SCARLET

Superconducting CAbles foR sustainabLe Energy Transition

1.09.2022 – 28.02.2027

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

D1.2: Feasibility of Elpipes

Lead partner: Vision Electric Super Conductors GmbH (VESC)

Authors: Peter Abrell, VESC
Wolfgang Reiser, VESC

Submission date: 30/08/2024

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

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

Document history

Issue date	Version	Changes made / Reason for this issue
06/02/2024	0.0	Initial version
28/08/2024	1.0	Submitted version

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EXECUTIVE SUMMARY

The goal of this deliverable is to describe the concept of Elpipes, make a statement about their feasibility and explain the reasoning behind it. The investigation of Elpipes was mandated in the EU call that funded the SCARLET project and was therefore given a dedicated task. This deliverable presents the outcome of this work.

Elpipes is a short form for electric pipelines. They are electric power transmission systems that use conventional conductors such as copper and aluminum, as well as sodium. The underlying idea is that rigid, pipe-like segments are used as a conductor instead of a flexible cable core. The resulting conductor has a hollow core and a large outer diameter. This allows for more thermal heat to be dissipated due to the increased surface area. As a result, Elpipes are supposed to operate at a higher power rating than conventional power cables. Elpipes are designed to achieve large conductor cross-sections to keep electric losses as low as possible.

The deliverable is organized as follows. Section 1 introduces the main components of Elpipes as specified in the corresponding patent and the scientific papers submitted by their inventor, Roger Faulkner. Elpipes are a high voltage direct current (HVDC) transmission system designed to transmit powers of more than 1 GW over 1000 km. The central objective is to achieve electrical losses of maximum 1% per 1000 km. This is done by increasing the cross-section of the conductor until the resistance is low enough. Elpipes consist of two main components: the pipe segments and the splice modules. The segments are the main element of Elpipes and the reason for the name. They hold the conductor within a protective steel conduit. The splice modules link two segments together and allow for a curvature of the transmission system. These parts are described as specified in the patent and no judgement on feasibility or effectiveness is made.

Section 2 uses simple engineering methods to qualitatively assess the main components of Elpipes. A major difficulty in completing the feasibility assessment is the lack of a complete Elpipe model. The scientific papers and the patent by Roger Faulkner distinctly define only boundary conditions such as resistive losses, voltage, and power levels. There are no defined specifications for any of the components, only several possible concepts to draw from. For example, the patent lists nine separate ways of structuring the conductor. Next to copper and aluminum, sodium is used as a conductor material. However, there is no clear statement whether sodium should or should not be used as a conductor, it is simply listed as another possibility. For the feasibility assessment, the elements that all these models and possibilities have in common are identified: the insulation, the high material demand due to the large cross-sections and the substantial number of splice modules needed. A cost analysis written by Faulkner is assessed to better understand the Elpipe concept.

In order to quantitively assess the feasibility, a basic model must first be created. Section 3 explicitly describes a model that is consistent with the source material. The intricate splice module is excluded due to its complexity. The model gives an estimation of the Elpipes composition, weight, and raw material cost in dependence of power, transmission length and conductor composition. Aluminum and

sodium are considered as conductor materials. In conjunction with a simulation the thermal performance of a 1 GW and a 4 GW Elpipe is modelled. The thermal results show that high-power Elpipes are not viable for transmission lengths below 300 km.

Ultimately, it becomes very clear that the Elpipes concept has major feasibility issues. For the conductor and insulation there are no manufacturing, construction, and installation methods defined. The cost calculations done by Faulkner are too optimistic. Extruding a conventional XLPE insulation onto the Elpipe segments or splices is not possible. This means that Faulkner's wrapped insulation must be used, which is a reliability and safety risk. These problems are particularly severe for the splice module, which acts as a thermal and electrical bottleneck.

Elpipes center around having large cross-sections to transmit substantial amounts of power with low losses. Refuting the design concept can be done by answering the question why conventional cables are not engineered with 1% losses per 1000 km in mind: cables become unwieldly, difficult to transport, difficult to install, and more expensive. Investing time and resources into a technology essentially consisting of exceptionally large, rigid cables with a complex wrapped insulation is not worthwhile.

1 ELPIPES OVERVIEW

Next to superconducting cables, Elpipes are also part of the SCARLET project. The following section will describe Elpipes as a technical concept without passing judgement on physical, economical, or environmental feasibility. The information is sourced directly from the inventor's publications and patents, which are all publicly available. Most information and images are directly taken from the patent. Analysis based on physical or technical data is not included.

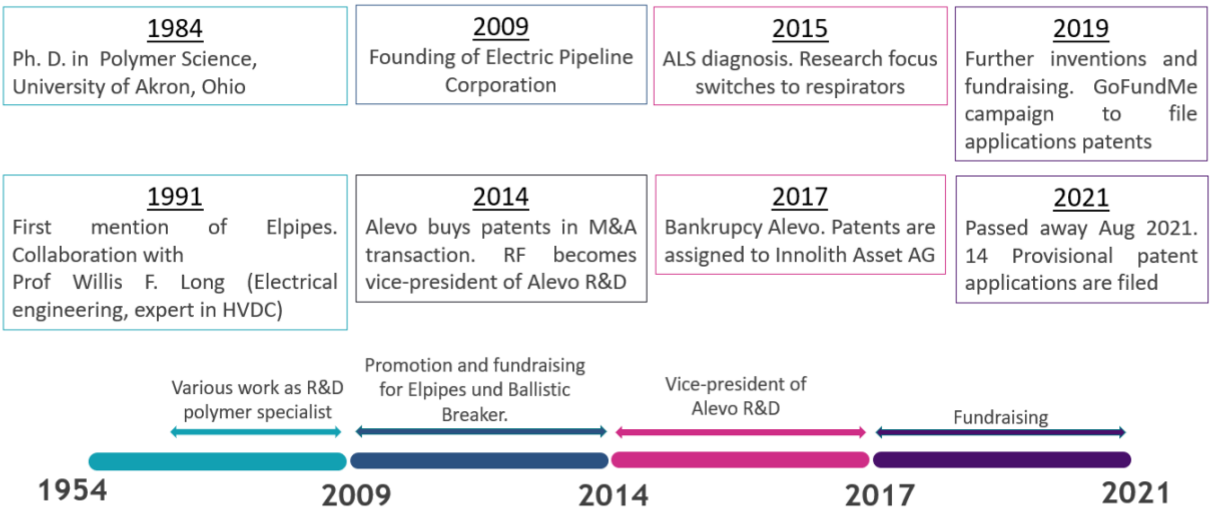
Elpipes are a novel alternative to conventional conductor (copper and aluminum) power transmission. They were invented by Roger Faulkner in 2009 and aim to reduce the following technical obstacles of high-power underground DC transmission:

- High voltage electrical insulation for conductors
- Removal of waste heat from conductors
- Accommodating thermal expansion and contraction of the conductors, insulation, splices, and housings
- Making low loss, high current, reliable electrical splices, and insulation in the field at low cost

The following sections will introduce the inventor, as well as describing and summarizing the most noteworthy features of the Elpipe concept.

1.1 Biography of Roger Faulkner

Roger Faulkner was born on July 24th 1954, in Cuyahoga Falls, Ohio. He achieved the academic grade of Ph. D. in Polymer Science from the University of Akron in 1984. The emphasis being on reactive polymer processing. From 1976 until 1989 he worked as a R&D polymer specialist at various companies including Goodrich and Monsanto. From 1990 until 2009 he had R&D leadership roles, for companies such as Seal Master and Erikson Materials.



1984
Ph. D. in Polymer Science, University of Akron, Ohio

2009
Founding of Electric Pipeline Corporation

2015
ALS diagnosis. Research focus switches to respirators

2019
Further inventions and fundraising. GoFundMe campaign to file applications patents

1991
First mention of Elpipes. Collaboration with Prof Willis F. Long (Electrical engineering, expert in HVDC)

2014
Alevo buys patents in M&A transaction. RF becomes vice-president of Alevo R&D

2017
Bankrupcy Alevo. Patents are assigned to Innolith Asset AG

2021
Passed away Aug 2021. 14 Provisional patent applications are filed

Figure 1. Roger Faulkner's professional timeline

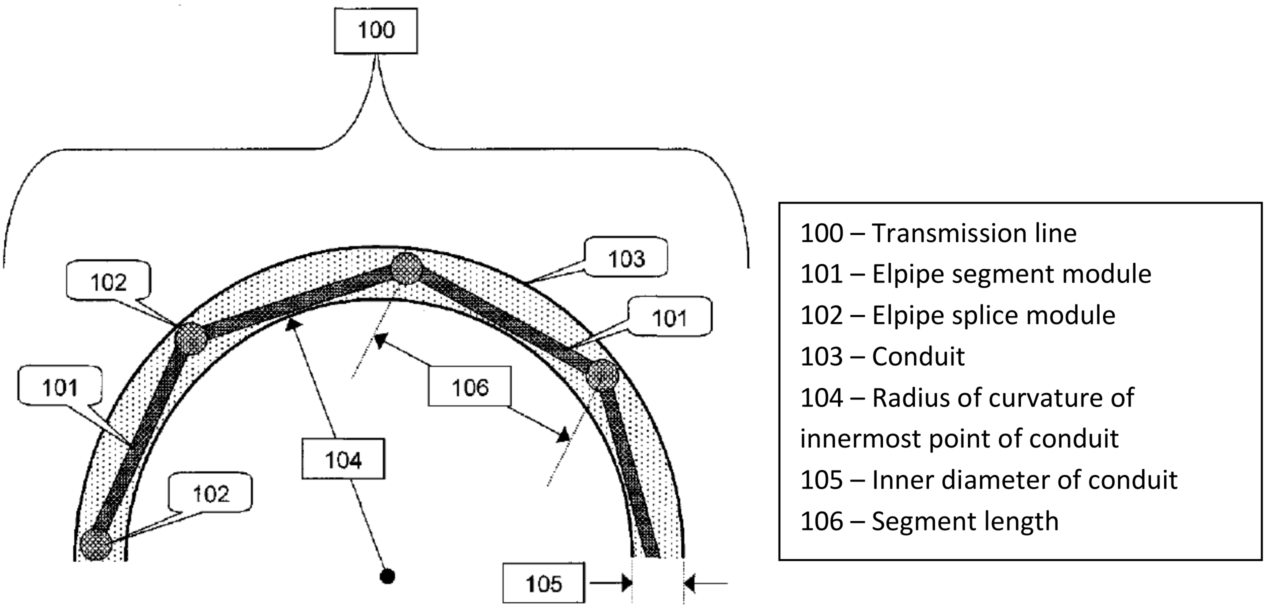
The electrical Pipeline Corporations was founded in 2009 with Ron Todd, his fellow inventor. The next years were characterized by promoting and marketing Elpipes and other patents such as the Ballistic Breaker. In 2014 Alevo Group SA acquired his patents in an M&A transaction and Faulkner assumed the role of vice-president of Alevo R&D. Faulkner was diagnosed with ALS in 2015, his personal research focus switching to respirator devices.

Alevo Group SA filed for bankruptcy in 2017. In the wake of bankruptcy, Faulkner's patents passed to Innolith Asset AG in Basel, Switzerland who remain the holders. As his ALS progressed, Faulkner created further inventions, mostly centered respirators and other utilities that improve the life disabled persons. He engaged in fundraising for his patents, over platforms such as Twitch.com and GoFundMe.com. Roger Faulkner passed away in June 2021, having filed a further fourteen provisional patent applications for inventions after his ALS diagnosis.

1.2 Concept summary

The patent describes Elpipes as modular, high capacity, passively cooled, non-superconducting, underground high voltage direct current electric power transmission lines of exceptionally low loss (1% per 1000 km) and competitive cost. The system is comprised of an elongated containment system, annular rigid primary conductors aligned end-to-end within the containment system, an annular primary insulator surrounding each of the primary conductors. Compliant conductive electrical splice members (102) connect the primary conductors and accomplish electrical continuity while allowing for axial misalignment between the conductors. A splice insulator surrounds each splice member.

Figure 2 shows the main components of an Elpipe transmission line (100). The segment modules (101) house the conductors and are connected to each other by splice modules (102). They are placed inside a protective conduit (103).



100 – Transmission line
101 – Elpipe segment module
102 – Elpipe splice module
103 – Conduit
104 – Radius of curvature of innermost point of conduit
105 – Inner diameter of conduit
106 – Segment length

Figure 2. Overview of the Elpipe concept, showing how a curvature can be achieved with straight segments [1]

Figure 3 depicts an Elpipe segment inside the conduit. Wheels are deployed that attach the segment or splice to the outer steel pipe and ease insertion or removal for maintenance.

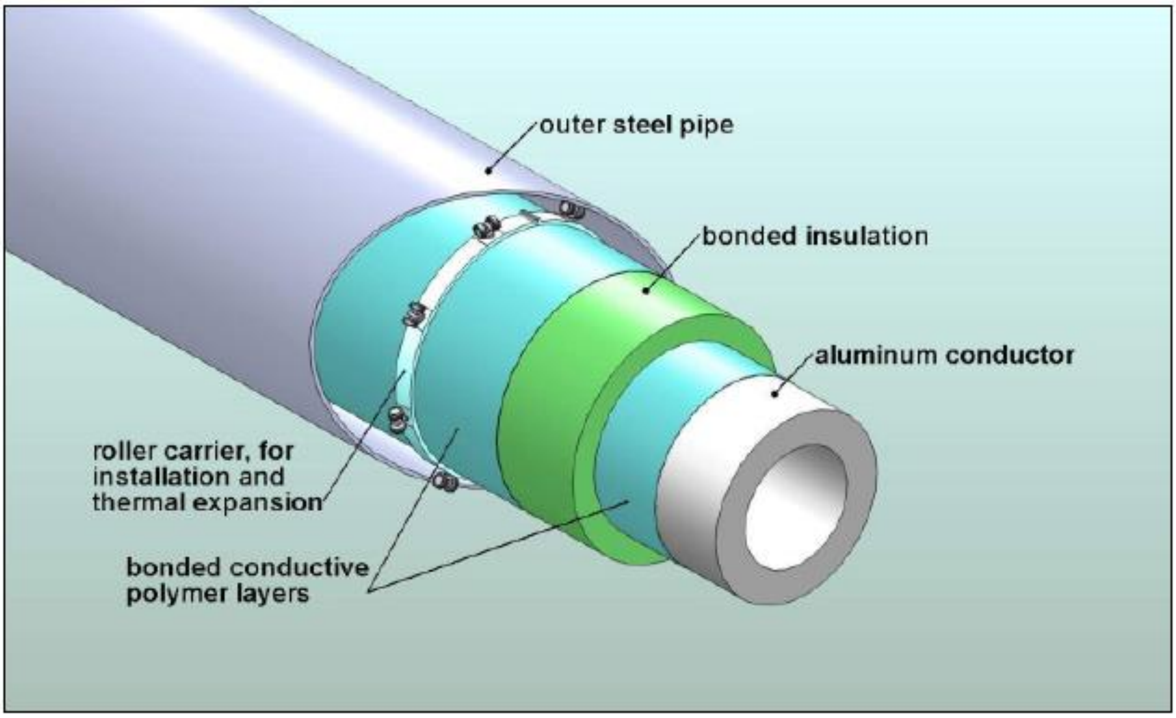
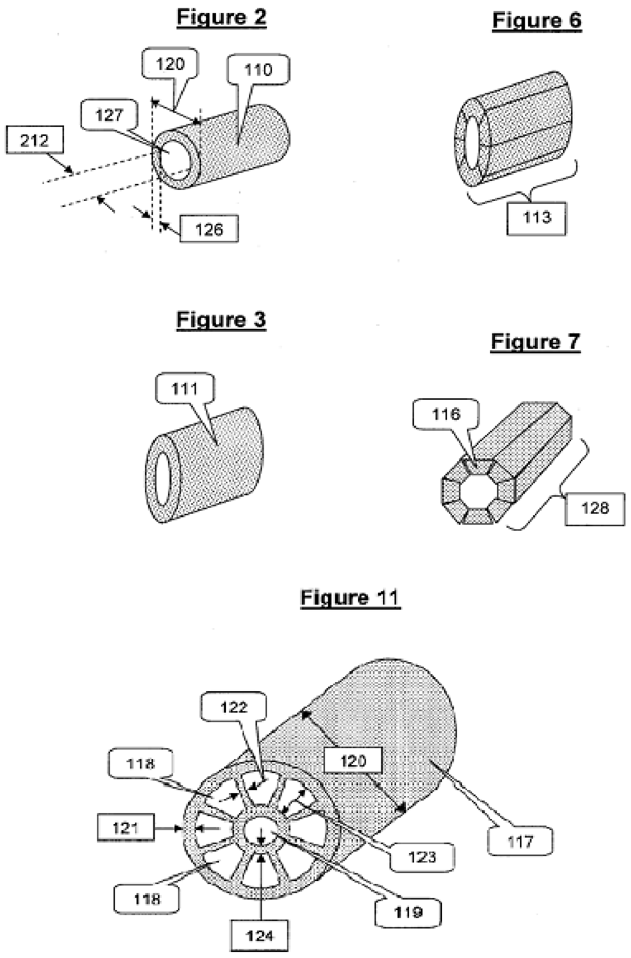


Figure 3. 3D representation of an Elpipe, showing a segment (see Figure 2, 101) and an outer steel pipe (conduit, Figure 2, 103) [2]

During Faulkner's promotion of Elpipes he authored several papers on the concept and its advantages compared to conventional power transmission. In [2] Faulkner describes a DC Supergrid in North America using a combination of Elpipes and superconducting cables. The paper highlights the advantages of an Elpipe, such as 1% I2R losses over 1000 km. What is not portrayed is how this figure is reached. It is described as the design efficiency [2]. As conventional conductors are used, reaching this efficiency is only possible by increasing the cross section of the conductor until the desired efficiency is achieved. For an aluminum based Elpipe this would mean that "10-20% of the project costs would consist of aluminum" [2].

1.2.1 Conductor

As shown in Figure 4, the conductors consist of either extruded aluminum pipes, circular and elliptical are possible (110, 111), or conductors formed by bundling together wedge-shaped conductors (128) to form a hollow keystone conductor. The wedge-formed conductors can be hollow and flooded by a liquid or at least a semi-solid conductor (118). This is where sodium is introduced. Sodium acts as a filler conductor that is poured into the keystone voids. According to Faulkner, a hollow keystone conductor based on a range of standardized component wedges allows for control of the resistance per kilometer of the Elpipe.



110 – Extruded pipe conductor, circularly cylindrical cross-section
111 – Extruded pipe conductor, elliptically cylindrical cross-section
113 – Elliptical-shaped hollow conductor
116 – Strip-cast solid conductor wedge
117 – Cylindrical conductor with keystone voids
118 – Keystone void
119 – Hollow core of complex circular extrusion
120 – Outside hollow keystone conductor with circular cross-section
121 – Outer wall thickness
122 – Rib subtended angle
123 – Void height
124 – Central cylinder wall thickness
126 – Conductor wall thickness
127 – Hollow core
128 – Octagonal hollow keystone conductor made from strip-cast wedges
212 – Conductor inner diameter

Figure 2. Different possibilities of conductor shapes and sizes [1]

Elpipes were designed to be used with conventional conductors such as copper and aluminum. However, sodium is also explicitly mentioned. [2] describes them as low-cost conductors.

It is not explicitly mentioned how the data points in Figure 5 are calculated, only that the design efficiency is set at 1% per 1000 km at 10 GW. Sodium can be seen as a cheaper conductor alternative for voltages below 1000 kVDC. While sodium's resistivity is almost triple that of copper, it is 1/10 less dense and cheaper per weight, making it an overall cheaper choice than even aluminum using past metal prices.

