



GRADO EN INGENIERÍA EN TECNOLOGÍAS
INDUSTRIALES

TRABAJO FIN DE GRADO
TECHNO-ECONOMIC OPTIMIZATION OF
SUPERCONDUCTING CABLES

Autor: Lourdes Platero de Heredia

Director: Loïc Queval

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

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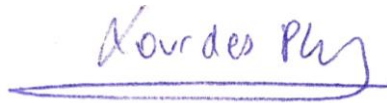
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Fdo.: Lourdes Platero de Heredia

Fecha: 10/07/2022



Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Loic Queval

Fecha: 10/07/2022





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My acknowledgments are addressed to Mr. Loïc Queval, who patiently guided me in the development of this work, teaching me not only the necessary knowledge in superconductivity and optimization, but also a rigorous and critical way of working. I hope to have learned these qualities well and I am sure that I will appreciate them even more in the future.

OPTIMIZACIÓN TÉCNICO-ECONÓMICA DE LOS CABLES SUPERCONDUCTORES

Author: Platero de Heredia, Lourdes.

Supervisor: Queval, Loïc.

Collaborating Entity: ICAI – Universidad Pontificia Comillas y CentraleSupélec

RESUMEN DEL PROYECTO

El objetivo de este proyecto es desarrollar un algoritmo que encuentre el cable óptimo a construir, dadas unas especificaciones y un caso de prueba. Este es un cable superconductor con un diseño específico. Para optimizarlo, se estudiará el mismo componente a componente, se definirán las variables del problema y las funciones objetivo, siendo estas el coste de instalación y los costes operacionales. Se implementará con un algoritmo de optimización metaheurístico MOPSO y se utilizará el criterio de Pareto para elegir las soluciones óptimas.

Palabras clave: Superconductividad, Cable, Optimización, HTS, CapEx, Opex, Pareto.

1. Introducción

La demanda creciente de energía y la necesidad de reducir el consumo para alinearse con los objetivos de desarrollo sostenible, hacen necesario encontrar maneras de extender las líneas de transporte de energía con menos pérdidas. En efecto, se estima que el 6% de la energía de la red eléctrica francesa se pierda por efecto Joule [1]. Además, la oposición que encuentra la construcción de líneas aéreas de alta intensidad por de los residentes hace preferible encontrar soluciones con un menor impacto visual, como son los cables subterráneos.

Para hacer frente a todas estas cuestiones, la entrada de los materiales superconductores en la industria eléctrica parece necesaria. Utilizándose en cables superconductores, estos permiten transportar grandes cantidades de energía a altas tensión con pérdidas muy limitadas. Además, su sección reducida y su implantación bajo tierra permite reducir el impacto visual mencionado.

Los materiales superconductores utilizados en este tipo de cable son los HTS, “High temperature superconducting”, que operan a 70K, permitiendo que estos sean más fáciles de implantar en aplicaciones industriales. A pesar del buen conocimiento de esta tecnología, sus aplicaciones comerciales son limitadas debido, en parte, a la falta de estandarización de su diseño, construcción y operación. Por eso, se han realizado estudios que pretenden establecer un marco estandarizado para el desarrollo de estos cables. Entre ellos destacan los trabajos de D.Kottonau y D.Noë.

El objetivo de este trabajo es profundizar en el estudio técnico económico de estos cables, realizando una optimización de los costes de instalación y operacionales.

2. Definición del Proyecto

La optimización del cable superconductor se realizará a partir de un caso de prueba dado, para unas especificaciones bien definidas. Se utilizará el caso de prueba definido en el TFG de Carmen Martin-Sanz y se utilizarán las especificaciones dadas en la tesis de D.Kottonau.

Los cables superconductores constan de 3 partes: el núcleo del cable, el criostato y las terminaciones. El núcleo del cable y el criostato pueden disponerse de varias maneras, lo que da lugar a diversas configuraciones del sistema de cables. Este sistema se refrigera con nitrógeno líquido (LN₂), que fluye dentro del cable. Existen 3 tipos de configuraciones posibles: monofásico-1-criostato, trifásico-1-criostato y trifásico-concéntrico, así como varios tipos de refrigeración posibles. El cable de prueba será monofásico-1-criostato, necesitándose 3 cables para construir el sistema trifásico, y el sistema de refrigeración de un sentido, fluyendo el nitrógeno líquido por dos fases y volviendo a la estación de refrigeración de estos dos por la última fase, que tendrá entonces el doble de flujo másico.

El núcleo del cable está compuesto por varias capas superpuestas. En la capa más baja se encuentra el tubo que sirve de soporte metálico y de conducto por el que circula el nitrógeno líquido y encima de este se enrollan las cintas superconductoras en varias capas para transportar la intensidad. Esto se recubre de aislante dieléctrico de Polipropileno con una pantalla HTS por encima, que sirve de aislante magnético. Encima de esto se pone una capa de conductor neutro, formada por cintas de cobre que sirven de soporte estructural y para transportar las corrientes de defecto. Todo esto se mete en un criostato que mantiene el cable a la temperatura de operación. Estas capas están bien representadas en la figura 1.

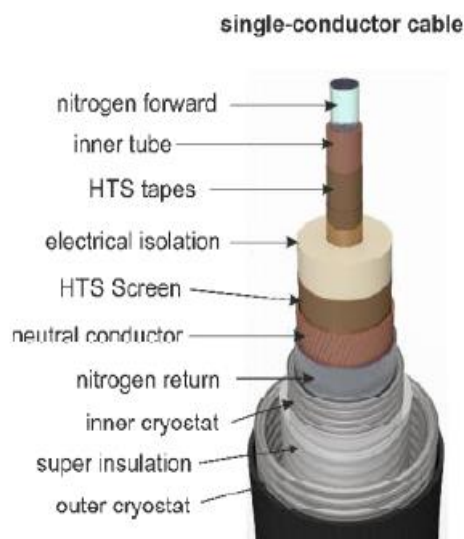


Ilustración 1: componentes de un cable superconductor [2]

Para realizar el estudio técnico económico, se eligen los parámetros de estos materiales y se hacen variar para encontrar la configuración que minimiza los costes de instalación y operacionales.

3. Descripción del modelo/sistema/herramienta

Para realizar dicha optimización, se definen claramente las funciones objetivo, las variables y su dominio y las restricciones. Entonces, se utiliza un algoritmo metaheurístico MOPSO (Optimización por enjambre de partículas), que recorre el espacio de soluciones

posibles guardando a cada iteración las posiciones de las partículas (valores de las variables) que minimizan las funciones objetivo. La elección de estas partículas se hace utilizando el criterio de Pareto, que es aquel que se emplea para el estudio de objetivos antagonistas. Estas soluciones, sobre el frente de Pareto, constituyen el espacio de aquellas partículas que no pueden mejorar un objetivo sin perjudicar al otro [3].

Tras un estudio del cable componente a componente, las variables escogidas son el diámetro del tubo interior, el ancho de la cinta superconductora, el ángulo de enrollamiento de esta y el tipo de tubo (liso o arrugado). Las funciones objetivo son, en un primer tiempo, la longitud de las cintas y las pérdidas del cable y, en un estudio más profundizado, el CapEx y el OpEx. El OpEx se calcula multiplicando las pérdidas por el precio de la electricidad y el CapEx se obtiene gracias a la siguiente tabla:

Componente	coste límite inferior [M€]	coste límite superior [M€]	Indicaciones
Material			
Costes del material HTS	Coste variable	Coste variable	25-50 €/kA/m
Material de aislamiento Tyvek	Coste variable	Coste variable	20-38 €/kg, densidad 340 kg/m ³
Criostato de línea con acoplamiento de soldadura	8,674	9,83	450-510 €/m
Costes de producción	Coste variable	Coste variable	10-15% de los costes materiales
Enfriador			
Refrigerador criogénico	4	5	4 unidades, 1.0–1.3 M€ por unidad
Equipo de enfriamiento	0,4	0,75	10-15% of costes del efrigerador criogénico
Conjuntos			
Terminación	1,2	1,8	12 piezas, 100-150 k€/pieza
Conectores	1,9	2,85	50-75 k€ /pieza, 38 piezas
Zanja para cables	1,12	1,6	350-500 k€/km
Conducto de cableado	1,6	2,4	500-750 k€/km
Tendido de cables	0,32	0,48	100-150 k€/km
Costes de ingeniería civil	3,040	4,480	Mitad de los costes de conjuntos
Total			
Costes fijos totales	22,254	27,560	

Tabla 1: costes de instalación de un cable superconductor

Los límites o restricciones del problema de optimización son los límites de temperatura y presión del cable, que están determinados por el rango de operación del nitrógeno líquido. Estos están representados en la figura 2.

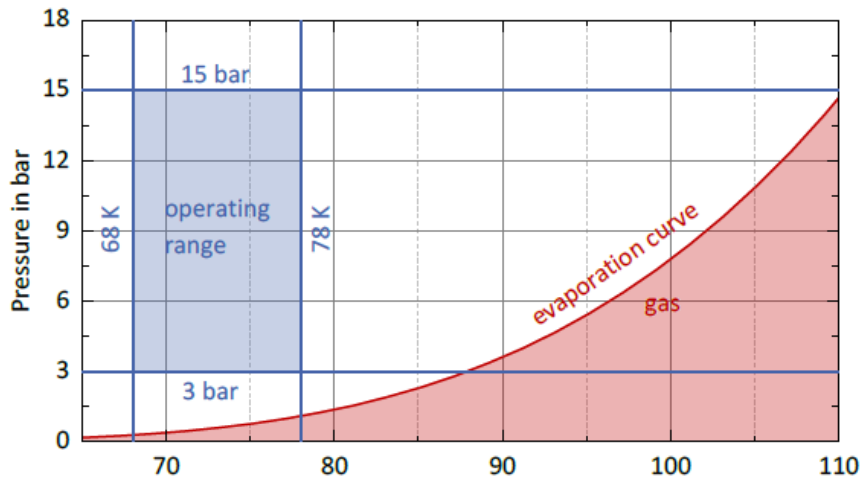


Ilustración 2: rango de operación del cable superconductor[2]

La implementación del problema de optimización se hará por pasos. En cada paso se añadirá una variable más al problema o se actualizarán las funciones objetivo. Este método permite verificar poco a poco que los resultados son coherentes y corregir los errores antes de pasar al siguiente paso. Al tratarse de una optimización heurística (intento y error), la solución no indica ni su sentido físico ni como se ha llegado a ella, así que para cerciorarse de que la solución es coherente, comparar con el paso anterior es una mejor manera de entenderlo que partir del problema completo.

4. Resultados

Realizando las optimizaciones finales, que tienen en cuenta como variables de optimización el ángulo de torsión (alfa), el diámetro del cable y la anchura de la cinta HTS y separando los dos frentes según el tipo de tubo interior, se llega a los resultados de las figuras 3 y 4.

El resultado obtenido al definir como funciones objetivo la longitud de la cinta HTS y las pérdidas anuales es el ilustrado en la figura 3. Su precio constituye hasta $\frac{3}{4}$ del coste total de la inversión, por lo que es una buena estimación del precio del cable. La solución obtenida es un frente de Pareto que se puede dividir en dos, según el tipo de tubo empleado.

Al definir como variables de optimización el CapEex y el OpEx, se pasa a tener un ólo frente óptimo, el constituido por los cables de tipo CT. Esto se debe a la traslación que sufre el frente de Pareto de los cables HC a la derecha, debido a la multiplicación de la longitud del cable por su precio, que agranda proporcionalmente las diferencias de precio entre ambos frentes.

