15$  kV ;  $\cos\varphi = 0.9$

## Active power

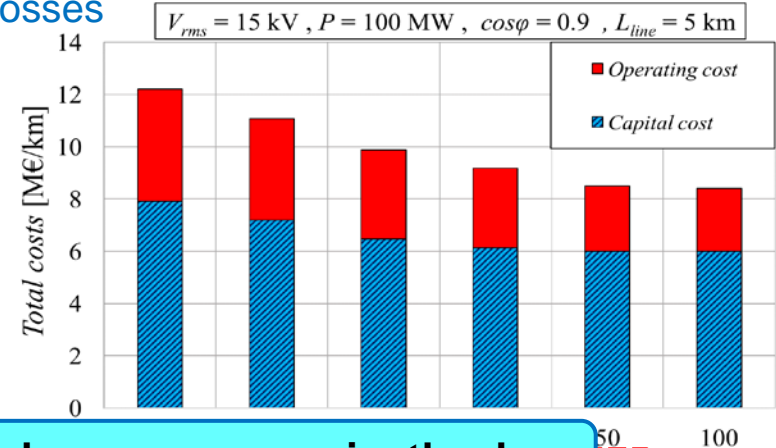


# OSCaR: examples of parametric analyses

## Voltage

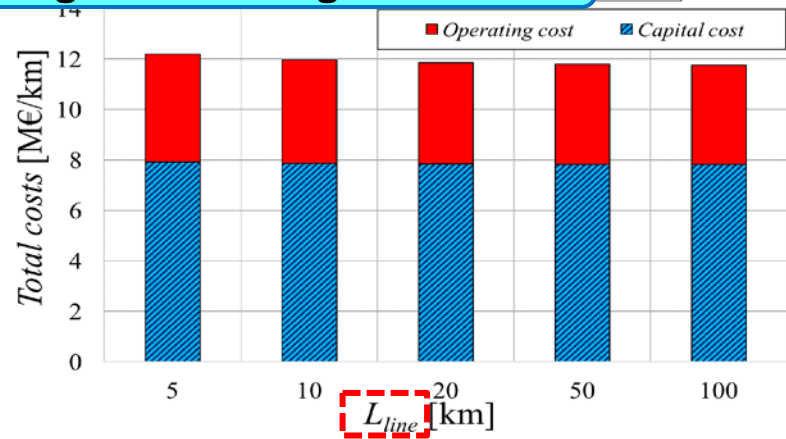
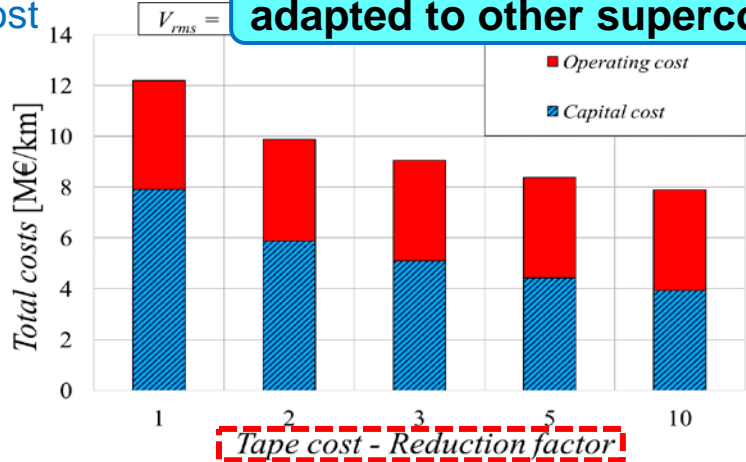


## AC losses



The methodological approach can conveniently be adapted to other superconducting cable configurations.

