WHITEPAPER

HOW LARGER CONDUCTOR CROSS-SECTIONS REDUCE COSTS AND CO_2 EMISSIONS

LAPP

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CONTENT

1 INTRODUCTION

Corporate Carbon Footprint (CCF), Product Carbon Footprint (PCF), Life Cycle Assessment (LCA), Digital Product Passport, Digital Twin and the topic of CO_2 reduction in general are increasingly being discussed alongside technical product properties and demanded or requested by industrial companies such as LAPP. For cables and wires[1], the choice of cross-section is a relevant technical parameter when selecting products. The respective copper content has a direct influence on CO_2 emissions.

As of today, CO_2 emissions are not considered during the design process of cables. The primary design criterion is the electrical resistance and the permissible heating of the material. This white paper examines the question of whether the conductor cross-section to be selected changes if not only the technical properties are taken into account, but also the CO_2 emissions and total cost of ownership (TCO) over the life cycle.

The background to the question is the assumption that the cross-section directly influences both the CO_2 emissions and the TCO. The correlations are shown in Table 1. A larger cross-section has the disadvantage of initially incurring a higher PCF and a higher purchase price. However, a larger cross-section causes lower energy losses, so that both emission and energy cost savings can be achieved.

Larger cross-section	CO emissions$_2$	Costs
Disadvantages	Initial higher PCF	Initial higher purchase price
Advantages	Lower losses → Reduction of emissions	Lower losses → Lower energy costs

Tabel 1: Disadvantages and advantages of a larger conductor cross-section

This white paper answers the following questions:

1. How must the cable cross-section be dimensioned to achieve the lowest CO_2 emissions over the entire product life cycle?
2. When is it worth choosing a larger cross-section?

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[1] In the following, the terms cable and wire are used interchangeably.

2 BASICS

Various standards must be observed when dimensioning cable lengths and cross-sections to suit the application. The DIN VDE 0298-4[1] for example, describes the maximum current carrying capacity of cables and wires depending on the type of installation. In addition, VDE 0100-520 Supplement 2[2] specifies maximum cable lengths for compliance with the permissible voltage drop. Furthermore, the requirements of the installed fuse must be taken into account. The primary intention of these standards is to avoid unacceptable heating of the cable. Instructions for selecting the appropriate cross-section for the application can be found in the LAPP white paper "Calculation and selection of the cross-section for cables in AC and DC systems"[3].

As of today, the standards mentioned do not take any further consideration of energy efficiency. Many customers try to determine the minimum possible cross-section to keep the acquisition costs as low as possible. The DIN VDE 0100-801[4] provides an indication that a differentiated approach to dimensioning may be necessary:

„In some applications (especially in the industrial sector), the most economical cross-sections can be much larger than those required for thermal reasons.

This standard refers to IEC 60287-3-2: Economic optimization of conductor cross-sections[5] in which the economic efficiency calculation is considered. However, the influence of the conductor cross-section on the energy balance of the cable and thus on the life cycle assessment is not explained. Only the DIN technical report CLC/TR 62125[6] provides general information on the factors influencing the life cycle assessment of cables and wires. Detailed procedures and calculation formulas are not defined.

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[1] Reference: DIN VDE 0298-4:2023-06 Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen: Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen, DIN VDE 0298-4, DIN VDE, Berlin, Jun. 2023.

[2] Reference: DIN VDE 0298-4:2023-06 Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen: Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen, DIN VDE 0298-4, DIN VDE, Berlin, Jun. 2023.

[3] U.I. Lapp GmbH, „Berechnung und Auswahl des Querschnittes für Kabel und Leitun-gen in AC- und DC-Systemen," Stuttgart, Jul. 2023.

[4] Reference: DIN VDE 0100-801:2020-10 Errichten von Niederspannungsanlagen: Teil 8-1: Funk-tionale Aspekte – Energieeffizienz, DIN VDE 0100-801, DIN VDE, Berlin, Okt. 2020.