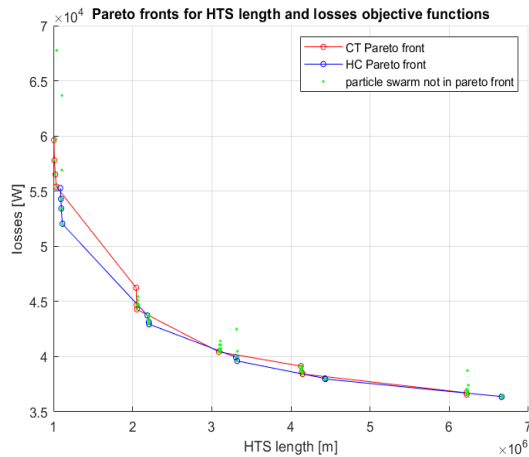


Ilustración 4: Frente de Pareto de funciones objetivo longitud del cable y pérdidas anuales

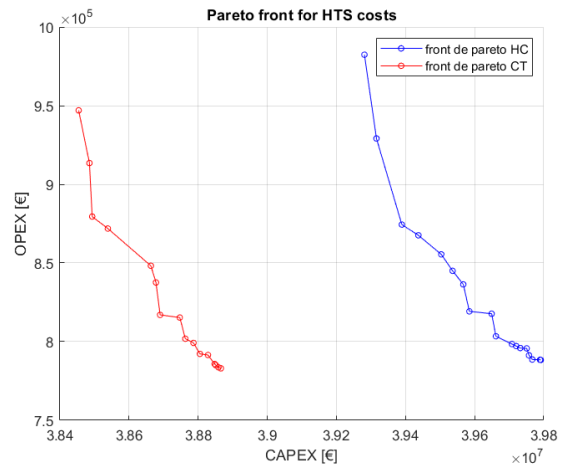


Ilustración 4: Frente de Pareto de funciones objetivo el CAPEX y el OPEX

5. Conclusiones

El cable óptimo es del tipo CT. Además, el único diámetro utilizable es el de 50 mm, para ambos tipos de tubo interior y para todas las configuraciones posibles.

Un tratamiento "paso a paso" ha permitido entender el impacto de la variación de cada parámetro de forma individual, partiendo de un resultado conocido. La evaluación de la sensibilidad del modelo a cada variable ha resultado útil, sobre todo para separar los frentes de Pareto según el primer tipo y para entender por qué la solución final está formada sólo por los puntos CT del primer tipo.

El criterio de Pareto ha demostrado su eficacia a la hora de reflejar la naturaleza antagónica de las dos funciones objetivo. La elección del algoritmo MOPSO para llegar a una solución óptima parece adecuada, ya que el algoritmo en este caso de estudio siempre converge.

Se han conseguido resultados claros e interpretables, así como un algoritmo altamente parametrizado que permite ser mejorado y actualizado a medida que se mejorará el conocimiento de esta tecnología

6. Referencias

- [1] Connaissance des Énergies: 'Combien de pertes de ligne en France'. (2017). Retrieved from Available: <https://www.connaissancedesenergies.org/electricite-a-combien-s-elevent-les-pertes-en-ligne-en-france-140520>
- [2] Kottonau. (2019). Kottonau, D.; Shabagin, E.; de Sousa, W. 'Evaluation of the Use of Superconducting 380 kV Cable'. KIT Scientific Publishing.
- [3] Ministère de l'Economie. (n.d.). <https://www.economie.gouv.fr/facileco/vilfredo-pareto>.

TECHNO-ECONOMIC OPTIMIZATION OF SUPERCONDUCTING CABLES

Author: Platero de Heredia, Lourdes.

Supervisor: Queval, Loïc.

Collaborating Entity: ICAI – Universidad Pontificia Comillas and CentraleSupélec

ABSTRACT

The aim of this project is to develop an algorithm that finds the optimal cable to build, given a set of specifications and a test case. This is a superconductor cable with a specific design. To optimize it, the latter will be studied component by component, the variables of the problem and the objective functions will be defined, being these the installation cost and the operational costs. It will be implemented with a metaheuristic optimization algorithm MOPSO and the Pareto criterion will be used to choose the optimal solutions.

Keywords: Superconductivity, Cable, Optimization, HTS, CapEx, Opex, Pareto.

1. Introduction

The growing demand for energy by and the need to reduce consumption to align with the sustainable development goals, make it necessary to find ways to extend power transmission lines with less losses. Indeed, it is estimated that 6% of the energy in the French power grid is lost due to the Joule effect [1]. In addition, opposition to the construction of high-intensity overhead lines from residents makes it preferable to find solutions with less visual impact, such as underground cables.

To address all these issues, the entry of superconducting materials into the electrical industry seems necessary. When used in superconducting cables, they make it possible to transport large amounts of energy at high voltages with very limited losses. In addition, their small cross-section and their underground installation reduce the visual impact mentioned above.

The superconducting materials used in this type of cable are HTS, "High temperature superconducting", which operate at 70K, making them easier to install in industrial applications. Despite the good knowledge of this technology, its commercial applications are limited due, in part, to the lack of standardization of its design, construction and operation. For this reason, studies have been carried out to establish a standardized framework for the development of these cables. Among them, the works of D. Kottonau and D. Noe stand out.

The objective of this work is to deepen in the technical-economic study of these cables, performing an optimization of the installation and operational costs. We propose to go further and to seek for the optimal configuration for each situation.

2. Project Definition

The optimization of the superconductor cable will be performed on the basis of a given test case, for well-defined specifications. The test case defined in the TFG of Carmen Martin-Sanz will be used and the specifications given in the thesis of D.Kottonau will be used.

Superconducting cables consist of 3 parts: the cable core, the cryostat and the terminations. The cable core and cryostat can be arranged in various ways, resulting in various configurations of the cable system. This system is cooled with liquid nitrogen (LN2), which flows inside the cable. There are 3 types of possible configurations: 1-phase-1-cryostat, 3-phase-1-cryostat and 3-phase-concentric, as well as several types of cooling possible. The test cable will be single-phase-1-cryostat, needing 3 cables to build the three-phase system, and the one-way cooling system, flowing liquid nitrogen through two phases and returning to the cooling station from these two through the last phase, which will then have twice the mass flow.

The cable core is composed of several overlapping layers. In the lowest layer is the tube which serves as a metal support and conduit through which the liquid nitrogen circulates and on top of this the superconducting tapes (HTS) are wound in several layers to carry the current. This is covered with Polypropylene dielectric insulator with a HTS screen on top, which serves as magnetic insulator. On top of this is placed a layer of neutral conductor, formed by copper tapes that serve as structural support and to carry the fault currents. All this is placed in a cryostat that keeps the cable at operating temperature. These layers are well represented in Figure 1.

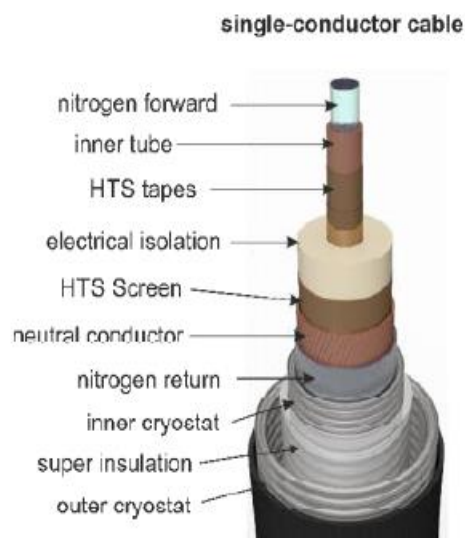


Figure 1: superconducting cable's components [2]

To carry out the technical economic study, the parameters of these materials are chosen and varied to find the configuration that minimizes the installation and operational costs.

3. Descripción del modelo/sistema/herramienta

To perform such optimization, the objective functions, the variables and their domain and the constraints are clearly defined. Then, a metaheuristic algorithm MOPSO (Particle

Swarm Optimization) is used, which runs through the space of possible solutions saving at each iteration the positions of the particles (values of the variables) that minimize the objective functions. The choice of these particles is made using the Pareto criterion, which is the one used for the study of antagonistic objectives. These solutions, on the Pareto front, constitute the space of those particles that cannot improve one objective without harming the other [3].

After a component-by-component study of the cable, the variables chosen are the diameter of the inner tube, the width of the superconducting tape, its winding angle and the type of tube (smooth or wrinkled). The objective functions are, at first, the length of the tapes and the cable losses and, in a more in-depth study, the CapEx and the OpEx. The OpEx is calculated by multiplying the losses by the price of electricity and the CapEx is obtained thanks to the following table:

Composant	lower bound cost [M€]	upper bound [M€]	specification
Material			
Material Costs HTS	variable cost	variable cost	25-50 €/kA/m
Insulation Material Tyvek	variable cost	variable cost	20-38 €/kg, density 340 kg/m ³
Line Cryostat with Weld Coupling	8,674	9,83	450-510 €/m
Production Costs	variable cost	variable cost	10-15% of material costs
Chiller			
Cryocooler	4	5	4 units, 1.0–1.3 M€ per unit
Chiller Equipment	0,4	0,75	10-15% of cryocooler costs
Sets			
Termination	1,2	1,8	12 pieces, 100-150 k€/piece
Sleeves	1,9	2,85	50-75 k€ /piece, 38 pieces
Cable Trench	1,12	1,6	350-500 k€/km
Wiring Duct	1,6	2,4	500-750 k€/km
Laying Of Cables	0,32	0,48	100-150 k€/km
Civil Engineering costs	3,040	4,480	Half set costs
Total			
Total fixed costs	22,254	27,560	

Table 1: superconducting cable's installation costs (CapEx)

The limits or constraints of the optimization problem are the temperature and pressure limits of the cable, which are determined by the operating range of the liquid nitrogen. These are represented in Figure 2.

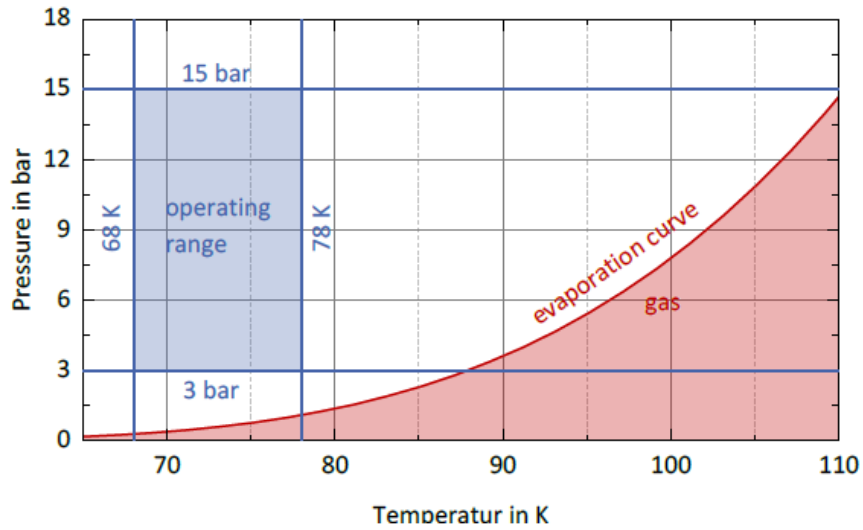


Figure 2: operation range of a superconducting cable [2]

The implementation of the optimization problem will be done in steps. At each step one more variable will be added to the problem or the objective functions will be actuated. This method allows to verify little by little that the results are consistent and to correct the errors before moving to the next step. As it is a heuristic optimization (trial and error), the solution does not indicate neither its physical meaning nor how it was arrived at, so to make sure that the solution is consistent, comparing with the previous step is a better way to understand it than starting from the complete problem.

4. Results

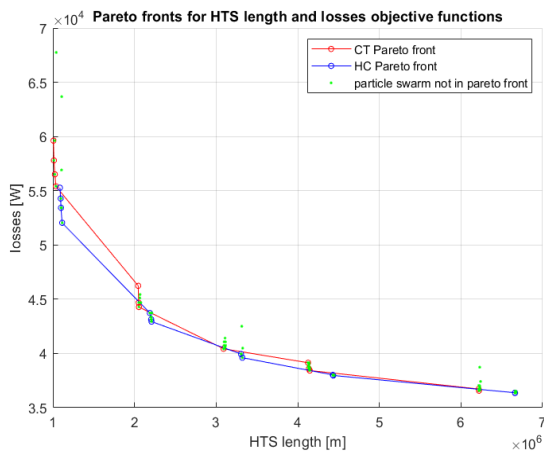


Figure 3: Pareto front for losses and HTS tape length

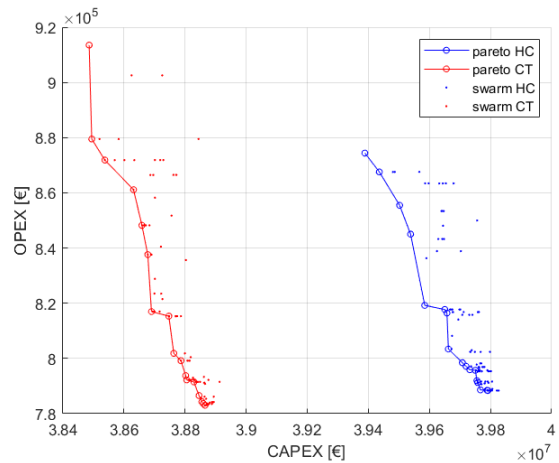


Figure 5: Pareto front for OpEx and CaPex

Performing the final optimizations, which take into account as optimization variables the twist angle (α), the former tube diameter and the HTS tape width, and separating the two fronts according to the type of inner tube, Figures 3 and 4 are obtained.

