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ELECTRICAL CONDUCTORS

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LIST OF ACRONYMS

- AC – Alternating current
- CAPEX – Capital Expenditure, or the money spend to buy, maintain, or improve fixed assets
- CCA – Copper-clad aluminium
- CMR – Carcinogenic / mutagenic / reprotoxic
- Cu – Copper
- Cu-ETP – Electrolytic tough pitch copper
- Cu-ETP1 – High purity electrolytic tough pitch copper
- Cu-FRHC – Fire-refined high conductivity copper
- Cu-OF – Oxygen-free copper
- DC – Direct current
- EROI – Energy return on investment
- ETS – Emission trading scheme
- FRHC – Fire-refined high-conductivity copper
- GHG – Greenhouse gas
- IACS – International Annealed Copper Standard
- ICMM – International Council on Mining and Metals
- LCA – Life-cycle analysis
- OPEX – Operational Expenditure, or the ongoing cost for running a product, business or system
- PBT – Persistent / bio-accumulative / toxic
- PoE – Power over ethernet
- ROI – Return on investment
- TCO – Total cost of ownership
- TSF – Tailing storage facility
- VRA – Voluntary risk assessment

1. SUMMARY: MATERIAL THAT ADDS VALUE

In little more than a century, electricity has become indispensable as our major energy carrier, both in industry and in everyday life. With the energy transition towards a low carbon economy, electricity's role will continue to grow. At the core of every electrical installation is electrically conductive material.

HIGH-CONDUCTIVITY COPPER

Copper (59 MS/m) and aluminium (37 MS/m) are the preferred conductive materials in electrical systems. The areas of application of both materials are relatively distinct and mainly related to the difference in density. As a general rule, copper is used as an electrical conductor for applications where minimizing the volume is important (e.g. wiring in electrical equipment), whereas aluminium is used where minimizing mass is important (e.g. overhead power transmission cables).

The electrical system is the largest sales market for copper, comprising approximately 70% of all the copper produced today. 52% of copper goes to wire and cable applications, including grid underground cables, building wires, and motor and transformer windings, and another 18% goes to electrical applications with specific conductor profiles, such as busbars, switching panel connectors, catenary wires and copper motor rotors. Electrical applications make use of high-conductivity copper, with high purity electrolytic tough pitch copper (ETP1), fire refined high conductivity copper (FRHC) and oxygen free copper (OF) as its main product categories. Their production processes have been refined over the years, resulting in consistently high quality.

OPTIMIZING THE CONDUCTOR CROSS SECTION

Increasing the cross-section of the electrical conductor is a cost-efficient way to improve the energy efficiency of the electrical connection. Indeed, international technical standards for cable sizing do not take energy efficiency into account but only safety and voltage drop. The conductor cross section that is economically optimal over the life-cycle of the system is therefore mostly substantially larger than the technical standard.

The energy savings that follow from an economically optimal conductor cross section also lead to a reduction in the greenhouse gas (GHG) emissions over the life time of the system, making such optimisation a highly cost-effective climate change mitigation measure.

Therefore, investing in additional conductor material to enhance the energy efficiency will pay off both from an economic and environmental point of view. It requires an investment at the purchase phase of the project, but this remains limited compared to the cost of the entire electrical system. On average, the electrical conductor represents only 2.6% of the system cost, next to cost factors such as shielding, insulation, mechanical support structures, cases, control & automation, design & engineering and maintenance.

THERMAL AND MECHANICAL PROPERTIES

The thermal conductivity is an important secondary parameter of an electrical conductor. Good thermal conductivity contributes to effective heat dissipation, limiting thermal stress on the insulation.

The conductor's mechanical properties are equally important, as they can prevent deformations during processing and use. Deformations can compromise electrical conductivity and create hot spots, reducing the energy efficiency, reliability and life expectancy of the electrical connection. In extreme cases, deformations and hot spots can even become a source of fire. The risk of creating deformations is particularly high at connections and joints, which require careful material choice, design and installation.

Copper in the energy transition

The use of electrical conductors will increase significantly in the coming 30 years due to the *energy transition*. This shift from fossil fuels to a carbon-neutral economy is a defining challenge for our generation. We have cost-effective and durable solutions at hand, but this does not make the task self-evident, given the enormous scale and limited time-frame during which we should make it happen. It will need investment in materials, with copper as a key element because of its excellent electrical conductivity. High-conductivity copper plays a vital role in renewable energy systems, energy efficient motors and cables, electric vehicles, electric heating and cooling systems and electric batteries. The copper industry has calculated that the energy transition as currently projected by the EU would require an additional 22.5 million tonnes of copper in the lead-up to 2050.

Copper in the circular economy

With an increased copper demand, copper recycling grows in importance. Copper can be recycled without downgrading, substantially reducing its life-cycle carbon footprint. This makes it an ideal electrical conductor material in a circular economy. It is mostly used in a pure state, and even where copper is alloyed or contains impurities, recycling is still possible and efficient. These foreign elements can be removed so that pure copper can be recuperated, ready to be re-used in any kind of application. Thanks to this high degree of recyclability, the stock of copper in use in electrical applications is not lost. An estimated two-thirds of the copper produced since 1900 is still in productive use, or an estimated 70 - 90 million ton of copper in Europe. This enormous stock, in its diverse range of end uses, is often referred to as the "urban mine".

As it is highly recyclable, copper conductor material has a high rest value at its end of life. Unfortunately associated with this advantage comes the theft risk. Theft can be particularly disruptive if it concerns working infrastructure. Examples of anti-theft programmes in France and South-Africa show that effective and feasible measures to counter copper theft exist.

Responsible copper mining

Because the demand for conductor material is growing and conductors have a long service life, there is a limited supply of used metals available for recycling into new products. The mining of copper ore fills the gap between the availability of secondary material and total demand. Copper is naturally present in the earth's crust, with global resources estimated to exceed 5,000 million tonnes (USGS, 2014 and 2017).

All major copper mining companies are members of ICMM, which is dedicated to safe, fair and sustainable mining. A risk assessment carried out by the European Commission showed that with the existing legislative framework, copper does not pose a risk to the environment or the health of workers or the general public.

Continuous innovation

Copper processing technology dates back more than 6000 years and is still evolving today. Production processes are continuously fine-tuned to maximise energy efficiency and minimise environmental impact. Fundamental innovation takes place in extraction and manufacturing processes, in the development of new copper materials, and in co-operations downstream in the copper value chain. In this way, copper will continue to take up its role as a strategic material for the carbon-neutral and cost-efficient energy economy of the future.

2. What is at stake?

Electrical conductors will continue to grow in importance over the next 30 years due to the energy transition.

Electrical conductors

Electrical conductivity is often thought of as guaranteed, but it can fluctuate greatly depending on the design and choice of material. The metal with the highest electrical conductivity is silver (63 MS/m), but it is too expensive for widespread use in electrical systems. Second on the list is copper (around 59 MS/m), and third is aluminium (around 37 MS/m) – the two most widely-used conductive elements found in electrical systems.

Maximizing conductivity can be important for three main reasons:

1) Minimizing energy losses, with all the associated economic and environmental advantages
2) Minimizing material costs – conductor material as well as insulation material and support structures
3) Minimizing installation size and weight, particularly necessary in some applications

The areas of application of copper and aluminium as electrical conductors are relatively distinct, and mainly depend on material properties other than conductivity (density is the main example). Most of these application areas are already long-established, with a few exceptions (e.g. copper die cast squirrel cage rotors for three-phase induction motors).

