Copper or Aluminium cable conductors, broadly compared in a life cycle perspective

Wim **BOONE**, Remco **BAL;** DNV GL**,** The Netherlands
wim.boone@dnvgl.com, remco.bal@dnvgl.com
Arnav **KACKER;** PE- International, Germany,
a.kacker@pe-international.com

ABSTRACT

In this paper, the results of three studies are presented. The first study concerns technical information on copper versus aluminium followed by a decision model how the selection process of the conductor material happens in practice. The second study is about the environmental performance of both conductor materials in a Life Cycle Assessment. The analysis finds that copper cables have lower net environmental impacts than their aluminium counter parts. Finally the third study deals with a complete Life Cycle Cost Analysis, resulting in the conclusion that both materials, although significantly different in raw material price can be considered to give equivalent solutions from a life cycle costing perspective.

KEYWORDS

Copper, Aluminium, Conductor, Cable, Material Properties, Modelling, Life Cycle Assessment, Life Cycle Cost Analysis, Asset Management, End of Life

INTRODUCTION

A cable conductor usually consists of copper or aluminium. Originally copper was the only conductor material used, later aluminium was introduced as a new conductor material. Copper and aluminium differ in properties and in raw material price. In particular the significantly lower raw material price presently plays an important role in the purchasing strategy of utilities. On the other hand it is well known that the initial costs have to be projected over a long term perspective in order to reliably show the ultimate price quality ratio.

In this paper, attention is first paid to the decision model of utilities when selecting the conductor material for their cables. What material properties are important? Is there a compensation to be expected for the initial higher raw material cost? Then a proper Life Cycle Assessment (LCA) will be applied, aggregating the environmental impacts associated with the manufacturing, recycling effort and credits through replacement of primary material replaced by recycled material on the market. Finally a Life Cycle Cost Analysis (LCCA) will be added. All costs over the entire lifetime of a cable will be considered, including initial CAPEX costs, O&M costs, cost of electric losses and residual value after decommissioning.

The three studies presented in this paper contribute thus to the complete picture of efficient conductor material use in power cables, leading to a conclusion that investment decisions should consider all relevant costs over the entire life cycle, and not focus on initial costs only.

TYPICAL PROPERTIES OF COPPER AND ALUMINIUM

Copper and aluminium differ in properties. The main differences are in specific conductivity and in specific weight. As the density of aluminium is about one third of that of copper, for equal conductance the weight of the aluminium conductor material is almost halved, however the cross-sectional are has to be increased by a factor of 1.6. For a quick overview the differences between copper and aluminium are presented in Table 1 on a relative scale, based on the specific values for copper = 100:

Table 1: Material properties

Material Properties	Comparative Values	
	Copper	Aluminum
Electrical resistivity	100	164
Density	100	30
Weight/unit resistance	100	53
Diameter/unit resistance	100	129
Elastic modulus	100	55
Hardness	100	44
Ultimate tensile stress	100	35
Melting point	100	61
Stress fatigue endurance limit	100	62
Thermal resistivity	100	158
Corrosiveness	1)	2)
Specific Heat	100	230
Thermal expansion	100	135

1) Copper is resistant to most organic chemicals

2) Aluminium may corrode quickly

When paying attention to the failure mechanisms [1] the major difference between copper and aluminium is that contrary to copper aluminium reacts with water and oxygen rather quickly [3][4][5]. The insulating layer of aluminium oxide is an advantage for reducing the skin effect for a stranded conductor, but is a clear disadvantage with connectors in joints.

DECISION MODEL

Utilities were asked in an international questionnaire about their motives to make a choice between copper and aluminium as cable conductor materials. Therefore in Table 2 the following list of criteria was presented with the request to give a score between (1 to 5):

Table 2: Questionnaire

Questionnaire for both LV and MV cables and accessories
1 Price
2 Radial size
3 Weight
4 Mechanical properties
5 Easiness of accessory installation
6 Easiness of repair
7 Cost of corrective maintenance
8 Company standard
9 Compatibility with existing cable network
10 Environmental concern
11 Expected problems with connectors
12 Any other factor

Although in the questionnaire information was collected on both LV and MV cable networks, we publish in this paper only the results for MV cables as there does not seem to be a major difference with the results of LV cables. The scores are given between brackets from high to low in Table 3:

Table 3: Results of questionnaire

	Cu	Al
1	Mechanical (24)	Price (48)
2	Connector (24)	Company standards (31)
3	Radial size (23)	Compatibility (27)
4	Repair (23)	Mechanical (20)
5	Accessory (22)	Weight (18)
6	Compatibility (22)	Accessory (18)
7	Environmental (21)	Environmental (18)
8	Company standards (21)	Connector (18)
9	Corrective maintenance (19)	Corrective maintenance (16)
10	Price (14)	Repair (11)
11	Weight (14)	Radial size (10)

For copper the following values received high scores:

- Mechanical properties
- Well-functioning connectors
- Radial size

For aluminium it is about the following values:

- Price
- Company standards
- Compatibility with existing network

As to be expected the lowest scores for copper and aluminium are respectively: weight and radial size.

In this survey the environmental aspects do not seem to score high, probably because when comparing copper and aluminium for the same current rating, there is little difference in losses and the conductors can be considered electrically equivalent.

Although it is clear that the price has a strong effect on the selection process, some technical aspects play a role as well. For copper these aspects are rather technical (mechanical, connector, radial size), as for aluminium the values seem to be more of an organizational nature. In other words aluminium conductor cable plays an important role because of its cost advantage. However the technical advantages of copper are obvious and copper continues to play its role in cable applications where these advantages weigh the most.

LIFE CYCLE ASSESSMENT (LCA)

This life cycle assessment has been conducted to compare the environmental impacts associated with electrically equivalent copper and aluminium variants of medium voltage cables [7].

These cables consist of a core conductor which is either copper or aluminium. The conductor is sheathed with an insulating plastic material which is usually cross linked polyethylene or polyvinyl chloride.

Besides these two basic components of cables, several other materials are used in the various products under consideration, which have also been included in the assessment of overall environmental impacts, such as: swelling tape, bedding, PE sheath, aluminium foil etc.

FUNCTIONAL UNIT

The functional unit is the basic quantity of the product in terms of which the environmental impacts are expressed (1 m of product, 1 kg of commodity etc.). For the purposes of this assessment, length of the cable has been considered to be the relevant measure of comparability on between copper and aluminium variants of power cables. Hence, the functional unit is – 1 m of power cable. This functional unit applies to the individual LCAs of all the aforementioned products.

SYSTEM BOUNDARIES

This LCA analyses the following stages of the product life cycle:

1. Manufacturing of cable component materials

2. Recycling effort of cables

3. Energy recovery from incineration

4. Environmental credits from material recovery

5. Landfill

The use stage losses of the power cables have not been evaluated in this study because electrically equivalent copper and aluminium variants of power cables have been assessed.

DATA USED

The data required to model the foreground system includes the bill of materials for the various types of power cables under consideration. This data was provided to PE INTERNATIONAL by DNV GL, upon the request of ECI

The upstream (background) data used for the LCA model is sources from GaBi Databases 2013 and refers to the latest published LCI inventories. Further information on representativeness of the data can be found in the GaBi documentation of the individual data sets [6].

ASSUMPTIONS AND APPROXIMATIONS

The limitation and assumption associated with this LCA are listed below:

1. The energy for the assembly of cables using the individual component materials has been excluded from the analysis. This energy consumption represents a relative small fraction of net environmental impact and is not expected to skew the representativeness of the overall results.

2. The transport of the raw materials to the production site and the transport of the finished product to the site of installation has not been accounted for. This impact is also relatively small in relation to the net impact per functional unit.

3. The packaging of the products has not been included in the scope of the manufacturing phase of the products.

4. The operational losses (losses incurred during transmission) have been excluded from the study by comparing electrically equivalent copper and aluminium cable variants.

5. The effort for installing the cables is outside the scope of the study.

MODELLING

A software model is generated with the GaBi software. The software model is a mathematical algorithm, which covers all potential input and output flows for material and energy for the considered scenarios.

The manufacturing processes of the cables require material and energy inputs. The production of these materials, in turn, has inputs and outputs associated with them and so on, up the chain. The finished cables, after their serviceable lifetime, enter the recycling stream where the material components are treated in different ways, until they end up back in the techno sphere, are landfilled, or enter the environment as emissions. The sum total of the upstream and downstream material and emission lists, in their basic forms, constitute the Life Cycle Inventory (LCI) of the product.