[5] Reference: IEC 60287-3-2:2012 Electric cables - Calculation of the current rating: Part 3-2: Sections on operating conditions - Economic optimization of power cable size, IEC 60287-3-2, IEC, Genf, Jul. 2012.

[6] Reference: DIN-Fachbericht CLC/TR 62125:2009-07 Umwelterklärung für TC 20: Kabel und isolierte Leitungen, IEC/TR 62125, DIN, Berlin, Jul. 2009.

In this document, two parameters are used to assess the selected conductor cross-section regarding costs and life cycle assessment:

1. **TCO:** Costs arising from the procurement, use and disposal of a product[7]
2. **CO_2 emissions:** Sum of CO_2 emissions resulting from the CO_2 footprint of the copper component and from losses during operation

2.1 ASSUMPTIONS FOR THE CALCULATION

1. **Consideration of the product life cycle up to the end of use, excluding disposal and recycling**

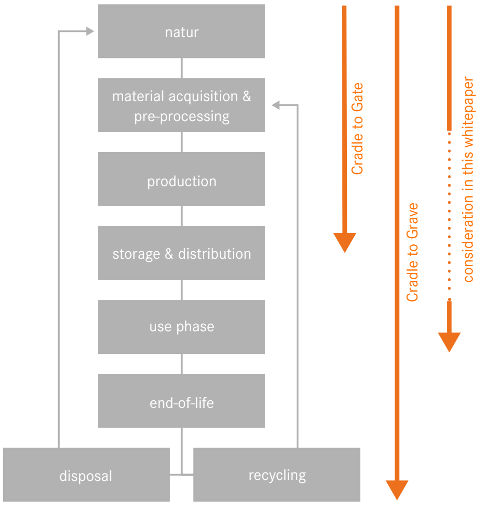

Illustration 1: LCA with different observation periods (cf. [8])

According to the Greenhouse Gas Protocol (GHP), a distinction is usually made between the Cradle to Gate and Cradle to Grave approach[8] as shown in Figure 1. Cradle to Gate considers all CO_2 emissions that occur from the extraction of raw until the product leaves the factory gate. Cradle to Grave, on the other hand, also includes emissions during the use phase and final recycling or disposal. In this white paper, an accounting is carried out or an accounting framework is selected that lies between these two approaches. The disposal or recycling and the production and logistics of the cables are not considered.

For this reason, the term PCF is not used below. According to DIN EN ISO 14067, the PCF is defined as the sum of greenhouse gas emissions and removals in a product system[9] and thus analogous to the Cradle to Grave approach of the GHP.

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[7] Reference: B. Flashar, „Qualitätskosten und Total Cost of Ownership (TCO),“ in Qualität neu denken: Innovative, virtuelle und agile Ansätze entlang der Wertschöpfungskette, M. Helmold, T. Laub, B. Flashar, J. Fritz und T. Dathe, Hg., 1. Aufl. Wiesbaden: Springer Fachmedien Wiesbaden; Imprint: Springer Gabler, 2023, S. 29–37.

[8] Reference: P. Bhatia, C. Cummis, A. Brown, L. Draucker, D. Rich und H. Lahd, Product Life Cycle Accounting and Reporting Standard. Washington, Genf: WRI; WBCSD, 2011.

[9] Reference: DIN EN ISO 14067:2019-02 Treibhausgase – Carbon Footprint von Produkten – Anforderungen an und Leitlinien für Quantifizierung, DIN EN ISO 14067, DIN EN ISO, Berlin, Feb. 2019.

2. **Insulation material is not taken into account**
   As the influence of the plastic on the overall balance is negligible, the CO_2 emissions of the insulation and jacket material are not included. The influence of the insulation and sheathing material and their percentage share are discussed in the outlook in chapter 4. t.