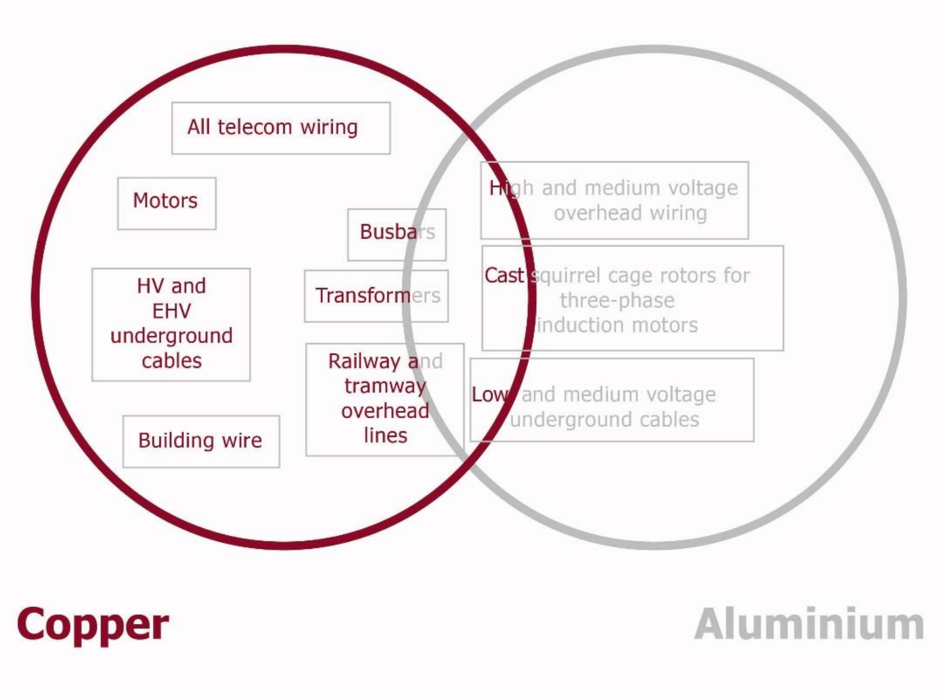

Figure 1 – Application domains of copper and aluminium in the electrical engineering sector; there is only a limited overlap [1].

In total, 50 million tonnes of copper is in use in the EU in electrical applications. Taking the copper price as €5,500 per tonne, this is worth €275 billion, while the total value of electricity systems in the EU amounts to approximately €10,000 billion [2]. This means that the core element – electrical conductors – represents about 2.75% of total system cost. Investing in the electrical conductors is often a sound decision because it can reduce life-cycle costs:

- through reduced purchase costs of other system elements;
- through lower energy losses and maintenance costs;
- by enhancing system technical performance.

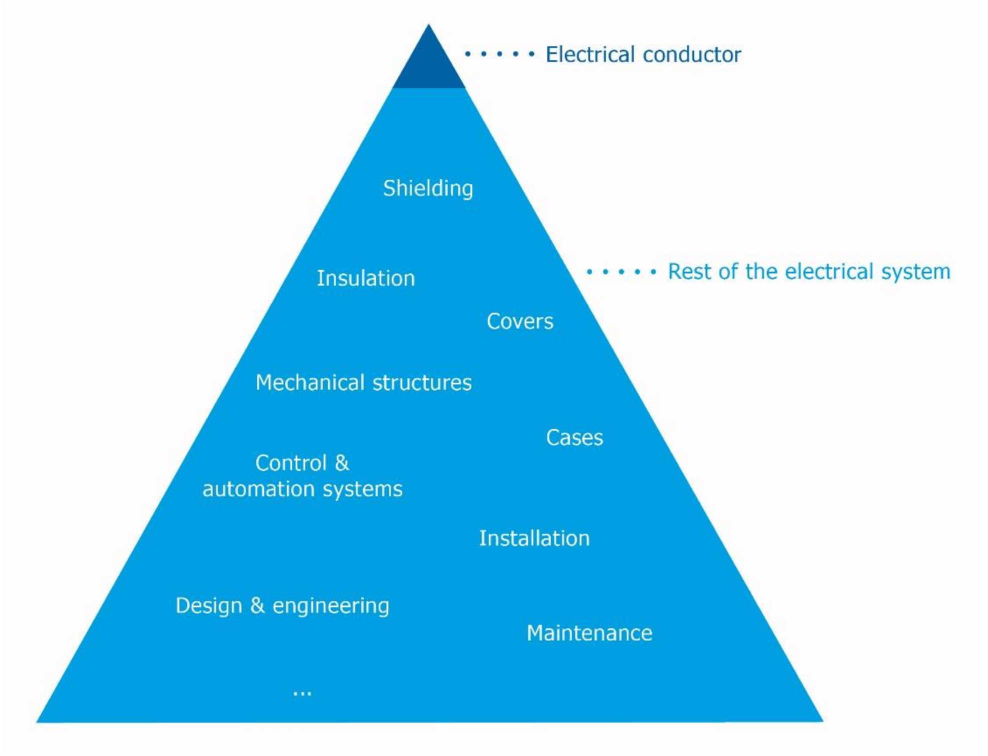

Figure 2 – Electrical conductors represent about 2.75% of the value of an electrical system.

THE ENERGY TRANSITION

The use of electrical conductors will increase significantly in the coming 30 years due to the *energy transition*.

The transition towards a low-carbon world is a defining challenge for our generation. We have cost-effective and durable solutions at hand, but this does not make the task self-evident, given the enormous scale and strict time-frame during which we should make it happen.

It is now already 20 years since the Kyoto Protocol and Europe has made encouraging progress. The major part of the transition, however, is still ahead of us. By 2050, EU carbon emissions should be reduced by 80-95% compared to 1990 levels, according to the Kyoto commitment. **The current EU roadmap aims for an 80% carbon emission reduction by 2050[1].**

[1] In the meantime, a goal of climate neutrality by 2050 has been suggested by the European Commission.

This target was set after the COP21 Paris Agreement in December 2015, which aims to limit temperature rise to well below +2°C compared to pre-industrial levels. The Agreement insists that all the signatory parties should reduce their greenhouse gas (GHG) emissions as soon as possible to reach this general target.

The scale of the required energy transition is massive and involves almost every sector of the economy. To decarbonise all our homes and buildings in time, a faster-than-usual renovation rate is imperative. Industry poses its own challenges because of the sheer volume of energy and process material used. Electricity production is making the fastest transition and has committed to decarbonise well before 2050. This will allow other sectors to *decarbonise through electrification*. One of these sectors is transport, which probably represents the biggest decarbonisation challenge of all. In parallel with electricity, hydrogen produced from renewable energy sources may be an alternative energy carrier and storage medium if cost-effective technologies are developed. Various forms of bioenergy will also play a role, but with responsible land-use and an acceptable energy return on investment (EROI) as constraints.

Notwithstanding these other options, **most of the decarbonised energy economy will be electrical**. Electricity's share in gross final energy consumption is expected to rise steeply from the current 26.5% (2016, [3]) to 60-70% over the next 30 years. This also means that the core element of electricity systems – the electrical conductor – will continue to grow, both in numbers of installed tonnes and in importance.

3. Copper in the world

After a long history of being used to make tools and in building, copper began to be used as an electrical conductor in the late 18th century. Today, electrical applications use high conductivity copper, which has a high degree of purity. Its production process has been refined over the years, resulting in consistently high quality.

A brief history of copper use

[4, 5]

Copper in pre-industrial times

Copper has played a major role in human history. It is thought to be the very first metal used by humans. Evidence of copper smelting goes back 7500 years when copper mines thrived in Belovode, current-day Serbia, and in the Timna Valley in Israel. The discovery that alloying copper with tin made the metal harder and more durable marked the transition from the Copper Age to the Bronze Age. With bronze, the art of metal casting began to develop, simultaneous with the development of the first writing in Mesopotamia. These events are generally considered to mark the end of the prehistoric era, some 5000 years ago.

From the Roman era, iron became the most widespread metal in Europe and Asia, but copper was still extensively used for its qualities of strength and durability. The ability of copper, bronze and brass to resist corrosion was prized for both functional and decorative applications.