The end-of-life (EoL) of power cables is a crucial phase in determining the net life cycle environ-mental impacts. To obtain a real-world market perspective of the cable recycling industry, European Copper Institute (ECI) solicited the services of a market-research consultant [8] to explore the expert estimations of quantities of cable recovered and recycled at their end-of-life in Europe. The results from this investigation were then used by PE INTERNATIONAL to model the EoL phase of the power cables life cycles, when they are used in tunnels/ducts (easy to recover) and when buried underground (recovery often uneconomical).

The market research bolsters this study by providing industry estimates on the collection rates of cables, the driving factors differentiating aluminium and copper cable recovery, the motivations of metal scrap traders and cable granulators in choosing and purchasing scrap etc. As a result, this directly affects the quantity of copper and aluminium cables that are recovered after decommissioning and consequently how large an environmental credit they receive upon recycling.

The recycling processes implemented in the model include the efforts for remelting the metal and account for the small material losses that occur during these processes. The environmental credits have been granted by using the inverse of the primary production LCIs for each metal to simulate the avoided burden.

The LCI is then translated into environmental impacts expressed in environmental impact categories (such as global warming potential and eutrophication) in the Life Cycle Impact Assessment (LCIA) step of the analysis.

RESULTS OF THE LIFE CYCLE IMPACT ASSESSMENT

The software model described above enables the calculation of various environmental impact categories. The impact categories describe potential effects of the production process on the environment. As different resources and emissions are summed up per impact category the impacts are normalised to a specific emission and reported in “equivalents”, e.g. Greenhouse gas emissions are reported in kg CO2 equivalents.

Environmental impact categories are calculated from “elementary” material and energy flows. Elementary flows describe the origin of resources from the environment as basis for the manufacturing of the pre-products and generating energy, as well as emissions into the environment, which are caused by a product system.

A set of impact assessment categories considered to be of high relevance to the goals of the project has been chosen [9].

Global warming potential and primary energy were chosen because of their relevance to climate change and to energy and resource efficiency. These impact categories are of high public and institutional interest, and are deemed to represent some of the most pressing environmental issues of our times. Additionally, acidification potential was included due to its relevance owing to the sulphuric nature of common copper ores.

It should be noted that the aforementioned impact categories represent impact potentials. This means that they are approximations of environmental impacts that could occur if the emitted molecules would: (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

Medium Voltage Cable

Table 4: Acidification Potential for 1 m MV cable

AP [kg SO_2-eq.]	Tunnel		Urban area	
	Cu	Al	Cu	Al
Total	0,016	0,019	0,021	0,026
Manufacturing	0,064	0,088	0,064	0,088
EoL	-0,049	-0,07	-0,07	-0,063

Table 5: Global Warming Potential for 1 m MV cable

AP [kg SO_2-eq.]	Tunnel		Urban area	
	Cu	Al	Cu	Al
Total	0,016	0,019	0,021	0,026
Manufacturing	0,064	0,088	0,064	0,088
EoL	-0,049	-0,07	-0,044	-0,063

Table 6: Primary Energy Demand (net calorific value in MJ) for 1 m MV cable

Primary Energy Demand [net]	Tunnel		Urban area	
	Cu	Al	Cu	Al
Total	108,5	122,5	119,3	146
Manufacturing	216,7	357,9	216,7	257,9
EoL	-108,1	-235,4	-97,3	-211,8

The tables above detail the environmental impacts associated with Cu and Al variants of medium voltage (MV) power cables, when used in ducts/tunnels and when buried underground in dense urban areas.

The life cycle environmental impacts are divided into the manufacturing and end-of-life phases. ‘Manufacturing’ phase refers to all the environmental impacts associated with the production process chain (including the supply chain related emissions of inputs) from the cradle (raw material extraction from the ground) to the factory gate (finished cable). The end-of-life or ‘EoL’ phase impacts are those associated with recycling the cable. This phase also includes the ‘environmental credits’ granted to the product to account for the energy produced through the incineration of plastics and the primary material production that is avoided due to the recovery of material from the cable.

The difference between the cable application in tunnels/ducts and urban areas is only in the EoL phase of the life cycle because the same cable is less likely to be dug up and recovered from a dense urban area than an accessible duct. As a result, cables buried in urban areas have a lower end of life recovery rate and thereby accrue fewer environmental credits from recycling.

INTERPRETATION

This investigation shows that for the environmental impact categories examined here, copper cables have lower life cycle impacts than aluminium cables. This is in large part due to the fact that copper cables are recovered to larger extent at the end of their serviceable lives. The higher scrap value that copper fetches on the market is a great driver for the recovery of disused cables. This recovery translates to larger environmental credits when the recycled copper re-enters the market.