Another advantage of a sodium conductor is increased overload potential. The endothermic melting of sodium at around 95°C increases the time the Elpipe can hold an overcurrent. While the Elpipe is being stressed with an overcurrent, the additional heat generation causes the sodium to melt and hold 95°C until it is completely melted. The maximum possible temperature of the Elpipe conductor is stated as 105°C [1].

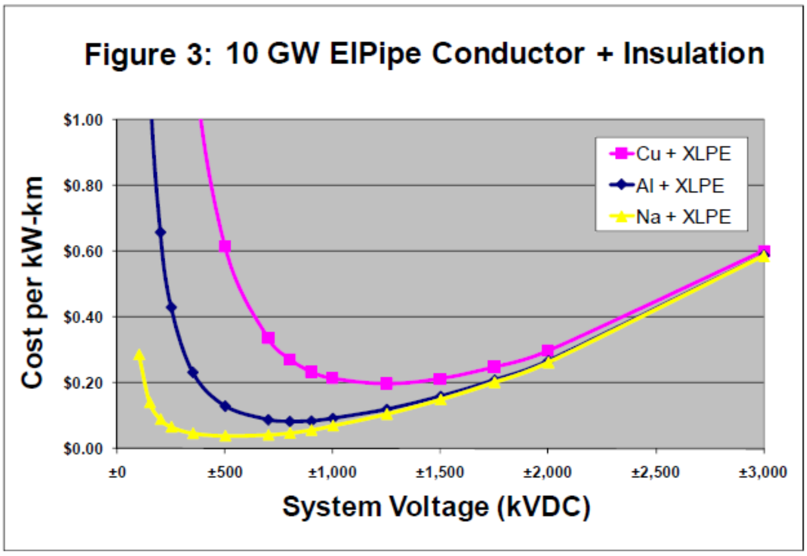


Figure 3. 10 GW Elpipe conductor and insulation cost in relation to transmission voltage [2]

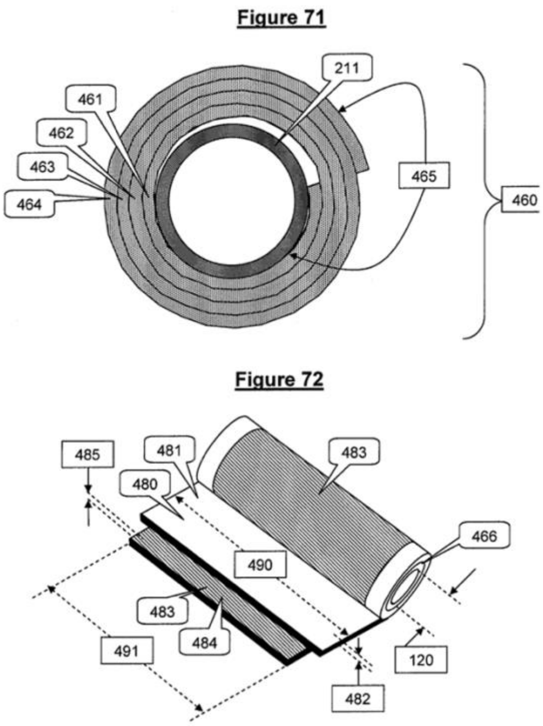
1.2.2 Insulator

According to the patent, the preferred insulation method is to have no mechanical attachment between the Elpipe conductor and the insulator. Five insulators are possible (p.33):

1. elastomers
2. plastics
3. thermoset and 2-part curing polymers
4. glass and ceramics
5. Hybrid designs involving both hard insulating materials and elastomers in nested designs

Elastomers are favored as layers of stretched elastomeric tape create a pressure that inhibits void formations between the elastomer and the material underneath. Elastomers can also be used as an overlap insulation between segment and splice module, see Figure 8, 336.

The insulation consists of multiple turns of a bilayer polymeric laminate. An insulating Layer A (480) with high DC voltage endurance and very high resistivity is used. Semiconductive layer B (483) has a lower resistivity and is placed on the outside of layer A. As a result, the overall voltage difference from the inner conductor to the outer environment can be nearly evenly distributed between each composite layer. This allows materials to be used at much higher voltage endurance limits and reduce voltage stress inversion, see [3] for further details.



120 – Outer diameter of conductor
211 – Pipe-shaped conductor, aluminium, with square end
460 – Conductor with spirally wound conductor
461-464 – Insulation layers
465 – Voltage from conductor to outer shield
466 – Spirally-wrapped insulation
480 – Insulation layer A
481 – Resistivity of layer A
482 – Thickness of layer A
483 – Semiconductor layer B
484 – Resistivity layer B
485 – Thickness layer B
490 – Width of layer A
491 – Width of layer B

Figure 4. Insulation of Elpipe segment [1]

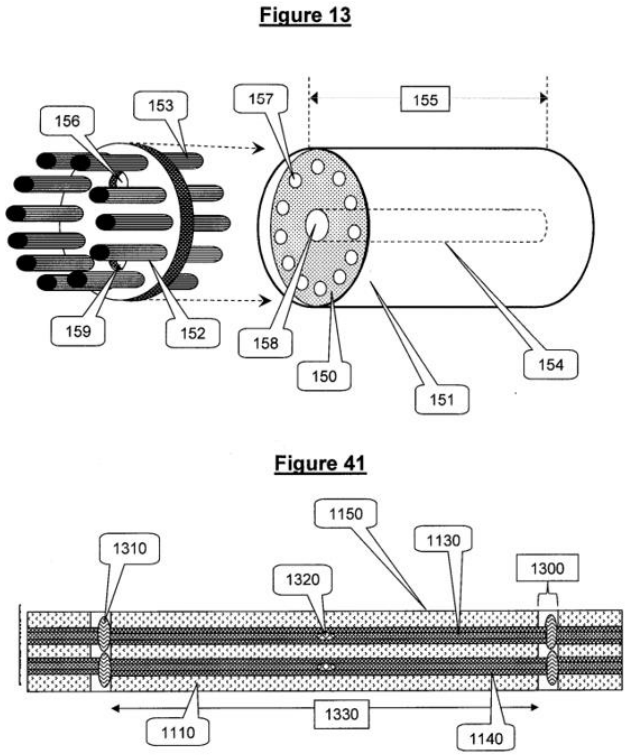
1.2.3 Splices

The splice modules link the segment modules together. The splice modules require a flexible conductor, wire mesh or looped wires, a liquid, or a soft metal such as sodium. The splice modules allow both axial and angular movement of the mating of the segment module conductive cores. In addition, the splice modules can compensate for some or all the thermal expansion and contraction of the aluminum conductor.

Figure 7 shows a sodium based Elpipe segment which can be designed to give much lower longitudinal expansion than the aluminum tube. This can be done by placing an expansion joint splice (1320) between conductor sections.

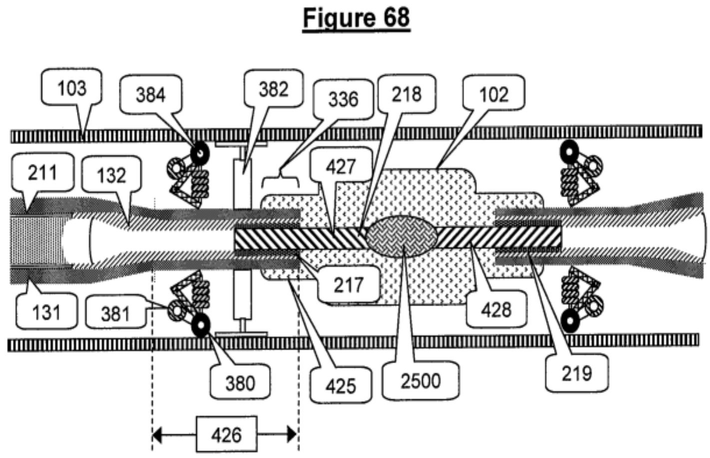
The splice modules are connected to the conductor segment by welding, crimping, soldering or through mechanical threads. The main goal of the connection is not increasing the average longitudinal resistance of the Elpipe whilst allowing for thermal expansion of the conductor.

Wheel carriages are deployed on a necked down region of an Elpipe (426) to accommodate both the wheel carriage assembly and the splice transition (see Figure 8). Air brakes (382) occur on only one side of the splice module so that the expansion/contraction between each set of locked air brakes corresponds to one segment module and one splice module. There is an overlap of nesting insulation (336). XLPE pipe-shaped insulation extends all the way to the end of the segment module (425). The center of the splice module consists of a braided tinned copper sleeve (2500) which is electrically linked to the Elpipe segments by copper rods (427).



150 – Volume filled by sodium
151 – Vessel
152 – End plate
153 – Connection rod
154 – Volume compensation device
155 – Conductor length
156 – Sodium fill hole
157 – Connection rod hole
158 – Pressure inside the compensation device, gas of volume compensation device
159 – Vacuum port
1110 – Heat transfer fluid
1130 – Hollow aluminum conductor
1140 – Primary insulator
1150 – Rigid, liquid tight vessel
1300 – Splice area, top
1310 – Compliant insulating threaded coupler
1320 – Eletrical expansion joint
1330 – Elpipe section

Figure 7. Connection between splice and segment and their implementation inside the conduit [1]

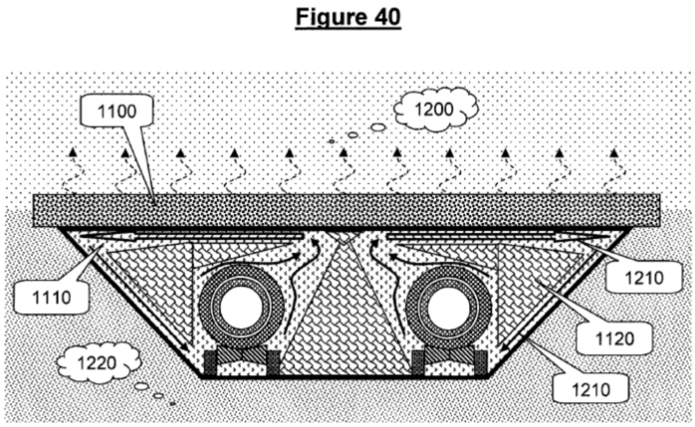


102 – Elpipe splice module
103 – Conduit
131 – Pipe shaped insulator that is biaxially oriented elastomer in the middle of the segment
132 – Splice transition conductor with square end
211 – Pipe-shaped conductor, aluminum
217 – Copper insert with right hand internal threads
218 – Threads
219 – Copper insert with left hand internal threads
336 – Insulation overlap
380 – Wheels on powered Elpipe carriage module
381 – Reversible variable speed and variable torque motor
382 – Brake
384 – Torque load cell on wheel
425 – Overlapping insulation collar
426 – Necked-down region
427 – Copper rod, right hand threaded
428 – Copper rod, left hand threaded
2500 – Braided tinned copper sleeve

Figure 8. Detailed overview of the features of a splice [1]

1.2.4 Thermal considerations

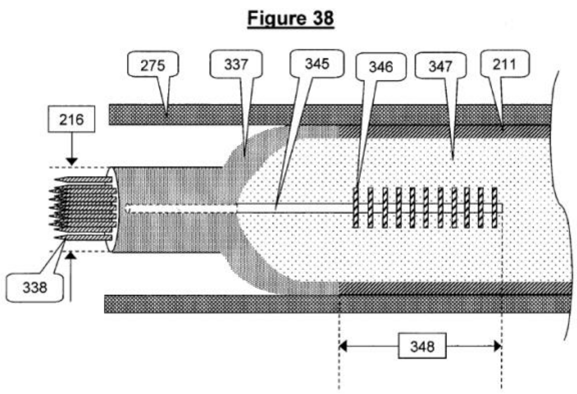
Heat is radiated from the top surface (1100) to the surrounding air (1200), unimpeded by vegetation. This surface can be made of concrete, for instance, to provide durability in weather while also clearly signaling to construction crews that they must not dig there. Since the surface is almost flush with terrain, this construction only minimally impacts vistas and need not impede wildlife and vehicle crossing. Optionally, a heat transfer fluid (1110) can be used to facilitate the removal of heat from the walls of the insulated conductors to the top surface of the vessel, as depicted in Figure 9.



1100 – Concrete slab
1110 – Heat transfer fluid
1120 – Closed-cell compressible foam
1200 – Ambient air
1210 – Currents in thermal fluid
1220 – Underground

Figure 9. Depiction of heat loss to the environment [1]

Heat pipes can be used to extract heat from the splice area and transport it out to the conductor (345) away from the splice. This is needed because the thicker electrical insulation within the splice area causes additional heat generation and resulting hot spots must be avoided.

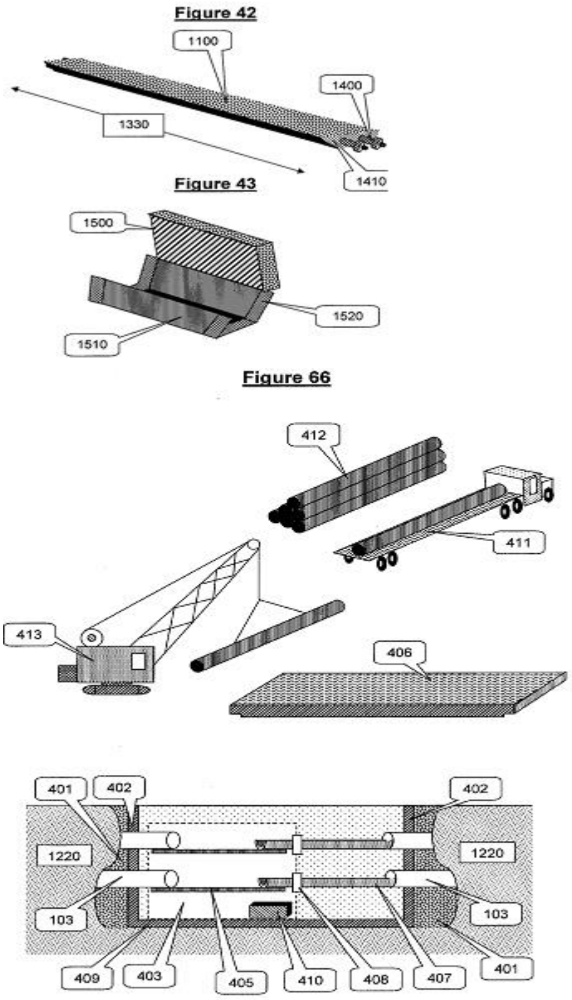


211 – Pipe-shaped conductor, aluminum
216 – Outer diameter of transition end
275 – Rigid pipe-shaped insulator; could be a plastic ceramic or glass pipe
337 – Perforating end segment type of splice transition conductor
338 – Electrically conductive needles
345 – Heat pipe
346 – Finned heat radiator
347 – Fill gas
348 – Heat pipe extension beyond splice transition conductor

Figure 10. Depiction of heat transfer from splice to segment module [1]

1.2.5 Construction

To assemble Elpipes, a flat-bottom trench with sloping walls is dug to the appropriate depth, for example 1.5 m. U-shaped coupling trays (1510) are placed in the trench at each splice area. The Elpipe sections (1330) are then placed into the trench. Elpipe sections are around 15 m long. This allows them to be transported by truck (411, 412).



103 – Conduit
401 – Sand/gravel backfill
402 – Wall
403 – Clean room working area
405 – Support rail
406 – Lid of maintenance vault
407 – Half-round conduit
408 – Inflatable seal
409 – Floor of maintenance vault
410 – Forced-air filter
411 – Truck
412 – Storage of Elpipe module segments
413 – Crane
1100 – Concrete Slab
1220 – Underground
1330 – Elpipe section
1400 – Insulated conductor before splicing
1410 – Bulkhead
1500 – Removable sealing lid
1510 – U-shaped tray
1520 – Sealing flaps

Figure 11. Details on the construction and transportation of Elpipes [1]

An economically advantageous option for installing Elpipe involves transporting longer segments via train directly from the factory to the installation site. This also allows the Elpipe sections to be longer and reduces the amount of splice modules needed, reducing the construction costs. Maintenance vaults can be used during construction to insert Elpipe segments and splices. This also allows Elpipe segments to be removed for maintenance.

1.3 Summary

Elpipes present new ideas concerning HVDC transmission lines and conductors. Instead of using cables, Elpipes consist of massive conductors that are polymer insulated and passively cooled by the surrounding environment. The insulated conductors are placed in a protective conduit. Faulkner created a highly modular conductor core consisting of diverse types of keystones that can be adjusted for a specific voltage and current requirements. The patent also considers sodium as a conductor, which is cheaper than copper or aluminum.

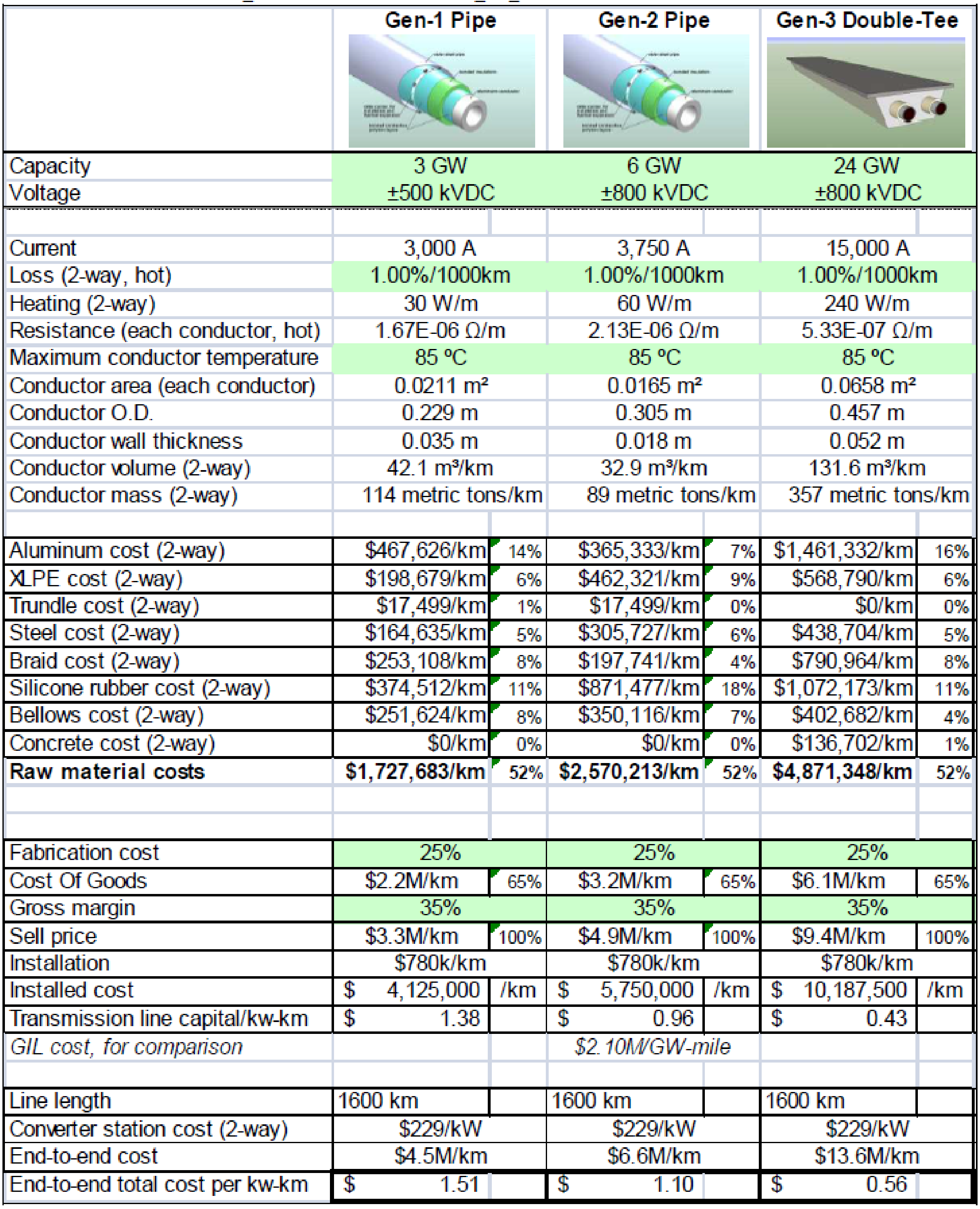
2 FEASIBILITY

Judging the feasibility of a technology is often done considering the technical, economic, and ecological features. The following section will analyze the available information about Elpipes and draw reasonable conclusions. Elpipes have never been constructed or tested, there is no data to base any evaluation on. Due to this, the information is based on Faulkner's papers and relevant information from the patent. The main difficulty in evaluating Elpipes is finding objective information on the topic. The papers themselves often lack critical information and many figures seem hand wavy with no explanation of how they were reached. Nonetheless, a generalized feasibility with reasonable assumptions is made.