The result obtained by defining as objective functions the length of the HTS tape and the annual losses is illustrated in Figure 3. Its price constitutes up to $\frac{3}{4}$ of the total investment cost, so it is a good estimate of the cable price. The solution obtained is a Pareto front that can be divided into two, depending on the type of pipe used.

By defining CapEx and OpEx as optimization variables, there is only one optimal front, the one constituted by CT type cables. This is due to the translation of the Pareto front of the HC cables to the right, due to the multiplication of the cable length by its price, which enlarges proportionally the price differences between both fronts.

5. Conclusions

The optimum cable is of the CT type. Moreover, the only usable nominal diameter is 50 mm, for both types of former type and for all possible configurations.

A "step-by-step" approach has allowed to understand the impact of the variation of each parameter individually, starting from a known result. The evaluation of the sensitivity of the model to each variable has proved useful, especially to separate the Pareto fronts according to the former type and to understand why the final solution is formed only by the CT points of the former type.

The Pareto criterion has proved effective in reflecting the antagonistic nature of the two objective functions. The choice of the MOPSO algorithm to arrive at an optimal solution seems appropriate, since the algorithm in this case study always converges.

Clear and interpretable results have been achieved, as well as a highly parameterized algorithm that allows it to be improved and updated as knowledge of this technology improves.

6. Referencias

- [1] Connaissance des Énergies: 'Combien de pertes de ligne en France'. (2017). Retrieved from Available: <https://www.connaissancedesenergies.org/electricite-a-combien-s-elevent-les-pertes-en-ligne-en-france-140520>
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Abbreviations Index

SC	Superconducting
HTS	High-Temperature Superconducting
AC	Alternate Current
DC	Direct Current
HVDC	High-Voltage Direct Current
OR	Outer Radius
IR	Inner Radius
LN2	Liquid Nitrogen
HC	Hollow Conductor
CT	Corrugated Tube
MOPSO	Multi-Objective Particle Swarm Optimisation
CAPEX	Capital Expenditure
OPEX	Operation Expenditure
YBCO	Yttrium-barium copper oxide
DN	Nominal Diameter

Capítulo 1. INTRODUCTION

1.1 MOTIVATION

The demand for energy transmission is growing strongly, especially due to the electrification of many processes. In addition, renewable energy sources have been deployed in the last decades in order to reduce the dependence to more polluting energy sources. As a result, there is a clear need to upgrade and expand the electric grid but this challenged by environmental questions and the public community affected by these extension plans. It seems therefore more essential than ever to develop new technologies that allow power transmission over very long distances that suit all stakeholders while minimizing losses.

In this context, the use of superconducting materials for power transmission seems necessary. Indeed, conventional cables are resistive in nature and therefore present losses by Joule effect. These losses are estimated at 20 TWh, i.e., 6% of the losses of the French network (Connaissance des Énergies: ‘Combien de pertes de ligne en France’, 2017). Superconducting cables, with zero electrical resistance and therefore no Joule losses, are a solution to this problem.

Moreover, local residents impacted by the transmission lines expansion demand for the use of underground cables and their protests have already led to cancellation of some overhead line projects in Germany, France and Spain (Heiko, et al., 2016). Indeed, overhead transmission lines cause several issues: visual impact, destruction and alteration of the natural landscape, possible impact on health, environmental impact, and reduction of the value of property (Heiko, et al., 2016). All these obstacles for specific projects are identified in the Priority Interconnection Plan (PIP) by the European Commission (European Commission, 2007). The extent of the visual and economic impact can be easily appreciated thanks to the figure 1 (Heiko, et al., 2016) which shows the amount of free area necessary to install a line. For each HVDC overhead transmission line, 50 km² of landscape per kilometer length of cable are compromised (Heiko, et al., 2016). Superconducting cable systems could

solve these problems as they can be buried underground and have a small diameter. Public acceptance would reduce project approval times and low-diameter underground cables could reduce environmental impact.

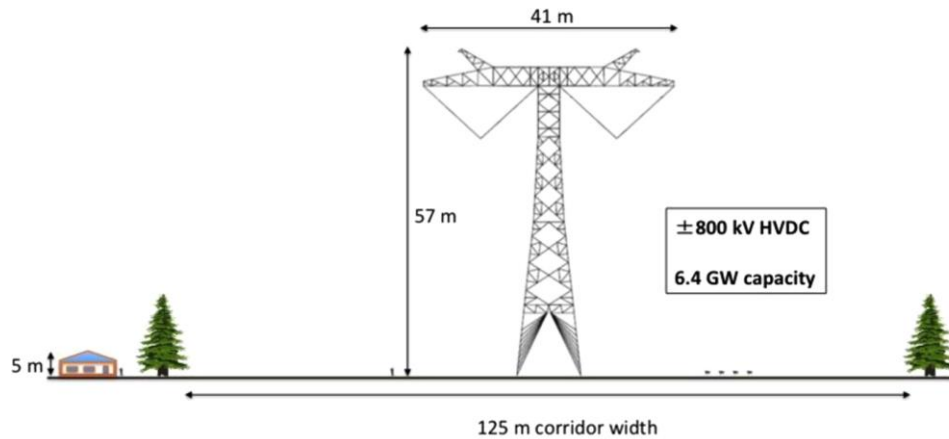


Figure 1: corridor needed for an overhead transmission line (Heiko, et al., 2016)

Despite the good knowledge of this technology, commercial applications remain limited partly due to a lack of standards concerning their design, construction, commissioning, and operation. Superconducting transmission lines are still considered to be in research state (ENTSO, 2018). Many efforts have been made to standardize superconducting wires and their feasibility has already been proven by theoretical and practical means. For example, in (Kottonau, 2019), the authors evaluate the use of superconducting 380 kV cables. However, this study only one conventional cable with one superconducting cable configuration having a predetermined configuration. We propose to go further and to seek for the optimal configuration for each situation.

The goal of this study is therefore to find the optimal superconducting cable configuration, for a given test case. The optimal configuration will minimize the capital expenditure and the operational expenditure while respecting the operational constraints of the cable (temperature and pressure).

1.2 SUSTAINABLE DEVELOPMENT GOALS (SDGs)

The need to limit electrical energy losses in its transportation arises from a desire to minimize costs and improve energy efficiency in order to align with sustainable development objectives.

These objectives, known as Sustainable Development Goals (SDGs) or Global Goals, must be central to the focus of engineering projects. They mark the evolution of our society towards better living conditions. They are interlinked and integrated with the global challenges we face every day, as poverty, inequality, climate change... In this project there is a contribution to a variety of them in a greater or lesser degree.

Goal 7: “Affordable and non-polluting energy”. One of the targets of this goal is "double the improvement in energy efficiency", which is the clear objective of this work, which seeks to minimize electrical energy losses. As these cables favour the expansion of the power grid, thus contributing to the “universal access to modern energy” goal. In addition, research is favoured, proposing a well-defined framework for the economic-technical study, which can be completed and improved in future research. Moreover, it is important to underline that minimizing losses minimizes the final carbon footprint produced when creating energy, since at the same carbon footprint, more energy will be obtained after its transport than if conventional cables were used.

Goal 9: “Water Industry, Innovation and Infrastructure” In this project we use cutting-edge technology and maximum efficiency to advance towards energy sustainability. Not only is the optimization of a boiler studied, but it is done with the use of the most recent and innovative technologies and materials in the sector, such as superconducting materials.

Goal 12: “Responsible consumption and production”. This goal is met by making a more responsible use of the natural resources used for energy production. By reducing losses, more energy is used and therefore the use of the resources employed is optimized.

“Goal 15: Life on land”. This goal is clearly pursued, since it seeks to end deforestation by reducing the corridor needed to build an overhead line. Thus, the following objectives are met: ensure conservation of mountain ecosystems, protect biodiversity and natural habitats.

Capítulo 2. STATE OF THE ART

During the last decades, the scientific community has been working on superconducting transmission lines and making them cost competitive. Some superconducting cables have already been commissioned. In practice, these lines consist of a liquid-nitrogen-cooled superconducting cable housed in a cryostat, but there are numerous possible architectures

In this document, we consider only two specific HTS AC cable architectures. They are strongly inspired from the work of Kottonau (Kottonau, 2019), together with the case study. The sizing code is adapted and improved from the one developed by Carmen Sanz-Martin (Garrido, 2021)

2.1 COMMERCIALIZATION OF SUPERCONDUCTING MATERIAL

Superconducting materials' current density vary between 1,000 and 10,000 A/mm². In contrast, conventional cable systems (copper and aluminium based) have current densities of 1 to 5 A/mm². The discovery of high-temperature superconducting (HTSC) conductors in 1986 was a major scientific breakthrough. It opened the possibility of applying this technology on a large scale, at a lower cost. These materials have zero resistivity when operated below their "critical temperature". Since then, the idea of making superconducting devices is becoming more and more real, tangible and, above all cost competitive. This is also partly due to the recent cost reduction of the HTS conductors, thanks to economy-of-scale. They are often manufactured in form of tapes, making them useful for a wide range of operations, as electric generators or magnetic resonance imagery (Heiko, et al., 2016). On the other hand, cryogenic envelopers are already used for liquified natural gas transfer and are therefore commercially available. The fact of using materials easily found in the market

makes this type of lines a standardizable project and therefore, applicable in large industrial projects at a reasonable price.

2.2 COMMISSIONED CABLES

As a result of the discovery of HTS, several HTS cables have already been commissioned worldwide and are in operation and fully integrated in the electric grid, but their length is low (few hundred meters) as well as their capacities (Heiko, et al., 2016). Some of them stand out among the others like *AmpaCity project* (Essen, Germany) and *Long Island Power Authority (LIPA)* (New York, USA). *AmpaCity project* is the largest SC system, going up to 1 km length, connecting two substations since 2014. It transports 40Mw and operates at 10 kV (Merschel, Noe, Nobl, & Stemmler, 2013). LIPA project was born in 2008 and consists of a 600-meter-long underground SC cable of 574 MW and connecting a power substation to an overhead line (EPRI, 2012). An overview of the commissioned HTS AC cables has been given in (Garrido, 2021)

2.3 CABLE SYSTEM ARCHITECTURE

Superconducting cables have 3 main components: the cable core, the cryostat and the terminations. The cable core and cryostat can be arranged in several ways, leading to a variety of cable system configurations. This system is cooled with liquid nitrogen (LN₂), that flows within the cable.

2.3.1 POSSIBLE CONFIGURATIONS

Superconducting cables operate at cryogenic temperature, which requires them to be used in a cryostat. The possible cable configurations are numerous and, today, there are two main families of configurations: warm and cold dielectric.

In the warm dielectric configuration, the dielectric insulator, cable screen and sheath are outside the cryostat, therefore at room temperature. The advantage of using these cables is

that they can be equipped with the insulator of conventional cables and the dielectric losses do not get into the cooling medium.

In the cold dielectric configuration, all the components are kept inside the cryostat. Dielectric losses should therefore be compensated by the cooling system. A shielding layer can be added to avoid any external magnetic field. In the configuration of cold dielectric cable, there are also 3 different types of configurations: 1-phase-1-cryostat, 3-phase-1-cryostat and 3-phase concentric

The 1-phase-1-cryostat, also known as single core cable, consists of one cable core housed in one cryostat. To form a 3-phase system, 3 single core cables are required. It is the configuration that is usually used at high voltage (110 kV in a 3-phase system).

The 3-phase-1-cryostat configuration, or three core cable, consists of three cable cores housed in a single line cryostat single. It allows the cable to have a smaller diameter and to therefore use a less amount of superconducting material in each phase but needs a shield for each phase, so the amount of HTS is still great. It is used allows fewer values of voltage, going from 30 to 100 kV.

Finally, the 3-phase concentric cable is, as the name implies, a cable system configuration where the cables are built one on top of the other. The line cryostat is unique and envelopes the last cable layer. It is the configuration that uses the lesser amount of HTS tape, and it is used in low voltage applications (10 to 50 kV).