3. **Constant load profile and symmetrical load (with three-phase connection)**
   Information on the determination of discontinuous and asymmetrical load profiles can be found at Fassbinder[10].

4. **Multi-core cables with two or three loaded cores**
   Since power supply cables usually have two or three loaded cores, the calculation is limited to these cases.

5. **Constant temperature of the conductor of 20 °C and its surroundings**
   The influence of temperature is discussed in the outlook in chapter 4.

Based on these five assumptions, the TCO and CO_2 emissions can be determined as a function of the conductor cross-section, as shown in Figure 2 schematically. All greenhouse gas emissions are summarized equivalently in the CO_2 emissions.

TCO	**General conditions**	**CO_2 emissions**
Purchase costs + Costs for power loss = TCO	Load profile over 5-30 years	CO_2 emissions from copper + CO_2 emissions for power loss = CO_2 emissions

Illustration 2: Methodology for determining TCO and PCF

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[8] Reference: P. Bhatia, C. Cummis, A. Brown, L. Draucker, D. Rich und H. Lahd, Product Life Cycle Accounting and Reporting Standard. Washington, Genf: WRI; WBCSD, 2011.

[10] Reference: S. Fassbinder, „Mehr Kupfer kostet weniger: Auslegung von Kabel- und Leitungsanlagen nach Lebensdauerkosten,“ ep Elektropraktiker, Jg. 1, 2017.

2.1 CALCULATION PROCEDURE

In general, every current-carrying conductor has losses. The size of the losses is significantly influenced by the selected conductor cross-section. The larger the cross-section, the lower the losses when the cable is energized. For fine-stranded copper cables (conductor class 5) in the three-phase AC network, the losses are shown in Figure 3 as a function of the nominal conductor cross-section. A single curve of the array represents the effective conductor current in a conductor. The maximum values correspond to the specified current carrying capacities in accordance with DIN VDE 0298-4[1].

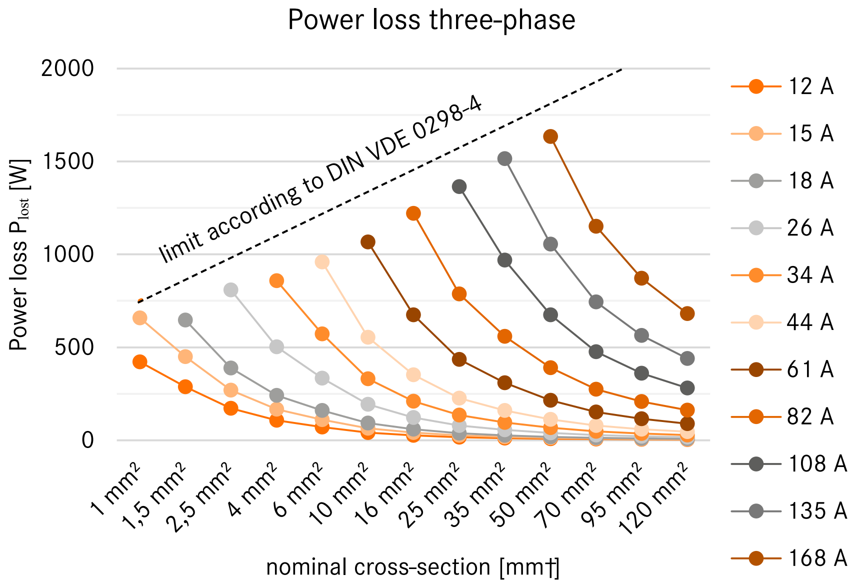

Illustration 3: Power loss as a function of the cross-section

Regardless of the type of network, the calculation of the power loss of the entire cable length is:

$$P_{lost} = n \cdot R_L \cdot I^2_L \qquad (2\text{-}1)$$

LEGEND

P_{lost} – power loss [W]
n – number of loaded cores
R_L – max.conductor resistance for length l [Ω]
I_L – RMS value of the conductor current A]

For DC networks and two-phase AC networks, applies $n = 2$, as the forward and return conductors must be. For three-phase AC networks must $n = 3$ be used. The common interlinking factor $\sqrt{3}$ does not apply here, as the power loss drops independently on each individual conductor..