Aluminium cables are recovered to a lesser extent than copper cables and hence, while theoretically completely recyclable, much of this potential is lost if the cables remain under-ground after use. The market statistics, thus, lead to aluminium being accorded lower environmental credits at the end of life.

LIFE CYCLE COST ANALYSIS

Power cables typically can be expected to operate 35-50 years or more. Investment decisions for cables are however mainly based on investment costs which neglect potential savings during the operational life of the cable. Cable total owning costs (hereafter called “life-cycle costs”) not only take into account the initial cable costs, but the costs to operate and maintain the cable over its life time as well. This requires that the total life-cycle costs be calculated over the life span of the cable which includes both CAPEX and OPEX. Doing so, it is possible to calculate the real economic choice between cables of different conductor material, such as copper and aluminium. Such a study is referred to as a life-cycle cost analysis (LCCA) which can be used to find the most cost-effective solution for a project with multiple options. Typical areas of expenditure which are included in calculating the life-cycle costs include purchase cost, operation and maintenance, residual value, losses and costs of disposal. All such costs are discounted and totalled to a present day value; known as the ‘net present value’ (NPV). The NPV is an accepted metric that can accurately summarize the discounted cash flows for all costs [10].

For this analysis, a model has been developed which can perform a LCCA for different cables. To make a good comparison, three copper and three aluminium conductor cables have been analysed to find the differences in costs. A 20 kV, 110 kV and a 400 kV cable of both conductor types has been used in this analysis. To compare the cables, the same transmission capacity should be used. Due to a difference in conductivity between the conductor materials, this is done by taking different cross-sections. To come to a comparable conductor, the standardized equivalent cross-sections, summarized in Table 7, have been chosen:

Table 7 : Cross-sections of the cables

Copper	Aluminium
400 mm^2	630 mm^2
1000 mm^2	1600 mm^2
1200 mm^2	2000 mm^2

Data used in this study

The availability of reliable cost data of assets in the power industry is found to be challenging, since these can be used for competitive purposes. Therefore commercial prices which are given by manufacturers are also not reliable as these prices might be more competitive in real life than when requested for analysis purposes. DNV GL has developed a cost database in which cost data has been gathered and stored for the last decade. This database is constantly updated and checked with the industry, which has resulted in good and reliable cost figures for all assets involved in the power sector. This allows for reliable cost and investment calculations and good estimates about costs over the lifetime of a power cable can be made.

For this study, failure data of a European DSO has also been analysed in order to see the impact of conductor material on failures. This data, which has been collected over the last years, comprises the conductor material of the cable and the cause of failure. This provides the opportunity to understand the impact of conductor material on failures.

Costs considered in this study

Installation costs

The costs associated with the installation method are related to several aspects of the environment and cable configuration: the type of soil, the trench depth, width and cover, the crossing of obstacles and the degree of urbanization. In most cases, special backfill material is needed to provide the necessary thermal profile.

Besides soil aspects, there are different ways to install a cable underground. In urban areas, there are more crossings with other infrastructure and more paving needs to be done, resulting in higher costs. Ducts or tunnels are also possibilities; however these are left out of this analysis. Also permits and labour is considered. The installation method is found to be independent of the conductor type and installation costs are therefore assumed equal for both kinds of conductor material.

Operation and maintenance (O&M) costs

Operating and maintaining an underground cable can be done in different ways and is mostly dependent on the approach of the system operator. Differences in O&M strategy between system operators are independent of the conductor material. Most TSO's and DSO's have both copper and aluminium conductor cables in their grid but do not make a distinction in O&M strategies between cables. O&M costs are therefore assumed equal between copper and aluminium solutions, though in practice, there may be differences due to different characteristics of these conductor materials.

Costs of electrical losses

Due to the difference in cross-sections between the conductor types, the compared cables have almost equal resistances and consequently almost equal losses.

Residual value and disposal cost

After a cable is no longer operational, the cable has a residual value. The residual value is mostly dependent on the conductor material and is therefore higher for copper than for aluminium. Since the price for aluminium and copper varies over time, it is difficult to predict the price over 50 years. However, when taking today's commodity prices as a best approximation, the NPV of a distant future cash-flow has a low economic impact today and has not been taken into account for the LCCA.