Figure 2 shows the three possible cold dielectric cable system configurations. (Kottonau, 2019)

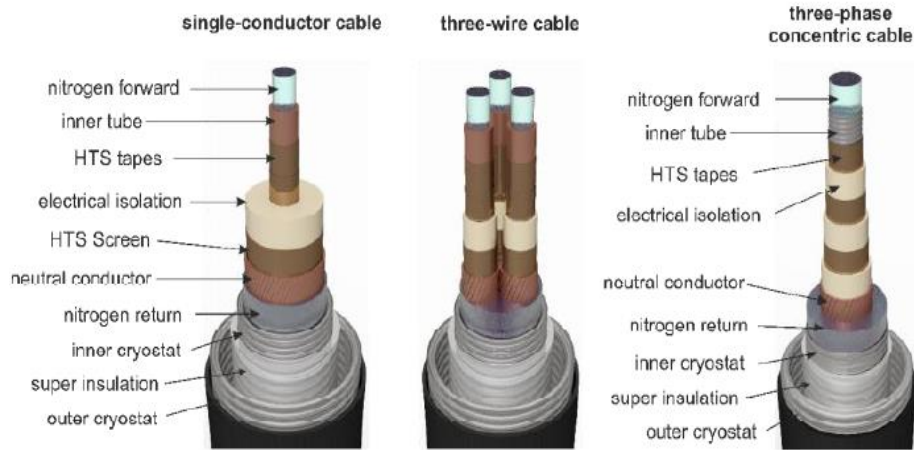


Figure 2 Available cold dielectric cable architectures (Kottonau, 2019)

2.3.2 COOLING SYSTEM

To ensure the proper operation of the cable, it must operate at specific temperature and pressure conditions, so that the liquid nitrogen (LN₂) remain liquid to circulate in the line cryostat and cool the cable core. The minimum operating temperature of the nitrogen is therefore set at 68 K to avoid solidification. To avoid boiling, the maximum temperature is set at 78 K and the minimum pressure at 3 bar. The maximum pressure allowed on the internal and external cryostat is 20 bar. Thus, for this study, the maximum operating pressure is set at 15 bar. Therefore, the operating range is limited by the blue area in Figure 3.

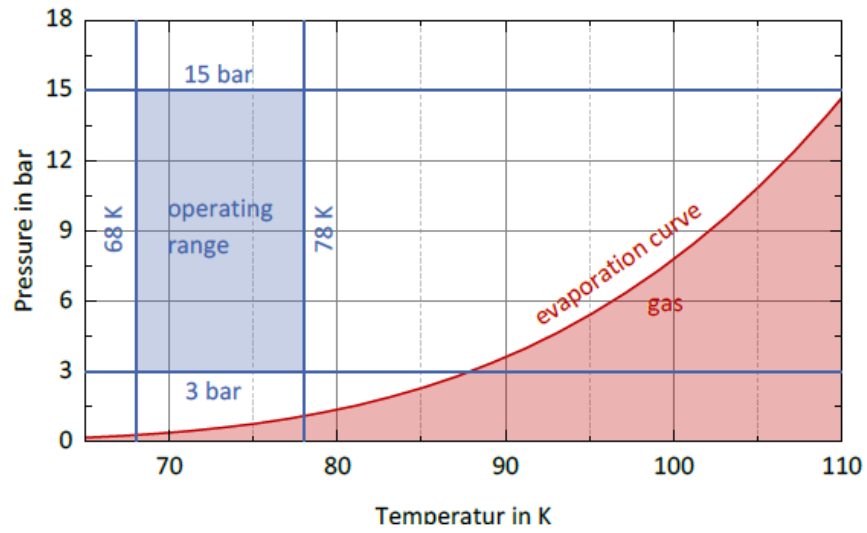


Figure 3 Operation range (Kottonau, 2019)

Capítulo 3. PROJECT DEFINITION

3.1 PROJECT OBJECTIVES

The aim of this project is to find the techno-economic optimal superconducting cable, i.e. the one with the minimum costs, in terms of installation and operation, for a given test case.

This work will be based on a specific cable configuration, i.e., a cable subject to precise specifications and with a specific architecture. The parameters that will be varied will act on certain characteristics of each element that composes that cable architecture, in order to satisfy those specifications with the lowest possible cost. As stated before, the cable configuration will be the one summarised in Kottonau's and Martin-Sanz's papers. In his work, Kottonau makes an in-depth study of a specific cable configuration, the 3-phase cable system with a one-sided cooling concept with a hollow core conductor form and a diameter of 50mm that satisfy a set of specifications detailed on Table 1. The cable on which the optimization in question is to be performed will be based on this description and is summarized in Martin-Sanz's work. This cable is inspired by all the state of the art explained in section 2 and is detailed in sections 3.1.1 and 3.1.2. The techno-economic analysis that this paper aims to complete is detailed in section 3.1.3.

Rated current per system	3600 A
Rated voltage	420 kV
Short-circuit data	63 kA for 300 ms
Route length	3200 m
Cable concept	Single conductor with two systems (with copper stabilization)
Cooling concept:	one-sided cooling concept

Table 1: case study specifications (Kottonau, 2019)

3.1.1 CABLE ARCHITECTURE

3.1.1.1 Cooling System

“One-sided cooling concept” refers to the way in which the liquid nitrogen flows in the former. The liquid nitrogen must flow through the three phases, and it needs to come back to the cooling system to be refrigerated again. The cold nitrogen flows through two phases and returns in the third one. As a result, the mass flow is doubled in that phase. As the LN2 flows in the cable and cools the conductor, its temperature increases. The third phase will therefore be the critical one, as its temperature is higher than at the beginning and, consequently, has less cooling potential. This is better detailed in Figure 4.

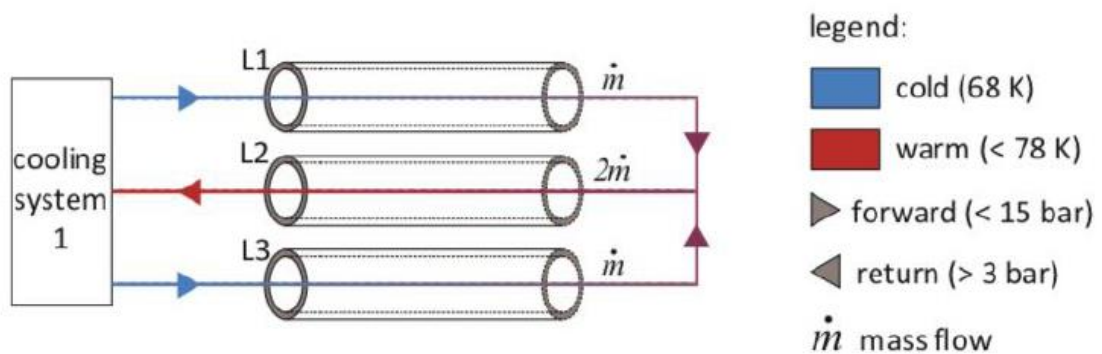


Figure 4: Cooling concept (Kottonau, 2019)

3.1.1.2 Cable Core

As stated in section 2.3, a superconducting cable is made up of a cable core housed in a cryostat and that cable core consists of several layers: former, HTS conductor, dielectric insulation, HTS shield and neutral conductor.

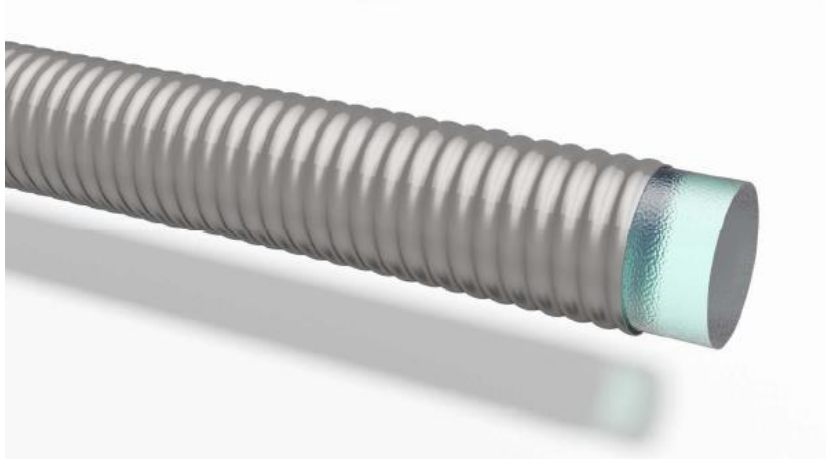


Figure 5: corrugated tube former concept (Noe, 2017)

The former is a hollow tube that is located in the lower layer of the cable. It serves as a mechanical support for the rest of the cable and the liquid nitrogen circulates inside it. In the event of a short circuit, this component would carry part of the current (Kottonau, 2019). In this study, two types of formers will be considered: Hollow Conductor (HC) former and the Corrugated Tube (CT) former. The latter is depicted in figure 5.

The HTS conductor layer is composed of yttrium barium copper oxide (YBCO) tapes (Figure 6) wound around the former with a certain twist angle α . To cover the whole surface of the former, the tapes will be placed next to each other and will also be superimposed in several layers in order to transport the required intensity. Figure 7 explains how the tapes are placed next to each other to cover the surface of a layer and the figure 8 how the tapes are wound around the cable and what α represents. The required number of tapes will therefore depend on the width and critical current of the tapes as well as their twist angle.

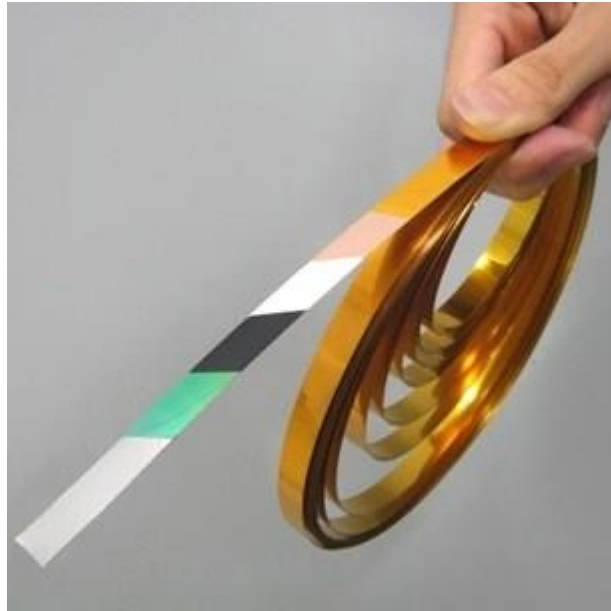


Figure 7: HTS tape (Fujikura)

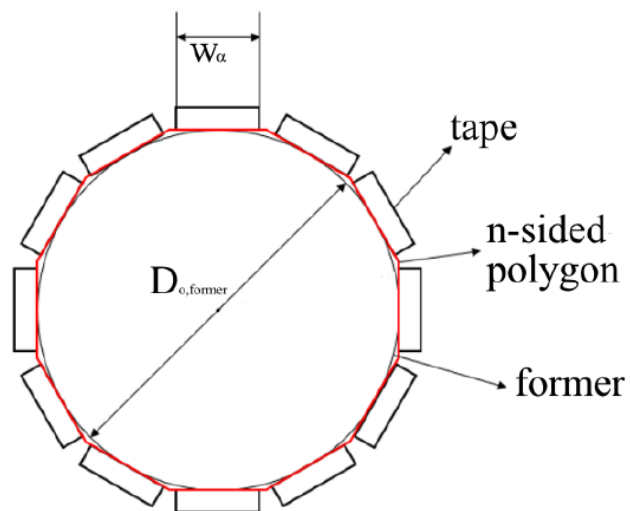


Figure 6: Schematic representation of the tape's disposal around the former
(Garrido, 2021)

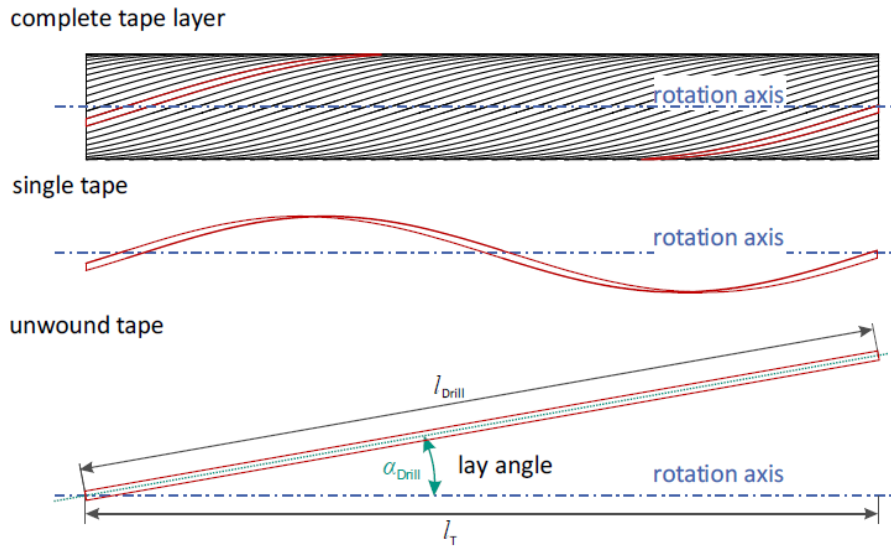


Figure 8: Schematic representation of the disposal of an HTS tape and the twist angle (Kottonau, 2019)

An electrical insulation layer is required. It is made out high-density polypropylene (Tyvek) (Kottonau, 2019).

