# MICRO-ALLOYED COPPER OVERHEAD LINE CONDUCTORS

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## SUMMARY

Transmission network operators are facing substantial and even contradictory challenges. A highly variable renewable energy supply and an increased focus on energy efficiency require a reinforcement of the grid, but the resistance against the construction of new lines has never been so high. Micro-alloyed copper conductors can be part of the solution. Their energy efficiency and their ability to cope with temporary capacity overloads are highly valued features. Those overloads are possible due to the higher resistance of copper against creep at high temperatures. The energy efficiency of the copper conductor compensates for its higher initial cost. As a result, the life cycle cost (LCC) of the micro-alloyed copper conductor is in the same range or lower than that of a steel reinforced aluminium (ACSR) conductor. This was calculated in two feasibility studies by the Dutch consultancy agency DNV KEMA: one on the construction of new lines, and one on the refurbishment of existing lines. The latter study also demonstrates why the higher specific weight of copper compared to aluminium does not require a reinforcement of the overhead line towers. Indeed, its mechanical strength makes a steel core superfluous, and even more importantly, the smaller cross section combined with hydrophobic coating results in a much lower wind and ice load, which is a decisive factor for determining the required strength of the towers. This makes the copper conductor particularly suitable for overhead lines in cold and windy climates.

*Figure 1 – Cross section of a micro-alloyed copper conductor for overhead line both in circular and trapezoidal wire.*

## INTRODUCTION: CHALLENGES FOR DISTRIBUTION AND TRANSMISSION SYSTEM OPERATORS

The energy landscape is in full transition. Changing market structures combined with an increasingly distributed, variable and unpredictable type of power generation complicates the electricity grid management. Transmission network operators are facing several substantial and even contradictory challenges.

**Renewable energy power stations are often built in remote areas**. New lines have to be built to connect them to the main grid and transport their production to the centres of demand.

The increasingly high share of renewable energy in power generation creates **a highly variable supply**. The grid is regarded as an important part of the solution to cope with this variability, as it enables an exchange of electrical energy from regions with a temporary surplus in supply towards regions with a temporary peak in demand. It requires a reinforcement of the grid to cope with this new type of energy exchange.

However, **resistance against the construction of new overhead lines has never been so high**. The construction of such lines in heavily populated areas has always been a challenge. Today, the uncertainty concerning the impact of electro-magnetic radiation and increasingly stringent local regulations add to this challenge. In less populated areas, the process to gain permission for new overhead lines can be even more complicated because of their visual impact on the landscape.

Due to the variable and unpredictable profile of renewable electricity production, transmission system operators are more often than ever forced to **run transmission lines at the limit of their capacity**. Their life would become easier if they would have some spare capacity which they can use from time to time. However, they are **limited by the maximum operational temperature** of the line conductor. Above this maximum temperature, the conductor material shows excessive creep and the mechanical integrity of the cable can no longer be guaranteed.

To make the situation even more difficult, there is **an increasing focus on the energy efficiency of transmission lines**. And deservedly so. After making substantial investments for improving the efficiency at the supply side and the demand side, it is about time to focus on the energy that is lost in between. According to the IEA, the world consumes over 20,000 TWh of electricity each year, of which 7% (or 1,400 TWh per year) is lost in the wires used to supply this power. There is still a high share of depletable fossil fuels in the energy mix that is used to produce this electrical power. Any improvement in energy efficiency makes us less dependable on these fuels and reduces the associated carbon emissions. Reducing the transmission line losses with one third would reduce the annual $CO_2$ emissions with 250 million tons[1], which is the equivalent of taking 50 million cars off the road. Such an energy efficiency improvement would also replace the need for 60,000 MW of new generation capacity, which represents welcoming breathing space in the transition towards a renewable energy economy. It would increase the energetic and financial efficiency of the entire electricity system. For all those reasons, regulators [1] are more and more paying attention to the energy efficiency of overhead lines and are shifting their main goal from minimizing the investment cost to minimizing the life cycle cost of the line. This, however, creates substantial additional challenges for transmission network operators.

To cope with all these challenges simultaneously, a type of conductor is needed that can replace the old conductors on existing rights of way, and that increases at the same time the energy efficiency, the capacity, and the overload capacity of the line. The micro-alloyed copper conductor (CAC) can answer to all these needs

[1] Counting with an average of 0.5 kg $CO_2$ emissions per kWh.

in one time. Overhead line conductors are traditionally a domain for aluminium, using either steel reinforced aluminium or aluminium alloys. Seeing copper as a material for overhead lines might come as a surprise, since it is a substantially heavier material. Weight, however, is not the most crucial characteristic of the conductor, as we will explain later.