## Tape cost

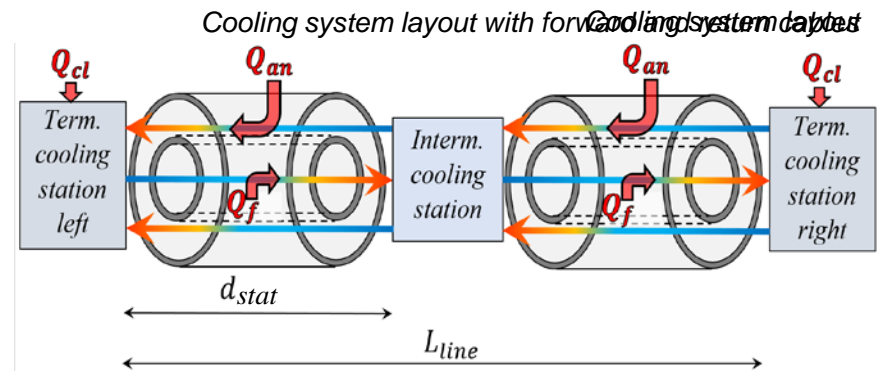
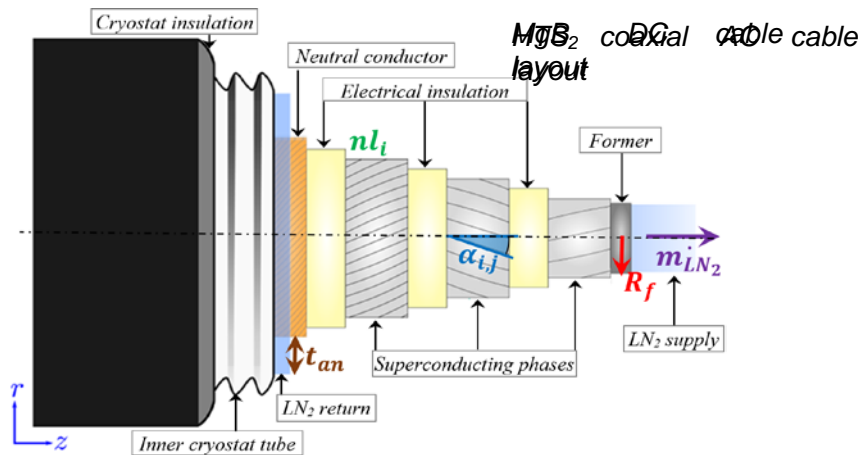


# OSCaR: application to $MgB_2$ DC cables

New cable architecture → adequate update of the cost indexes, constraints and losses terms.



The methodology remains the same.



$$C_{tot} = \underbrace{C_{MgB_2} + C_{ins} + C_{cool} + C_{Cu} + C_{stat\_cap} + C_{cryo} + C_{vac} + C_{ter} + C_{cab} + C_{lay}}_{\text{Capital costs}} + \underbrace{C_{stat\_op} + C_{man} + C_{dis}}_{\text{Operating costs}}$$