The HTS shield layer serves as a magnetic insulator and is composed of at least one layer of HTS tapes, placed on top of the electrical insulator. Each tape is connected at both ends to another tape so that the electric current induced in each tape is of equal magnitude and opposite direction, cancelling the electromagnetic field outside the cable. (Masuda T, 2015)

Finally, a neutral conductor layer, made up of copper tapes forming one or several layer, is used as a structural support and to carry fault currents.

All of this is then housed in a cryostat that prevents from any heat exchange from the outside and repeated three times to create a 3-phase system. Figure 9, Figure 10 and Figure 11 depict the above-described geometry, for HC and CT former types.

It should be noted that the cable design changes depending on the former type used. Thus, an HC type cable will have 12 layers and CT type 11. This is better detailed in figures 10 and 11, where it is shown that HC tube requires an additional copper layer, made of copper wires.

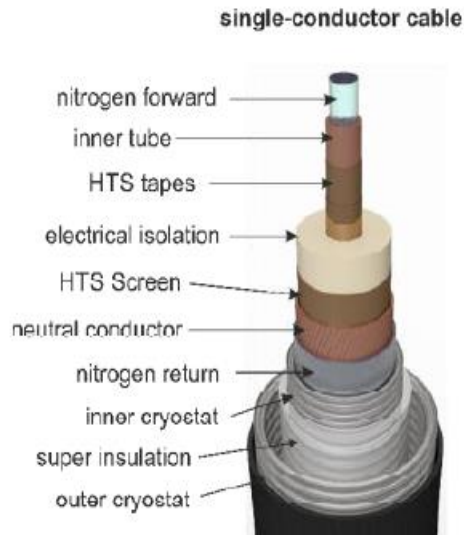


Figure 9: final cable layout

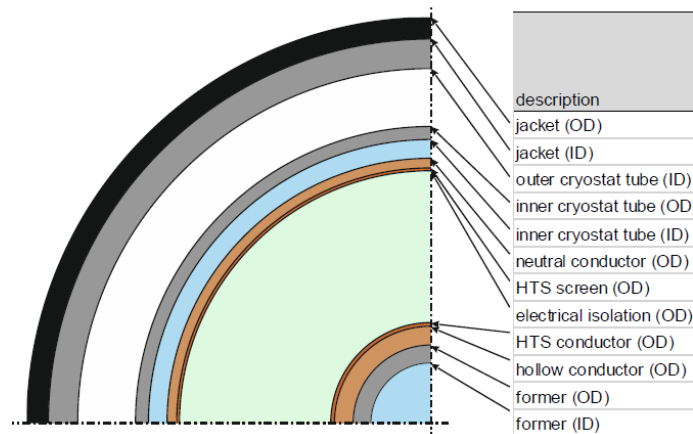


Figure 10: quarter section of HC former type SC cable with layers description

(Kottonau, 2019)

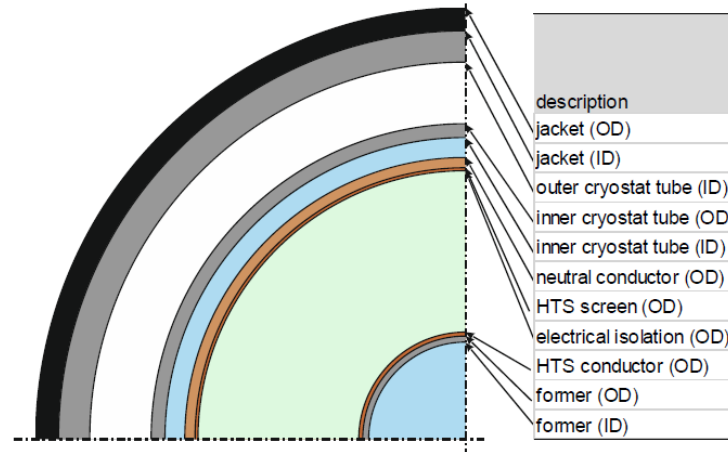


Figure 11: quarter section CT former type SC cable with layer description
(Kottonau, 2019)

3.1.2 TECHNO-ECONOMIC ANALYSIS

In (Kottonau, 2019) the authors calculate the CapEx for a specific cable configuration and a given test case the hollow conductor former of 50 mm diameter and 4mm HTS tapes. This is detailed in Table 2. This study aims to generalise this table to other cable designs.

Resources	Low costs T€	High costs T€	Specification
Superconducting cable	20,690	34,520	
Material costs HTS	9,320	18,640	YBCO -SC tape 4 mm, $I_c=150$ A, 25-50 €/kA/m, 2 system 2485, 2 km
Insulation material Tyvek™	815	1,548	DuPont Tyvek™, 100 m foil 75 g/m ² , cost 20-38 €/kg, density 340 kg/m ³ , volume per cable 20.1 m ³ , mass per cable 6800 kg, cost per cable 258 k€
Line cryostat with weld coupling	8,674	9,830	CryoTherm, rigid cryostat tube DN 100, 450-510 €/m, 12 m single length, 6 x 3200 m
Production costs	1,881	4,503	Assumption: Labour costs correspond to approx. 10-15% of material costs
Chiller	4,400	5,750	
Cryocooler	4,000	5,000	Air Liquide, 4 units TBF-175, cooling line 16.5 kW @ 77 K, € 1.0–1.3 million per unit
Chiller equipment Sets	400 3,100	750 4,650	Assumption: Accessories costs correspond to approx. 10-15 % of the cryocooler costs.
Termination	1,200	1,800	Nexans, single-phase terminations, 100-150 T€, 6 pieces (internal communication)
Sleeves	1,900	2,850	Nexans, sleeves, 50-75 T€/piece, each approx. 500 m one sleeve (internal communication), 38 pieces
Civil engineering	3,040	4,480	Assumption: civil engineering costs halved, with approx. halved excavation costs
Cable trench	1,120	1,600	350-500 k€/km [Osw07]
Wiring duct	1,600	2,400	500-750 k€/km [Osw07]
Laying of cables	320	480	100-150 k€/km [Osw07]
Total system costs	31,230	49,400	

Table 2: economic analysis for the given case study (Kottonau, 2019)

3.2 METHOD

To carry out the optimization, the HTS cable sizing model developed at GeePs laboratory will be coupled with an optimization algorithm

This section details how the optimization variables (parameters to be optimized), the objective functions and the optimization constraints have been defined. As the optimization

algorithm is metaheuristic, the solution obtained is a local optimum that might be difficult to be interpreted. In an attempt to understand the solution, we will start from a simplified problem for which the solution is known. Then we will complexify the problem step by step, and compare the results with the previous step.

Given the contradictory nature of the two chosen objective functions, the Pareto front that represents the set of optimal solutions will be systematically presented. The decision maker will have to choose one point of the Pareto front.

3.2.1 OPTIMIZATION ALGORITHM

3.2.1.1 MOPSO

The algorithm used for the optimization of the cable system is a well-known metaheuristic algorithm called MOPSO.

“Loosely speaking, heuristic means to find or to discover by trial and error. Here meta-means beyond or higher level, and metaheuristics generally perform better than simple heuristics.” (Yang, 2011). The provided solution will therefore not be a result of a deeper understanding of the system, but of the coupling of it with an iterative algorithm that looks for the solution of a “black-box problem”.

This algorithm optimizes a problem from a population of candidate solutions, called a particle swarm, by moving these particles through the search space according to mathematical rules that take into account the position and speed of the particles. The motion of each particle is influenced by its best local position found so far (“individual best” or “cognitive acceleration”), as well as by the best global positions found by the other particles as they traverse the search space (“swarm best” or “social acceleration”), its inertia and a random factor. This equation motion is described in Equations 1 to 2. (Khandelwal, 2021)

$$\left\{ \begin{array}{l} v_i = W v_i + c_1 r_1 (P_{best,i} - x_i) + c_2 r_2 (g_{best} - x_i) \\ x_i = x_i + v_i \end{array} \right. \quad \begin{array}{l} (1) \\ (2) \end{array}$$

where

v_i	Velocity of the i^{th} particle	$P_{best,i}$	Personal best of the i^{th} particle
x_i	Position of the i^{th} particle	g_{best}	Global best
r_1, r_2	Random numbers	c_1, c_2	Acceleration coefficients
W	Inertia weight		

This dynamic will cause each particle to converge to a global minimum, exploring a large part of the search space. The theoretical basis of this approach is to quickly converge the particle cloud to the best solutions. The operation of this algorithm is described in Figure 12. The version used is that of Judicaël Aubry, dated September 25, 2013. (Aubry, 2011)

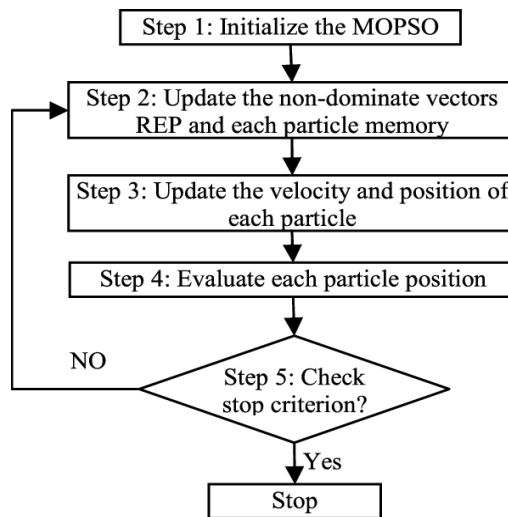


Figure 12: MOPSO optimisation diagram (Yi Wang, 2018)

3.2.1.2 Pareto front

MOPSO aims at minimizing the value of the objective functions for all particles, while respecting the constraints. The result of this optimization is a swarm of particles. In order to choose the “best” particles of this swarm, i.e. those which minimize the objective functions, only those which are optimal in the sense of Pareto (Pareto optimal) will be retained.

The optimum in the sense of Pareto can be defined as "a situation in which the satisfaction of one individual cannot be improved without reducing the satisfaction of another person" (Ministère de l'Economie). antagonistic objectives can thus be taken into account simultaneously. The Pareto front, i.e., the set of Pareto optimal particles for a bi-objective problem, is represented in Figure 13.