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[1] Reference: DIN VDE 0298-4:2023-06 Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen: Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen, DIN VDE 0298-4, DIN VDE, Berlin, Jun. 2023.

Likewise, the power factor $\cos\varphi$ of the load is irrelevant. The maximal possible conductor resistance can be determined for the respective conductor type from DIN EN 60228 (VDE 0295)[11] or Table 11 of the LAPP catalogue and adapted to the length .

The TCO is calculated from the sum of the costs for the cable and the costs resulting from the power loss:

$$TCO = C_{initial} + C_{lost} \tag{2-2}$$

Whereby

$$C_{lost} = C_{energy} \cdot P_{lost} \cdot Y \cdot D \cdot H$$

LEGEND

$C_{initial}$ – Costs cable [€]
C_{lost} – Costs losses [€]
C_{energy} – Costs energy [€/kWh]
Y – years of operation
D – operating days per year
H – operating hours per day

Similarly, the CO_2 emissions $CO_{2,total}$ can be determined using the emission factor for the initial purchase of the cable and the emission factor for the ongoing power loss. The emission factors consider the global warming potential (GWP) of all greenhouse gases for a period of 100 years (GWP100) according to the GHP standard[8].

$$CO_{2,total} = CO_{2,initial} + CO_{2,lost} \tag{2-3}$$

Whereby

$$CO_{2,initial} = m_{Cu} \cdot EF_{Cu}$$

And

$$CO_{2,total} = EF_{energy} \cdot P_{lost} \cdot Y \cdot D \cdot H$$

LEGEND

$CO_{2,initial}$ – emissions copper [kg CO_2e]
$CO_{2,lost}$ – emissions power loss [kg CO_2e]
m_{Cu} – copper mass fraction for conductor lenght l [kg]
EF_{Cu} – emission factor copper $\left[\frac{\text{kg } CO_2\text{e}}{\text{kg}}\right]$
EF_{energy} – emission factor electricity mix $\left[\frac{\text{kg } CO_2\text{ek}}{\text{kWh}}\right]$

When considering TCP and CO_2 emissions, the dependencies shown in Figure 4 emerge for an exemplary cable and its application. It should be emphasized that the nominal cross-section, which is designed in accordance with current regulations, is 2.5 mm². However, the most economical cross-section is several cross-section classes higher, both from a TCO perspective and from a CO_2 emissions perspective. In this example, the most economical cross-section would be 6 mm², while the cross-section with the lowest CO_2 emissions would be 16 mm². The respective optimum depends on the boundary conditions such as rated current, duration of use and variable costs.