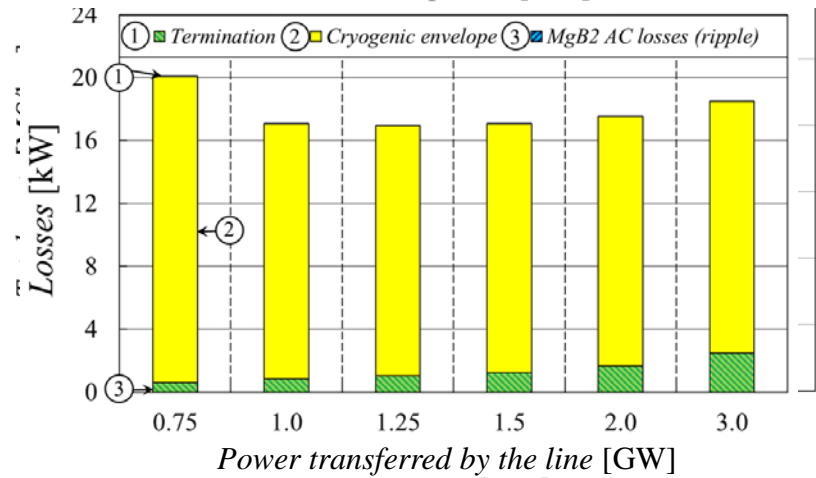
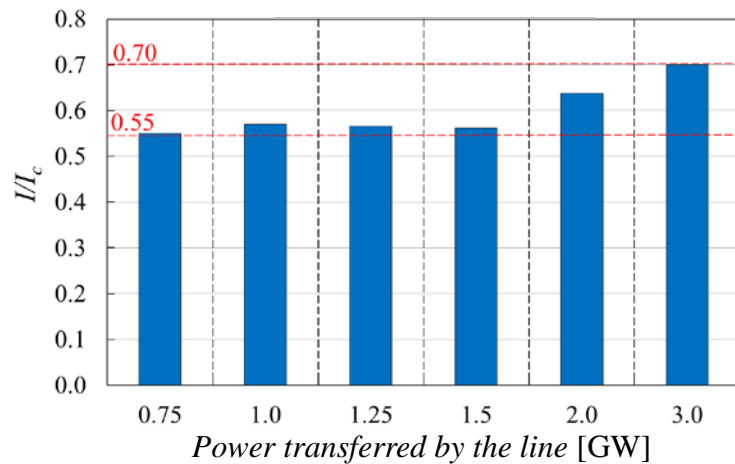
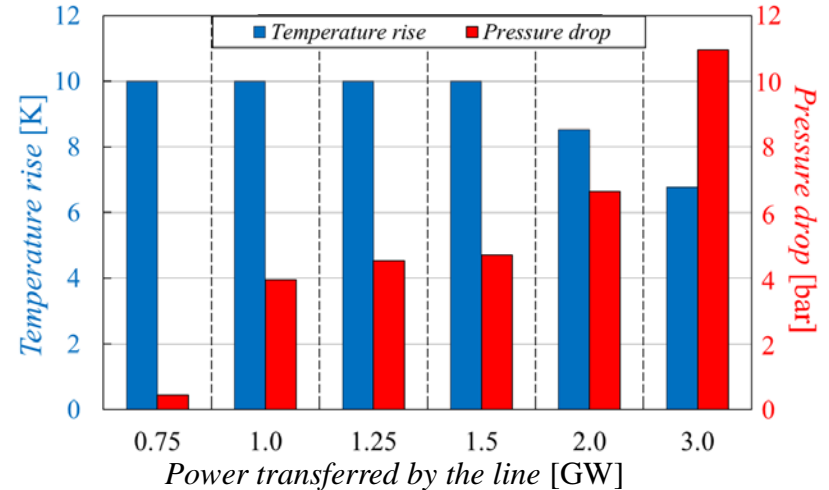
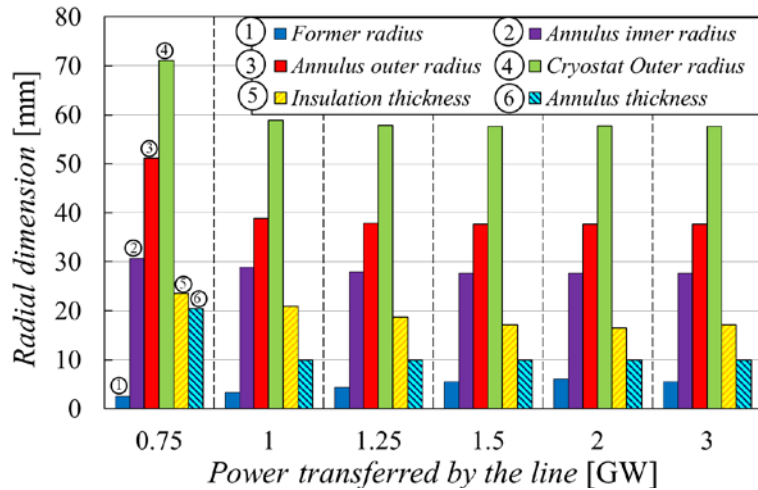
- $C_{MgB_2}$  = cost for the total length of  $MgB_2$  wires;
- $C_{ins}$  = cost for the insulator;
- $C_{cool}$  = cost for the cryogenic fluid (closed cycle);
- $C_{Cu}$  = cost for copper (neglecting other materials);
- $C_{stat\_op}$  = capital cost for all the cooling stations;

- $C_{vac}$  = cost for the vacuum system;
- $C_{ter}$  = cost for terminations at the cable ends;
- $C_{cab}$  = cost for cabling;
- $C_{lay}$  = cost for cable laying into the tunnel;
- $C_{cryo}$  = cost for the cryostat.

- $C_{stat}$  = cost for the electricity needed to operate all the cooling stations;
- $C_{man}$  = cost for cable maintenance over its life-time (40 years);
- $C_{dis}$  = cost for cable dismantling.