## COMPARING THE BASIC CHARACTERISTICS OF VARIOUS TYPES OF OVERHEAD LINE CONDUCTORS

The Dutch research and consultancy agency on energy and sustainability DNV KEMA analyzed the technical and financial differences between two types of steel reinforced aluminium conductors (ACSR) and the innovative micro-alloyed copper conductor (CAC) [2, 3]. The following three conductors have approximately the same current carrying capacity at 80°C:


*Figure 2 – Comparing three different types of overhead line conductors*

From left to right, the initial investment cost for the conductor rises, but the energy losses decrease. Later in this paper we will discuss how those reduced energy losses have a positive effect on the total Life Cycle Cost of the line for average loading conditions. The basic technical characteristics of those three types of conductors are as follows:

| | **ACSR Hawk** | **ACSR Eagle** | **CAC 185** |
|---|---|---|---|
| Cross section (mm2) | 280 | 350 | 185 |
| Current capacity at 80°C (A) | 630 | 700 | 700 |
| Current capacity at 150°C (A) | - | - | 1115 |
| Weight (kg/km) | 982.3 | 1301.8 | 1652 |
| Electrical resistance (Ohm/km) | 0.1195 | 0.103 | 0.09 |
| Tensile strength (kN) | 85 | 123.6 | 93 |
| Elasticity (kN/mm2) | 77 | 81 | 32 |
| Thermal expansion (1/°C) | 0.0000189 | 0.0000178 | 0.000017 |
| Max operational temp (°C) | 80°C | 80°C | 150°C |

*Table 1: basic characteristics of ACSR and CAC overhead line conductors.*

Note that the micro-alloyed copper conductor has a much smaller cross section for a similar level of current carrying capacity at a certain operating temperature. Micro-alloyed copper has sufficient mechanical strength of its own to do without steel reinforcement. Combined with the higher electrical conductivity of copper, this results in a far smaller conductor section for the same line capacity. This capacity per cross section is further enhanced due to the reduction of the skin effect. Indeed, in the copper CAC conductor, an insulating coating is applied to each separate wire inside the conductor, resulting in an equal current flowing through the central wires as through those at the outside of the conductor. The higher conductivity of copper and lower skin effect also results in a reduction of the energy losses, as shown in table 1. **The maximum operating temperature of the micro-alloyed copper conductor is much higher** than that of its ACSR counterparts.

At first sight, the higher weight and lower elasticity could be seen as disadvantages of the copper conductor. In practice, this is not the case, because:

1) The strength of the towers for overhead lines is not so much determined by the weight of the conductor, but more by **resistance against forces created by wind and ice**. The smaller cross section of the conductor, the lower these forces will be.
2) The high annealing temperature of copper (> 300°C) makes it **easier to apply surface coating** on the copper conductor without being concerned about a potential change of the mechanical properties of the material. Certain types of surface coating can make the conductor hydrophobic, preventing ice load.

As a result, the micro-alloyed copper conductor becomes a technically feasible and financially attractive alternative to ACSR conductors.

The ability to apply coating on the copper conductor also brings along another advantage: it enables a surface treatment that **reduces Corona losses** as well as the energy losses and the noise levels that are related to that. Especially in wet climates, Corona losses can become a substantial source of irritation for passers-by, adding to the negative image of high voltage overhead lines. It prevents corrosion as well. Copper is much less affected by environmental corrosion than aluminium. In addition, if a coating is applied on each strand of the copper conductor, corrosion practically disappears.

# ECONOMIC ANALYSIS

## NEW LINES WITH REDUCED LIFE CYCLE COST [1]

As mentioned earlier, European grid regulators have a growing intention to reduce energy losses. Consequently, their focus is shifting from a minimizing the investment cost of new lines, to minimizing the entire life cycle cost of the line. This life cycle cost (LCC) consists out of five distinctive parts:

1) Towers and foundations (supply and install)
2) The conductor
3) The stringing of the conductor
4) Operational maintenance
5) Energy losses