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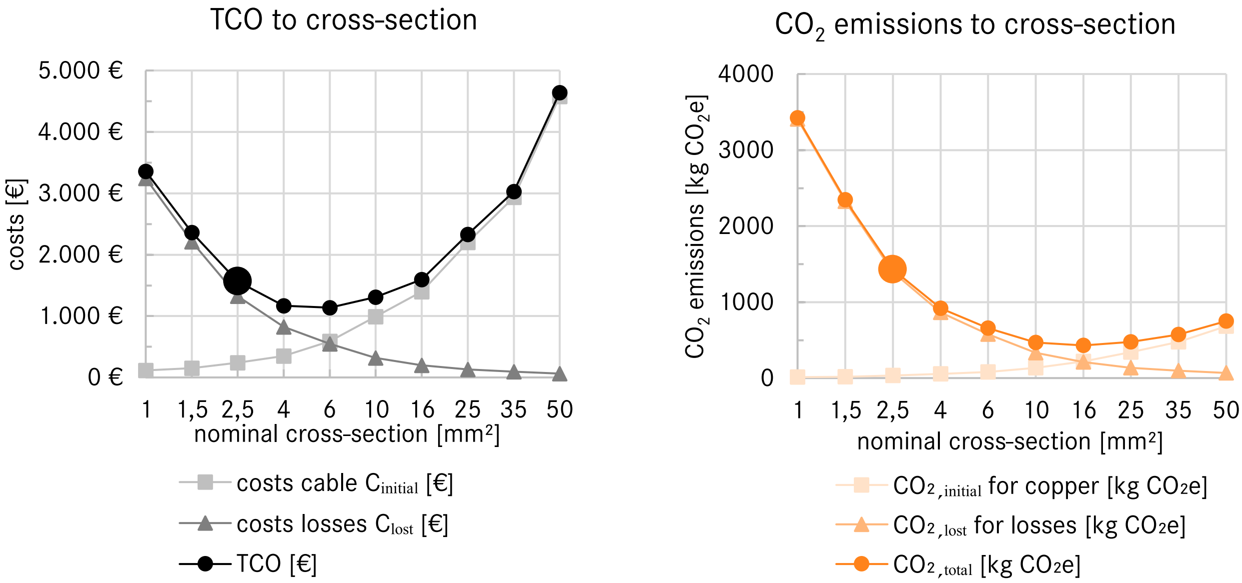
[8] **Reference: P. Bhatia, C. Cummis, A. Brown, L. Draucker, D. Rich und H. Lahd, Product Life Cycle Accounting and Reporting Standard. Washington, Genf: WRI; WBCSD, 2011.**



Illustartion 4: TCO and CO2 emissions as a function of the nominal conductor cross-section

The procedure described here for determining the conductor cross-section is a practice-oriented recommendation for action. For insurance and legal reasons, LAPP cannot accept any liability for the actual planning of an electrotechnical system.

3 CALCULATION EXAMPLE

In the following, the example of a ventilation unit is used to show the potential savings that can be made both financially and in terms of CO_2 emissions if the cable is designed with more than just thermal integrity in mind. A four-core fine-stranded, unshielded cable with PVC as insulation and sheath material is used as the supply cable.

The period under review is:

- 10 years, 220 days per year, 16 hours per day

The conditions of the facility are:

- 11 kW power, 3-phase AC
- corresponds to 16 A effective conductor current
- 50 m cable length

According to DIN VDE 0298-4, the minimum nominal cross-section of the cable to comply with the current carrying capacity should be 1.5 mm^2[1]. According to DIN VDE 0100-520, the maximum cable length for a conductor current of 16 A with a nominal cross-section of 1.5 mm^2 is limited to 34 m[2]. To comply with the maximum permissible voltage drop, the cross-section must be increased by one step to 2.5 mm^2[2].

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[1] Reference: DIN VDE 0298-4:2023-06 Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen: Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen, DIN VDE 0298-4, DIN VDE, Berlin, Jun. 2023.

[2] Reference: DIN VDE 0298-4:2023-06 Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen: Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen, DIN VDE 0298-4, DIN VDE, Berlin, Jun. 2023.

The online tool on the LAPP website can be used to determine the voltage drop.

The power loss for a nominal cross-section of 2.5 mm² is as follows according to formula 2-1

$$P_{lost} = n \cdot R_L \cdot I_L^2 = 3 \cdot 7{,}98\ \Omega \cdot 16\ \mathrm{A}^2 \cdot \frac{50\ \mathrm{m}}{1000\ \mathrm{m}} = 306{,}4\ W$$

With an electricity price of € 0.35/kWh, Formula 2-2 results in loss costs over the period under review of

$$C_{lost} = C_{energy} \cdot P_{lost} \cdot Y \cdot D \cdot H = 0{,}36\ \frac{€}{\mathrm{kWh}} \cdot 306{,}4\ W \cdot 10 \cdot 220 \cdot 16 = 3.775{,}24\ €$$

Together with the acquisition costs, the TCO of the nominal cross-section of 2.5 mm² for 50 m cable length is

$$TCO = C_{initial} + C_{lost} = 124{,}67\ € + 3775{,}24\ € = 3.899{,}91\ €$$

If the cable were to be designed solely according to the aspect of the lowest purchase price, 30 times the purchase price would have to be paid to the energy supplier within ten years due to the power loss. The calculation shown can now be carried out for each cross-section and displayed graphically (see Figure 5).