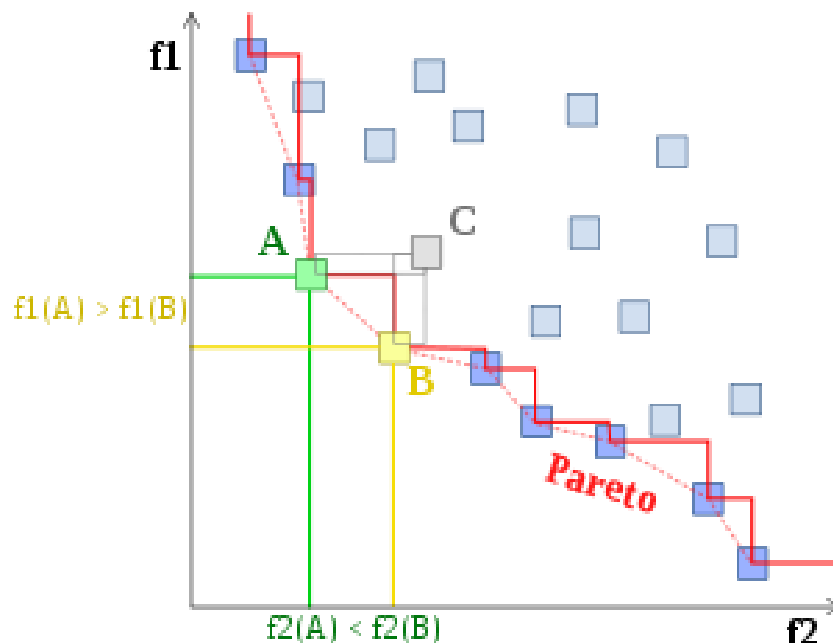


Figure 13: Pareto front on bi-objective function (Lyes Tighzert, 2018)

3.2.1.3 Implementation of the algorithm

The bi-objective optimization problem is formulated as:

$$\left\{ \begin{array}{l} \text{minimize } f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \quad (3) \\ g(x) \leq 0 \quad (4) \\ x = (x_1, x_2, \dots, x_n) \in D^n = [lb_1, ub_1] \times [lb_2, ub_2] \times \dots \times [lb_n, ub_n] \quad (5) \\ y = (y_1, y_2, \dots, y_m) \in \mathbb{R}^m \end{array} \right.$$

The method for choosing the variables of the optimization variables x and their domain D is explained in section 3.2.2 and the objective functions f_1 and f_2 are detailed in section 3.2.4. Finally, the constraint function $g(x)$ is the one that rejects infeasible cable configurations, those with operating points, outside the limits established in Chapter 2 and visible in Figure 3. This is detailed in section 3.2.4.

3.2.2 DEFINITION OF THE OPTIMIZATION VARIABLES

First, we need to define the optimization variables. The difficulty here is related to the larger number of parameters. A selection must be made considering expert knowledge about the technical and economic feasibility of modifying each parameter.

The parameters that were considered as optimization variables are those listed in the specifications defined by Kottonau (Table 1) and those related to the geometry of the cable design described in the thesis of Martín-Sanz (Garrido, 2021). In the following list, we discuss each one of them and explain why they were selected or not as variables for the optimization:

- **Length of cable:** It is not considered as an optimization variable since it is defined in the specifications of the case study.
- **Nominal voltage, rated current, frequency:** They are not considered as optimization variable since they are defined in the specifications of the case study. It could be relevant to change the nominal voltage, the rated current and the frequency. A modification of the nominal voltage and rated current would require the use of transformers, which are not considered in this study. The modification of the frequency would require the use of an AC/AC converter, which is out of the scope of this thesis.
- **LN2 mass flow:** To change the LN2 mass flow, a cryogenic pump model would be needed. This is out of the scope of this thesis.
- **Thickness of the mantel layer and neutral layer:** They are assumed constant since their design is not expected to vary much for a given rated current.
- **Diameter of the former tube:** this parameter can take as value 32, 40 and 50mm according to (Kottonau, 2019). Kottonau reported only results considering a DN equal to 50 mm. This is probably because this is the only DN leading to a feasible cable configuration for the set of parameters considered in that study (see Figures 6.4 and 6.5 from (Garrido, 2021)). We will explore here other set of parameters and conclude whether other cable DN are possible
- **Forming concept:** There are two types of formers, the hollow conductor (HC) and the corrugated tube (CT). Kottonau reported mainly the results considering the HC former. We will explore both types of former and compare them
- **Twist angle α :** Kottonau fixed the angle at which the HTS tape is wrapped around the former (twist angle) at 15 degrees. We consider that it is technically feasible to realize a cable with a twist angle varying between 0 and 30 degrees.
- **Width of the superconducting tape:** tapes are commercially available in different width. Therefore, the width of the HTS tape is considered as an optimization variable. Note that the tape critical current depends on the tape width. The available tape widths and corresponding critical current can be found on the manufacturer's website (Superpower Inc.). They are summarized in Table 3. Considering that the tape

characteristics are inhomogeneous along the tape length, we consider a current margin. The data of Table 4 constitute, from our point of view, a better representation of today's materials available on market. Nevertheless, the data of Table 3 could also be considered for future works if some improvements were done in this field.

Tape width [mm]	2	3	4	6	12
Critical current [A]	75	112.5	150	225	450

Table 3: characteristics of the superconducting tape (Superpower Inc.)

Tape width [mm]	2	3	4	6	12
Critical current [A]	50	75	100	150	300

Table 4: characteristics of the superconducting tape with security factor

3.2.3 DEFINITION OF OBJECTIVE FUNCTIONS

We will proceed in 4 steps. Each step will have its own optimization problem.

For the steps 1 to 3, we consider the minimization of the HTS tape length and of the HTS losses. The HTS tape length is a proxy for the capital cost. The HTS losses is a proxy for the operation cost. Note that the tape length and losses are technical indicators: we are performing here a technical optimization of the cable system.

For the step 4, we consider the minimization of the CapEx and of the OpEx. Note that the CapEx and OpEx are economic indicators: we are performing here a techno-economic optimization of the cable system.

3.2.3.1 OPEX

For the *OpEx*, the losses first the sum of the annual losses in the cable and will be replaced by the cost of annual losses, so the same cost multiplied by the cost of electricity, so in euro, which is more consistent with the economic study conducted.

$$Losses_{currentlead} = Losses_{th} + Losses_e \quad (6)$$

$$Losses_{annual} = Losses_{dielectric} + Losses_{cryostat} + Losses_{currentlead} + Losses_{termination} \quad (7)$$

$$OpEx = Losses_{currentlead} \cdot c_{elec} \quad (8)$$

where

c_{elec}	Cost of electricity [€/Wh]
$Losses_{th}$	Current lead thermic annual losses [€/Wh]
$Losses_e$	Current lead electric annual losses [€/Wh]

3.2.3.2 CAPEX

The CapEx is split into fixed costs (CF) and variable costs (CV)

$$CAPEX = CF + CV \tag{9}$$

where

- CF Fixed costs [€]
- CV Variable costs [€]

The fixed costs CF are those that don't vary with the amount of HTS tape used, nor with the diameter of each layer. The values of these components will be directly taken from Table 2 (Kottonau, 2019). These are:

- Line Cryostat With Weld Coupling
- Cryocooler
- Chiller Equipment
- Termination
- Sleeves
- Cable Trench
- Wiring Duct
- Laying Of Cables

Variable costs will be, once again, inspired from Table 2. These are:

- Material Costs HTS: their value will be calculated by the algorithm, adding the amount of HTS tapes from the conductor and HTS shield layer. Its cost is directly proportional to the length of tapes used. Its cost is detailed in equation:

$$Cost_{HTS} = L_{HTS,tot} \cdot P \tag{10}$$

where

- p Price [€/m]

$L_{HTS,tot}$ Total HTS tape length [m]

- Insulation Material Tyvek: considering each layer as a thick hollow cylinder, and using Kottonau's price indications, this layer's costs will be calculated:

$$IR = OR - \delta \quad (11)$$

$$V = \pi \cdot (OR^2 - IR^2) \quad (12)$$

$$Cost = V \cdot \rho \cdot p \quad (13)$$

where,

IR	Inner Radius	[m]
OR	Outer Radius	[m]
δ	Layer Thickness	[m]
V	Volume	[m ³]
$Cost$	Insulation total cost	[€]
ρ	Density	[kg/m ²]
p	Price	[kg/€]

- Production costs: they make up to 10% (lower bound factor) and 15% (upper bound factor) of material costs (Kottonau, 2019) and are calculated

$$Cost = (Cost_{HTS} + Cost_{insul} + Cost_{line}) \cdot c \quad (14)$$

where

$Cost_{HTS}$	Material costs HTS	[€]
$Cost_{insul}$	Insulation Material Tyvek	[€]

$Cost_{line}$	Line Cryostat With Weld Coupling	[€]
c	Factor	[-]

Taking all of this into account, Table 2 can be replaced by Table 5.:

Composant	lower bound cost [M€]	upper bound [M€]	specification
Material			
Material Costs HTS	variable cost	variable cost	25-50 €/kA/m
Insulation Material Tyvek	variable cost	variable cost	20-38 €/kg, density 340 kg/m ³
Line Cryostat with Weld Coupling	8,674	9,83	450-510 €/m
Production Costs	variable cost	variable cost	10-15% of material costs
Chiller			
Cryocooler	4	5	4 units, 1.0–1.3 M€ per unit
Chiller Equipment	0,4	0,75	10-15% of cryocooler costs
Sets			
Termination	1,2	1,8	12 pieces, 100-150 k€/piece
Sleeves	1,9	2,85	50-75 k€ /piece, 38 pieces
Cable Trench	1,12	1,6	350-500 k€/km
Wiring Duct	1,6	2,4	500-750 k€/km
Laying Of Cables	0,32	0,48	100-150 k€/km
Civil Engineering costs	3,040	4,480	Half set costs
Total			
Total fixed costs	22,254	27,560	

Table 5: CapEx calculation by component (Kottonau, 2019)

All in all, a new expression of the lower and upper bound of *CapEx* can be calculated. The equation that represents this cost is the following:

$$CAPEX = [22.254, 27.560] + CV \quad (15)$$

3.2.4 DEFINITION OF THE OPTIMIZATION CONSTRAINTS

The constraints are those that allow to know if the cable configuration is feasible or not. An infeasible cable will have a negative objective function and will correspond to the configurations that have temperatures and pressure of LN2 outside the limits set by in section 2.

$$y_1 = P_{in} - P_{maxLN2} \quad (16)$$

$$y_2 = P_{minLN2} - P_{out} \quad (17)$$

$$y_3 = T_{opminLN2} - T_{maxLN2} \quad (18)$$

$$y_4 = T_{opmaxLN2} - T_{maxLN2} \quad (19)$$

$$y_5 = T_{opminsh} - T_{minHTS} \quad (20)$$

$$y_6 = T_{opmaxsh} - T_{maxHTS} \quad (21)$$

$$y_7 = T_{opmincon} - T_{minHTS} \quad (22)$$

$$y_8 = T_{opmaxcond} - T_{maxHTS} \quad (23)$$

where

$$H(y) = \begin{cases} 0, & y \leq 0 \\ 1, & y > 0 \end{cases} \quad (24)$$

with

$$y = (y_1, y_2, \dots, y_8) \in \mathbb{R}^8$$

where

$y_1 = P_{in}$	Pressure of LN2 at inlet	[Pa]
$y_2 = P_{out}$	Pressure of LN2 at outlet	[Pa]
$y_3 = T_{opmaxLN2}$	Maximal operational temperature for LN2	[K]
$y_4 = T_{opminLN2}$	Mininal operational temperature for LN2	[K]
$y_5 = T_{opmaxsh}$	Maximal operational temperature for HTS shield layer	[K]
$y_6 = T_{opminsh}$	Minimal operational temperature for HTS shield layer	[K]
$y_7 = T_{opmaxcon}$	Maximal operational temperature for HTS conductor layer	[K]
$y_8 = T_{opmincond}$	Minimal operational temperature for HTS conductor layer	[K]
P_{minLN2}	Minimal operational pressure allowed for LN2	[Pa]
P_{maxLN2}	Maximal operational pressure allowed for LN2	[Pa]
T_{minLN2}	Minimal temperature for LN2	[K]
T_{maxLN2}	Maximal temperature for LN2	[K]
T_{maxHTS}	Maximal operational temperature for HTS tapes	[K]
T_{minHTS}	Mininal operational temperature for HTS tapes	[K]

Capítulo 4. ANALYSIS OF RESULTS

In this chapter, we describe the 4 steps carried out so that the reader can follow the method that has been followed.

4.1 STEP 1

First, we test our algorithm on a problem for which we know the solution. We start by testing the problem that was studied manually (without using an optimization algorithm) in Martin-Sanz's thesis (Garrido, 2021) shown in figures 14 and 15.