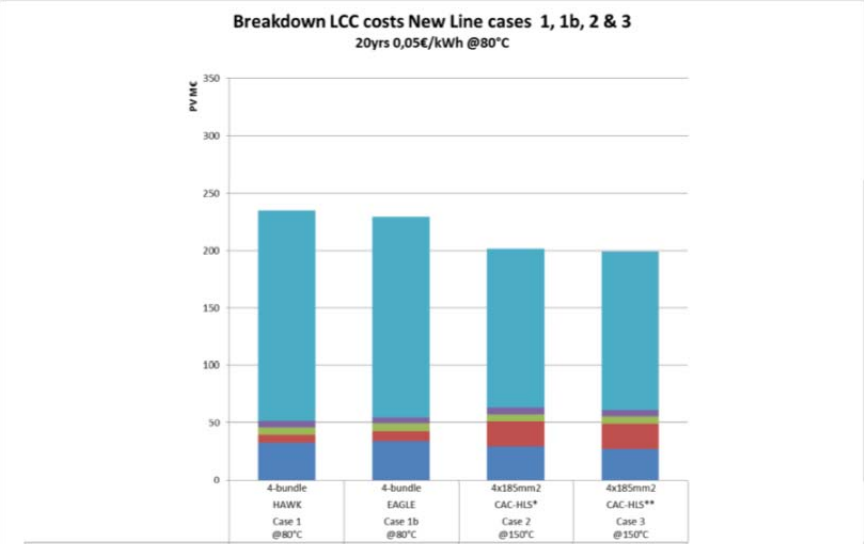
The feasibility study by DNV KEMA [1] calculated those five parts for several different types of conductors and for different scenarios. In all of those scenarios, the energy losses represent by far the largest share of the LCC.

Their share ranges between 40% and 80%, depending on the type of conductor, the duration of the life cycle, the load profile, and the electricity price.

Assume the following conditions:

- Load profile:
  - 100% of the load during 25% of the time
  - 80% of the load during 20% of the time
  - 40% of the load during 55% of the time
- Electricity price: 5 c€ /kWh
- Life cycle duration: 20 years

Those assumptions lead to the following LCC calculations:




| | 4-bundle HAWK Case 1 @80°C | 4-bundle EAGLE Case 1b @80°C | 4x185mm2 CAC-HLS* Case 2 @150°C | 4x185mm2 CAC-HLS** Case 3 @150°C |
|---|---|---|---|---|
| 7 Load profile 2/0.05€/20yr | 183,456,971 | 174,938,027 | 138,047,321 | 138,047,321 |
| Maintenance costs net present value 20yrs | 5,714,070 | 5,714,070 | 5,714,070 | 5,714,070 |
| Stringing conductor | 6,758,088 | 6,758,088 | 6,758,088 | 6,758,088 |
| Supply conductor | 6,758,088 | 8,444,190 | 21,708,934 | 21,708,934 |
| Supply and install towers & Foundations | 32,335,000 | 33,945,000 | 29,190,000 | 27,040,000 |

*The CAC-HLS has different thermal properties than ACSR
**The CAC-HLS calculated without ice load

*Figure 3 – Comparing the life cycle cost of a new line with a copper conductor and the same line with an ACSR conductor.*

The micro-alloyed copper conductor is approximately 3 times more expensive than the ACSR conductors, but the conductor price represents only a small share of the total LCC. This higher investment cost is largely compensated for by the lower cost of energy losses (a reduction by at least 20%). As a result, the higher cost of the conductor is paid back in less than 5 years. The costs of stringing the conductor, of supplying and installing the towers, and of operational maintenance are of a similar order of magnitude for all three the conductor types. The total life cycle cost of the micro-alloyed copper conductor is reduced by 14.3% compared to the ACSR Hawk.

Note that the energy losses in the conductor can also be reduced by increasing the cross section of the ACSR conductor, as it is the case with the ACSR Eagle compared to the ACSR Hawk. However, the loss reduction is not as substantial as with the micro-alloyed copper conductor, and nearly all of the investment that is gained in this way is lost again because of the higher cost of towers and tower foundations. Indeed, the larger conductor cross section results in higher wind and ice loads, requiring tower reinforcements.

Taking all the advantages of the micro-alloyed copper conductors into account, they prove to be particularly suitable for linking new large scale wind power generation parks with the main grid. First of all, a life cycle cost philosophy is normally applied when assessing the economic feasibility of wind parks. Second, the small cross section of the copper conductor make it a preferred choice in windy regions, as it limits the wind load and avoids the need to reinforce the towers on the line. And last but not least, the fact that copper conductors can be submitted to capacity overloads of up to 60% is a major advantage for transporting the variable output of the wind park to the main grid.