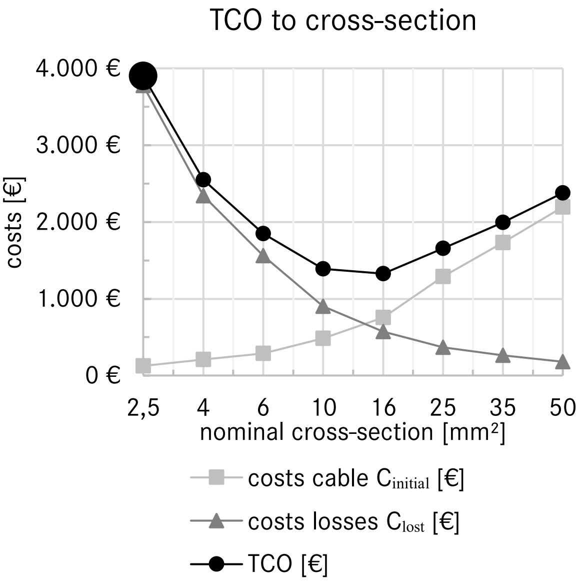

Illustration 5: TCO of the supply line to the ventilation system as a function of the nominal conductor cross-section

In this example, the optimum TCO is achieved with a nominal conductor cross-section of 16 mm². Compared to the standard design of 2.5 mm², the example showed savings of 66 % or 2571 € over the period under consideration - despite the higher purchase price of the cable. The investment in the larger conductor cross-section therefore pays for itself after just the second year.

The following emission factors are used to calculate CO_2 emissions:

- $EF_{energy} = 0{,}368\ \frac{\text{kg CO}_2\text{e}}{\text{kWh}}$ - Average for Germany 2022[12]
- $EF_{Cu} = 3{,}956\ \frac{\text{kg CO}_2\text{e}}{\text{kg}}$ - according to the International Copper Alliance[13]

Using the copper number, which is noted in the data sheet for 1 km of cable length, the CO_2 emissions for the copper weight of a supply cable with a nominal cross-section of 2.5 mm² and a length of 50 m can be determined:

$$CO_{2,initial} = m_{Cu} \cdot EF_{Cu} = 4{,}8\ \text{kg} \cdot 3{,}965\ \frac{\text{kg CO}_2\text{e}}{\text{kg}} = 19{,}0\ \text{kg CO}_2\text{e}$$

In addition, the already calculated power loss also causes CO_2 emission. According to formula 2-3, these are as follows for the nominal cross-section

$$CO_{2,lost} = EF_{energy} \cdot P_{lost} \cdot Y \cdot D \cdot H =$$
$$0{,}368\ \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \cdot 306{,}4\ \text{W} \cdot 10 \cdot 226 = 3969{,}4\ \text{kg CO}_2\text{e}$$

The total CO2 emissions for the period under review are as follows (formula 2-3)

$$CO_{2,total} = CO_{2,initial} + CO_{2,lost} = 19{,}0\ \text{kg CO}_2\text{e} + 3969{,}4\ \text{kg CO}_2\text{e} = 3988{,}4\ \text{kg CO}_2\text{e}.$$

Analogous to TCO consideration, this calculation can be carried out for each cross-section, resulting in the diagram in figure 6.

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[12] Reference: European Environment Agency. "Greenhouse gas emission intensity of electricity generation in Europe | European Environment Agency's home page." Accessed on: 10 July 2024. [Online.] Available: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1

[13] Reference: V. Tuazon, "Copper Environmental Profile: Global 2023," International Copper Association, Washington, 2023.