Results

The model calculates the NPV of all costs and compares the total costs of the cables. As general input, the parameters are used which are found in table 8.

Table 8: Chosen parameters

Chosen parameters	
Interest rate:	3%
Area:	Urban
Electricity price:	50 EUR/MWh
Lifetime:	50 year
Number of phases:	3
Length:	1 km

It is found that the difference in costs between copper and aluminium conductor cables over its operational lifetime has significantly decreased. The difference in costs over the operational lifetime is found to be around 3% for all cases, and in some cases, copper even becomes the lowest LCC solution. With a purchase cost difference of 700% between a copper and an aluminium conductor this is a significant decrease.

In the tables below the total lifetime costs (in EURO) are found per compared cross-section. In Table 9 the conductor materials between copper and aluminium are compared for both 20 kV and 110 kV. The difference between the costs is found to be relatively low.

Table 9: Lifetime costs comparison between copper and aluminium 20 kV and 110 kV

	20 kV	110 kV
Al 400 mm^2	€767.000	€867.000
Cu 630 mm^2	€722.000	€849.000

In Table 10 the lifetime costs between copper and aluminium cables are compared for 400 kV. For this the 1.000mm^2 and 1.600 mm^2 cross-sections are compared and the 1.200 mm^2 and 2.000 mm^2. Also for 400 kV cables the difference in cost is found to be low.

Table 10: Lifetime costs comparison between copper and aluminium 400 kV

	400 kV
Al 1.000 mm^2	€1.556.000
Cu 1.600 mm^2	€1.559.000
Al 1.200 mm^2	€1.663.000
Cu 2.000 mm^2	€1.627.000

Main result of this analysis is that the significant purchase price difference between raw copper and aluminium is only a small part of the total costs over the lifetime of an underground cable. Over the lifetime of a cable, the price of the cable itself is only a small portion of the total costs. In many occasions decisions are taken based on the short term costs but the impact on the long term is often not included. This study has given more insight in the total costs associated with underground cables. It has resulted in an almost negligible difference in costs between cables with copper and aluminium conductors. Hence, other factors than costs may become leading in the choice between copper and aluminium.

CONCLUSIONS

This paper contains three studies comparing copper and aluminium solutions for power cable. These studies demonstrate clearly the superiority of copper, although there is a difference in initial costs. However such initial conductor and cable costs represent only a negligible (a few percentage) portion of the total life cycle cost.

Therefore, life cycle thinking, looking at the total costs and risks of a cable system, should be the recommended perspective for sustainable T&D systems, in order to benefit optimally from the technical advantages of copper as a conductor material.

There is some limited uncertainty about installation and O&M costs. T&D utilities can make their own calculations using richer internal databases tailored to their unique situation and specific operations.

The LCA study has found some indications that power cable is insufficiently recycled at the end of life, due to economic and logistic reasons. From an environmental stewardship perspective, T&D utilities should increasingly consider installation practices that make it easier to recover these cables at the end of life.

REFERENCES

[1] R. Bodega eo, *Selecting the optimized conductor for design*, Jicable 2011 B.10.1

[2] G. F. Moore, *"Electric Cables Handbook"*, 3rd Edition, BICC Cables, Blackwell Science Ltd., ISBN 0-632-04075-0, 1997

[3] A. Mak, P.Eng. – Senior Field Applications Engineer, *"Corrosion of Steel, Aluminium and Copper in Electrical Applications"*, Alcan Cable, 2002.

[4] G.J.Luzzi *Gass pressure build up in Aluminium conductor cable*, IEEE Trans.on PAS ,Vol,PAS-101, No 6 June 1982

[5] S.Pelissou, J. Cote , eo. *Influence of corroded conductors on the performance of MV extruded cables,* Jicable ,03

[6] GaBi 6.3 dataset documentation for the software-system and databases, PE INTERNATIONAL AG, Leinfelden-Echterdingen, 2013 (http://documentation.gabi-software.com/)

[7] EN ISO 14040:2009-11 Environmental management - Life cycle assessment - Principles and framework

[8] Market research report, Recycling of power cables in Europe, 2014, Mr. Volker Schneider, ECI

[9] Guinée et al, An operational guide to the ISO-standards, Centre for Milieukunde (CML), Leiden, the Netherlands, 2001

[10] K. Blok, Introduction to Energy Analysis, ISBN 978-908594-016-6, 2007