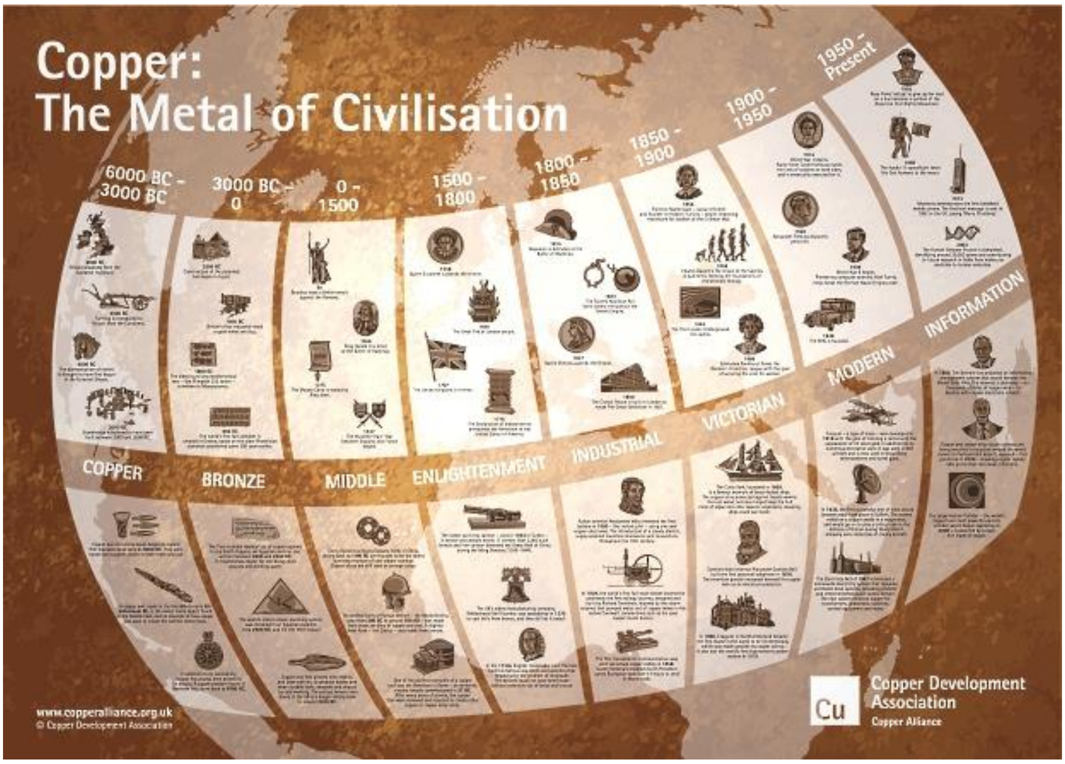

Figure 3 – Copper use over the centuries.

Copper as an electrical conductor

The first practical use of copper as an electrical conductor was in the late 18th century. Benjamin Franklin proved that lightning and electricity were the same phenomenon and erected lightning rods to protect buildings. The first lightning conductors were made from iron. When Saint Paul's Cathedral in London was struck by lightning in 1772, portions of the conductor glowed red-hot as a result of the electrical discharge, leading to the use of copper instead of steel for this kind of application. By this time it was already known that copper and silver had the lowest electrical resistance of all metals, although nobody understood exactly why. From the early 19th century, copper lightning rods were installed on ships' masts to protect the vessels during thunderstorms.

The first recorded uses of electric cables were for igniting explosions in mines and for telegraphy. Cooke and Wheatstone installed the first commercial electric telegraph in 1837, along a stretch of the London and North-Western Railway between Euston and Chalk Farm. In 1843, a similar installation was put into service between Paddington Station and Slough, on the Great Western Railway. These systems employed copper conductors and required five wires supported in grooved wooden blocks.

With the development of telegraph and telephone systems, the size and complexity of copper cables and their insulation was growing rapidly. As a result, the technology of manufacturing, laying and repairing copper cables was already mature by the time commercial electricity supply emerged towards the end of the 19th century.

The very first electrical power system was built in 1881 in Godalming, England. Two waterwheels supplied electricity to seven arc lamps and 34 incandescent lamps. Soon, the electrical power industry was flourishing in both the United States and Europe. Local networks – with either direct (DC) or alternating current (AC) – were dedicated to providing electric lighting.

In 1891, Westinghouse installed their first 100 horsepower (75 kW) synchronous electric motor in Telluride, Colorado. In the same year, the very first long distance (175 km) high-voltage (15 kV) three-phase transmission line was built between a hydro-electric power station in Lauffen am Neckar and the Electric Engineering Exhibition in Frankfurt am Main, Germany. It was used to supply electric lighting for the exhibition rooms and to drive a pump that powered an artificial waterfall – the event's showpiece. When the exhibition closed, the power station continued in operation to provide electricity for the nearby city of Heilbronn, which thus became the first place to be equipped with a power supply using three-phase AC.

A similar power line was built in 1895 from the generation station at Niagara Falls to the city of Buffalo, where it supplied an AC power distribution system. This marked the end of the "War of the Currents" between AC and DC. AC has been the standard for power transmission and distribution systems ever since.

At the beginning of the 20th century, electrical power in Europe and the US experienced rapid expansion and grew into the system we know today, where copper plays a major role.

Power is supplied to the grid by:

- Thermal power stations (fired by coal, natural gas, oil or biomass)
- Nuclear power stations
- Renewable energy installations (driven by wind, solar, hydro or tidal energy)

The grid itself comprises:

- AC transmission grid at high voltage (> 70 kV)
- AC distribution grid at medium (> 1 kV and <70kV) or low voltage (< 1 kV).

This grid supplies the electrical power to railways and to industrial, commercial and residential consumers. The power is used in a wide variety of applications such as electrical appliances, lighting, electronic equipment, motors, space heating, process heating and electrolysis.

Copper use today

Approximately 70% of all the copper produced today is used in electrical applications, from electric and electronic equipment, cables, building wiring, busbars and catenary wires, to electric motors and transformers.

This figure has been rising steadily over the past century and is expected to increase further in the coming years. The copper industry has calculated that the energy transition as currently projected by the EU would require an additional 22.5 million tonnes of copper in the lead-up to 2050.

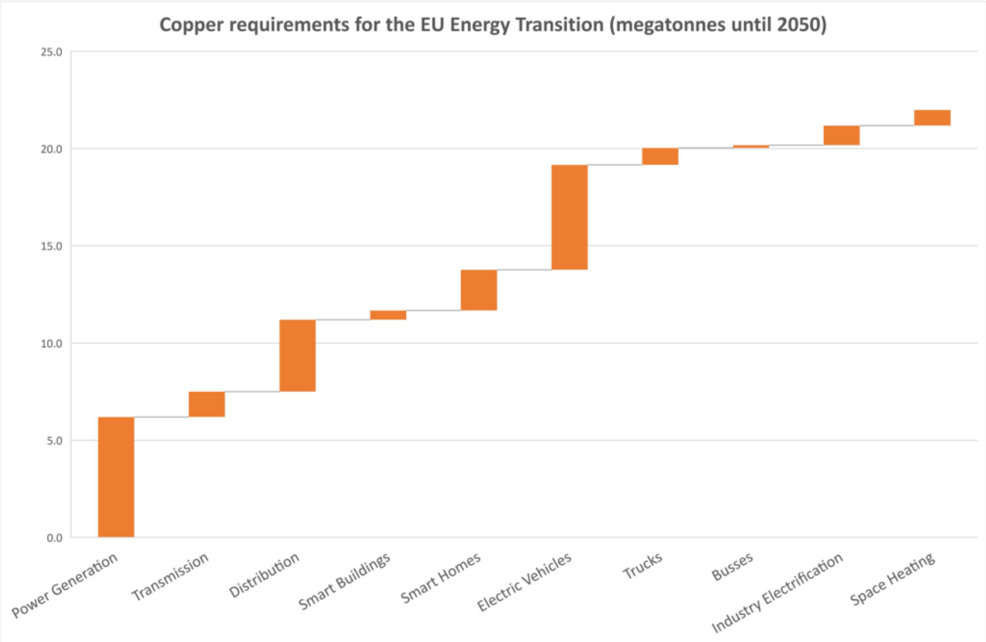

Figure 4 – The 22.5 million tons of copper needed for the EU energy transition split down per sector.

Apart from their high electrical conductivity, copper and copper alloys are also prized for their heat conductivity and for their mechanical, anti-corrosive and aesthetic qualities. This leads to applications in heat exchangers, architectural features (such as roofing, doors and guttering), shipbuilding, aquaculture and jewelry.

HIGH-CONDUCTIVITY COPPER

High-conductivity copper has a high degree of purity for maximum electrical conductivity. It is the first choice for manufacturing bulk conductors such as cables, busbars, transformer and motor windings, and motor rotors.