2.1 Economic feasibility

Reference [4] gives a breakdown of costs regarding Elpipes of different powers and voltages, as shown in Table 1. A comparative calculation was done to better understand certain results and phrases. The suffix 2-way is used for some data points. A bipolar system is used where two phases each transport 3 kA of current. To better understand the origin of the figures seen above, a recalculation was done and can be seen in Table 2.

Table 1: A cost breakdown of Elpipes as seen in [4]



	Gen-1 Pipe		Gen-2 Pipe		Gen-3 Double-Tee	
Capacity	3 GW		6 GW		24 GW	
Voltage	±500 kVDC		±800 kVDC		±800 kVDC	
Current	3,000 A		3,750 A		15,000 A	
Loss (2-way, hot)	1.00%/1000km		1.00%/1000km		1.00%/1000km	
Heating (2-way)	30 W/m		60 W/m		240 W/m	
Resistance (each conductor, hot)	1.67E-06 Ω/m		2.13E-06 Ω/m		5.33E-07 Ω/m	
Maximum conductor temperature	85 °C		85 °C		85 °C	
Conductor area (each conductor)	0.0211 m^2		0.0165 m^2		0.0658 m^2	
Conductor O.D.	0.229 m		0.305 m		0.457 m	
Conductor wall thickness	0.035 m		0.018 m		0.052 m	
Conductor volume (2-way)	42.1 m^3/km		32.9 m^3/km		131.6 m^3/km	
Conductor mass (2-way)	114 metric tons/km		89 metric tons/km		357 metric tons/km	
Aluminum cost (2-way)	$467,626/km	14%	$365,333/km	7%	$1,461,332/km	16%
XLPE cost (2-way)	$198,679/km	6%	$462,321/km	9%	$568,790/km	6%
Trundle cost (2-way)	$17,499/km	1%	$17,499/km	0%	$0/km	0%
Steel cost (2-way)	$164,635/km	5%	$305,727/km	6%	$438,704/km	5%
Braid cost (2-way)	$253,108/km	8%	$197,741/km	4%	$790,964/km	8%
Silicone rubber cost (2-way)	$374,512/km	11%	$871,477/km	18%	$1,072,173/km	11%
Bellows cost (2-way)	$251,624/km	8%	$350,116/km	7%	$402,682/km	4%
Concrete cost (2-way)	$0/km	0%	$0/km	0%	$136,702/km	1%
Raw material costs	**$1,727,683/km**	52%	**$2,570,213/km**	52%	**$4,871,348/km**	52%
Fabrication cost	25%		25%		25%	
Cost Of Goods	$2.2M/km	65%	$3.2M/km	65%	$6.1M/km	65%
Gross margin	35%		35%		35%	
Sell price	$3.3M/km	100%	$4.9M/km	100%	$9.4M/km	100%
Installation	$780k/km		$780k/km		$780k/km	
Installed cost	$ 4,125,000	/km	$ 5,750,000	/km	$ 10,187,500	/km
Transmission line capital/kw-km	$ 1.38		$ 0.96		$ 0.43	
GIL cost, for comparison			*$2.10M/GW-mile*			
Line length	1600 km		1600 km		1600 km	
Converter station cost (2-way)	$229/kW		$229/kW		$229/kW	
End-to-end cost	$4.5M/km		$6.6M/km		$13.6M/km	
End-to-end total cost per kw-km	$ 1.51		$ 1.10		$ 0.56	

Table 2: Comprehension calculation (right side) of 3 GW Elpipe as seen in [4] (left side)

Faulkner's Calculation			Break Down Calculation for Phase			
Capacity	3	GW	**Power**	1.50	GW	
Voltage	500	± kVDC	**Voltage**	500	kVDC	
			Length	1000	km	
Current	3,000	A	**Current (per phase)**	3000	A	
Loss (2-way, hot)	1	%/1000km	**Loss**	1	%/1000km	(1)
Heating (2-way)	30	W/m	**Heating (per phase, per meter)**	15	W/m	
			Reference Temperature	20	°C	
Maximum Conductor Temperature	85	°C	**Operating Temperature**	85	°C	
Resistance (each conductor, hot)	1.67	μΩ/m	**Resistance needed**	1.67E-06	Ω/m	(2)
			Resistance (1 Phase)	1.67	Ω	
			Aluminium Resistivity at 85°C	3.39E-08	Ωm	(3)
Conductor Area (each conductor)	0.0211	m^2	**Conductor Area (hot resistivity)**	0.0203	m^2	(4)
Conductor Diameter	0.1639	m	**Conductor Diameter**	0.1609	m	(5)
Conductor O.D.	0.2290	m	**Conductor O.D.**	0.2290	m	
Conductor wall thickness	0.0350	m	**Conductor wall thickness (w)**	0.0350	m	w
			Conductor Radius (r1)	0.1145	m	r1
			Conductor Area (pi*[r1^2-(r1-w)^2])	0.0213	m^2	
			Total Area (Conductor + Hollow Core)	0.0412	m^2	
			Ratio Conductor Area/Total Area	0.5179		
			Conductor Volume (Phase)	21.33	m^3/km	
			Total Volume (1 Phase)	41.19	m^3/km	
Conductor volume (2-way)	42.1	m^3/km	**Conductor Volume (2 Phases)**	42.66	m^3/km	
			Density of Overall Phase (Ratio of Faulkners Calculation)	2.71	MT/m^3	
Conductor mass (2-way)	114	MT/km	**Mass for 2 Phases**	115.52	MT/km	

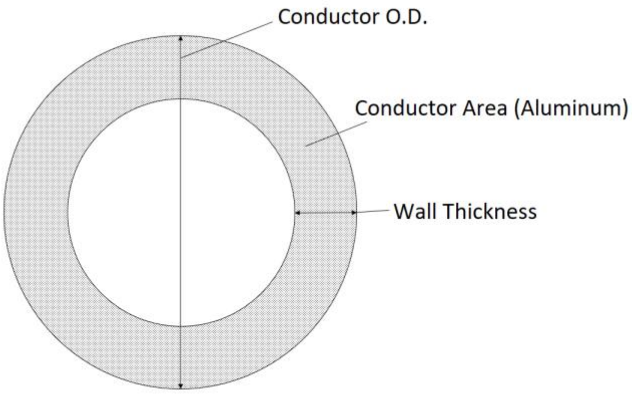
$$P_{loss} = (1-\eta)\frac{P}{1000\ km} \tag{1}$$

$$R = \frac{P_{loss}}{I^2} \tag{2}$$

$$\rho_{Al,85°C} = \rho_{Al}\left(1+\alpha_{Al}\left(T-T_{ref}\right)\right) \tag{3}$$

$$A = \rho_{Al,85°C}\frac{l}{R} \tag{4}$$

$$d = 2\sqrt{\frac{A}{\pi}} \tag{5}$$



The calculations on the right side of the table were done using basic electrical engineering equations, seen above. The current of one phase was assumed to be 3 kA and carrying 1.5 GW of power, two phases then total to 6 kA and 3 GW. This is consistent with Faulkner's approach, as he specified a two-way heating of 30 W/m, which is only possible with 3 GW of power over 1000 km.

$$P_{loss} = (1-\eta)\frac{P}{1000\ km} = (1-0.99)\frac{1.5\ GW}{1000\ km} = 15\,\frac{W}{m}$$

Next, the required resistance to achieve 1% loss was calculated.

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

$$R = \frac{15\frac{W}{m}}{3000A^2} \cdot 1000 \cdot 10^3 m = 1.67\,\Omega$$

Using the resistance, the cross-sectional area and diameter were determined using aluminum's electric resistivity at 85°C.

$$\rho_{Al,85°C} = \rho_{Al}\left(1 + \alpha_{Al}(T - T_{ref})\right) = 2.65 \cdot 10^{-8}(1 + 4.29 \cdot 10^{-3}(85 - 20)) = 3.39 \cdot 10^{-8}\Omega m$$

$$A = \rho_{Al,85°C}\frac{l}{R} = 3.39 \cdot 10^{-8}\ \Omega m \cdot \frac{1000 \cdot 10^3\ m}{1.67\ \Omega} = 0.0203\ m^2$$

$$d = 2\sqrt{\frac{A}{\pi}} = 2\sqrt{\frac{0.0203\ m^2}{\pi}} = 0.1609\ m$$

The conductor diameter represents the diameter of a circle that will yield the needed conductor area.

The next value mentioned is the conductor O.D. (outer diameter). Here the hollow core is included. The conductor O.D. (r1*2) is the hollow core with wall thickness (w) added. The wall thickness represents the conductor radius that is added onto the hollow core. Faulkner's values were used from this point onwards. The conductor area and total area can then be described as:

$$A_c = \pi(r_1^2 - [r_1 - w]^2) = \pi(0.1145m^2 - [0.1145\ m - 0.035\ m]^2) = 0.0213\ m^2$$

$$A_T = \pi \cdot r_1^2 = 0.0412\ m^2$$

The ratio of conductor area by total area results in:

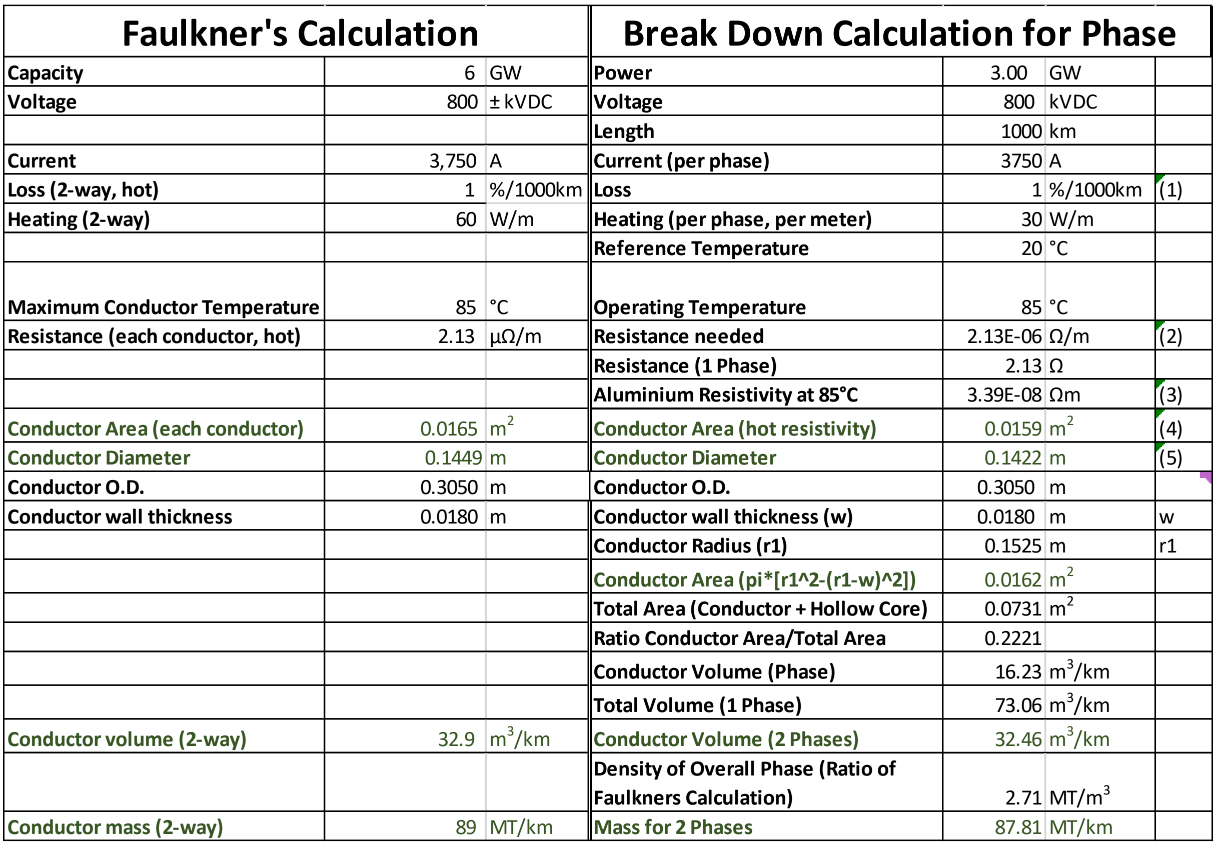
$$\frac{A_c}{A_T} = \frac{0.0213\ m^2}{0.0412\ m^2} = 0.5179$$

With the areas the phase conductor and total volume per km can be defined.

$$V_c = A_c \cdot 10^3\ m = 0.0213\ m^2 \cdot 10^3\ m = 21.33\frac{m^3}{km}$$

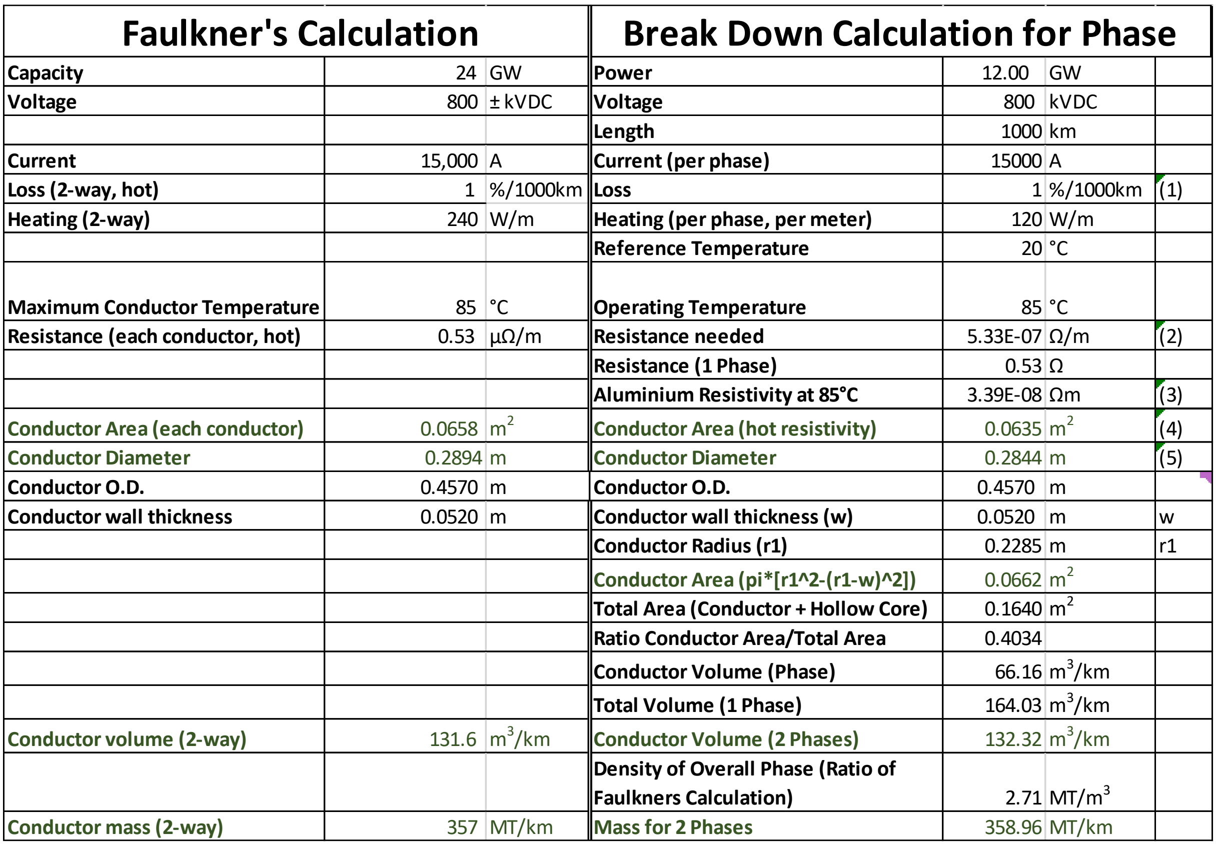
The process was repeated for the 6 and 24 GW Elpipes.

Table 3: Comprehension calculation (right side) of 6 GW Elpipe as seen in [4] (left side)



Faulkner's Calculation			Break Down Calculation for Phase			
Capacity	6	GW	**Power**	3.00	GW	
Voltage	800	± kVDC	**Voltage**	800	kVDC	
			Length	1000	km	
Current	3,750	A	**Current (per phase)**	3750	A	
Loss (2-way, hot)	1	%/1000km	**Loss**	1	%/1000km	(1)
Heating (2-way)	60	W/m	**Heating (per phase, per meter)**	30	W/m	
			Reference Temperature	20	°C	
Maximum Conductor Temperature	85	°C	**Operating Temperature**	85	°C	
Resistance (each conductor, hot)	2.13	µΩ/m	**Resistance needed**	2.13E-06	Ω/m	(2)
			Resistance (1 Phase)	2.13	Ω	
			Aluminium Resistivity at 85°C	3.39E-08	Ωm	(3)
Conductor Area (each conductor)	0.0165	m^2	**Conductor Area (hot resistivity)**	0.0159	m^2	(4)
Conductor Diameter	0.1449	m	**Conductor Diameter**	0.1422	m	(5)
Conductor O.D.	0.3050	m	**Conductor O.D.**	0.3050	m	
Conductor wall thickness	0.0180	m	**Conductor wall thickness (w)**	0.0180	m	w
			Conductor Radius (r1)	0.1525	m	r1
			Conductor Area (pi*[r1^2-(r1-w)^2])	0.0162	m^2	
			Total Area (Conductor + Hollow Core)	0.0731	m^2	
			Ratio Conductor Area/Total Area	0.2221		
			Conductor Volume (Phase)	16.23	m^3/km	
			Total Volume (1 Phase)	73.06	m^3/km	
Conductor volume (2-way)	32.9	m^3/km	**Conductor Volume (2 Phases)**	32.46	m^3/km	
			Density of Overall Phase (Ratio of Faulkners Calculation)	2.71	MT/m^3	
Conductor mass (2-way)	89	MT/km	**Mass for 2 Phases**	87.81	MT/km	

Table 4: Comprehension calculation (right side) of 24 GW Elpipe as seen in [4] (left side)

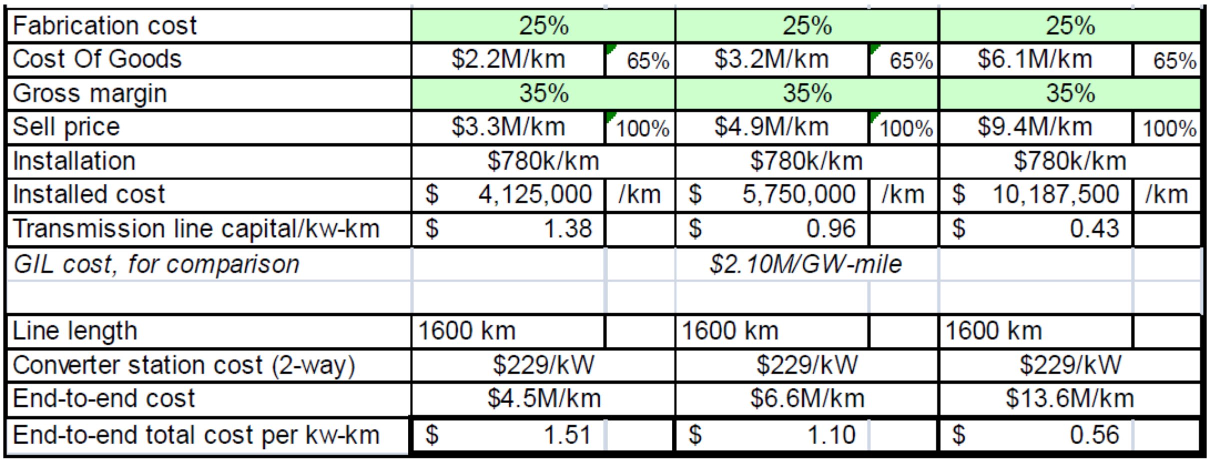


Faulkner's Calculation			Break Down Calculation for Phase			
Capacity	24	GW	**Power**	12.00	GW	
Voltage	800	± kVDC	**Voltage**	800	kVDC	
			Length	1000	km	
Current	15,000	A	**Current (per phase)**	15000	A	
Loss (2-way, hot)	1	%/1000km	**Loss**	1	%/1000km	(1)
Heating (2-way)	240	W/m	**Heating (per phase, per meter)**	120	W/m	
			Reference Temperature	20	°C	
Maximum Conductor Temperature	85	°C	**Operating Temperature**	85	°C	
Resistance (each conductor, hot)	0.53	µΩ/m	**Resistance needed**	5.33E-07	Ω/m	(2)
			Resistance (1 Phase)	0.53	Ω	
			Aluminium Resistivity at 85°C	3.39E-08	Ωm	(3)
Conductor Area (each conductor)	0.0658	m^2	**Conductor Area (hot resistivity)**	0.0635	m^2	(4)
Conductor Diameter	0.2894	m	**Conductor Diameter**	0.2844	m	(5)
Conductor O.D.	0.4570	m	**Conductor O.D.**	0.4570	m	
Conductor wall thickness	0.0520	m	**Conductor wall thickness (w)**	0.0520	m	w
			Conductor Radius (r1)	0.2285	m	r1
			Conductor Area (pi*[r1^2-(r1-w)^2])	0.0662	m^2	
			Total Area (Conductor + Hollow Core)	0.1640	m^2	
			Ratio Conductor Area/Total Area	0.4034		
			Conductor Volume (Phase)	66.16	m^3/km	
			Total Volume (1 Phase)	164.03	m^3/km	
Conductor volume (2-way)	131.6	m^3/km	**Conductor Volume (2 Phases)**	132.32	m^3/km	
			Density of Overall Phase (Ratio of Faulkners Calculation)	2.71	MT/m^3	
Conductor mass (2-way)	357	MT/km	**Mass for 2 Phases**	358.96	MT/km	

Only 22% of the conductor O.D. is comprised of conductor for the 6 GW Elpipe, while the 3 and 24 GW versions are at 52% and 42% respectively.