# OSCaR: application to MgB<sub>2</sub> DC cables



**CASE STUDY** : Line length = 10 km ; V<sub>rms</sub> = 220 kV

# Thank you for the attention!

Further questions:  
[andrea.musso@rse-web.it](mailto:andrea.musso@rse-web.it)

## References

[1]	G. Chen et al., «Polypropylene Laminated Paper (PPLP) Insulation for HVDC Power Cables,” 12th IEEE International Conference on the Properties and Applications of Dielectric Materials, 2018.
[2]	W. Kim et al., “Comparative Study of Cryogenic Dielectric and Mechanical Properties of Insulation Materials for Helium Gas Cooled HTS Power Devices”, IEEE Trans. On Appl. Supercond., vol. 17, no.4, p. 7700605, 2017.
[3]	N Hayakawa et al., 2014 J. Phys.: Conf. Ser.,507, 032021.
[4]	“Superconducting Cables”, Prof. Dr.-Ing. Mathias Noe, Karlsruhe Institute of Technology Institute for Technical Physics, EUCAS Short Course Power Applications, September 17th 2017, Geneva
[5]	W. T. B. de Sousa et al., “An open-source 2D finite difference based transient electro-thermal simulation model for three-phase concentric superconducting power cables,” Supercond. Sci. Technol, vol. 34, 2021.
[6]	D. Kottonau et al., “Design Comparisons of Concentric Three-Phase HTS Cables,” IEEE Trans. On Appl. Supercond., vol. 29, no. 6, Sept. 2019.
[7]	A. P. Malozemoff et al., “High-temperature superconducting (HTS) AC cables for power grid applications,” Superconductors in the Power Grid Materials and Applications, Woodhead Publishing Series in Energy, pp. 133-188, 2015.
[8]	D. Kottonau et al., “Evaluation of the Use of Superconducting 380 kV Cable,” KIT Scientific publishing, 2020.
[9]	J. Choi et al. “A Study on Insulation Characteristics of Laminated Poly-propylene Paper for an HTS Cable,” IEEE Trans. On Appl. Supercond., vol. 20, no. 3, 2010.
[10]	D. S. Kwag et al. “A Study on the Composite Dielectric Properties for an HTS Cable,” IEEE Trans. On Appl. Supercond., vol. 15, no. 2, 2005.
[11]	W. Pi et al., “Insulation Design and Simulation for Three-Phase Concentric High-Temperature Superconducting Cable Under 10-kV Power System”, IEEE Trans. On Appl. Supercond., vol. 29, 2019.
[12]	A. Morandi, “HTS dc transmission and distribution: concepts, applications and benefits,” Supercond. Sci. Technol., vol. 28, p. 123001, 2015.
[13]	N. Hayakawa, “Insulation technologies for HTS apparatus,” ESAS Summer School on HTS Technology for Sustainable Energy and Transport Systems, Bologna-Italy, Jun. 2016.
[14]	W. T. Norris, “Calculation of hysteresis losses in hard superconductors carrying AC isolated conductors and edges of thin sheets,” J. Phys. Appl. Phys., vol. 3, no. 4, pp. 489–507, Apr. 1970.
[15]	S. Wimbush and N. Strickland, “Critical current characterisation of SuNAM SAN04200 2G HTS superconducting wire,” Figshare Dataset, <a href="https://doi.org/10.6084/m9.figshare.5182354.v1">https://doi.org/10.6084/m9.figshare.5182354.v1</a> , 2017.
[16]	T. Takahashi et al., “Dielectric Properties of 500 m Long HTS Power Cable”, IEEE Trans. On Appl. Supercond., vol. 15, 2005.
[17]	H. Suzuki et al., “Electrical insulation characteristics of liquid nitrogen impregnated laminated paper insulated cable”, IEEE Transactions on Power Delivery, vol. 7, 1992.
[18]	G. Wypych, “HDPE high density polyethylene, Handbook of Polymers,” Elsevier, ISBN 9781895198478, pp. 150-156, 2012.
[19]	L. Trevisani, “Design and simulation of a large scale energy storage and power transmission system for remote renewable energy sources exploitation,” Ph.D. Dissertation, University of Bologna, Italy, 2006.
[20]	D. S. Kwag et al. “A Study on the Composite Dielectric Properties for an HTS Cable,” IEEE Trans. On Appl. Supercond., vol. 15, no. 2, 2005.
[21]	F. Herzog, “Cooling unit for the AmpaCity project – One year successful operation”, Cryogenics, vol. 80, 2016.
[22]	Roy Zuijderduin, “Integration of High-Tc Superconducting Cables in the Dutch Power Grid of the Future,” Ph.D. Thesis, Delft University of Technology, The Netherlands, 2016.