## COMPETITIVE UPGRADE OF EXISTING LINES [2]

For the refurbishment of an existing line with new conductors, the life cycle cost (LCC) consists only out of four parts:

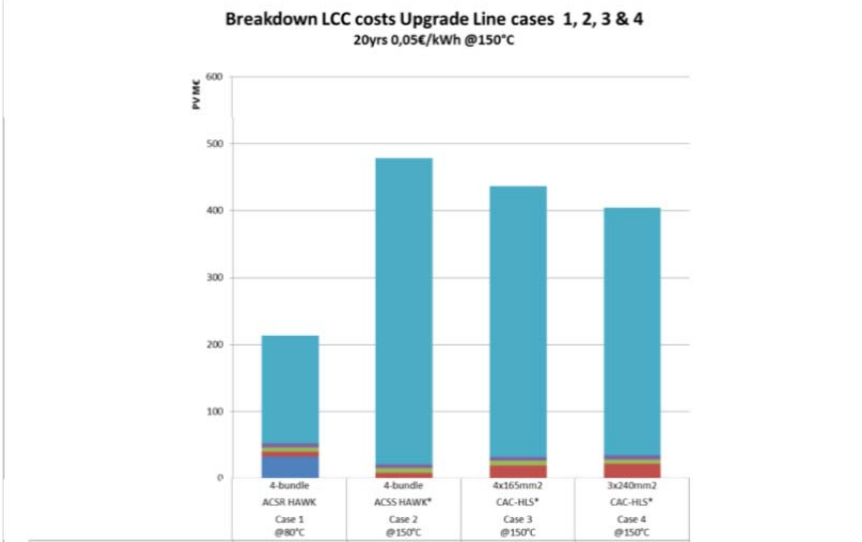
1) The conductor
2) The stringing of the conductor
3) Operational maintenance
4) Energy losses

In a second study by DNV KEMA [2], this Life Cycle Cost for a line upgrade was calculated for different scenarios. As could be expected, the energy losses represent an even larger share of the total LCC as in the case of a new line, ranging between 85 and 95% depending on the type of conductor, the duration of the life cycle, the load profile, and the electricity price.

Assume again the following conditions:

- Load profile:
    - 100% of the load during 25% of the time
    - 80% of the load during 20% of the time
    - 40% of the load during 55% of the time
- Electricity price: 5 c€ /kWh
- Life cycle duration: 20 years

Those assumptions lead to the following LCC calculations for refurbishing a line with an ACSS Hawk or with a CAC-165 conductor:




| | 4-bundle ACSR HAWK Case 1 @80°C | 4-bundle ACSS HAWK* Case 2 @150°C | 4x165mm2 CAC-HLS* Case 3 @150°C | 3x240mm2 CAC-HLS* Case 4 @150°C |
|---|---|---|---|---|
| 3 Load profile 1/0.05€/20yr | 161,609,194 | 457,552,717 | 404,279,739 | 370,490,407 |
| Maintenance costs net present value 20yrs | 5,714,070 | 5,714,070 | 5,714,070 | 5,714,070 |
| Stringing conductor | 6,758,088 | 6,758,088 | 6,758,088 | 6,758,088 |
| Supply conductor | 6,758,088 | 8,445,120 | 19,354,878 | 21,115,218 |
| Supply and install towers & Foundations | 32,335,000 | 0 | 0 | 0 |

*The CAC-HLS has different thermal properties than ACSR
**The CAC-HLS calculated without ice load

*Figure 4 – Comparing the life cycle cost of a line refurbishment with a copper conductor and the same line refurbishment with an ACSR conductor*

The conductor losses of the CAC-165 are more than 10% lower than those of the ACSS HAWK. As a result, even though the initial investment is approximately 70% higher, the life cycle cost of the refurbishment with copper conductor is 8.5% lower compared to the refurbishment with an ACSS HAWK conductor. Other conductor cross sections, load profiles, electricity prices, and life cycle durations lead to slightly different results, but with similar conclusions [2].

# UNIQUE TECHNICAL SOLUTIONS

## THE ADVANTAGE OF A HIGHER MAXIMUM OPERATING TEMPERATURE

One of the most interesting features of the micro-alloyed copper conductor for overhead lines is the higher maximum operating temperature compared to ACSR conductors.