The source paper was submitted in February 2011, at which the monthly average price of aluminum according to WestMetall was 2530 $/t [5]. The total manufacturing cost of the conductor is set at 4102 $/t for the 3 GW version, this leaves 1575 $/t, or 38%, for direct labor and manufacturing overhead.

Table 5: Cost estimation for 3 GW, 6 GW and 24 GW Elpipes by Roger Faulkner [4]



Fabrication cost	25%		25%		25%	
Cost Of Goods	$2.2M/km	65%	$3.2M/km	65%	$6.1M/km	65%
Gross margin	35%		35%		35%	
Sell price	$3.3M/km	100%	$4.9M/km	100%	$9.4M/km	100%
Installation	$780k/km		$780k/km		$780k/km	
Installed cost	$ 4,125,000	/km	$ 5,750,000	/km	$ 10,187,500	/km
Transmission line capital/kw-km	$ 1.38		$ 0.96		$ 0.43	
GIL cost, for comparison			*$2.10M/GW-mile*			
Line length	1600 km		1600 km		1600 km	
Converter station cost (2-way)	$229/kW		$229/kW		$229/kW	
End-to-end cost	$4.5M/km		$6.6M/km		$13.6M/km	
End-to-end total cost per kw-km	$ 1.51		$ 1.10		$ 0.56	

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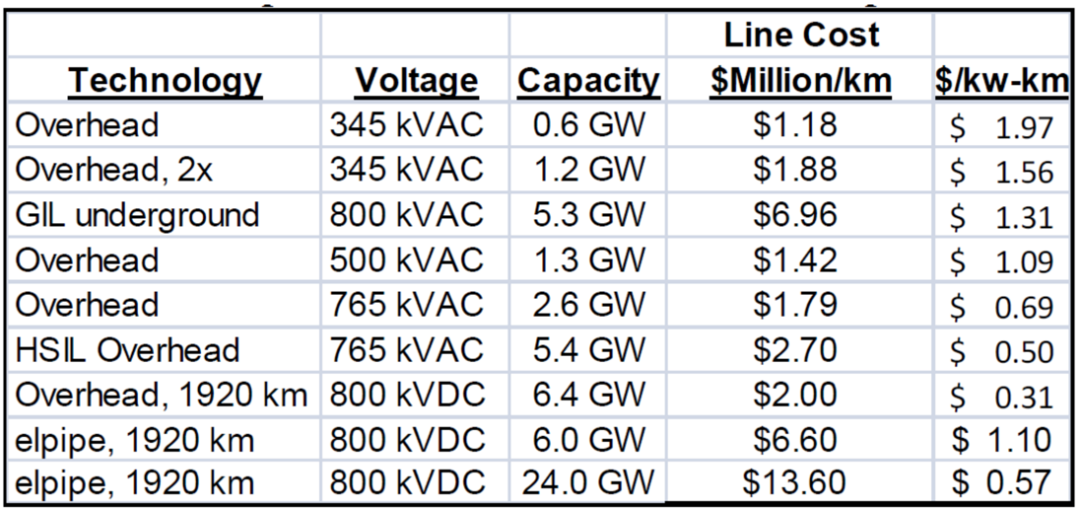
Fabrication costs are assumed to be 25%. The estimated cost of installation is set at 780 k$/km. This results in a transmission line capital of 1.38 $/km/kW. The underground GIL cost is given as 2.1 M$/GW/mile which equates to 1.25 $/km/kW. Right of way costs are excluded in the cost estimation.

Table 6: Comparative costs of transmission options by Faulkner [4]



			Line Cost	
Technology	**Voltage**	**Capacity**	**$Million/km**	**$/kw-km**
Overhead	345 kVAC	0.6 GW	$1.18	$ 1.97
Overhead, 2x	345 kVAC	1.2 GW	$1.88	$ 1.56
GIL underground	800 kVAC	5.3 GW	$6.96	$ 1.31
Overhead	500 kVAC	1.3 GW	$1.42	$ 1.09
Overhead	765 kVAC	2.6 GW	$1.79	$ 0.69
HSIL Overhead	765 kVAC	5.4 GW	$2.70	$ 0.50
Overhead, 1920 km	800 kVDC	6.4 GW	$2.00	$ 0.31
elpipe, 1920 km	800 kVDC	6.0 GW	$6.60	$ 1.10
elpipe, 1920 km	800 kVDC	24.0 GW	$13.60	$ 0.57

The paper's cost calculation concludes that Elpipes will cost more than overhead lines but will be cheaper than underground GIL cables. This is done on the basis of 6 GW Elpipe that spans almost 2000 km. The Elpipe's cost is 1.1 $/kW/km compared to 1.31 $/kW/km for underground cables. The cost described in the paper is the initial investment cost to build and install the transmission line.

Elpipes are larger, require more material, and are harder to transport and install than traditional cables. Cables can be transported on spools, whereas Elpipes consist of rigid 30 m tubes. Every segment and splice must be linked in the field, inside the construction trench. A cable can simply be unspooled. All this would lead to higher manufacturing, transportation, installation, and maintenance costs.

Total cost of ownership was not considered in the paper. This is surprising, as Elpipes design efficiency is a major selling point. Increased efficiency leads to reduced losses and operating costs compared to a conventional cable with an efficiency of around 95%. Considering two 6 GW transmission lines with efficiencies of 95% and 99%, 4000 full load hours per year, results in an energy losses difference of 0.96 GWh (1.2 - 0.24 GWh). Suggesting that Elpipes can be cheaper and at the same time more efficient than conventional DC cables is illogical. Higher efficiency results from larger cross-sections and more conductor material, which causes a costlier transmission system.

The most complex element in the Elpipe system is the splice module, which appears every 30 m along the transmission line.

2.2 Technical feasibility

Technical feasibility can be divided into three parts: electrical, mechanical, and thermal. The electrical sections will examine sodium as a conductor and the novel insulation method described in [3], which was specifically developed for Elpipes.

2.2.1 Electrical

Judging the electrical performance of Elpipes is only superficially possible, as no specific design exists to model. The patent encompasses a large variety of possibilities for conductor and splices. The constant element throughout the various design possibilities is the use of sodium and the novel insulation method outlined in [3]. These two elements will be studied in greater detail in the following section.

2.2.1.1 Sodium as a conductor

The Elpipe patent and a multitude of Faulkner's papers mention the use of sodium as a conductor. It is described as a filler conductor, used to fill voids within the extruded aluminum keystones. Sodium is the most abundant alkali metal. It is a soft, ductile metal and melts at around 98°C. The volume change when melting is 2.7% at 1 Bar. Table 7 shows resistivity and density of sodium compared to copper and aluminum. While sodium has a higher resistivity than copper, it is less dense and cheaper, according to Faulkner.

Table 7: Copper, sodium and aluminum compared based on electrical resistance

	Resistivity (nΩm)	Density (kg/m³)	Resistivity Relative to Copper	Density Relative to Copper	Price (USD/t)
Copper	16.78	8,960	1.00	1.00	9,184 [6]
Sodium	47.62	971	2.84	0.11	2,406 [7]
Aluminum	29.67	2,702	1.77	0.30	2,619 [6]

Table 8: Cross-sectional area to achieve a resistance of 2.78 Ω over a length of 100 km for copper, sodium, and aluminum. Resulting weight and costs are listed and compared in relation to copper.

	Required Area (m²)	Required Volume (m³)	Required Weight (t)	Conductor Price (USD)	Price Relative to Copper
Sodium	1.71E-03	171	166	400,496	0.08
Copper	6.04E-04	60	541	4,970,455	1.00
Aluminum	1.07E-03	107	289	755,951	0.15

The use of sodium as a conductor is not a novelty. A 1979 study by the U.S. Department of Energy [8] examines the use of sodium in distribution cables. The study is based on operative experiences of the Nacon Corporation which produced and operated underground sodium distribution cables in the 1960s. Analysis was done on sodium and aluminum cables that are equal in overload ampacity, at 95°C and 130°C respectively. Voltage levels were specified at 600 V, 15 kV, 25 kV and 35 kV. The 600 V cables consist of a conductive aluminum or sodium core, surrounded by polyethylene. The kV class/level aluminum cable consisted of stranded aluminum conductors with polyethylene insulation and concentric neutral wires placed around the semiconducting shield outside the electric insulation. The sodium cable had the same design, only instead of stranded aluminum, a solid core of sodium was used as a conductor.

The study found that sodium distribution cables incur 10% less owning and operating costs. The resulting sodium cable is also lighter and exhibits increased flexibility compared to its aluminum counterpart. The thermal expansion coefficient of sodium ($70\ 10^{-6}$ m/m/K) is higher than that of aluminum ($21 - 24\ 10^{-6}$ m/m/K) and closer to polyethylene ($108\text{-}200\ 10^{-6}$ m/m/K), resulting in less mechanical stress.

Concerning the electrical performance, the study concluded that sodium was equivalent or better than aluminum. The sodium cable had a lower electrical resistance, with a ratio R_{Na}/R_{Al} of 0.71 to 0.74. Sodium also had a better corona performance and voltage endurance due to its smooth surface. Furthermore, the sodium conductor has increased overload potential. The endothermic melting of sodium at around 95°C increases the time sodium cables can hold an overcurrent, see Figure 12.

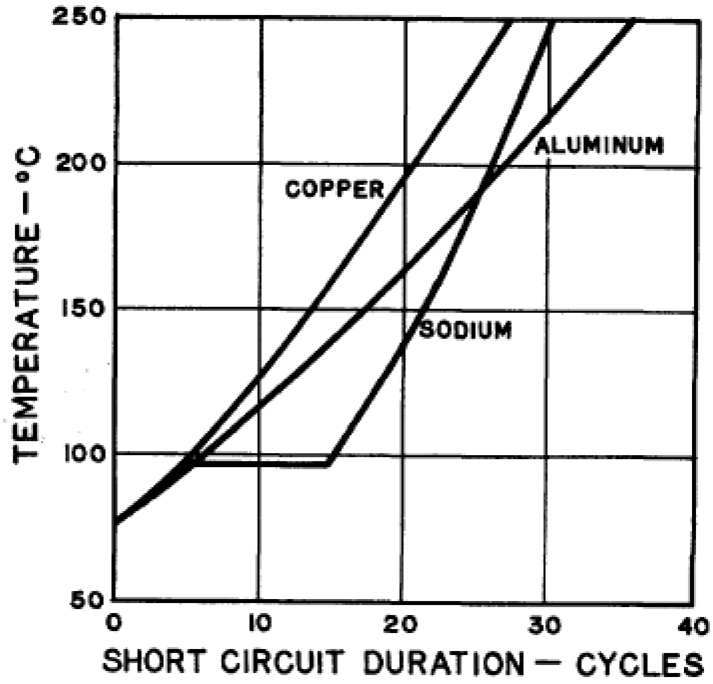


Fig. 6. Short-circuit characteristic for sodium, copper, and aluminum conductors having equal resistance at 25°C; operating temperature before short circuit: 75°C; current density: 0.04 per circular mil of sodium.

Figure 12. Temperature of sodium, copper, and aluminum with regards to short circuit duration [9]

However, electrical requirements to enable large scale use of sodium cables were never completed. The sodium cable lacked a reliable, cost-efficient connector that can insulate itself from moisture and vapor. The DoE study concluded that without such a connector, a lifetime of 40 years cannot be achieved [8]. In relation to Elpipes, the splices assume the role of the connectors.

The main safety concerns regarding a sodium conductor are centered around its reaction with water. The exothermic reaction forms sodium hydroxide and hydrogen. The latter may ignite due to the exothermic nature of the reaction. Special training for service and installation personnel is needed. Removal and disposal of decommissioned cables is also more hazardous. The reaction with water is also the cause for most failures. 98.7% of failures can be attributed to terminal failures due to moisture penetrating the terminal and causing the conducting area to diminish. Less conductive area results in increased resistance and overheating, causing the polyethylene insulation to fail [8].

In conclusion, sodium as a conductor has electrical, mechanical, and economic advantages to conventional aluminum conductors. It is understandable why Faulkner introduced them into Elpipes. What is still unknown is the combination of both conductors. [9] and [8] only give insight into conductors consisting purely of sodium. However, Elpipes use a mix of sodium and conventional conductors. Further investigation is needed to judge the compatibility of the two conductors. Using sodium will result in negative effects on system reliability.

2.2.1.2 Insulation

The rigid Elpipe segments are not rolled on a reel for transport. This makes it possible to use a range of insulation materials and methods. With the use of spirally wrapped insulating and semiconductive layers a circular leakage current can be achieved. The resulting leakage current along the semiconductive material greatly reduces the inhomogeneity of local voltage stress, in such a way that the voltage stress inversion due to the thermal gradient in the insulation will be drastically reduced [3].

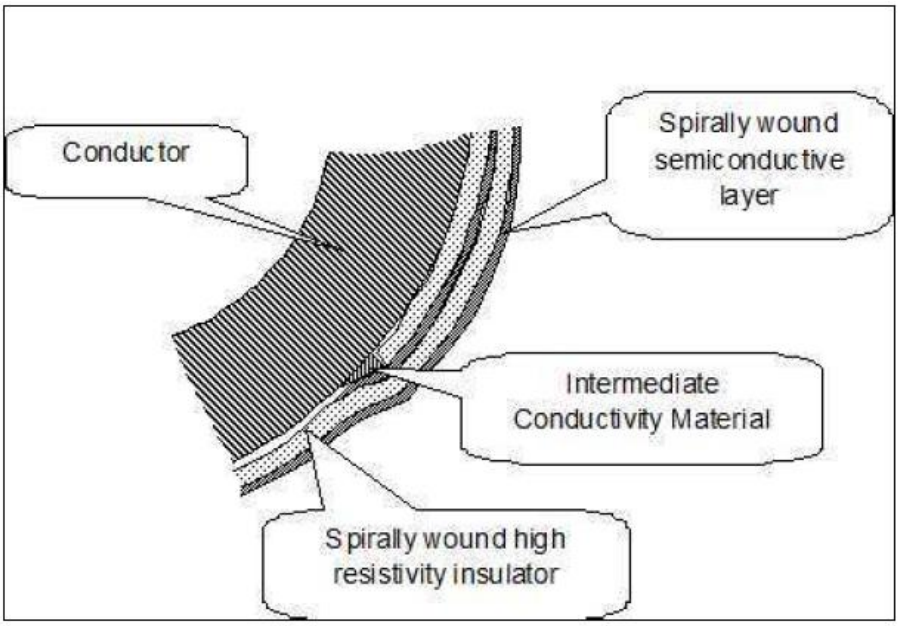


Figure 13. Spiral wound insulation surrounding an Elpipe segment [3]

Voltage stress inversion is a phenomenon that occurs in HVDC cables. It is defined as the extra voltage stress when grounding or reversing the voltage polarity. This extra stress is due to charges accumulating inside the insulation. The accumulation is the result of negative temperature coefficient of the insulation material which causes a conductivity gradient inside the insulating material. The resulting conductivity is highest closest to the conductor. The conductivity gradient then causes a current near the conductor that cannot be transported away fully by the less conductive outside portion of the insulation, which in turn causes a buildup of charges. During grounding or polarity change, these charges cause extra stress on the insulation. The goal of the spiral semiconducting layer is to diffuse these charges by allowing a steady current through the insulation which inhibits the accumulation of charges.

There are several unresolved issues that stand in the way of making the insulation a viable option. Thermally, the Elpipe in the paper performs well. This is due to the specified conductor radius of 0.2 m and the short insulations thickness of 0.02 m. To clarify, the paper modelled a 1000 km Elpipe with following design parameters:

Table 9: Design parameters of Elpipe defined in [3]

Voltage	800 kV
Power	12 GW
Maximum conductor loss	60 W/m
Thickness of insulating film	75 µm
Thickness of semiconductive film	25 µm
Inner insulation radius (a)	0.2 m
Outer insulation radius (b)	0.22m
Number of spiral turns	200
Burial depth of pipe	2.0 m
Insulation heat conductivity (k)	0.3 W/m/K
Soil heat conductivity	1.0 W/m/K

The temperature change of the insulation is modelled with the following formula:

$$Q\frac{ln\left(\frac{b}{a}\right)}{2\pi\cdot k} = 60\cdot\frac{ln\left(\frac{0.22}{0.2}\right)}{2\pi\cdot 0.3} = 3.03\ K = \Delta T$$

With the values specified in Table 9, the above equation yields a temperature difference in the XLPE of 3.03 K. The main factor contributing to this low value is the relationship between inside and outside radius, which at ln(0.22/0.2)=ln(1.1)=0.01. To achieve 1% losses of 6 GW at 1000 km, 800 kV, 7.5 kA, a resistance of 0.94 Ω is needed. For aluminum this results in a conductor area of 0.028 m^2 radius of 0.1 m:

$$A_{conductor} = \rho\cdot\frac{l}{R} = 2.7\cdot 10^{-8}\ \frac{1000\cdot 10^{3}}{0.94} = 0.028\ m^2$$

This means that in this model, only 50% of the area inside the inner insulation radius is made up of conductive material.