The following are a few common categories of high-conductivity copper that are available on the market:

- Electrolytic tough pitch copper (Cu-ETP)
- Fire-refined high conductivity copper (Cu-FRHC)
- High purity electrolytic tough pitch copper (Cu-ETP1)
- Oxygen-free copper (Cu-OF)

COPPER MICRO-ALLOYS

For some applications, such as signal cables in harnesses, connector strips, commutators and catenary wires, the mechanical properties of high-conductivity copper need to be enhanced. This is achieved by micro-alloying: small quantities of particular alloying elements are added to improve certain mechanical characteristics. The ease with which copper can form alloys with other elements results in a wide range of materials tuned to specific electrical applications.

A commonly used micro-alloy is copper-silver. Adding 0.03 to 0.1% of silver to pure copper raises its softening temperature without compromising the electrical conductivity. Silver also improves the mechanical properties, especially the creep resistance. The material is used in applications that require a resistance to softening at high temperature (e.g. commutators) or in which the material has to cope with continuous high stresses at elevated temperatures (e.g. large motors or alternators). [10, p. 17] Signal cables for automotive is another application of the copper-silver micro-alloy.

The addition of 0.1 to 0.7% of magnesium to copper results in a material with improved strength, solderability and resistance to corrosion, without giving in too much on the electrical conductivity (CuMg0.2 has 62%-82% IACS). Applications for copper-magnesium can be found in telecommunication cables and catenary wires (e.g. for high speeds trains), as well as in cables, switches and relays for automotive. [6]

Copper-tin alloys (0.04-0.55% tin) have increased strength, ductility and softening resistance at the expense of conductivity. The tin content is determined by a tradeoff between conductivity and strength. Applications include automotive conductor signal cables and grooved contact wires for railway, as well as connector pins, switches, relays, terminals and busbars. [6]

THE COPPER PRODUCTION PROCESS

[7]

The way from copper ore to a copper end product goes through the following processes:

I) Mining

The copper ore is taken out of the earth, crushed and ground into powder.

II a) The path of pyro-metallurgical processing

i. **Pre-processing**. The copper powder is enriched using a flotation process. Unwanted material sinks to the bottom and is removed. The end result of this process, usually executed by the mining company, is called copper concentrate.

ii. **Pyro-metallurgical processing.** The copper concentrate is mixed with low grade copper scrap and subjected to a thermo-chemical process of roasting, smelting and air-blowing. The resulting material is known as blister copper.

iii. **Electrolysis.** Blister copper is cast into anode plates and subjected to electrolysis. This is the final step of purification. The resulting cathode plates contain copper of 99.99% purity.

II b) The path of hydro-metallurgical processing ("leaching"). Leaching offers an alternative process to the former three steps. It starts directly from copper ore, without the need for any pre-processing. It has the major advantage that it can be used on ore with no more than 0.1% of copper content. First, the ore is treated with dilute sulphuric acid which is allowed to trickle slowly down through the ore over a period of months, dissolving the copper to create a weak solution of copper sulphate. The copper is then recovered through electrolysis.

III) **Manufacturing copper semi end products.** The copper cathode plates from the electrolysis process are melted and alloyed depending on the end-use application. The resulting material is drawn into wires or extended tubes, or rolled into strips which are sold for use in the manufacture of a wide variety of end-use appliances.

Copper can usually be recycled without technical complication, saving energy and copper ore. When starting from copper scrap, three paths can be followed, depending on the purity of the scrap and the type of installation in which it is processed.

1. Low grade scrap can be subjected to a pyro-metallurgical process, followed by electrolysis. The copper cathode plates are then used to manufacture the copper semi end products (wires, tubes or strip).

2. Medium grade scrap can be subjected to a pyro-metallurgical process and then directly melted to manufacture copper wires, tubes or strip, without the intermediate purification step of electrolysis to produce ETP copper.

3. High grade scrap can be melted directly, together with copper cathode plates coming from electrolysis, to manufacture copper wires, tubes or strip.

More on copper recycling in Chapter 8 – Copper in the Circular Economy.

4. PHYSICAL PROPERTIES

Following improvements in refinery techniques, high-conductivity copper (ETP1) reaches or exceeds 101% IACS.

Thermal conductivity is an important secondary parameter of electrical conductors. Good thermal conductivity contributes to effective heat dissipation, limiting thermal stress on the insulation.

The conductor material's mechanical properties are important in ensuring that deformations do not occur during processing and use, compromising electrical conductivity and creating hot spots.

CONDUCTIVITY

THE BASICS OF ELECTRICAL CONDUCTIVITY

The creation of electrically conductive metals goes back to the origins of the universe. After the Big Bang, free electrons started to spread out through the empty space. Some of these electrons were picked up by hydrogen atoms, and some of the electrically-loaded hydrogen atoms ended up in massive stars where, in large quantities, they were compressed together leading to new and larger atoms emerging: the electrically conductive metals. These supergiant stars later exploded to become supernovae, catapulting the newly created metals into space. 4.5 billion years ago, the earth inherited some of these conductive metals, such as copper, gold and silver. [8]

The electrons originating from electrically-loaded hydrogen atoms became what we know as valence electrons, located in the outer shell of the atoms. They have a higher degree of freedom than other electrons allowing them to travel through the metal lattice. Under the influence of an electric field, they move towards the valence electrons in neighbouring atoms which, in turn, move in a similar way. The valence electrons in the metal move much like snooker balls colliding with each other to pass along their electric charge.

The energy transfer is strongest when a valence electron collides with just one single other valence electron. If a single electron strikes multiple other electrons, each of those will carry only a fraction of the energy, weakening the chain reaction. Silver, gold and copper atoms have a single valence electron that moves with little resistance. Semi-conductor metals have a higher number of valence electrons – usually four or more. Although they can conduct electricity, they are less efficient at achieving this. [8] [9]

THE CONDUCTIVITY STANDARD

[10]

In 1913, the International Electrotechnical Commission (IEC) adopted the German standard for the electrical conductivity of copper. This International Annealed Copper Standard (IACS) has become the main reference for electrical conductivity, and the conductivity of copper and aluminium alloys are usually expressed in terms of IACS.

The IACS standard describes the following properties at 20°C:

Properties of 100% IACS Copper at 20°C	
Volume conductivity, σ_v	58 MS/m
Density, *d*	8,890 kg/m^3
Temperature coefficient of resistance, α	0.00393 /K

Table 1

The following values can be derived from this:

Derived properties of 100% IACS Copper at 20°C	
Volume resistivity, ρ_v (= 1/σ_v)	1.7241 mΩcm
Mass conductivity, σ_m (= σ_v /*d*)	6,524 Sm^2/kg
Mass resistivity, ρ_m (= 1/σ_m)	153.28 µΩkg/m^2

Table 2

Since 1913, copper processing technologies have improved substantially and, as a result, routine production of high-conductivity copper can reach or exceed 101% IACS.

Pure silver has a conductivity of 106% IACS, while the electrical conductivity of pure aluminium is 61% IACS.

The European conductivity standard for copper cathodes and copper rod

European Standards EN 1977 and EN 1978 stipulate minimum conductivity values for copper cathodes and copper rod. ETP1 copper must have a minimum conductivity of 101% IACS, whereas ETP copper and fire-refined high-conductivity copper (FRHC) must have a minimum of 100% IACS.

The international conductivity standard for conductors or insulated cables

International Standard IEC 60228 stipulates a maximum electrical resistance (or minimum conductivity) for the conductors of insulated cables. For a plain copper conductor with a cross-sectional area of 1 mm^2, the standard stipulates a maximum resistivity of 18.1 Ohm/km. This corresponds to a conductivity of approximately 97% IACS.

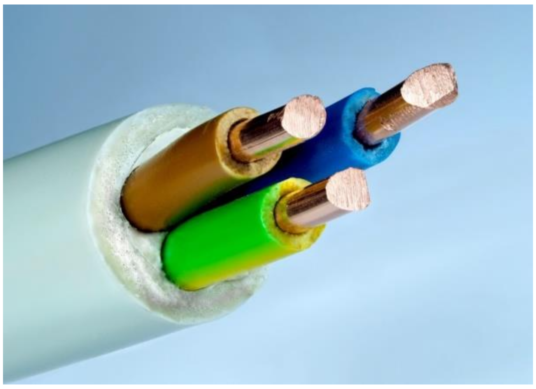

Figure 5 – Electrical cable 3 x 2.5 mm with solid copper conductors (photo: Petar Milošević, licensed under Creative Commons CC-BY-SA-3.0).