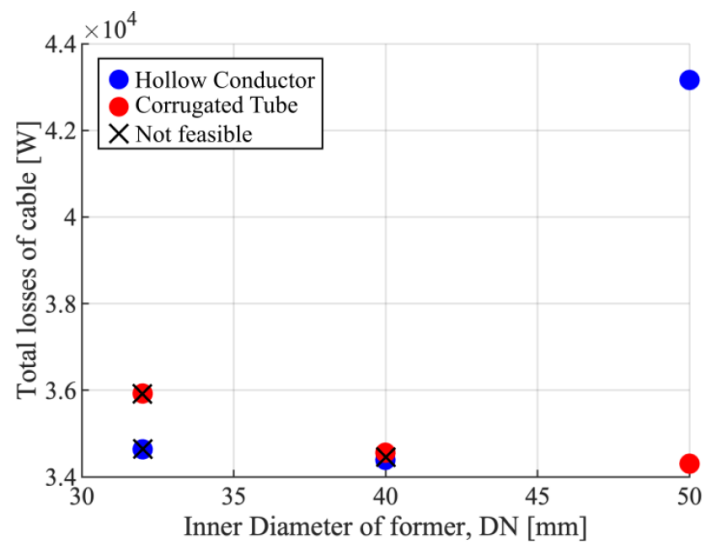


Figure 14: Total losses of system as a function of DN and former type (Garrido, 2021)

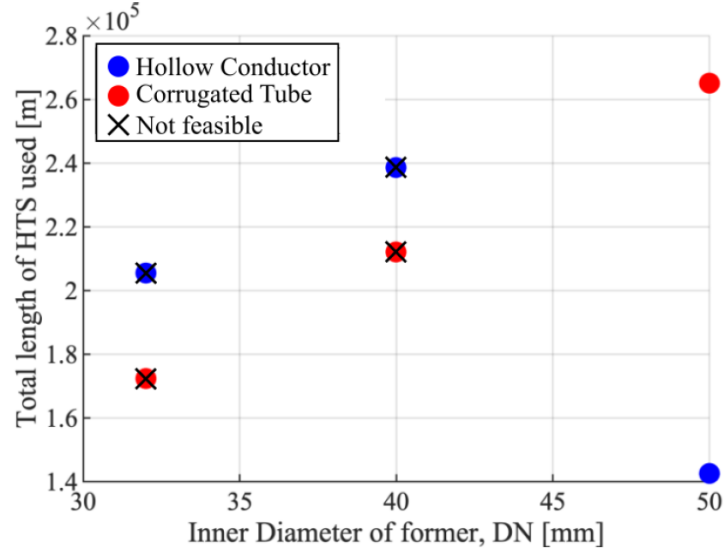


Figure 15: Total length of HTS material as a function of DN and former type (Garrido, 2021)

For the step 1, we will perform one optimization for CT former and one optimization for HC former (the former type is not an optimization variable). The optimization problem of is formulated as:

$$\left. \begin{aligned} & \text{minimize } \begin{bmatrix} \text{length}(DN) \\ \text{losses}(DN) \end{bmatrix} & (25) \\ & DN \in \{32, 40, 50\} \text{ mm} & (26) \\ & H(y) \leq 0 & (27) \\ & y = 0 \end{aligned} \right\}$$

The result is plotted in figures 16 and 17: and it can be seen that length and losses values are similar in both cases. From the manual results, and projecting them on the optimization axes, the diameter of each point of the front can be deduced. From this it can be said that there are points of 3 diameters for the 2 configurations at the front. All 3 diameters are optimal according to the Pareto criterion although not feasible as figures 16 and

17indicate. A smaller diameter implies a shorter cable length in the case of the CT type but not in the HC. In the HC, a diameter of 50 mm implies higher costs than a CT. As for losses, the opposite can be said: a smaller diameter implies lower losses in the case of the HC type but not in the CT type.

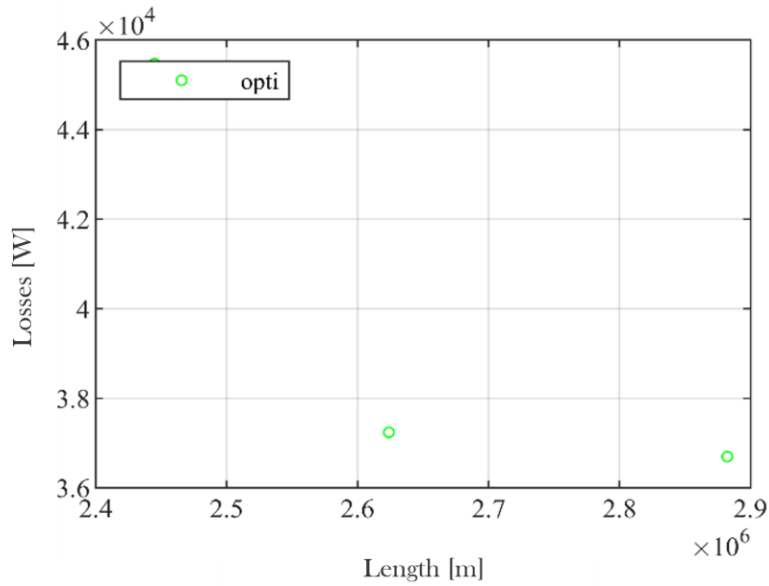


Figure 17: Step 1 Pareto front for HC former type

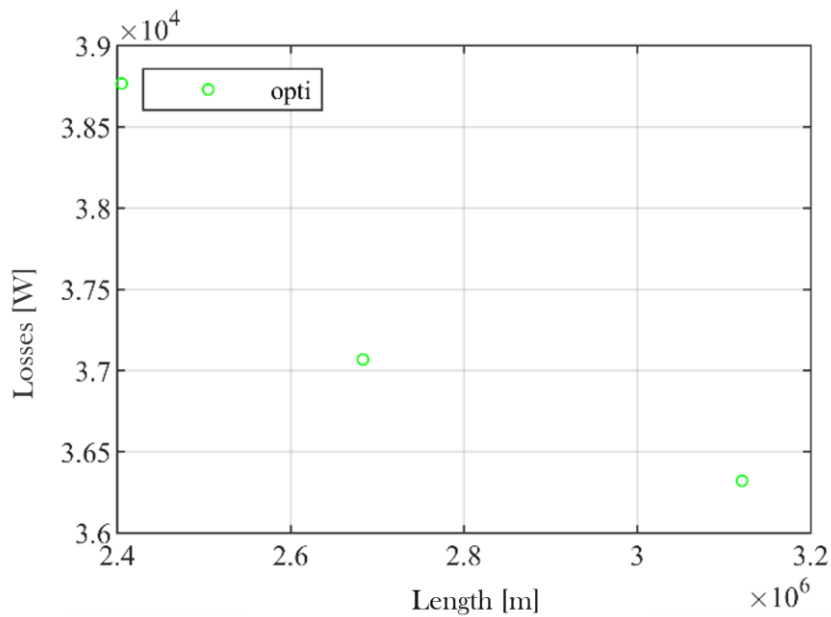


Figure 16: Step 1 Pareto front for CT former type

4.2 STEP 2

For this step, we add the twist angle α to the optimization variables of the problem.

For the step 2, we will perform one optimization for CT former and one optimization for HC former (the former type is not an optimization variable). The optimization problem of is formulated as:

$$\left\{ \begin{array}{l} \text{minimize } \begin{bmatrix} \text{length}(DN, \alpha) \\ \text{losses}(DN, \alpha) \end{bmatrix} \quad (28) \\ DN \in \{32, 40, 50\} \text{ mm}, \alpha \in [0, 30] \text{ deg} \quad (29) \\ H(y) \leq 0 \quad (30) \\ y = \{ P_{in}, P_{out}, T_{opmaxLN2}, T_{opminLN2}, T_{opmaxsh}, T_{opminsh}, \\ T_{opmaxcon}, T_{opmincond} \} \quad (31) \end{array} \right.$$

This step is divided into three steps in order to understand the impact of the new variable and the constraints. For the sake of simplicity, these results will not be shown and the most important conclusions will be explained in the following sections.

4.3 Step 3

For this step, we add the width of the HTS tape to the optimization variables of the problem. As a reminder, the critical current will increase as its width increases.

For the step 3, we will perform one optimization for CT former and one optimization for HC former (the former type is not an optimization variable). The optimization problem of is formulated as:

$$\left. \begin{aligned} & \text{minimize } \begin{bmatrix} \text{length}(DN, \alpha, \text{width}) \\ \text{losses}(DN, \alpha, \text{width}) \end{bmatrix} & (32) \\ & DN \in \{32, 40, 50\} \text{ mm}, \alpha \in [0, 30] \text{ deg}, w \in \{2, 3, 4, 6, 12\} \text{ mm} & (33) \\ & H(y) \leq 0 & (34) \\ & y = \{ P_{in}, P_{out}, T_{opmaxLN2}, T_{opminLN2}, T_{opmaxsh}, T_{opminsh}, \\ & \quad T_{opmaxcon}, T_{opmincond} \} \end{aligned} \right\}$$

The results are shown in Figure 18 and 19. We observe three major features.

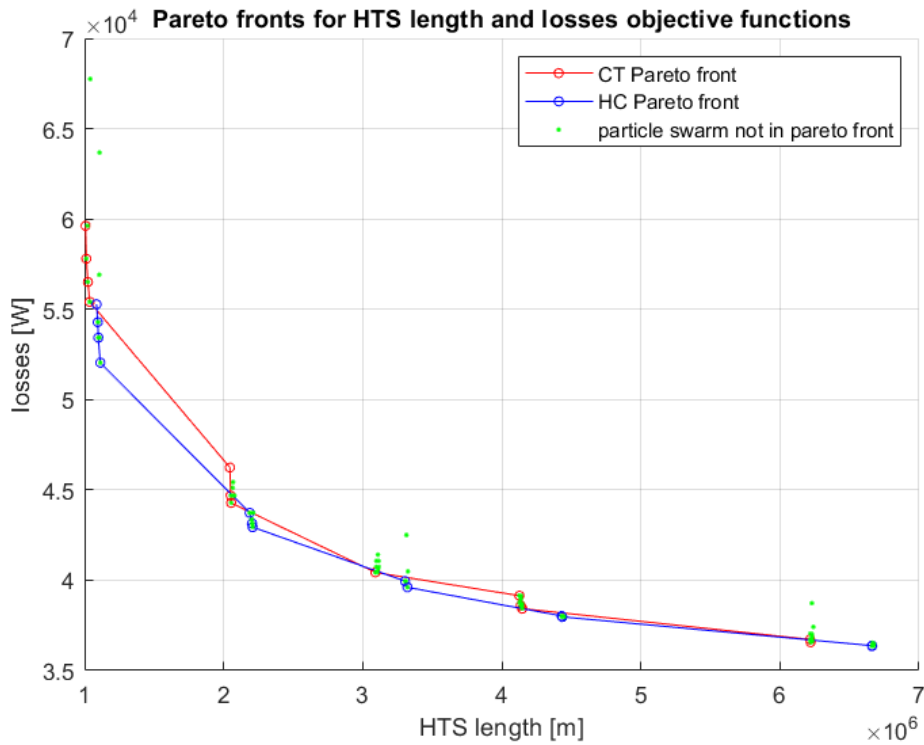


Figure 18: Pareto front for losses and HTS tape length

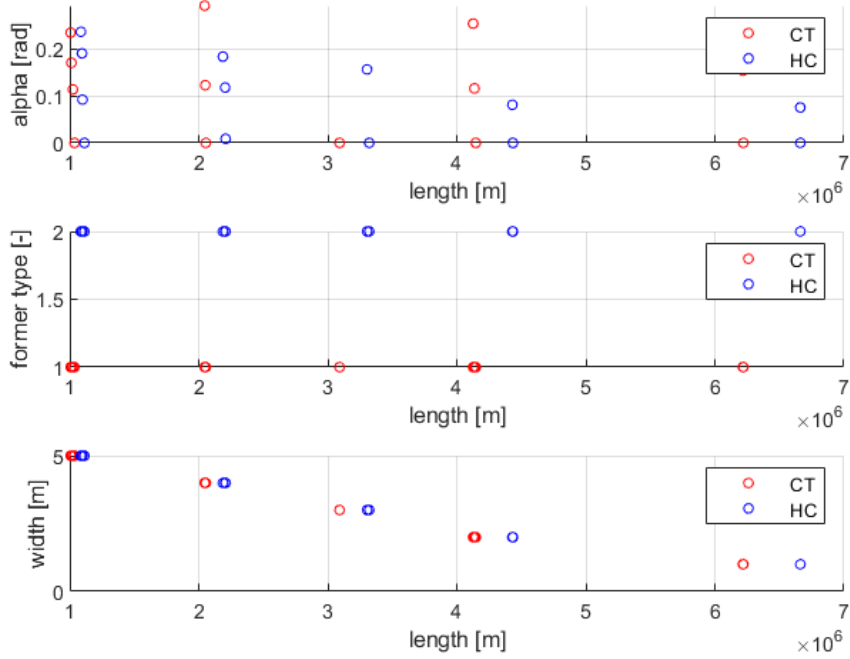


Figure 19: parameters variation with respect to length

First the appearance of a front of optimal solutions, corresponding to the compromise between two antagonistic objective functions, is now obvious. Decreasing the length of HTS wire implies increasing the losses.