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

$$\frac{A_{conductor}}{A_{inner\ insul.radius}} = \frac{0.1m^2 \cdot \pi}{0.2m^2 \cdot \pi} = 0.5$$

The hollow core is the main reason for the low temperature difference illustrated in the paper. Without the hollow core, the inner insulation radius is a = 0.1 m, the outer insulation radius is b = 0.1 + 0.02 = 0.12 m. Resulting in $ln\left(\frac{0.12}{0.1}\right)$=0.18 and:

$$\Delta T_{nohollowcore} = \Delta T \frac{ln\left(\frac{0.12}{0.1}\right)}{ln\left(\frac{0.22}{0.2}\right)} = 54.5\ K$$

The paper deals with hypothetical materials, the insulator being modelled closely to XLPE, as seen by the thermal conductivity of 0.3 W/m/K. No specific semiconductor compounds are mentioned, only a list of needed characteristics to fulfill:

“the case considered above was limited to two materials that both conform to equation 3 (conductivity in dependance of temperature and field strength):

$$\sigma = \sigma_0 \exp\left[\alpha(T - T_0)\exp\left(\beta(E - E_0)\right)\right]$$

„the change of resistivity with temperature must be less in the semiconducting film than the insulating film, preferably near zero or weakly in the opposite direction (reduction of conductivity with increasing temperature in the semiconducting film), or

- the thickness of the semiconducting film must change with its radial position to maintain constant conductivity of the semiconducting film even though the temperature is changing, or
- the intrinsic conductivity of the semiconducting film must change with its radial position“ [3]

The proposed homogenous electric field stress distribution will be challenging to achieve. Manufacturing the of semiconducting layer will be difficult as the conductivity needs to change in accordance with length, as each subsequent wrap is 2πd longer [3]. Dimensioning the semiconductive layer is important to realize the benefits of the proposed insulation:

“if relative resistivity with temperature is the same in the semiconducting film layer and the insulating film layer, and if the thickness of the two layers is the same, a thermal stress inversion will still occur.”

If this is not realized, the wrapped insulation is reduced to higher heat losses than conventional XLPE insulation, 2 W/m compared to 6.6 W/m [10].

800 kVDC is not a common commercially used DC voltage level. HVDC cables are produced for 525 kVDC, up to 625 kVDC recently. A 500 kVDC cable by ZTT has an XLPE thickness of 34 mm, 14 mm more than the proposed wrapped insulation. The insulation needs to withstand an average electric service stress of 40 kV/mm, a far shot from the design withstand of 10 -15 kV/mm of XLPE. 800 kVDC projects have been realized in the past, for example the 1980 km UHVDC line connecting Xiangjiaba and Shanghai, China in 2010. However, the project uses overhead lines.

Conventional HVDC insulation is attached to the conductor sheath with extrusion, while the wrapped insulation is layered around the conductor with 200 turns. This layering increases the chance of particles to be caught in between insulation layers. These particles then cause sections in the insulation with higher conductivity resulting in higher field strengths which reduces the lifespan of the insulation. The paper describes a workaround, with two semiconductive layers working as an equipotential surface:

"in order to minimize the potential effects of particles, it is reasonable to consider using insulating films that are coated with semiconductor on both surfaces. […] contaminants that are limited to the area between two semiconductive surfaced films will not amplify the electric field, as they are effectively in a Faraday cage between the two semiconductive layers."

Furthermore, since the insulation is not a homogeneous mass, temperature changes will cause mechanical forces to pull and push the layers apart, a factor not considered in the paper. This would also create areas in which the electric field strength is variable, therefore reducing the lifespan of the insulation.

It is important to understand that the Elpipe design does not allow for conventional XLPE insulation. Conventional XLPE insulation is applied to a cable via extrusion. The Elpipe conductor is made up of multiple rigid aluminum keystones and extruding XLPE insulation over it is not possible. This leaves no other options than to use the spiral wrapped insulation.

The leakage current in the semiconductive layer can lead to severe safety concerns. The radial distance between the semiconductive layers is 75 µm. A short circuit between layers will result in hotspots which in turn could short circuit further layers, leading to a cascading short circuit across the semiconductive layers and cause a failure of the insulation. At the same time the leakage current is a necessity. Without it, the semiconductive layer will accumulate space charges until the outside of the insulation reaches the same potential as the conductor. These problems are further intensified for the splice module. It is unclear how the insulation between two Elpipe segments is supposed to be bridged.

To conclude, the novel insulation design has multiple feasibility issues. Like other Elpipe concepts it is a purely theoretical construct. The exact materials and manufacturing processes are unknown, especially for the semiconductive layer. The manufacture and installation of the conductor itself is also unknown. The article specifies that it can be wrapped around, however with no permanent fixation on the conductor, the layers will loosen and tighten with temperature changes. The resulting mechanical stress could cause the insulation to loosen grip, which would lead to a shutdown of the transmission line. The necessary leakage current increases the electrical losses and thermal load on the insulation. Furthermore, there are safety concerns that arise out of the leakage current and short circuits of semiconductive layers.

2.2.2 Mechanical feasibility

There are elements that will be subject to mechanical stress. The conductor will expand and contract due to changes in temperature. In the patent this stress can be offset with the use of a volume compensation device (see Figure 7, number 154).

The wheels that move the Elpipe segments inside the conduit (see Figure 8, number 380) will carry the weight of a whole Elpipe segment. Assuming a weight of 290 kg/m (Table 2) and a length of 30 m per segment, the weight of an Elpipe segment totals to 8.7 T. No indication is made of how many wheels are supposed to be used. Figure 3 shows that 8 wheels are equally spread out around the segment, while diagrams in the patent hint at fewer wheels. Using fewer wheels will cause reliability to increase since there are fewer moving parts that can fail. Larger wheels however will also cause the conduit to increase in size. An equilibrium between size, reliability and cost must be found. The patent also states that the wheels will be motorized and equipped with sensors. This seems highly cost inefficient as the Elpipe segments are only moved during maintenance, which ideally should occur as rarely as possible. While being unused for large periods, the copper motor coils can oxidize and cause malfunctions. The power supply for the motors would also stretch for the entire transmission line. The high current of the Elpipe could cause EMI, compromising the performance of the motor wheels.

The Elpipe splices are composed of different materials. Copper rods, tinned copper, aluminum, and elastomer are all used. The mechanical stress resulting from start-up and shutdown of the transmission could damage the splice modules. No blueprint or detailed diagram of a splice module exists. The patent only lists basic drawings and explanations. This makes further feasibility analysis only conjecture.

2.3 Sustainability and ecological considerations

Judging the environmental impact of Elpipes can be done by conducting a life cycle assessment of each of the components. A full analysis should include environmental, social, and economic factors. Since the specific manufacturing process for Elpipes is unknown, only primary resources will be considered. The most essential elements for an Elpipe are copper, aluminum and sodium.

Table 10: Averaged environmental sustainability indicators of primary aluminum, copper, and sodium ore

	Specific Energy Consumption [kWh/t]	**Green House Gas Emissions [t CO_{2e}/t]**	**Water Consumption [m^3/t]**
Aluminum	15,700 [11, p. 12]	18 [11, p. 13]	10 (excluding China) – 18 (including China) [12]
Copper	6,167 [13, p. 14]	2.6 [13, p. 14]	74 [13, p. 14]
Sodium	8,410 [14]		

Aluminum has a much higher specific energy consumption and greenhouse gas emissions than copper. Since aluminum also has a higher resistivity, more aluminum is needed compared to copper. The energy costs of Elpipes can be reduced by incorporating sodium, as it only requires around half the energy to produce and is less dense than aluminum.

Elpipes are designed with larger cross-sections and therefore they require more materials, increasing the upfront CO_{2e} footprint. Increased efficiency will counteract this. Table 11 shows a rough estimation of the yearly saved energy.

Table 11: Rough estimation of yearly energy saved for underground cables and Elpipes

	Power (GW)	Full load hours (h/a)	Losses (%)	Electric Losses (MWh/a)	Yearly Difference (MWh/a)
XLPE Cable	1	4000	5	200,000	- 160,000
Elpipe	1	4000	1	40,000	
XLPE Cable	4	4000	5	800,000	- 640,000
Elpipe	4	4000	1	160,000	

The Elpipe will use 5 times the amount of aluminum that a conventional cable will use ($m_{Elpipe} = 5 \cdot m_{XLPE}$), while the losses of the XLPE cable will be 5 times higher ($5 \cdot \ Eloss_{XLPE} = \ Eloss_{Elpipe}$). Depending on the CO2e emissions per MWh (e_{MWh}) generated in the local region, following comparison can be made:

$$CO_{2e}(a) = \left(m_{Elpipe} - m_{XLPE}\right) \cdot c_{Al} - \left(Eloss_{XLPE} - Eloss_{Elpipe}\right) \cdot e_{MWh} \cdot a$$

$$CO_{2e}(a) = \frac{4}{5} m_{Elpipe} \cdot c_{Al} - \left(4 \cdot Eloss_{Elpipe}\right) \cdot e_{MWh} \cdot a$$

The break-even point is reached when $CO_{2e}(a) = 0$, therefore the time in years when the Elpipe is more emission efficient is:

$$a = \frac{\frac{4}{5} m_{Elpipe} \cdot c_{Al}}{4 \cdot Eloss_{Elpipe} \cdot e_{MWh}} = \frac{m_{Elpipe} \cdot c_{Al}}{5 \cdot Eloss_{Elpipe} \cdot e_{MWh}}$$

For the 3 GW Elpipe from Table 2 this yields following results:

$$m_{Elpipe} = 115.5 \frac{t}{km} \cdot 1000\ km = 115{,}500\ t$$

$$c_{Al} = 18 \frac{t\ CO_{2e}}{t}$$

$$Eloss_{Elpipe} = 3\ GW \cdot 1\% \cdot 4000\ h = 120\ GWh = 120 \cdot 10^3\ MWh$$

$$e_{MWh} = 0.732\ \frac{t\ CO_{2e}}{MWh}\ [15]$$

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$$a = \frac{115{,}500\ t \cdot 18 \frac{t\ CO_{2e}}{t}}{5 \cdot 120 \cdot 10^3\ MWh \cdot 0.732\ \frac{t\ CO_{2e}}{MWh}} = 4{,}7\ a$$

After around 5 years the emissions due to the additional raw materials are compensated for by the increased energy efficiency. This depends on the specific emissions of electrical power (e_{MWh}). For example, 0.732 is a value specified by the German government [15] for saved electric energy due to efficiency. Power infrastructure is built to last around 40 years. This shows that the large material demand for Elpipes can be compensated by increased efficiency. Other sustainability indices, for example water consumption, are not compensated for by efficiency.

2.4 Conclusion

Economically, it is problematic to assume that Elpipes are cheaper than cable alternatives. The design efficiency alone means that a large amount of conductive material is used. Compared to cables, further auxiliary equipment such as wheels and splices are needed, leading to higher investment and maintenance costs. Due to the large cross sections and the hollow core, Elpipes require more space than conventional transmission. The use of sodium would decrease Elpipe investment costs at the expense of system reliability.

A major difficulty concerning Elpipes is the number of splices needed. Assuming an Elpipe segment is 30 m long, a 1000 km transmission Elpipe would consist of over 30 000 segments and splice modules. The substantial number of splices and segments will make it difficult to achieve a high system reliability, even with exceedingly high, time independent reliability rates. To illustrate the problem, Table 12 and Table 13 show assumptions and a basic reliability calculation. It is assumed that the yearly failure rate for splice modules and segments is 1/100.000.

Table 12: Elpipe assumptions for reliability example

Length of Segment	30	m
Length of Splice	3	m
Transmission Length	1000	km
Number of Splices (One Phase)	30304	
Number of Segments (One Phase)	30303	
Reliability Splice	0.99999	1/a
Reliability Segment	0.99999	1/a
Total Reliability One Phase	0.55	1/a
Total Reliability Both Phases	0.30	1/a

$$R_{phase} = R_{splice}^{n} \cdot R_{segment}^{n}$$

$$R_{2phase} = R_{splice}^{2n} \cdot R_{segment}^{2n}$$

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Table 13: Resulting transmission line failure rates

Operation Time (a)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Failure Chance Splice	0.26	0.45	0.60	0.70	0.78	0.84	0.88	0.91
Failure Chance Segment	0.26	0.45	0.60	0.70	0.78	0.84	0.88	0.91
Failure Change Splice or Segment (One Phase)	0.45	0.70	0.84	0.91	0.95	0.97	0.99	0.99
Failure Chance Splice or Segment (Both Phases)	0.70	0.91	0.97	0.99	1.00	1.00	1.00	1.00

$$F_{splice}^{a} = 1 - R_{splice}^{n\cdot a};\ \ F_{segment} = 1 - R_{segment}^{n\cdot a}$$

$$F_{2phase}^{a} = 1 - R_{phase}^{n\cdot a}$$

$$F_{2phase}^{a} = 1 - R_{2phase}^{n\cdot a}$$

[8] showed that most failures of sodium-based distribution cables were due to moisture leaking into the system over the connecting terminals. The splice modules are analogous to a connecting terminal, as they connect two segments together. This makes them a reliability risk. Considering the high number of splice modules needed, it becomes clear that a high system reliability is impossible for a distance of 1000 km, even when excluding the use of sodium. This theme extends to other parts of the Elpipe concept, for example the wheels, their related motors, and sensors.

Increasing the length of a segment would reduce these difficulties. The patent particularly highlights the construction of Elpipes near railway lines. The segments could then be transported by rail, allowing for longer lengths. However, this limits construction locations. It needs to be seen if the Elpipe can carry away the waste heat if it is overgrown by vegetation or other extreme environmental occurrences take place.

3 EXEMPLARY MODEL

Bringing Elpipes into perspective with other prevalent power transmission systems will show whether it is worth investing further research and development into the concept. A major difficulty in assessing Elpipes is the lack of a concrete model. The following sections will define a model according to the concepts outlined in the patent and papers written by Faulkner.

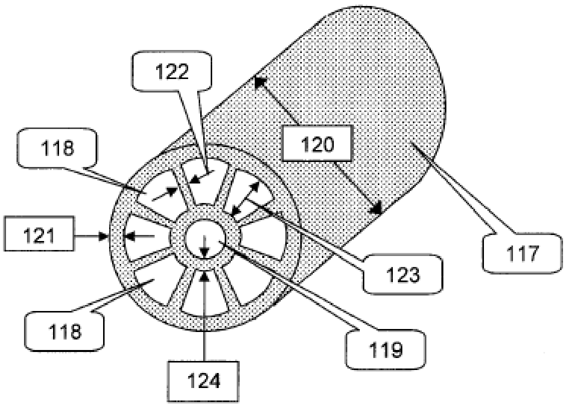
3.1 “Best Possible” Elpipe model

The first question is whether to include sodium. It is mentioned throughout the patent, but Faulkner chose to discard sodium in some papers. As seen in the previous chapters, sodium is a cheap, lightweight conductor. However, due to its reactivity with air and moisture it can become a danger to the reliability and safety of the system. To make Elpipes as cost effective as possible, sodium will be included. A program will be written that outlines the basic dimensions of the Elpipe with regard to input power, voltage, and distance. The conductor composition will be varied to evaluate the economic importance of sodium.

3.1.1 Segment and conductor

When it comes to the segment and the conductor the first question that comes to mind is what keystone is best suited. Since sodium is used, a keystone with a void must be used. The amount of sodium is then defined by the voids inside the keystone. Maximizing the amount of sodium will yield the best economic outcome, therefore the keystone arrangement with the most volume for sodium must be used. The proportions of aluminum and sodium are important to accurately define the cross-sectional area needed to achieve 1% loss per 1000 km.

Figure 14 shows the most applicable keystone. Eight keystone voids and a hollow core can be filled with sodium in this segment. The patent mentions volume compensation devices that are placed inside the sodium areas to allow for temperature dependent expansion and contraction. Going forward these will not be included.



117 – Cylindrical conductor with keystone voids
118 – Keystone void
119 – Hollow core of complex circular extrusion
120 – Outside hollow keystone conductor with circular cross-section
121 – Outer wall thickness
122 – Rib subtended angle
123 – Void height
124 – Central cylinder wall thickness

Figure 14. Conductor with one of the largest proportions of sodium [1]

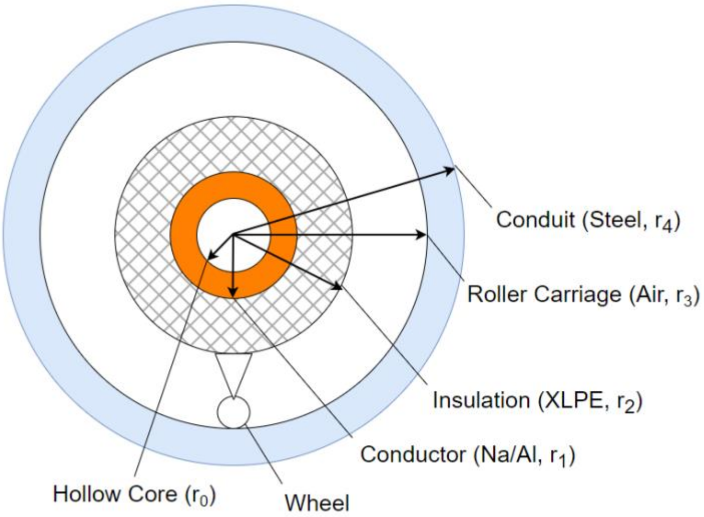


Figure 15. Cross section view of the Elpipe and how the radius of the conduit can be described

Electrically, the conductor can then be modelled by two parallel resistances: one for sodium and one for aluminum. R_{El} is the needed resistance to achieve 1% loss per 1000 km along a phase, defined by the power and voltage scenarios. The ratio x between Na and Al can be used to determine the areas of Na and Al.

$$\frac{1}{R_{El}} = \frac{1}{R_{Al}} + \frac{1}{R_{Na}} = \frac{1}{\rho_{Al}\frac{l}{A_{Al}}} + \frac{1}{\rho_{Na}\frac{l}{A_{Na}}} = \frac{A_{Al}}{\rho_{Al}\cdot l} + \frac{A_{Na}}{\rho_{Na}\cdot l}$$

$$x = \frac{A_{Na}}{A_{Al}} \rightarrow A_{Na} = x\cdot A_{Al};\ \frac{1}{R_{El}} = \frac{A_{Al}}{\rho_{Al}\cdot l} + \frac{x\cdot A_{Al}}{\rho_{Na}\cdot l}$$

$$A_{Al} = \frac{1}{R_{El}}\left(\frac{1}{\rho_{Al}\cdot l} + \frac{x}{\rho_{Na}\cdot l}\right)^{-1}$$

The insulation is modelled with XLPE as a material. To insulate a 500 kV cable 34 mm will be chosen according to existing 500 kV cables [16].

The size of the hollow core will be modelled according to [4]. As seen in 2.1, about half of the area within the conductor outer diameter is made up of air. Therefore, the hollow core will be specified to have the same area as the conductor.

$$k = \frac{A_{conductor}}{A_{core}}$$

$$A_{core}\cdot k = A_{conductor} = \pi\cdot r_0^2\cdot k = \pi\cdot(r_1^2 - r_0^2) \rightarrow$$

$$r_1 = \sqrt{k+1}\cdot r_0$$

$$k = 1 \ \rightarrow\ r_1 = \sqrt{2}r_0$$

3.1.2 Splices

Splice modules are intricate and consist of multiple parts. Accurately defining each functional part would go beyond the scope of this work. Other than connecting two segments and allowing for axial and radial movement, the splices have two defining features:

1. A reduction of the cross-sectional area, leading to areas with greater resistance compared to a segment.
2. Increased heat generation in the splice (which is transported away by heat fins, see Figure 10)

The reduction in the cross section can be compensated by increasing the conductor cross sectional area according to length and area ratio. The cross-sectional areas of the conductor, calculated in the previous section, are then multiplied by the inverse of the average area.

$$x = \frac{A_{splice}}{A_{seg}}; \bar{A} = \frac{length\ splice \cdot x + length\ segment \cdot 1}{Total\ length} = \frac{l_{splice} \cdot x + l_{seg}}{l_{splice} + l_{seg}}$$

$$Compensation\ Factor = \frac{1}{\bar{A}}$$

3.1.3 Conduit

The conduit is the protective element that houses the segments and splices. Each conduit will house one phase; therefore, two conduits will be required, as can be seen in Figure 11. The conduits are made from steel and will be 50 mm thick (arbitrarily chosen).