Influences on electrical conductivity

Oxygen content and impurities

Impurities, for instance from the combustion gas in the burner, can get dissolved within the copper, meaning that they become part of the crystalline structure. This reduces the electrical conductivity. To avoid that this would happen, the oxygen content is kept at a certain level. In the presence of oxygen, impurities will be taken in by Cu_20 or form other oxides, which are insoluble and remain in the material as impurities on an atomic level (little islands of tough material), having little effect on conductivity. However, an oxygen excess reduces the conductivity again. Keeping the right oxygen balance is therefore one of the major requirements to reach ETP or ETP1 conductivity standards.

Advanced refining techniques and the use of electric furnaces instead of gas burners can reduce impurities to such a low level that the presence of oxygen becomes superfluous. The result is high-conductivity oxygen-free copper (Cu-OF with oxygen content below 10 ppm), which is used in particular niche markets.

Symbol	Number (unwrought / wrought)	Mass resistivity (Ωg/m2)	Min. conductivity (% IACS)
Unalloyed coppers			
Cu-ETP1 and Cu-OFE	CR003A / CW003A	0.15176	101.0
Cu-ETP and Cu-OF	CR004A / CW004A/ CR008A / CW008A	0.15328	100.0
Cu-FRHC	CR005A / CW005A	0.15328	100.0
Phosphorous-containing copper			
Cu-PHC	CR020A / CW 020A	0.15328	100.0
Silver-bearing ETP or OF coppers			
CuAg0.04	CR011A / CW011A / CR017A / CW017A	0.15328	100.0
CuAg0.07	CR012A / CW012A / CR018A / CW018A	0.15328	100.0
CuAg0.10	CR013A / CW013A / CR019A / CW019A	0.15328	100.0
Phosphorous deoxidised silver-bearing copper			
CuAg0.04P	CR014A / CW014A	0.15596	98.3
CuAg0.07P	CR015A / CW015A	0.15596	98.3
CuAg0.10P	CR016A / CW016A	0.15596	98.3

Table 3 – Conductivity properties of principal types of high-conductivity copper ([10] and DIN EN 1977).

Copper alloys

The electrical and mechanical properties of high-conductivity copper (ETP1) are excellent for most electrical applications. Specific niche applications, however, require higher tensile strength, higher thermal stability, lower creep, better wear resistance or easier machinability. A wide variety of copper alloys have been developed, with single or multiple additives, to achieve the properties required.

All the additives, with the exception of silver, decrease electrical conductivity – how much depends on the extent to which the addition is soluble in copper and the extent to which the copper crystal lattice structure is distorted by the solute. Not only does the type of alloying element influence conductivity, it is also affected by the alloying process.

COPPER-CLAD ALUMINIUM (CCA)

[11]

Copper-clad aluminium (CCA) conductors consist of an aluminium core of generally 60 to 80% of the diameter, surrounded by copper cladding. Aluminium reduces the weight and cost compared to copper cable of the same cross-section.

The conductivity of a CCA cable is difficult to define because it depends on the frequency. Because of the skin effect, a high frequency current mainly flows at the surface of the cable. In a CCA cable, such current flows entirely in the copper layer, making CCA cables suitable for pure high-frequency data transmission application, such as coaxial cables.

Figure 6 – Copper-clad aluminium (CCA) cables are unsuited for power transmission (photo: Thomas Horton, Fushi Copperweld, licensed under Creative Commons CC-BY-SA-3.0)

CCA cables are, however, unsuited for any kind of power supply. They do not comply with any recognised international (IEC), European (EN) or American (ANSI/TIA-568-C.2) standards for power cables. If used for power transmission, CCA cables may:

- Fail basic transmission performance tests during commissioning;
- Exhibit poor flexibility, leading to failed connections during installation or operation;
- Produce higher than expected temperatures in the cable;
- Suffer from aluminium oxidation at the points of connection, which can reduce their lifetime.

The use of CCA for ***Power over Ethernet*** applications (PoE and PoE*plus*) is potentially dangerous [11]. These Category 5 (Category 5e in North America) cables are used for both data transmission and to charge electronic devices. According to the latest standard IEEE 802.3at, they should be capable of carrying currents of up to 300 mA per conductor. CCA cables are not suited to carry such current, and certainly not in balanced PoE cables where the thermal impact is already a concern. The temperature increase in CCA cables will be twice as much as in solid copper conductors. They will overheat quickly, compromising the physical integrity of the cable and resulting in a fire risk.

In case of doubt it is better to avoid CCA altogether and opt for a pure copper solution instead.

CCA cables are also problematic for material recycling at end-of-life (see Chapter 8).

DENSITY

Copper is approximately three times heavier than aluminium for the same volume. Their respective **densities** are:

- Copper: 8,890 kg/m^3 (100% IACS copper)
- Aluminium: 2,700 kg/m^3 (pure Al, 61% IACS)

Conductivity and resistivity are usually measured per volume. Aluminium has a volume conductivity that is 61% the conductivity of copper (IACS). Or, inversely, the **volume resistivity** of copper is 61% that of aluminium:

- Copper: 17.2 nΩm
- Aluminium: 28.2 nΩm

Due to aluminium's lower density, however, its **mass resistivity** is lower than that of copper:

- Copper: 153 µΩkg/m^2
- Aluminium: 76.14 µΩkg/m^2

In summary, copper is a better electrical conductor than aluminium for the same cable conductor volume, but aluminium is a better electrical conductor than copper for the same cable conductor weight.

Therefore, as a general rule, copper is used as an electrical conductor for applications where minimising volume is important (e.g. wiring in electrical equipment), whereas aluminium is used where minimizing mass is important (e.g. overhead power transmission cables), although there are also exceptions to this rule (e.g. critical automotive wiring). However, factors such as connection reliability, ease of processing and handling, corrosion resistance, and thermal conductivity also play a role in the choice of electrical conductor. See Chapter 5, *Design and Operational Properties*.

THERMAL PROPERTIES

Thermal conductivity is an important secondary parameter in electrical conductors. Indeed, temperature rise and voltage drop are the phenomena limiting a conductor's current-carrying capacity. Of the two, temperature rise is usually the decisive factor. Any safe temperature rise in cable conductors is limited by the ability of the insulation to withstand thermal stress. The principal way to avoid a sharp temperature rise is to limit energy losses in the conductor. Secondly, good thermal conductivity contributes to effective heat dissipation, which can also mitigate the temperature rise. Sufficient heat dissipation is also important to limit the temperature rise and postpone any loss of functionality during exposure to fire.

The difference in the thermal conductivity between pure copper and pure aluminium is of a similar order of magnitude as their difference in electrical conductivity. The thermal conductivity of aluminium is 57% of the thermal conductivity of copper [12]:

- Copper: 386 W/m°C
- Aluminium: 220 W/m°C

Thermal expansion is another important parameter in the design of electrical appliances and cables. Each material has its own *linear thermal expansion coefficient*, defined as the relative change in cable length for each degree of temperature change. The linear thermal expansion coefficient of aluminium exceeds that of copper by 35%:

- Copper: 17 x 10^{-6} /°C
- Aluminium: 23 x 10^{-6} /°C

Differences in thermal expansion and contraction between two elements in an electrical connection can lead to excessive mechanical stress that compromises the durability of the connection. See Chapter 5 – *Design and Operational Properties*.

MECHANICAL PROPERTIES

The mechanical properties of a conductor are important in ensuring that deformation does not occur during processing and use.

Typical mechanical properties of ETP1, OF1, ETP, OF and Cu-PHC copper			
0.2% Proof strength (N/mm2)	**Tensile strenght (N/mm2)**	**Elongation (%)**	**Hardness (HV)**
75-370	200-400	50 - 5	45-130

Table 4 – Mechanical properties of ETP1, OF1, ETP, OF and Cu-PHC copper [10].