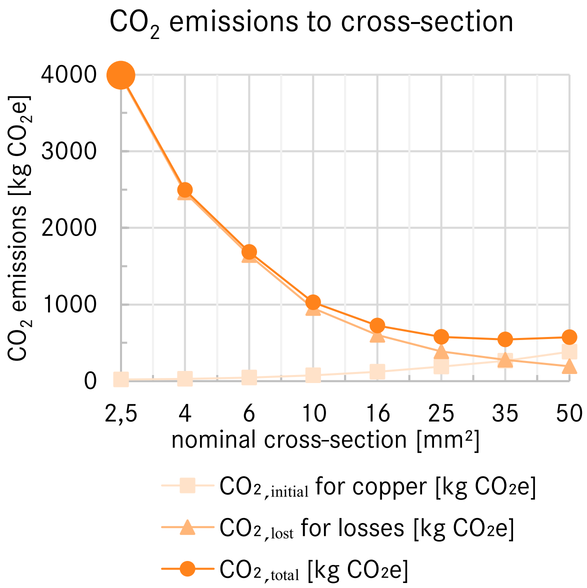

Abbildung 6: CO2 emissions of the supply line to the ventilation system as a function of the nominal conductor cross-section

The optimum of the curve for CO_2 emissions is at a nominal cross-section of 35 mm². Particularly with cross-sections close to the standard design, the CO2 emissions are generated almost entirely by the power loss emissions. With a design exclusively from this perspective, 86 % or 3446 kg CO_2e of the CO_2 emissions could be saved in the example compared to the standard design. It can also be seen that the optimum of TCO and CO_2 emissions can be achieved with different nominal cross-sections.

4 OUTLOOK

To simplify the calculation, some influencing factors are not taken into account in this document. If power loss occurs on the cable, this is primarily converted into thermal energy. This has a negative effect on the conductivity of the copper and therefore also increases the losses. As the heat distribution within a cable depends on the number of conductors, the insulation material, and the cross-section (among other things) an exact statement for each cross-section can only be determined experimentally or by simulation.

Furthermore, the influence of the insulation material on the CO_2 emissions is neglected. In the ventilation example shown, a relative error of 0.4 % is tolerated for the cross-section according to the standard design. The value of 2.88 kg CO_2e is used for calculation as the emission factor for PVC[14].

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[14] Reference: G. Bourgault, "ecoinvent 3.10 Dataset Documentation: market for polyvinylchloride, suspension polymerised - GLO - polyvinylchloride, suspension pol-ymerised," ecoinvent Association, Zürich, 2024.

It should also be noted that the emission factor of copper is in the range of 1.495 kg CO_2 e [15] to 7.0 kg CO_2 e [16]. However, as the influence of copper on the total CO_2 emissions is negligible compared to the emissions of the power loss, a higher or lower emission factor for copper has no influence on the optimum.

The decision in favour of a larger cross-section should also consider that the additional financial outlay at the time of purchase is repaid by recycling at the end of the product's life. In addition, copper can be recycled indefinitely without any loss of quality[17].

When selecting the cross-section, the optimum of TCO and CO_2 emissions must be taken into account in addition to compliance with the applicable standards and adherence to set boundary conditions, such as practicability in terms of installation space and connection.

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[15] Reference: J. Mühlenfeld und D. Cholakova, "Environmental Profile of Aurubis Copper Cathode," Aurubis AG, Hamburg, Dez. 2023.
[16] Reference: G. Bourgault, "ecoinvent 3.10 Dataset Documentation: market for copper, cathode - GLO - copper, cathode," ecoinvent Association, Zürich, 2024.
[17] Reference: Deutsches Kupferinstitut, "Recycling von Kupferwerkstoffen," Düsseldorf, Jun. 201