Second, the optimal points are discretized and clustered. This can be explained by looking at Figure 19. The length of the tapes increases as the width of this one decrease, which is logical since the area covered by the tape must be the same. A wider tape will be required if the length of the tape is wanted to be low since the area to cover remains the same. Moreover, this increase in the cost function for all configurations with a CT form type (at equal tapes width) also results in a decrease in losses. The results seem to be grouped by tape width, which have a very large impact in both cost functions, and, on a smaller scale, by shape type.

Third, the pareto front for the CT and HC formers are almost identical. But looking closely, we can see that for a given cluster, the HTS tape length is always smaller for the corrugated tube CT than for the hollow conductor HC. From these results, it seems that one could equally chose both the HC for CT former type.

4.4 STEP 4

For this step, we will replace the objective functions by the CAPEX and the OPEX.

For the step 4, we will perform one optimization for CT former and one optimization for HC former (the former type is not an optimization variable). The optimization problem is formulated as:

$$\left\{ \begin{array}{l} \text{minimize } \begin{bmatrix} CAPEX(DN, \alpha, width) \\ OPEX(DN, \alpha, width) \end{bmatrix} \quad (35) \\ DN \in \{32, 40, 50\} \text{ mm}, \alpha \in [0, 30] \text{ deg}, w \in \{2, 3, 4, 6, 12\} \text{ mm} \quad (36) \\ H(y) \leq 0 \quad (37) \\ y = \{ P_{in}, P_{out}, T_{opmaxLN2}, T_{opminLN2}, T_{opmaxsh}, T_{opminsh}, \\ T_{opmaxcon}, T_{opmincond} \} \end{array} \right.$$

The results are shown in Figure 21 and 20.

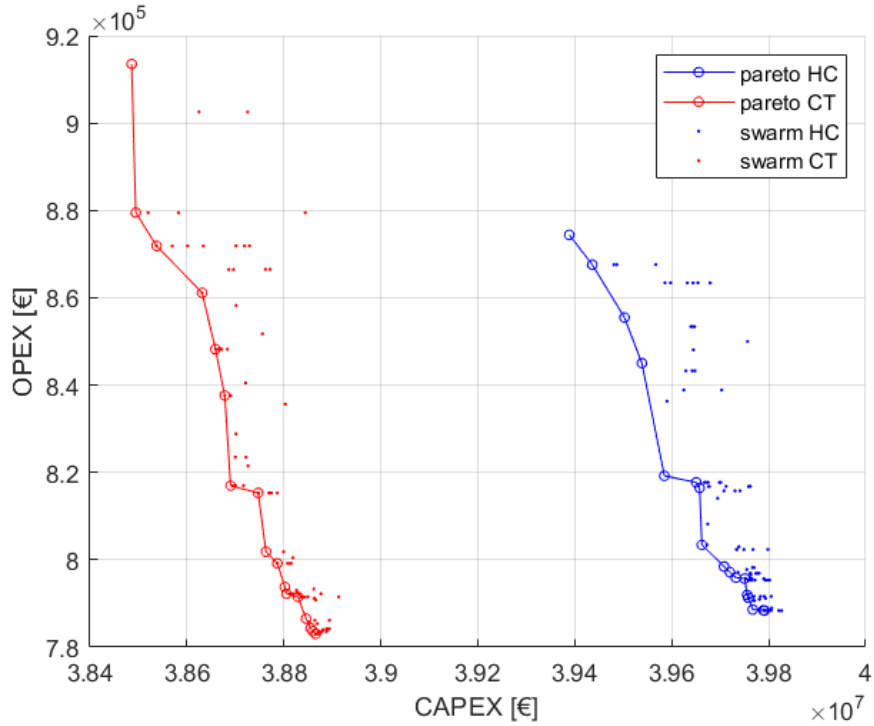


Figure 21: Pareto front for CapEx and OpEx objective functions

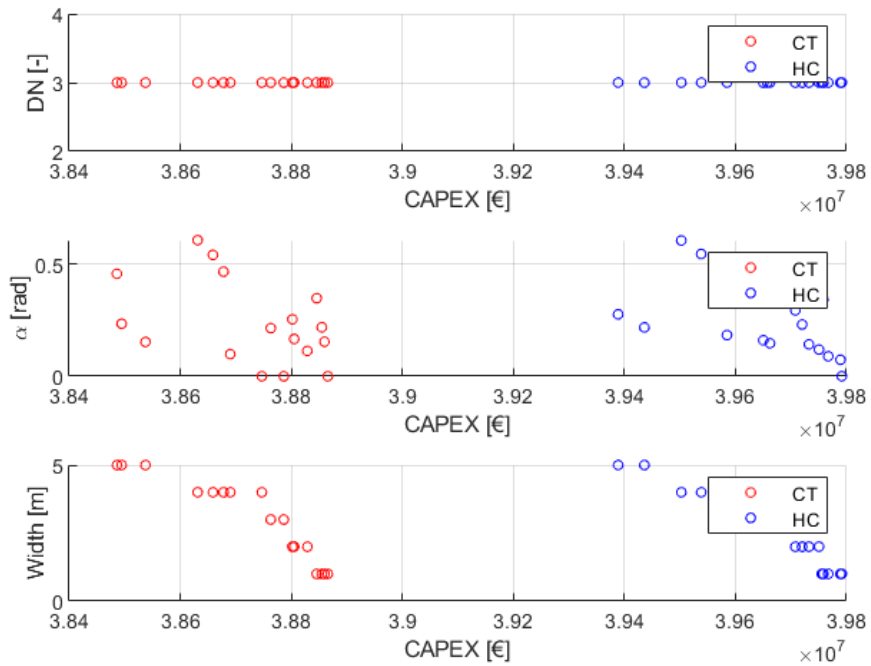


Figure 20: Parameters variation with respect to CapEx

We observe 4 major features.

Firstly, and most importantly, the translation of HC front towards positive abscissae. This leads any cable configuration using HC former type outside the Pareto front. This result is better understood when new objective functions are added separately. Adding the *OpEx* to the optimization results in multiplying the former objective function by a coefficient greater than 1 (electricity price). Thus, the differences in losses that were small before, now become larger, leaving in the real Pareto front most of the configurations that uses CT former type and to a lesser extent, those that use HC former type. When *CaPex* is defined as the objective length of the cable is multiplied by its price, which is very high, so a translation towards positive abscissae occurs. It is worth remembering that the variable costs of the *CaPex* (equations 8 to 12), i.e., in the part that will affect the optimization, are mostly composed of the cost of the superconducting tape. This causes the cable with the former type using more superconducting tape length to see its Pareto front shifted towards positive abscissae to a greater extent, producing a bigger difference between both curves. One curve result is being lower in *CaPex* than the other in all of its points, thus, optimal. Fixed costs do not cause this difference since the same amount is added to both types of former tube.

Secondly, the results remain clustered as before, so it can be stated that the tape width plays an important role in the optimization. Cable configurations with similar tape widths will have similar costs.

Thirdly, All angles between and 0 y 30 acceptable and there is no clear relationship between this variable and the finals costs of the cable.

Finally. the only admitted diameter is 50 mm, no feasible cable configuration is found with other diameters.

A deeper analysis can be done comparing the results obtained in (Garrido, 2021) (Kottonau, 2019). Moreover, the only usable diameter is 50 mm, for both types of former and for all possible configurations. Analysing the results in an analytical way, and adding

only the points of the front edges, i.e. the one that minimizes the *OpEx* and maximizes the *CaPex* and vice versa, Table 6 is obtained.

	CapEx (M€)	OpEx (k€)	Former type	DN (mm)	Twist angle (rad)	HTS tape width (mm)
Min OpEx and Max CAPEX	38,454	946,982	CT	50	0.57	5
Min CAPEX and Max OpEx	38,865	783,020	CT	3	0	1

Table 6: Results and values for upper and lower bound of Pareto front

According to table 6, an economy of 411.000 € euros in installation will result, in the best case, in a loss of 163.000 € every year. The importance of finding the optimal cable is therefore extremely important as it allows to make remarkable economies.

Capítulo 5. CONCLUSIONS

5.1 *CONCLUSIONS ON METHODOLOGY*

A "step by step" treatment has made it easier to tackle the problem that seemed overwhelming at first sight. This allows to clear up problems that may appear little by little and to understand which variables are relevant at each stage and to understand the impact of the variation of each parameter individually, starting from a known result.

Previous studies (Kottonau and Garrido) used a sizing model to manually size a superconducting cable system. In this thesis, the sizing model was coupled with a bi-objective optimization algorithm. This allows us to automatically find local optimal solutions.

The case study was improved by defining relevant techno-economic objective functions: the capital expenditure (*CAPEX*) and the operational expenditure (*OPEX*).

The method can be easily adapted to account for more optimization variables, more complex objective functions, and additional optimization constraints.

5.2 *CONCLUSIONS ON RESULTS*

For a simple objective function, which considers the total installation costs as the cable length, a clear solution of two Pareto fronts is obtained, constituted by the points having the same type of former, which cross each other. Nevertheless, cables with a HC former type have always slightly cheaper installation costs

This is very different from the one obtained when the objective functions are enriched, leading to the conclusion that only cables of Corrugated Tube former type are optimal.

For this case study and adopted cable configuration: DN 50 is the only feasible configuration. This explains why Kottonau reported only the results on this configuration. This is in agreement with the results of Garrido.

Clear and interpretable results have been achieved, as well as a highly parameterized algorithm that allows itself to be improved and updated as knowledge of this impressive technology advances.

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APPENDIX

Code for obtaining objective functions

```
%% Eco analysis

% CAPEX (lb, ub and mean)

%HTS tape cost
HTS_lb_cost_per_meter = HTStape.HTS_cost_lb*HTStape.Ic0/1e3; %[€/m]
HTS_ub_cost_per_meter = HTStape.HTS_cost_ub*HTStape.Ic0/1e3; %[€/m]

UGC_supra.cost.HTS_lb = UGC_supra.L_HTStot*HTS_lb_cost_per_meter; %[€] HTS cost
UGC_supra.cost.HTS_ub = UGC_supra.L_HTStot*HTS_ub_cost_per_meter; %[€] HTS cost

%UGC_supra.cost.total = sum(struct2array(UGC_supra.cost)); %[€] total cost

%insulation material cost
if cableA.former_type=="CT"
    insul_layer=4;
else
    if cableA.former_type=="HC"
        insul_layer=5;
    end
end
end
OR=table2array(cableA.design(insul_layer,"outer_radius"));
thickness=table2array(cableA.design(insul_layer,"thickness"));
IR=OR-thickness;
vol=pi*((OR^2)-(IR^2))*3200;
insul_cost_lb=vol*UGC_supra.insulation_price_lb;
insul_cost_ub=vol*UGC_supra.insulation_price_ub;

%HTS costs
HTS_lb=UGC_supra.cost.HTS_lb;
HTS_ub=UGC_supra.cost.HTS_ub;

%production costs:
prod_lb=0.1*(HTS_lb+insul_cost_lb+8674000);
prod_ub=0.1*(HTS_ub+insul_cost_ub+9830000);

%chosen CapEx
% CV_lb=HTS_lb;
% CV_ub=HTS_ub;
CV_lb=HTS_lb+prod_lb+insul_cost_lb;
CV_ub=HTS_ub+prod_ub+insul_cost_ub;
% CV_lb=prod_lb; %test
% CV_ub=prod_ub; %test
```

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```
UGC_supra.CF=[22254,27560]*1e3;
CAPEX=[UGC_supra.CF(1)+CV_lb, UGC_supra.CF(2)+CV_ub];

% %all variable costs
%
CV_lb=UGC_supra.cost.HTS_lb+insul_cost_lb+0.1*(UGC_supra.cost.HTS_lb+insul_cost_lb+8674000);
%
CV_ub=UGC_supra.cost.HTS_ub+insul_cost_ub+0.1*(UGC_supra.cost.HTS_ub+insul_cost_ub+9830000);

%CAPEX
UGC_supra.CAPEX_0= (CAPEX(1)+CAPEX(2))/2; % moyenne de ub et lb;

% OPEX
C_loss = sys.c_elec*UGC_supra.AElosses.total; % [€/year] annual cost of losses
UGC_supra.OPEX_0 = C_loss;
```