However, these properties can vary depending on the product form and the mechanical and thermal history of the material. For instance, cold-working has the effect of raising tensile strength, proof strength and hardness, but reduces elongation.

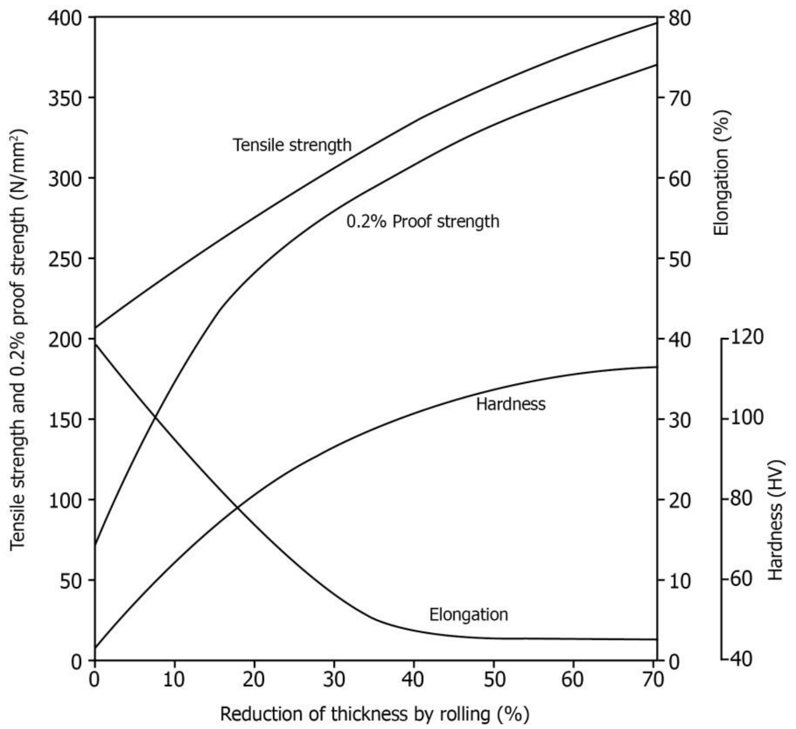

Figure 7: Effect of cold-rolling on the mechanical properties of high-conductivity copper strips.

TENSILE STRENGTH

High-conductivity copper before treatment has a tensile strength of 150-170 N/mm^2. Hot working increases the tensile strength to 200-220 N/mm^2. Cold working further increases tensile strength, but the final value depends on the shape and cross-section.

YIELD STRESS RESISTANCE

Yield stress is the stress required to produce a particular amount of permanent deformation. It is defined as the stress at which a certain percentage of elongation (usually 0.2%) occurs. As with tensile strength, yield stress resistance increases with the amount of cold work put into the material. A high yield stress resistance is required for drawing cables through conduits and trunking structures without deformation.

HARDNESS

Hardness is measured at the outer skin of the material. Annealing reduces hardness. While a degree of hardness can be good to avoid scratches and nicks during the process of creating conductor connections, reasonable elasticity (low hardness) is required for ease of cable handling.

CREEP RESISTANCE

Creep is a time and temperature dependent property. It describes the non-recoverable deformation of material under prolonged stress. The ability to resist creep is of prime importance to design engineers.

COPPER VERSUS ALUMINIUM

The mechanical properties of annealed copper and aluminium differ significantly. Key values are listed in the following table.

Characteristic for equal ampacity	Copper	Aluminium
Weight for the same conductivity (comparative)	100	54
Cross-section for the same conductivity (comparative)	100	156
Creep resistance: temperature for reaching 0.022% creep under 1000 h of 26 N/mm2 stress [13]	150°C	20°C
Tensile strength for same conductivity (comparative)	100	72
Annealed		
Tensile strength – N/mm^2	200	50–60
Proof strength: 0.2% proof stress for annealed material – N/mm^2	75–120	20–30
Hardness – Vickers Pyramid Number (HV)	45–60	
Half Hard		
Tensile strength – N/mm^2	250	85–100
Proof strength: 0.2% proof stress for annealed material – N/mm^2	120–180	60–65
Hardness – Vickers Pyramid Number (HV)	70–95	
Hard		
Tensile strength – N/mm^2	250–400	
Proof strength: 0.2% proof stress for annealed material – N/mm^2	180–370	
Hardness – Vickers Pyramid Number (HV)	90–130	70

Table 5 —Physical properties of copper and aluminium [14], [10, p.9].

Oxidation and corrosion

Copper forms two different oxides, **both of which are electrically conductive**. When a clean copper surface is exposed to the atmosphere, the red-coloured cuprous oxide (Cu_2O) is formed. At room temperature this will slowly darken to a thicker black layer of cupric oxide (CuO). This black oxide film is tightly adherent, slowing down its further growth. Exposure of copper surfaces to rainwater, usually containing carbon dioxide and oxides of sulphur, will result in the formation of a green patina which is adherent, protective, and electrically conductive.

Physical contact between two dissimilar metals such as copper and aluminium combined with the presence of moisture results in galvanic corrosion. Without proper termination and connection equipment, galvanic corrosion will ultimately make an aluminium to copper connection fail.

5. DESIGN AND OPERATIONAL PROPERTIES

The international standards for cable sizing do not take energy efficiency into account, only safety and voltage drop. The economically optimal conductor cross-section is therefore often significantly larger than the standard.

When designing and installing an electricity network, extra care is required at connections and joints which, if designed or installed inadequately, can become sources of higher electrical resistivity, ultimately causing physical damage or even fire.

ENERGY EFFICIENCY

Optimizing the energy efficiency of electrical connections reduces the financial losses and CO_2 emissions associated with energy losses. In many cases it will also improve reliability and durability, since heat produced by energy losses accelerates equipment ageing.

The energy efficiency of an electrical conductor can be improved in two ways:

1) **Using a conductor material with higher electrical conductivity**

2) **Enlarging conductor cross-section**

The energy loss is inversely proportional to the cross-section, and can be calculated at a point in time using the formula:

$$P_{loss} = I^2 \times \rho \times \text{length} / A$$

where:

I is the current in the conductor (depending on the load)

ρ is the specific electrical resistance of the conductor

A is the cross-sectional area of the conductor

"length" is the length of the cable

This means that for energy efficiency reasons alone, the conductor could be infinitely large. However, conductor material also has a financial and environmental cost, in addition to practical constraints. These need to be balanced with energy efficiency to determine the optimal cross-section from an economic or environmental point of view (see Chapter 6).

The **international technical standards for cable sizing** (IEC 60364-4-43 and IEC 60909) **do not take energy efficiency into account**, only safety and certain power quality issues. According to these standards, the minimum cross-section of a cable is defined by the most stringent of three restrictions:

- The thermal impact of the maximum rated current
- The voltage drop created by the maximum rated current
- The electro-dynamic impact of the strongest short-circuit current

In most cases, the minimum cross-section derived from these standards will still be much less than the economic and environmental optima, for which energy loss is the decisive factor.

According to the applicable standard, a cable with a rated current of 100 A and a nominal voltage of 230 V, for example, should have a minimum cross-section of 25 mm^2 to avoid excessive heat production. The economic optimum depends on market and operational conditions. Assuming electricity costing €100/MWh, cable costing €0.30/(mm^2 x m), a 10-year lifetime, and interest at 7.5%, the following calculations can be made:

- At an average loading of 65% for 3,700 hours per year (42% of the time), the economically optimal cable section would be 71.77 mm^2, or **nearly three times the technical standard.**

- At an average loading of only 40% for 1,400 hours per year (16% of the time), the economically optimal cable section would be 44.12 mm^2, or **nearly twice the technical standard**.

VOLUME AND WEIGHT DEPENDENT APPLICATIONS

While copper's high conductivity is deployed to reduce energy losses, it also minimises conductor volume per unit of power. A compact conductor has various advantages: the cable requires less insulation material, it can operate with smaller support structures, and is easier to handle. In applications such as switching boards, compact electrical appliances, or low-current conduit and trunking systems, space is limited and volume reduction is essential.