ACSR conductors have a maximum operating temperature of around 80°C to avoid excessive creep of the conductor material. Copper has a much higher temperature resistance against creep and can be heated up to a temperature of at least 150°C trouble-free. This means that, even though the nominal capacity will keep the conductor temperature at 80°C, the cable can take occasional short-term overload currents without any danger or lasting implication. For instance, the ACSR Eagle aluminium conductor and the CAC 185 copper conductor both have nominal currents of 700 A at 80°C. However, the ACSR Eagle conductor cannot be overloaded to avoid higher temperatures, while the CAC 185 can be loaded with up to 1115 A, heating the conductor up to 150°C. The latter corresponds with an overload of more than 60%.

Such an overload should be short term because of the higher energy losses compared to the nominal situation, but it can help transmission network operators serving emergency situations. For instance:

- **Complying with the N-1 safety criteria**. A network should be able to cope with the sudden break down of one line or power station without evolving into a black-out. In such a condition, other lines have to take over the power that was transported over the line that broke down, or other power stations that are situated further away from the centres of consumption have to take over from the power station that broke down. In both cases, the power lines that are still functioning receive additional power to create a new equilibrium. To avoid that in such a situation, certain lines become overloaded and risk to break down as well, new lines are built to ensure spare capacity, peak generation plants are built to ensure local supply, and phase-shift transformers are installed to direct the power towards lines with spare capacity. The use of micro-alloyed copper conductors can avoid these kinds of investments.

- **Transporting short-term peak productions from wind farms**. What should be the capacity of transmission lines connecting remote wind farm with the grid? Such a wind farm will generate its maximum output only during a very short time of the year. So the question is whether it is economically worthwhile to choose the nominal capacity of the transmission line according to this maximum output. This dilemma can be solved by using micro-alloyed copper conductors. Even though the nominal capacity of this line can be set at a lower value, it will still be able to supply the occasional maximum output to the grid. This can be crucial for ensuring the economic feasibility of a wind farm.

## BETTER PERFORMANCE IN EXTREME WEATHER CONDITIONS

The international standard EN 50341 – 1:2001 [4] prescribes four categories of extreme weather conditions for which the performance of overhead lines should be tested:

- LC 1a – Extreme wind at design temperature (10°C)
- LC 1b – Wind at minimum temperature (-20°C)
- LC 2c – Unbalanced ice loads, different ice loads per span (-5°C)
- LC 3 – Combined wind and ice loads (-5°C)

Micro-alloyed copper conductors have an advantage over ACSR conductors in all four those categories. Thanks to the smaller diameter of the conductor, it will catch less wind. Thanks to the high annealing temperature of copper, several types of coating can be applied on the conductor without being concerned about a potential change of the mechanical properties of the material. Coating can make the conductor hydrophobic, significantly reducing the risk on ice load.

These characteristics make the micro-alloyed copper conductors particularly suitable for overhead lines in cold, humid and windy climates.

## REDUCTION OF CORONA LOSSES

The Corona losses on high voltage line conductors represent only a minor share of the energy losses, but they result in a noise that is perceived as irritating by many people. Corona losses are particularly high in humid environments. Thanks to the high annealing temperature of copper, an anti-Corona coating can be applied on the micro-alloyed copper conductors in an uncomplicated way, reducing the Corona losses to a level that can hardly be perceived by the human ear. This can be an important element for the acceptance of high voltage overhead lines in densely populated areas in a humid climate.

## CONCLUSION

Micro-alloyed copper conductors offer an interesting alternative to steel reinforced aluminium conductors for high voltage overhead lines.

Although copper is a heavier material, the micro-alloyed copper conductor does not require a reinforcement of the overhead line towers. Indeed, its mechanical strength makes a steel core superfluous. And even more importantly, the smaller cross section combined with hydrophobic coating result in a much lower wind and ice load, which is a decisive factor for determining the required strength of the towers. This makes the copper conductor particularly suitable for overhead lines in cold and windy climates.

The lower electrical resistance of copper combined with a reduced skin effect result in significantly lower energy losses compared to ACSR conductors. Those energy losses comprise the main part of the life cycle cost, especially for the refurbishment of a line, but also for new lines. Consequently, even though the copper conductor requires a higher investment cost (approximately 70%), its life cycle cost will in many cases drop beneath that of ACSR conductors.

One of the most interesting features of the micro-alloyed copper conductor for overhead lines is the higher maximum operating temperature compared to ACSR conductors. This makes it possible to charge the conductor with overloads of at least 60% without compromising the mechanical properties. Such an overload should be short term because of the much higher energy losses compared to the nominal situation, but it can help transmission network operators to comply with the N-1 safety criteria and to cope with short periods of very high renewable energy production.

## REFERENCES

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[4] CENELEC standard EN 50341 – 1:2001:

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