The conductor and insulation rest on wheels inside a roller carrier that touch the outer steel pipe. No material is specified to fill the space between insulation and steel pipe; therefore, it will be modelled by air at atmospheric pressure (1 bar) and temperature (20°C). The roller carriage will have a thickness of 250 mm to account for the use of wheels. The wheels will not be included in the thermal or electrical model.

3.2 MATLAB and Simscape model

With the previous assumptions an electrical and thermal model can be created. After specifying the input parameters, the program defines all relevant thermal and electric values and inputs them into the thermal and electrical model. The goal is to create some tangible values and data that can approximate the operation of an Elpipe.

The materials used consist of sodium, aluminum, XLPE and steel. The conductor will function as a heat source with a connected thermal mass that is connected to the surrounding soil via conductive and convective heat transfer through the insulation, roller carriage and conduit wall. Example radiuses for 1 and 4 GW Elpipes with 100 km transmission length and 1:1 ratio of sodium and aluminum are given in Table 14.

Table 14: Resulting phase dimensions for 1 and 4 GW Elpipe, with a transmission length of 1000 km and a 1:1 ratio of Na/Al

Power (GW)	**1**	**4**
r_0 = hollow core (m)	0.051	0.102
r_1 = radius conductor (m)	0.072	0.144
$r_2 = r_1$ + thickness XLPE (m)	0.106	0.178
$r_3 = r_2$ + roller carriage thickness (m)	0.356	0.428
$r_4 = r_3$ + conduit wall thickness (m)	0.406	0.478
$r_5 = r_4$ + burial depth (m)	1.406	1.478
Mass conductor (kg/m)	15.387	63.764
Mass XLPE (kg/m)	17.893	31.980
Mass air in roller carriage (kg/m)	0.473	0.617
Mass conduit (kg/m)	942.2	1,117.1
Total Mass (kg/m)	978.35	1,213.4

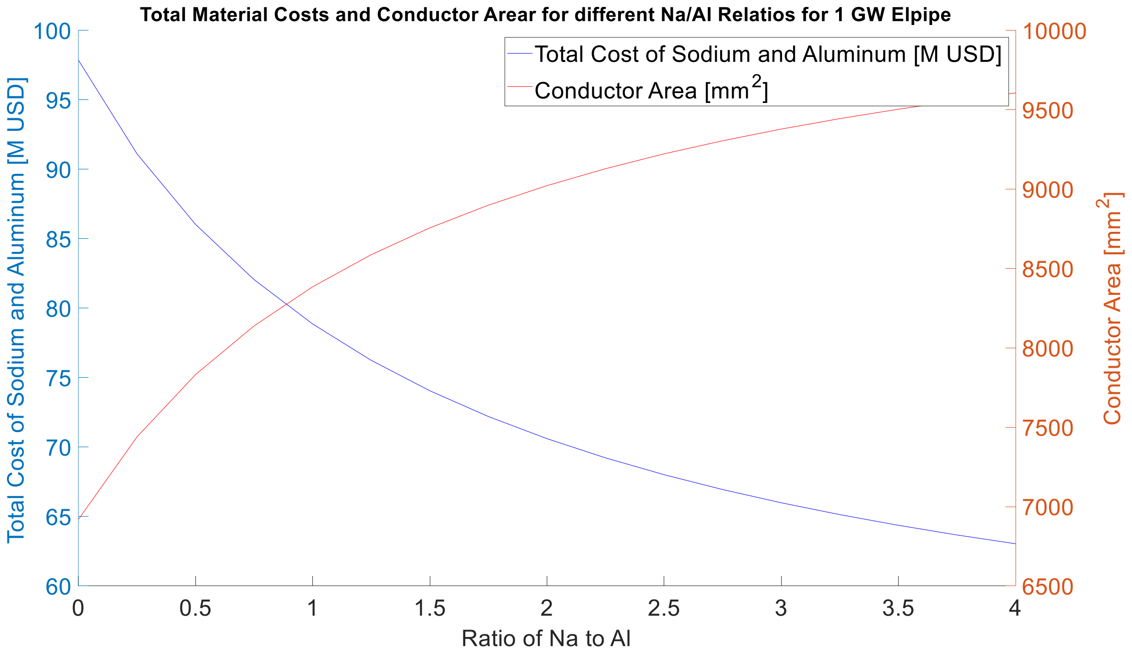


Figure 16. How the Na/Al ratio affects phase cost and conductor area for a 1000 km, 1 GW Elpipe

Increasing the Na/Al ratio reduces material cost but increases conductor area, as presented in Figures 16 and 17.

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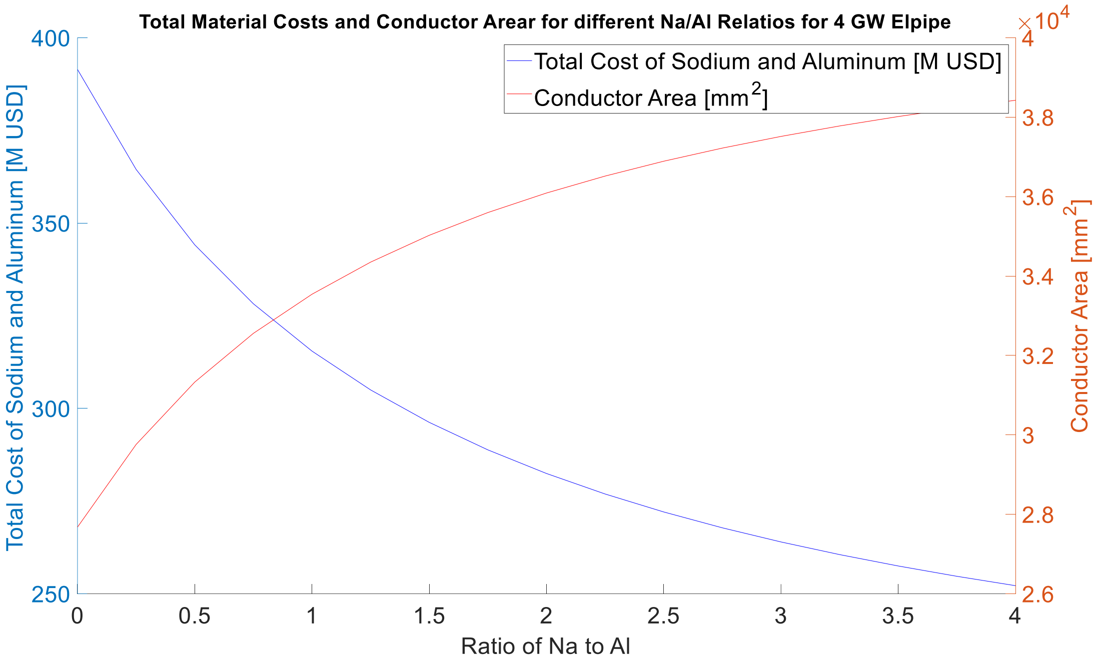
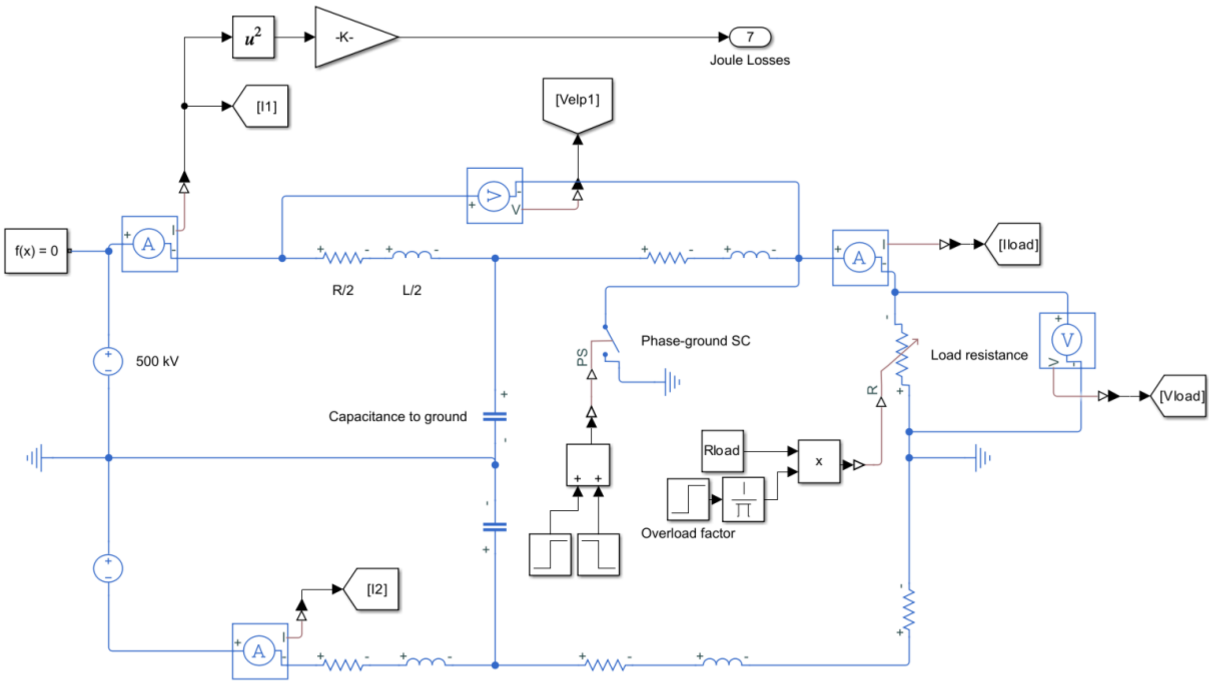


Figure 17. How the Na/Al ratio affects phase cost and conductor area for a 1000 km, 4 GW Elpipe

3.2.1 Electrical model

The electrical model simulates the operation of the transmission line. It includes both phases, resistances, inductance, and capacitance. Significant voltages and currents are determined. With the phase current and Elpipe resistances, the electrical losses are calculated and inputted in the thermal model. Example results will be shown for 1 and 4 GW Elpipes with a transmission length of 1000 km and a 1:1 ratio of sodium and aluminum.



The inductance is calculated using the following formula designed for DC cables:

$$L = \frac{\mu_0}{\pi} l \left(\ln\left(\frac{d}{r_1}\right) + \frac{1}{4} \right)$$

Where μ_0 is the permittivity of free space, l the transmission length in meters, d the distance between the phases (set to 4 m) and r_1 the radius of the conductor.

The capacitance to ground is calculated using the cylindrical capacitor formula with multiple dielectrics. It can be calculated using:

$$C = \frac{2\pi \cdot \varepsilon_0 \cdot \varepsilon_1 \cdot \varepsilon_2}{\ln\left(\frac{r_2}{r_1}\right) \varepsilon_1 + \ln\left(\frac{r_3}{r_2}\right) \varepsilon_2} l$$

ε_0 is the permittivity of free space, $\varepsilon_1$the permittivity of XLPE, $\varepsilon_2$the permittivity of air, $r_1$the radius of the conductor, r_2 the radius of XLPE and r_3 the radius to the inside of the conduit.

A leakage current through the insulation of the Elpipe is possible. The Elpipe is connected to the surrounding soil through the wheels. They will be assumed to be perfectly conductive so the resistivity and geometry of the XLPE determine the leakage current. The heat generation from the leakage current will be included in the thermal model.

$$R_{leak} = \rho \frac{1}{A} = \int_{r1}^{r2} \rho_{XLPE} \frac{dr}{2\pi r} = \frac{\rho_{XLPE}}{2\pi} \ln\left(\frac{r_2}{r_1}\right) = \left[\frac{\Omega}{m}\right]$$

$$P_{leak} = I_{leak} U = \frac{U^2}{R_{leak}} = \left[\frac{W}{m}\right]$$

Table 15: Example electrical values for a 500 kV, 1000 km, 1:1 Na/Al Elpipe

Power (GW)	**1**	**4**
Phase Resistance (Ω)	5	1.25
Inductance (mH/km)	17.1	14.3
Capacitance (pF/km)	1.71	3.34
Leakage Current (nA/m)	41.1	75.1
Leakage Power (µW/m)	20.56	37.45

Since a DC transmission is simulated, inductance and capacitance are only significant during changes in operation. The model includes options to simulate an overcurrent or short circuit in the middle of the transmission line.

3.2.2 Thermal model

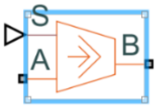
Table 16 shows the values for densities, thermal conductivity, and heat capacity used in the simulation. Low density polyethylene is used to model the insulation.

Table 16: Values used in the thermal model

	Sodium	Aluminum	XLPE (LDPE)	Steel	Soil
Density (kg/m³)	9,70	2,700	930	7,850	1,300
Thermal Conductivity (W/m/K)	141	237	0.33	45	0.83
Heat Capacity (kJ/kg/K)	1.23	0.9	2.17	0.42	0.73

The thermal model is comprised of 6 main parts:

1. **Controlled heat source**. The I^{2}R losses per meter are taken from the electrical model and input to the heat source. Heat resulting from the leakage current is added to the thermal mass of the insulation.



2. **Thermal masses**. Mass and heat capacity is needed for each of the materials. Mass is calculated using the radii and densities seen before. Thermal masses are described by the heat flow Q:

$$Q = c \cdot m \frac{dT}{dt}$$

The conductor, XLPE, air in roller carriage, steel conduit and surrounding soil are modelled in the simulation. Mass is derived from the radius.

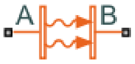
3. **Conductive heat transfer**. A cylindrical heat transfer model is available in Simscape. The outer and inner diameter (d_{out}, d_{in}) of the cylinder must be input in addition to the thermal conductivity k. Temperature B corresponds to the inside temperature of the cylinder, while temperature A represents the cylinder wall. The area between the inside and outside radii conducts heat. It is described by:

$$Q = 2\pi \cdot k \frac{L}{ln\left(\frac{d_{out}}{d_{in}}\right)}(T_A - T_B)$$

Two conductive heat transfers are included in the model. The first takes place between the conductor and the XLPE with $d_{out} = 2 \cdot r_2$ and $d_{in} = 2 \cdot r_1$. XLPE's thermal conductivity is used. The second conductive heat transfer takes place between the conduit wall and the surrounding soil. r_3 and r_4 are used to calculate the diameters and the thermal conductivity of steel is used.

4. **Convective heat transfer**. Energy transfer between a solid and a fluid in motion. In the model it is used to determine the heat transfer between the insulation and the air in the roller carriage as well as heat lost to the atmosphere from the surrounding soil. Area and heat transfer coefficient k (W/K/m^2) must be known.

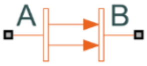
$$Q = k \cdot A(T_A - T_B)$$



The convective heat transfer inside the roller carriage is split into two parts to be able estimate the temperature of the air. The area of each convection is defined by $A_{conv} = \pi \cdot \frac{(r_3^2 - r_2^2)}{2}$. The air heat transfer coefficient is set to 100 W/K/m^2.

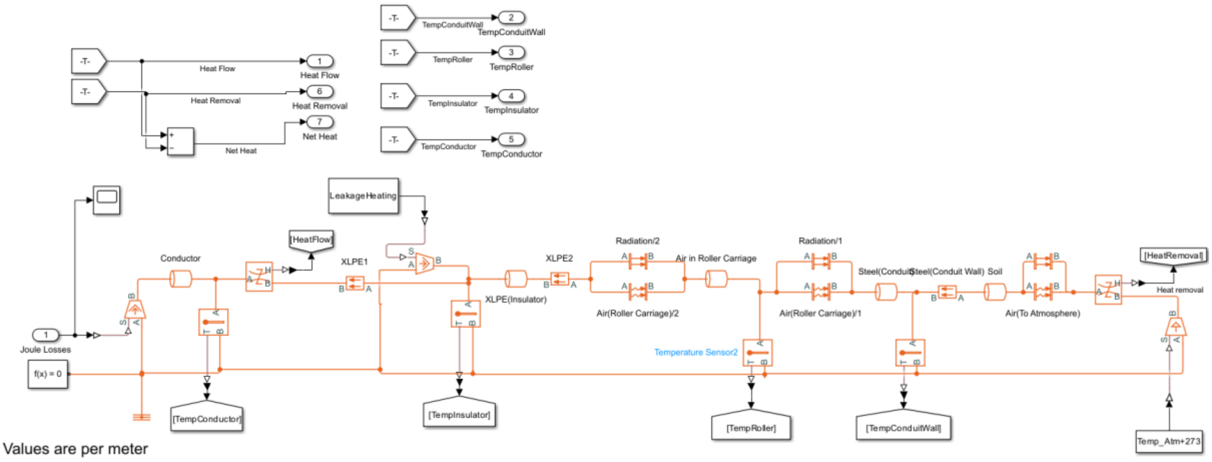
5. **Radiative heat transfer**. Radiative heat transfer takes place between the insulation and conduit wall, as well as from soil to atmosphere. The radiating area must be estimated, and radiation coefficient k is set to 4*10^{-8} W/K^4/m^2.

$$Q = k \cdot A(T_A^4 - T_B^4)$$



The radiative areas in the model are calculated in the same way as the convective areas.

6. **Controlled temperature source**. Sets the temperature at a given point to the described input value. In the simulation, the atmosphere temperature (20°C) is placed behind radiative and convection heat transfer from the surrounding soil. A heat flow sensor measures the amount of heat lost to the environment.



The most important temperature to estimate is the temperature of the insulation. To achieve a more realistic outcome, the thermal conductivity of the insulation will be modelled temperature dependent. The insulation was defined to be XLPE, which is made up of low-density polyethylene (LDPE). Figure 18 describes the relationship between thermal conductivity and temperature for LDPE.

Thermal conductivity ranges from 0.34 W/m/K at 20°C to 0.25 W/m/K at 100°C. In this area the relationship is linear. The values are implemented via tabulated data, achieved by two vectors.

```
XLPE_T_vector = linspace(20+273, 100+273, 100);
XLPE_Tcond_vector = linspace(0.34, 0.25, 100);
```

The vectors linearly approximate the characteristic seen in Figure 18 with 100 data points. The program then adjusts the thermal conductivity during calculations according to the temperature of the insulation.

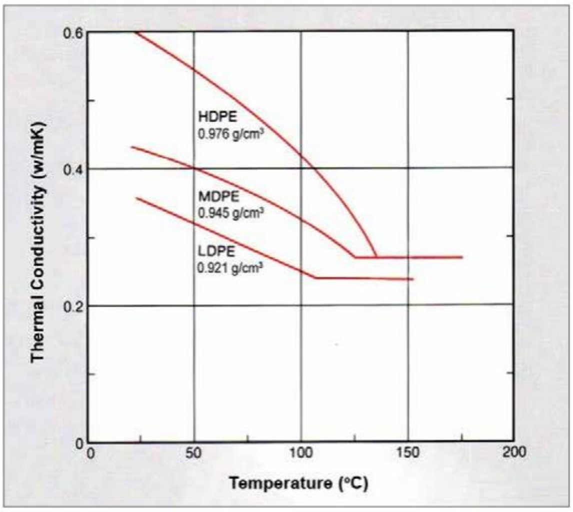


Figure 18. Thermal conductivity of polyethylene in dependence of temperature according to [17]

3.2.3 Simulation

Different parameters will be altered to see how the model responds. The most important metric is the conductor temperature. If it is above 90°C the model will not be feasible.