The following table compares the respective volumes and weights of copper and aluminium three-phase XPLE/SWA PVC conductors with the same current-carrying capacity (ampacity) of 300 A:

Characteristic for equal ampacity (300 A)	Copper	Aluminium
Cross-section mm^2	95	150
Weight (kg/m)	5.51	4.5

Table 6—Cross-section and weight of three-phase XPLE/SWA PVC conductors with an ampacity of 300 A.

EASE OF PROCESSING AND HANDLING

Its high electrical conductivity combined with its low bending radius makes copper an ideal conductor material for low-current applications using space-constrained conduit and trunking systems [15].

Characteristic for equal ampacity (300 A)	Copper	Aluminium
Cross-section mm²	95	150
Minimum bending radius (mm)	302	479
0.2% proof stress (N/mm²) for annealed material	≤ 120	20–30

Table 7 — Minimum bending radius and proof stress of three-phase XPLE/SWA PVC conductors of 300 A [15].

The proof stress of copper cables allows them to be drawn through conduits and trunking structures with minimal risk of necking, stretching or breaking. Due to the low stiffness of copper cable, the risk of bending leading to kinks that are difficult to remove is equally low. A stretched, necked or kinked cable will reduce current-carrying capacity and increase energy loss, which could result in dangerous overheating.

Reliability of connections

[16]

When designing and installing an electricity network, extra care is required at the discontinuities of the conductors, such as connections and joints, which can become sources of higher electrical resistivity resulting in local ***hot spots***. In extreme cases these can cause physical damage and lead to fire. Four issues must be considered: thermal cycling, the formation of surface contaminants, the effect of careless installation practices and galvanic corrosion.

Thermal cycling

[17]

Variation in current will result in temperature variation in the conductor, making it expand or contract. Linear thermal expansion will result in mechanical forces at cable terminations, depending on the coefficient of expansion, Young's Modulus and the conductor's cross-section.

Connections to a copper conductor can withstand temperature cycles caused by load variations without significant degradation, and forces are evenly distributed at the conductor joint. This results in low energy losses, fewer temperature variances, and a durable connection.

Where a contact surface involves dissimilar materials, for example an aluminium conductor connecting to a copper, brass or plated steel terminations, the difference in thermal expansion can result in surface damage and loose contacts over time. This can lead to overheating, arcing and potential fire risk. These issues can be avoided by using a bi-metallic copper/aluminium pin or lug termination, although this solution will be bulkier and more costly.

Galvanic corrosion

Physical contact between two dissimilar metals, such as copper and aluminium, combined with the presence of moisture results in galvanic corrosion. An aluminium to copper connection could ultimately fail through galvanic action in two ways: electrically because contact area is reduced or mechanically through severe corrosion in the aluminium connector. Bi-metal terminations or other special equipment can avoid this type of corrosion.

Effects of careless installation practices

Scratches and nicks may occur in the process of stripping insulation from a conductor prior to termination, which in high voltage cables can lead to peaks in the electrical field affecting the cable insulation. Where a copper conductor is used, the risk of such deformation is limited because of the low relative hardness of the material.

Application in hostile environments

Conductors used in aggressive chemical environments at industrial production sites are subject to accelerated corrosion. The use of copper as a conductor is the only guarantee that corrosion will be limited and will not affect the electrical properties, energy efficiency or mechanical strength of the conductor.

Fire safety cables

[18]

Cables, including fire safety cables, are electrically specified based on how their performance requirements under normal conditions. How cables are required to perform electrically under fire conditions is rarely, if ever, specified. Fire Safety Regulations such as the EU Construction Product Regulation (CPR) only discuss the possible smoke generation by overheated cable insulation, but stay silent about the change in electrical properties of the cable under high temperatures. Nevertheless, this is an essential consideration for cables that must remain functional under fire conditions. The German standard DIN 4102-12 (also available in English translation) briefly mentions the issue in their *Explenatory notes* on the last page.

Cables expected to retain functionality and provide power to essential equipment when exposed to fire (such as water pumps, sprinklers and smoke fans) must be appropriately selected and sized. In addition to specifying appropriate insulation, design engineers must take the increased electrical resistance at elevated temperature into account, since it affects current-carrying capacity, voltage drop, short circuit capacity and the conductor's mechanical strength. Special care should be taken to ensure that a conductor's current-carrying capacity is not unduly compromised in a fire if it is to supply electricity to pump motors or elevators crucial for firefighting, as these can draw high starting currents. Circuit protection and related parameters must also be adapted to fire conditions. In particular the touch voltage level must be designed to function with significant higher loop impedance than normal.

For information on calculating the cross-section of cables that must remain functional during a fire, see *Annex: Calculating the optimal cable cross-section / Minimum conductor cross-section for cables that must remain functional during a fire* [18].

6. PURCHASE COST AND REDUCTION OF TCO

For most applications, the cost of the electrical conductors represents only a small proportion of the total CAPEX cost of the electrical equipment or installation. However, conductors can be responsible for a major share of the TCO because of energy losses and unexpected failures. If appropriate purchase and design decisions are made, durable electrical connections can be created with limited energy losses and better reliability.

Calculation examples show that the additional investment cost for an economically optimal conductor cross-section can be gained back several times over the life time of the cable.

THE PURCHASE COST OF ELECTRICAL CONDUCTORS

During the five year period between 1 January 2013 and 1 January 2018, the price of high grade copper varied from $4,500 (€3,700) to $8,000 (€6,500) per tonne [19], while over the same period, aluminium varied between $1,450 (€1,200) and $2,250 (€1,850) per tonne [20]. By weight, the cost of aluminium is approximately 30% of that of copper.

To achieve the same electrical conductivity as a copper conductor, an aluminium conductor would have to be 65% thicker. Since aluminium is 3.3 times lighter than copper, an aluminium conductor will cost roughly 16% (30% x 1.65 x 0.33) of the equivalent copper conductor.

However, a greater conductor cross-section also means that more insulation material is required. As a result, aluminium cables cost 30 to 60% the price of a copper cable for the same electrical conductivity.

It would be misleading, however, to focus too much on the cable purchase cost, for two reasons.

1) The conductor purchase cost is only a small fraction of the total investment cost (CAPEX) of the electrical device or installation they are a part of.
2) The investment cost is only one part of the total cost of ownership (TCO) of the conductor, which also includes a significant operational cost (OPEX), dominated by the energy consumption. The OPEX also includes maintenance and reliability factors.

SHARE OF THE CONDUCTOR IN THE TOTAL INVESTMENT COST (CAPEX)

For most electrical applications, the cost of the conductor material is only a small fraction of the total investment cost.

The relative weight of the conductor material in a device can be viewed as an initial approximate indicator of conductor cost relative to total purchase cost. The following figures indicate the typical average relative weight of copper conductor material in various devices:

- Refrigerators: 1%
- Washing machines: 2%
- Computers: 4%

- Transformers: 17%
- Microwave ovens: 8%
- Electric rail locomotives: 8%
- Electric motors: 10%

Take for example an 11 kW induction motor of efficiency class IE3. Such a motor typically weighs 15 kg and could cost €500 [21]. If the copper content is 10%, the motor will contain approximately 1.5 kg of copper, which will cost around €10. This represents a little over 2% of the purchase cost of the motor.

INVESTING IN ENERGY EFFICIENCY PAYS OFF (OPEX)

Electrical conductors can be the source of significant energy losses over their (long) service life. Increasing the cross-section of the conductor reduces these energy losses. Specifying a cross-section that surpasses the technical standard can be an investment that pays itself back several times over the life time of the conductor. There are, of course, ultimate limits to the increase in conductor size. The optimum economic cable cross-section will be the point where the sum of the investment cost and the cost of energy losses is at a minimum.

This economic optimum conductor size is not always used in practice. There are several reasons for this:

1) Knowledge gap. The technical standard is often seen as the best option, whereas in fact it only represents the minimum for safety and reliability, and does not take energy efficiency into account.
2) Split budgets. The electrical conductor purchaser is often not responsible for paying the electricity bill, and therefore does not have life cycle cost awareness.
3) Difficulties in calculating the optimal cross-section. The calculation requires the load to be estimated over the life time of the conductor. An approximation, however, can be achieved using typical values for a particular sector or application (see next subchapter).
4) Lack of available investment capital. The conductor cost, however, represents only a small proportion of the cost of the entire electrical device or installation (see previous subchapter).