3.2.3.1 Temperatures after start-up

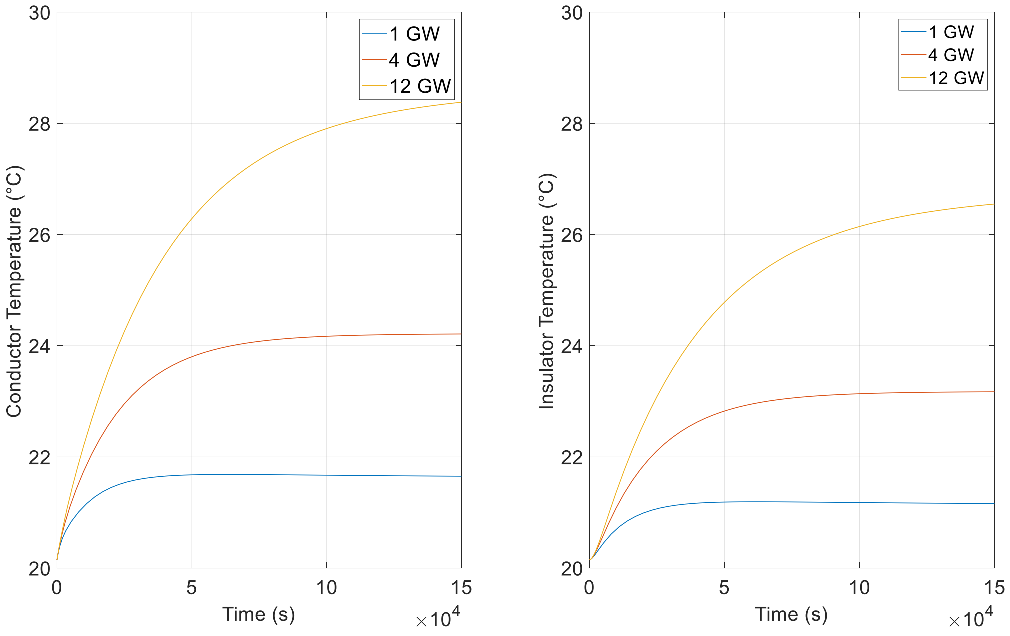


Figure 19. Temperature values during start-up of the Elpipe, 1000 km, Na/Al =1

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Figure 19 and Figure 20 show the conductor and insulation temperatures of 3 different Elpipes directly after start-up. The transmission length is 1000 km. Thermally the Elpipes perform very well, with a small temperature difference over the insulation of around 1 - 6°C, even up to 12 GW. This can be attributed to several design specifications. Firstly, the design efficiency of 99% results in low input heat and large cross-sections. Secondly, the hollow core increases the heat convectional area ln(r2/r1).

$$Q\,\frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi\cdot k} = (T_A - T_B)$$

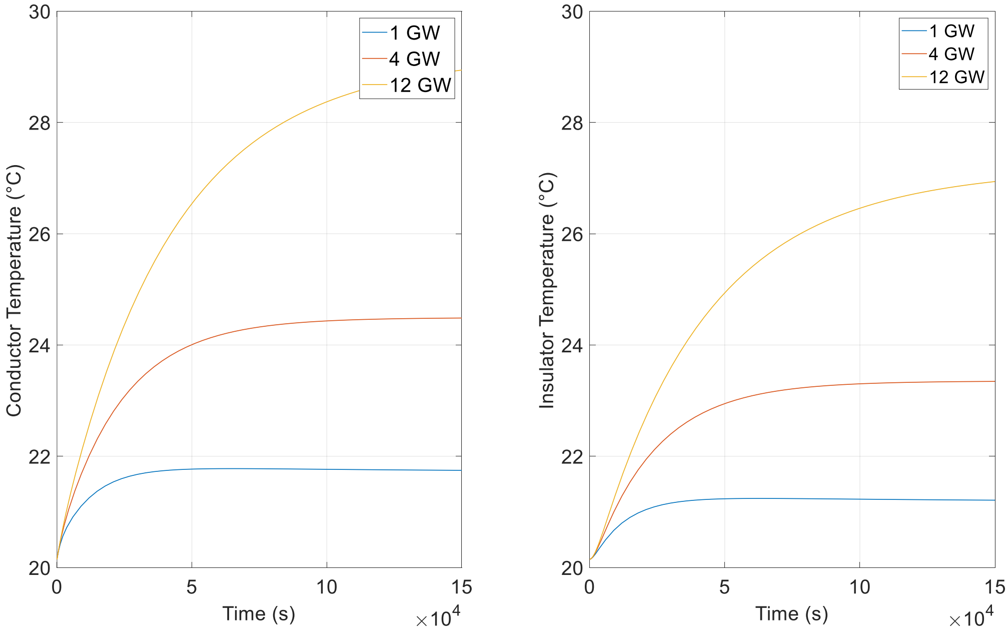

Figure 20. Temperature values during start-up of the Elpipe, 1000 km, Na/Al =0

3.2.3.2 Effect of transmission length on temperature

Reducing the transmission length will result in smaller cross-sections as the length decreases and the needed resistance stays constant. The per meter heating will increase. Reducing the conductor cross-section also reduces the size of the hollow core, as it is specified to be the same area as the conductor. With reduced radii the heat transfer from the conductor to the soil will be greatly reduced as the thickness of the insulation stays constant. This means that there is a minimum transmission length, that when reached, causes the temperature of the conductor to increase to unacceptable levels. Figure 21 and Figure 22 show the steady state temperatures of conductors for varied transmission lengths and conductor compositions.

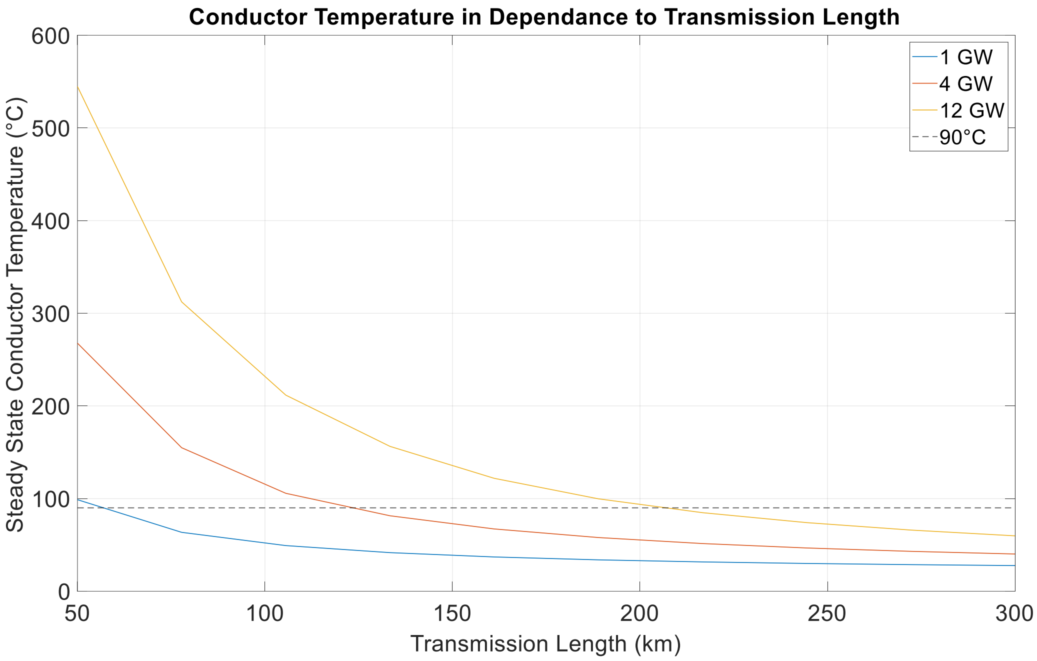

Figure 21. Steady state conductor temperature with varied transmission length, Na/Al=1

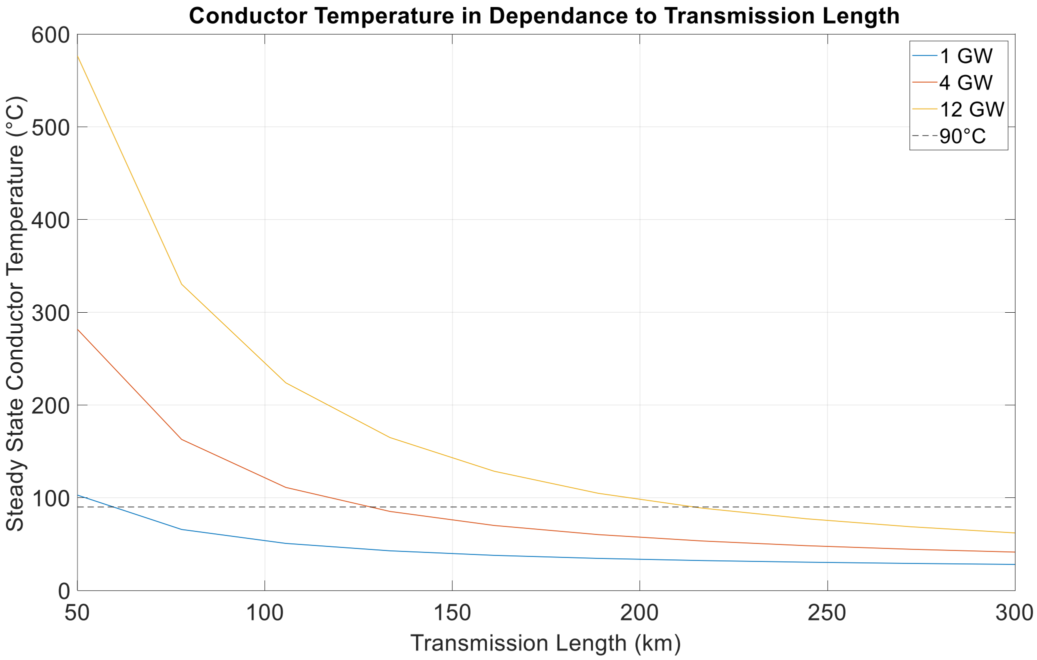

Figure 22. Steady state conductor temperature with varied transmission length, Na/Al=0

The simulations show that the 1 GW Elpipe model is feasible for transmission lengths upwards of 60 km. For the 4 and 12 GW Elpipes this is 130 and 220 km respectively. The addition of sodium decreases this distance marginally since sodium increases the cross-sections due to its higher resistivity.

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3.2.3.3 Effect of conductor composition on temperature

Figure 23 and Figure 24 show how the ratio between sodium and aluminum affects the conductor temperature. Introducing more sodium in the conductor decreases its temperature.

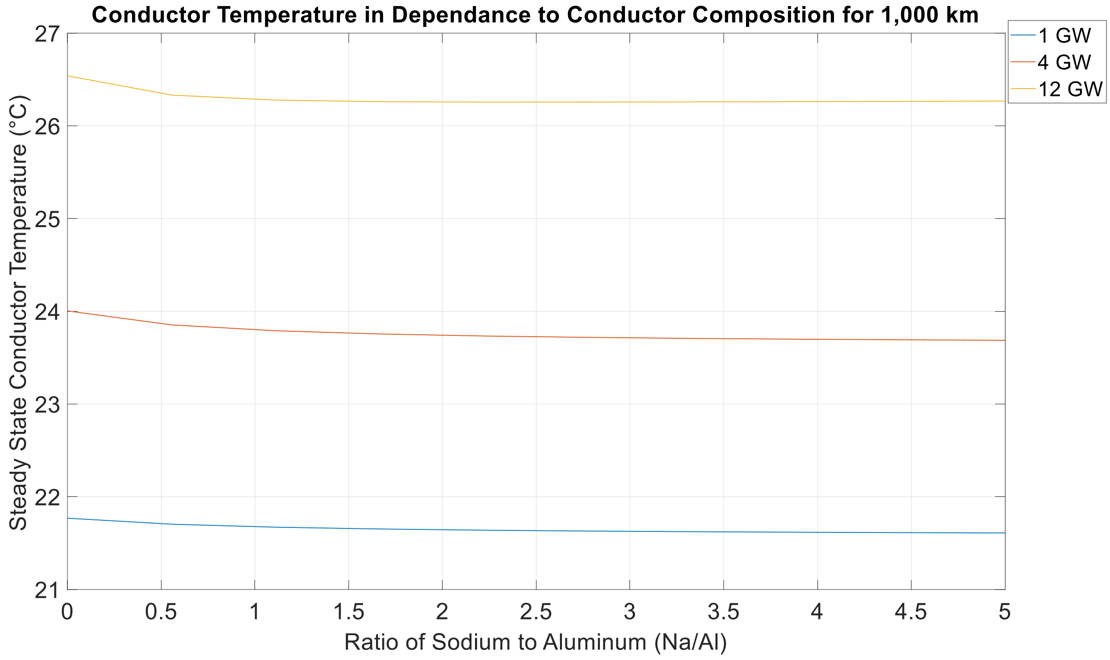


Figure 23. Conductor temperature in dependance to composition for a 1000 km Elpipe

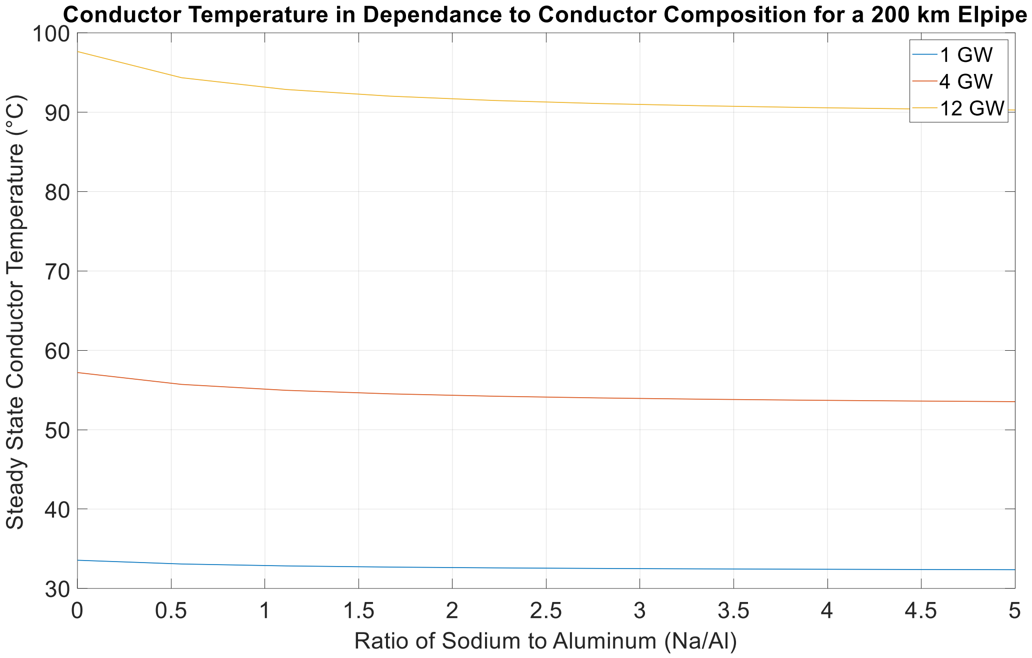
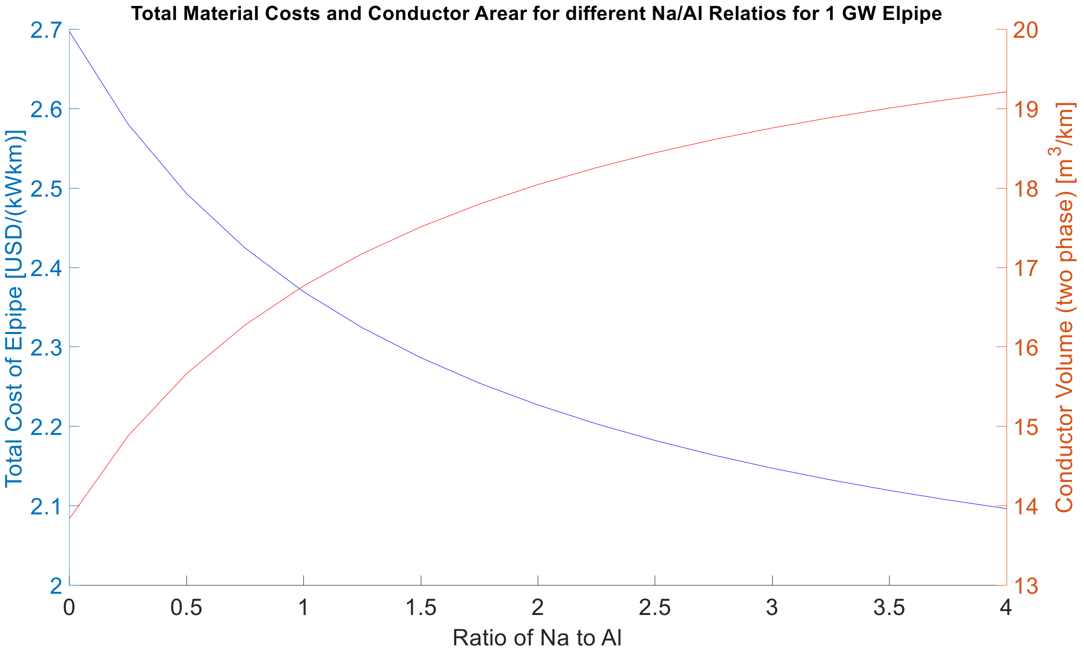
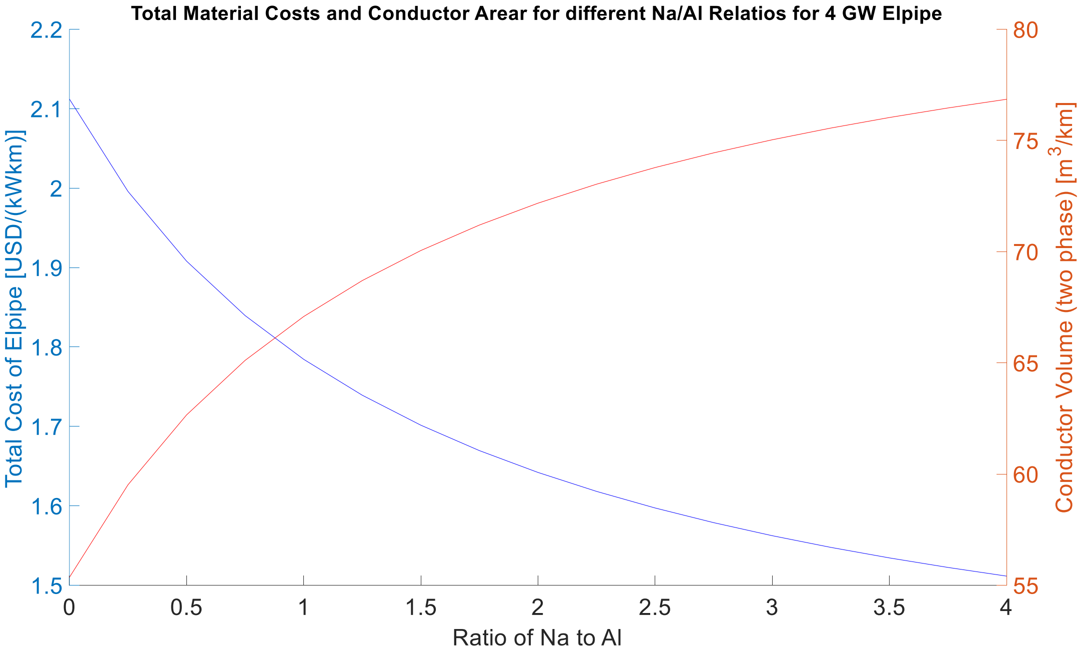


Figure 24. Conductor temperature in dependance to composition for a 200 km Elpipe

3.2.3.4 Cost estimation for 1000 km Elpipe in dependance of transmission power

A cost estimation according to Faulkner's calculation in 2.1 can be seen below for a 1 GW, 4 GW and 12 GW Elpipe, respectively. Faulkner assumed 38% margin on conductor fabrication. After this, the conductor costs accounted for 27% of the total raw material cost. To this a manufacturing margin of 25% and a gross margin of 35% were added. Installation costs of 780 k$/km and converter costs of 229 $/kW are added to the total cost as well. The total cost is then divided by transmitted power in kW and transmission length in km to achieve a cost in $/kW/km.





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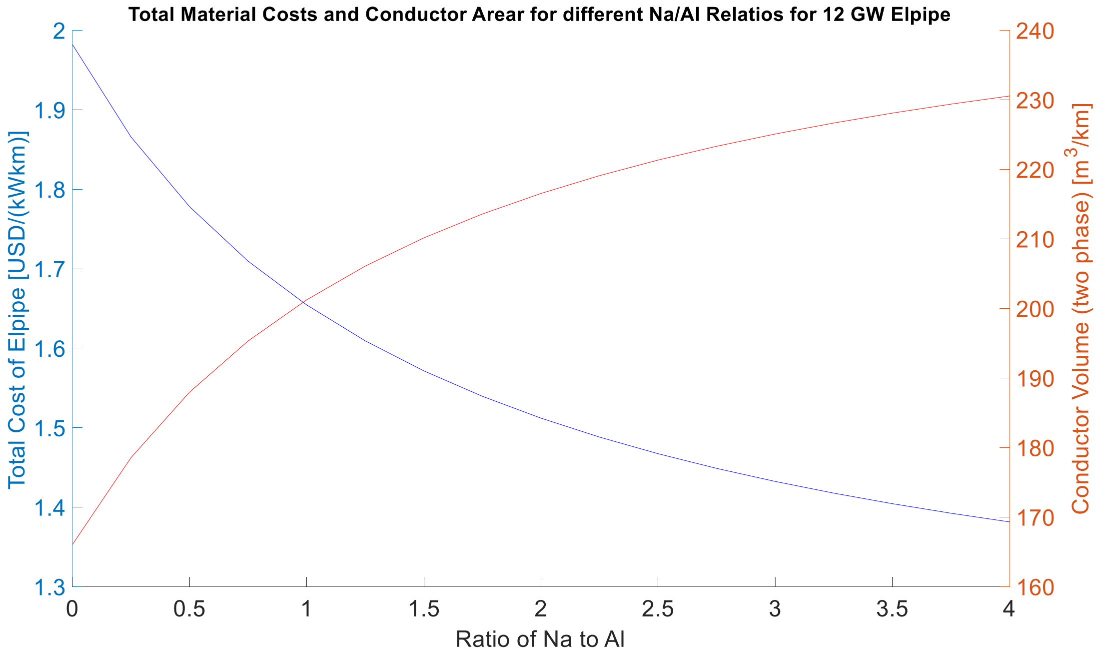


The use of sodium can reduce the overall investment cost by roughly 30% across the transmission powers. Relative cost decreases with increased transmission power. The models cannot achieve a price below 1.4 USD/kW/km, making them costlier than conventional cables, according to Faulkner.

3.3 Comparison to HVDC Line

The direct competitor to Elpipes is a HVDC line, so it makes sense to compare Elpipes and HVDC directly. The costs for a HVDC line will be sourced from the German transmission system operators in the network development plan [18]. This states that a new bipolar 525 kV DC ground cable line with a capacity of 2 GW will cost approximately 7.6 million EUR/km, including installation. The cost of installing such a 525 kV connection is set at 3.9 million EUR/km. By subtracting the installation costs, this leaves 3.7 million EUR/km for the 2 GW DC cable.

The costs for the 1 GW Elpipe were estimated at 2.7 USD/kW/km. For a bipolar 2 GW line this will translate to roughly 5 million EUR/km, 1.3 million EUR/km more expensive than a regular HVDC line. The splices will contribute a substantial amount to the overall cost of an Elpipe and are not included.

Next to the conductor, each splice will need a total of 16 wheels, 8 for each end of the splice. Motors and sensors are also required, see Figure 25. These components will be needed every 30 m. For 1 phase, for 1 km, this makes 544 wheels, motors, torque sensors and brakes. On top of that, 34 inclinometers and control modules are needed.

Figure 35

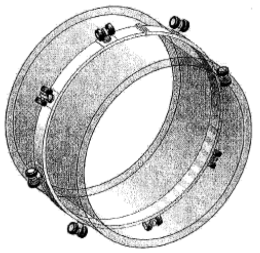
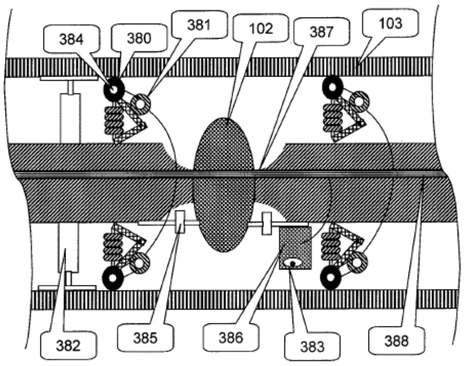


Figure 36



102 – Elpipe splice module
103 – Conduit
380 – Wheels on powered Elpipe carriage module
381 – Reversible variable speed and variable torque motor
382 – Brake
383 – Inclinometer
384 – Torque load cell on wheel
385 – Load cell between segment module and splice module
386 – Control module
387 – Intranet connection
388 – Power cable

Figure 25. Top: the 8 wheels of the splice module that hold the Elpipe in place. Bottom: Overview of a splice module [1]

The price of the motors, wheels and torque sensors can be incorporated in the cost of the Elpipe. The weight of a segment is used to approximate a drive torque, with the drive torque and a given speed, the power is estimated. This power is then used to estimate the cost of the motor following a price booklet [19]. The power needed to move a segment at 9 km/h is estimated to be 28 kW. One motor then equates to 2 kW, which results in a price of 850 EUR per motor. A wheel will be priced at 500 EUR, and a torque sensor at 100 EUR. The resulting costs are displayed in Table 17.

Table 17: Cost comparison between a HVDC line and an Elpipe including the extra costs for motors, wheels, and sensors

Cost Element (Mil. EUR/km)	**2 GW Elpipe**	**2 GW HVDC**
Segment	5	3.7
Wheels	0.5	-
Motors	0.9	-
Torque sensors	0.1	-
Construction	4.3	3.9
Total	**10.8**	**7.6**

Including the wheels, motors and torque sensors will cause the price to increase by roughly 1.5 million EUR/km. Including the increased the construction cost by a conservative 10 % compared to a HVDC line, results in the Elpipe costing 42% more than a conventional HVDC line. It is to be noted that the needed control module, inclinometer and brakes are not included.

3.4 Conclusions from Elpipe model

The model shows that the basic Elpipe is thermally feasible for high transmission distances and powers. The splice modules were not included, and these are thermal bottle necks as the splice cross-sections are smaller. This means that in reality a worse thermal feasibility can be expected than calculated by the model. A rough cost estimate was done, comparing a 2 GW bipolar Elpipe with a HVDC counterpart. At the very least, the Elpipe will be 42 % more expensive than the HVDC line.

4 CONCLUDING REMARKS

The Elpipes concept can be briefly summarized as a conventional transmission system with exceptionally large cross sections. To make this thermally feasible, a hollow core is introduced to increase heat conductivity. This means that a hollow core and conductor of great size that requires rigid conductor sections are needed. The rest of the patent is built around enabling this concept.

Judging the feasibility can then be simply done by answering the question why conventional power cables are not built with an efficiency of 99%. It makes the cables expensive, unwieldly, and difficult to install and maintain. This is amplified for the Elpipes concept, as they need additional parts such as wheels and splice modules, further increasing cost and failure rates. Using sodium in the conductor can decrease cost and increase thermal performance. However, reliability and safety will suffer, and maintenance will become more difficult.

Overall, Elpipes do not appear viable. There are no details on manufacturing, installation, or maintenance. Since extruding an Elpipe is not possible, conventional XLPE insulation is not feasible. This leaves the wrapped insulation as an option. However, as described before, there are reliability and safety concerns. The greatest problem is posed by the splice modules. These intricate connections between segments act as a thermal and electrical bottleneck and are not described in detail. They are complex and composed of many individual parts which complicates manufacturing and installation as well as increasing costs.

In view of these facts and given the amount of work that flowed into this deliverable, one cannot refrain from wondering why this very obscure topic emerged, at the title level, in an EU call dedicated to high-end power transmission technology; it was mentioned alongside superconducting cables, which are a well-studied and demonstrated technological innovation, with many prototypes already integrated in grids worldwide.

We believe that this objective and detailed analysis shows that Elpipes are not viable based on sound scientific and technological methods.

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APPENDIX A: MAIN MATLAB PROGRAMS

```
%This mfile uses the specified parameters to create Elpipe specifications.
%It calculates:
%   Radii, masses, electric and thermal specifications for the simscape
%   model

%% Parameters

%Elpipe Fundamental Parameters
RatioNaAl = 1;                          %Area Ratio of Sodium to Aluminum,
RatioNaAl=(Area Na)/(Area Al)
RatioCoreCond=1;                        %Area Ratio of Hollow core and conductor
RatioCoreCond=(Area Hollow core)/(Area Conductor)
TransmissionLength=1000;                %kmeter
LengthSegment=30;                       %meter
LengthSplice=3;                         %meter
AreaRatioSpliceToSegment=2/3;           %The ratio of cross-section between splice
and segment.
BurialDepth=1;                          %m
d_Phases=4;                             %Distance between phases, m
Temp=90;                                %Operating Temperature
InsulationThickness=0.034;              %m 0.034m in Datasheet for 500 kV cable
(ztt cable)
ConduitWallThickness=0.05;              %Thickness of steel wall
RollerCarrierThickness=0.25;            %Thickness of Wheels
Temp_Atm=20;                           %Ambient Temperature

%Power Scenario
TotalPower=4;                               %GW
Voltage=500;                                %kV
DesignEfficiency=0.01;
CurrentperPhase=TotalPower/2/Voltage/10^-3;  %kA
LossPerPhase=TotalPower*DesignEfficiency/2;  %GW
LossPerPhasePerMeter=(LossPerPhase*10^9)/(TransmissionLength*10^3); %W/m
ResistancePerPhase=LossPerPhase*10^9/(CurrentperPhase*10^3)^2; %Ohm
ResistancePerPhasePerMeter=LossPerPhase*10^9/(CurrentperPhase*10^3)^2/(Transmissio
nLength*10^3); %Ohm/m

%Prices
PriceSodium= 2.406;                     %USD/kg
PriceAluminum=2.619;                    %USD/kg

%Densities
DensitySodium=0.97*10^3;                %kg/m^3
DensityAluminum=2.7*10^3;
DensityXLPE=930;
DensitySteel=7850;
DensitySoil=1300;
DensityAir=1.297;                        %25°C, dry, 1bar

%Thermal Resistivity
AlThermResistance = 0.0042;             %Km/W
SteelThermResistance=0.0222;
XLPEThermResistance=3.0303;
```

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

```
SoilThermResistance=1.2;
AirThermalResistance300K=2.62*10^-2;

%Temperature Dependant Conductivity
%XLPE
XLPE_T_vector = linspace(20+273, 120+273, 100);
XLPE_Tcond_vector = linspace(0.34, 0.25, 100);


%Electrical Resistivity
XLPEResistivity = 10^14;                %Ohm.m

%Fluids
AirHeatTCoef=75;                        %W/K/m^2 50-100 for Air

%Heat Capacities
InsulCapacity=2170;                      %J/kg/K
RollerCapacity=700;                      %Air
ConduitCapacity=420;                    %Steel
SoilCapacity=2000;                      %Soil organic matter
CapaAl=900;                             %Aluminum
CapaNa=1230;                            %Sodium


%% Conductor Area is calculated in m^2

[ConductorArea, SodiumArea, AluminumArea] = CrossSectionArea(RatioNaAl,
ResistancePerPhase, TransmissionLength, Temp);
%Conductor Areas are calculated with resistance per phase, and elpipe composition
CompensationFactor=SpliceAreaCompensation(LengthSplice,LengthSegment,
AreaRatioSpliceToSegment);
%Compensation factor is calculated to account for splices

ConductorArea=ConductorArea*CompensationFactor; %Compensation factor is applied
SodiumArea=SodiumArea*CompensationFactor;
AluminumArea=AluminumArea*CompensationFactor;

%% Phase Dimensions (radii of the sections) are calulated with Conductor Areas

if RatioCoreCond > 0
    Elp_Radius(1)=sqrt(ConductorArea/pi/RatioCoreCond); %Hollow core
    Elp_Radius(2)=Elp_Radius(1)*sqrt(RatioCoreCond+1);  %Conductor O.R.
else
    Elp_Radius(1)=0;                                    %If no hollow core is
specified
    Elp_Radius(2)=sqrt(ConductorArea/pi);
end
Elp_Radius(3)=InsulationThickness+Elp_Radius(2);    %Conductor O.R. + Insulation
Elp_Radius(4)=RollerCarrierThickness+Elp_Radius(3); %Conductor O.R. + Insulation +
Roller Carrier Thickness
Elp_Radius(5)=ConduitWallThickness+Elp_Radius(4);   %Conductor O.R. + Insulation +
Roller Carrier Thickness + Steel
Elp_Radius(6)=Elp_Radius(5)+BurialDepth;            %Conductor O.R. + Insulation +
Roller Carrier Thickness + Steel + Burial Depth

%% Mass and Densities of Phase Sections are calculated with the Radii
```

```
ConductorDensity=(RatioNaAl*DensitySodium+DensityAluminum)/(RatioNaAl+1);
%Conductor Density is calculated using the Ratio of Na/Al
ConductorCapacity=(RatioNaAl*CapaNa+CapaAl)/(RatioNaAl+1);
%Conductor Heat Capacity is calculated the same way
ConductorMass=ConductorDensity*pi*(Elp_Radius(2)^2-Elp_Radius(1)^2);
%Conductor Mass is calculated [kg/m]

fprintf ("\nConductor Density is: %2.2f kg/m^3", ConductorDensity)
fprintf ("\nConductor Heat Capacity is: %2.2f J/kgK" + ...
    "\nConductor Mass is %2.2f kg/m\n****************************",
ConductorCapacity,ConductorMass );

InsulMass=pi*(Elp_Radius(3)^2-Elp_Radius(2)^2)*DensityXLPE;      %Masses of
sections are calcualted [kg/m]
RollerMass=pi*(Elp_Radius(4)^2-Elp_Radius(3)^2)*DensityAir;
ConduitMass=pi*(Elp_Radius(5)^2-Elp_Radius(4)^2)*DensitySteel;
SoilMass=pi*(Elp_Radius(6)^2-Elp_Radius(5)^2)*DensitySoil;
TotalMass=ConductorMass+InsulMass+RollerMass+ConduitMass;


%%  Thermal Model

Temp_Start=20;                    %Starting Temperature of Elpipe
Temp_Start_Conductor=Temp_Start;
Temp_Start_XLPE=Temp_Start;
Temp_Start_Roller=Temp_Start;
Temp_Start_Steel=Temp_Start;

%% Electrical Model

XLPEResistance=XLPEResistivity/2/pi*log(Elp_Radius(3)/Elp_Radius(2));    %Ohm/m
LeakageCurrent=Voltage^2/XLPEResistance;                                 %A/m
LeakageHeating=Voltage*LeakageCurrent;                                   %W/m

Permeability=1;
E_Permittivity=8.8541*10^-12;
L_Permittivity=4*pi*10^-7;
Dielectric_XLPE=2.3;
Dielectric_Air=1;
R=ResistancePerPhase/TransmissionLength;                               %Ohm/km
Rload=(Voltage/CurrentperPhase-ResistancePerPhase);                    %Ohm
L=L_Permittivity*TransmissionLength*10^3/pi*(log(d_Phases/Elp_Radius(2))+0.25)/100
; %%H/km
C_Ground=2*pi*Dielectric_XLPE*E_Permittivity/(log(Elp_Radius(3)/Elp_Radius(2))*Die
lectric_XLPE+log(Elp_Radius(4)/Elp_Radius(5))*Dielectric_Air)/100; %F

%Initialises SC values, must have values for simscape to work
t_sc_on= 50^12;              %Start of short circuit
dt_sc= 1*10^-12;            %Duration of short ciruit
t_sc_off=t_sc_on+dt_sc;       %End of short ciruit

OverloadFactor=1.25;
t_overload=2.5*10^12;
t_overload_off=t_overload+300;
```

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

```
function [ConductorArea, SodiumArea, AluminumArea] = CrossSectionArea(RatioNaAl,
Resistance, TransmissionLength, Temp)
%This function determines the cross-sectional area needed to achieve
%a certain resistance. Inputs are transmission distance, ratio of Na to
%Al,resistance and operating temperature.
%Al and Na are seen as two parallel resistances. With the formula R=p*l/A
%the Areas of Na and Al are determined
TransmissionLength=TransmissionLength*10^3; %Change to m from km
pNa20=4.2e-8;       %(Ohm.m)
pAl20=2.65e-8;      %(Ohm.m)

TcoeffNa=3.26e-3;   %1/K
TcoeffAl=3.8e-3;    %1/K

pNaHot=pNa20*(1+TcoeffNa*(Temp-20));    %
pAlHot=pAl20*(1+TcoeffAl*(Temp-20));    %

AluminumArea=(RatioNaAl/(pNaHot*TransmissionLength)+1/(pAlHot*TransmissionLength)
...
    )^-1/Resistance;
AluResistance=pAlHot*TransmissionLength/AluminumArea;
SodiumArea=RatioNaAl*AluminumArea;
SodiumResistance=pNaHot*TransmissionLength/SodiumArea;
ConductorArea=AluminumArea+SodiumArea;

fprintf ("\n**********Per Phase**************\nTo achieve a resistance of" + ...
    " %2.2f OHm over %2.2f km at %2.2f °C a Conductor Area of %f m^2 " + ...
    "is needed\nOf that Aluminum is %f m^2 and \n\t\tSodium is %f m^2" + ...
    " \nAlu-Resistance is %2.2f Ohm\nSodium Resistance is %2.2f Ohm\n" ...
    ,Resistance, TransmissionLength*10^-3, Temp, ConductorArea, AluminumArea, ...
    SodiumArea, AluResistance,SodiumResistance)
End
```

```
function [CrossSectionCompensationFactor] = SpliceAreaCompensation(LengthSplice,
LengthSegment,AreaRatioSpliceToSegment)
%SPLICEAREACOMPENSATION The function gives back a factor that compensates
%the smaller cross-section of the splice by averaging the overall
%cross-sectional area
TotalLength=LengthSplice+LengthSegment;
Average=(AreaRatioSpliceToSegment*LengthSplice+LengthSegment)/TotalLength;
CrossSectionCompensationFactor=1/Average;
End
```

APPENDIX B: MATERIAL PROPERTIES USED

	Copper	Tin	Aluminum	Sodium	XLPE
Linear Thermal Expansion Coefficient (10^{-6}m/m/K)	17	21	23	70	10
E Modul (GPa)	117	47	69	10	0.6
Density (g/cm^3)	8.96	7.25	2.70	0.97	0.93
Res. Temperature Coefficient (1/K)	4.29 x 10-3	4.2 x 10-3	3.8 x 10-3	3.26 x 10-3	
Resistivity at 20°C (Ωm)	1.724 x 10-8	11.0 x 10-8	2.65 x 10-8	4.2 x 10-8	10^14
Thermal Conductivity (W/m/K)	401	66.6	237	141	0.33
Heat Capacity (kJ/kg/K)	0.385	0.228	0.9	1.23	2.174

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