CALCULATING THE OPTIMAL CROSS-SECTION

The power losses in a cable at a given moment in time can be calculated using the following formula:

$$P_{loss} = I^2 \times (\rho/A) \times \text{length}$$

where:

I is the current in the conductor (depending on the load)

ρ is the specific electrical resistance of the conductor

A is the cross-section of the conductor

“Length” is the length of the cable

This energy loss figure should be multiplied by the total time of operation over the lifetime of a cable to obtain total lifetime energy losses. It can be seen that the energy losses are inversely proportional to the cross-section of the conductor. The investment cost of the cable, however, increases roughly in line with its cross-section. The economic cable cross-section will be the point where the sum C_{Total} of the investment cost $C_{Investment\ [S]}$ and the cost of the energy losses $C_{Losses\ [1/S]}$ goes through a minimum.

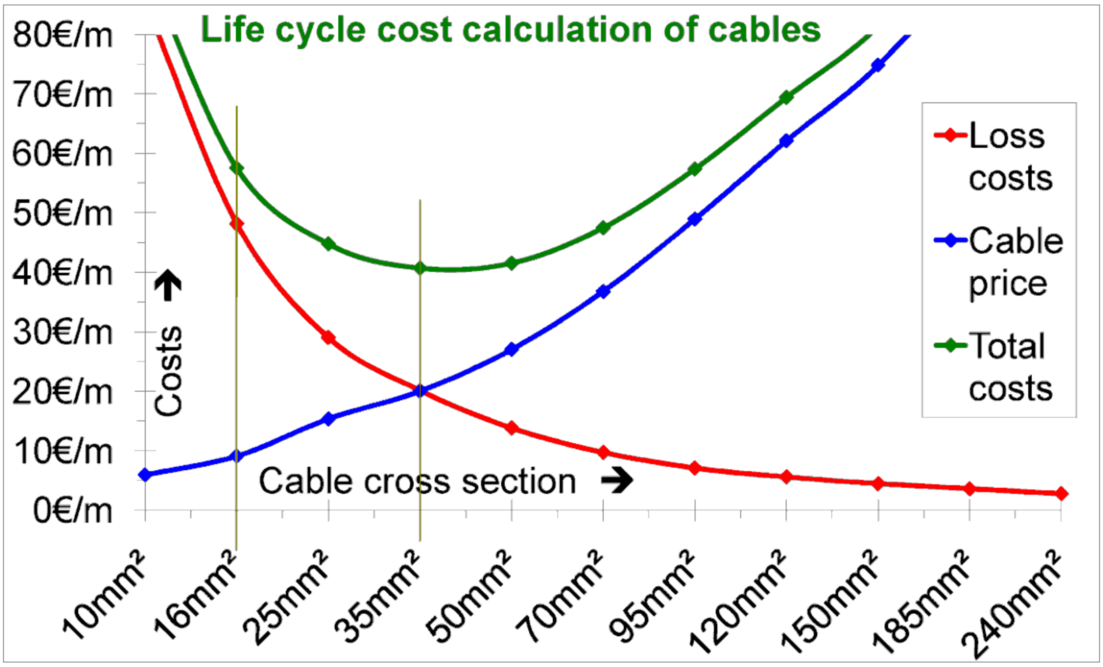

Figure 8 – Determining the cable cross-section with minimum life cycle cost.

Even though the basic principle is simple, calculating the cable section S leading to the lowest life cycle cost $C_{Total} = C_{Investment\ [S]} + C_{Losses\ [1/S]}$ introduces some complexities. In addition to the rated current and cable price, other case-specific influencing factors apply:

- Cable economic life time
- Interest rate over cable life time
- Average electricity tariff over cable life time
- Time that the cable will be loaded over its life time
- Average relative loading when the cable is loaded

We can aggregate all the listed factors into one **operational and financial value F**.

$$F = (P_{loading})^2 \times t_{hours} \times T_{ariff}[€/kWh] \times N_{(i,\ n)}$$

The following table gives average values for F for a number of sectors.

Industry	Interest	N (year)	Energy price (euro/MWh)	Loading	T (hours)	F (euro/W)
Iron	7.5%	10	100	65%	3700	**7.62**
Non-ferrous	7.5%	10	100	35-45%	2730	**5.62**
Paper	7.5%	10	100	65%	3700	**7.62**
Chemical	7.5%	10	100	40%	1400	**2.88**
Datahotel	7.5%	5	100	25-75%	2735	**3.32**
Office	7.5%	10	100	20-40%	1182	**2.43**

Table 8 – The F value for a number of major industrial and commercial sectors.

In general industrial conditions, F will vary between €0.50 and €20/W. The average value of F across all European industry sectors is €4.24/W. For a long-term investment in a cable that will be constantly loaded close to its rated power, F can be greater than €50/W.

The optimal cross-section A can then be calculated using:

$$A^2 = I_r^2 \times \rho \times F / C_c$$

where:

I_r is the rated current of the connection

ρ is the specific resistance of the conductor material

F is a financial and operational value varying per sector

C_c is the cable price per meter and per mm^2 cross-section.

If the specific resistance of high conductivity copper at a typical operating temperature of 105°C is 0.02059 mΩ*mm (0.01724 µΩ*cm for 100% IACS at 20 °C) and $(0.02059)^{1/2} = 0.1435$, the optimal cross-section in mm^2 can be calculated using the following formula:

$$\mathbf{A = I_r \times 0.1435 \times (F/C_c)^{1/2}}$$

See Annex for a more detailed discussion of this formula.

To calculate **the financial gain associated with choosing the economically optimal cross-section**, the cost of the losses has to be estimated for both the standard case and the optimized case. This can be done with the following formula:

$$\mathbf{C_L = 1/A \times I_r^2 \times 0.02059 \times F}$$

where:

C_L are the capitalized energy losses in €/m over a period of 10 years

A is the cable cross-section expressed in mm^2

I_r is the rated current in Ampère

F is the operational and financial value in €/Watt

See Annex for a more detailed discussion of this formula.

To estimate the additional investment cost of the optimized cable, the cost per metre of cable (3 phases + neutral) can be estimated at €0.30/(mm^2 x m) at the current copper price.

Cable cross-section calculation example

Assume a cable in the steel industry will carry a rated current of 200 A. The F factor for the iron sector is €7.62/W. This assumes an average loading of 65%, an average operating time of 3,700 hours per year, an interest rate of 7.5% and an economic lifetime of 10 years. If the cost per metre of cable is estimated to be €0.30/(mm^2 x m), the most economical conductor cross-section for this cable will be:

$$A = 200 \times 0.1435 \times (7.62/0.30)^{1/2} = 144.64\ mm^2$$

150 mm^2 is the nearest standard cross-section available. According to the technical standard, the minimum conductor cross-section for this cable would be only 53 mm^2, with 70 mm^2 the nearest standard cross-section available.

The price difference in investment cost between a 70mm^2 and a 150 mm^2 cable can be estimated at 24 €/m.

The 10-year-losses for the 70 mm^2 cable in €/m will be $(200)^2$ x 0.02059 x 7.62 / 70 = 89.65 €/m

The 10-year losses of the 150 mm^2 cable in €/m will be $(200)^2$ x 0.02059 x 7.62 / 150 = 41.84 €/m

This means that the reduction in energy losses will save 47.81 € per meter of cable in 10 year time, or about 200% of the additional investment cost.

The investment will be gained back in 5 years and after 10 years there will be an accumulated financial gain of 23.81 € per meter of cable.

If we do the same calculation for a cable that has a one-size-up from the standard cross section, or 95 mm^2, we find that the investment is gained back already in 3 years, but the financial gain after 10 years is slightly less with 16.09 € per meter of cable.

A selection of optimal cable cross-sections

The following table provides a selection of optimal cross-sections per rated current I_r for offices as well as for the iron and paper sectors, calculated with a cable price of €0.30/(mm^2 x m). It also shows the comparison with the standard cross-section. Note that the economically optimal cross-sections are between 2.5 and 12.5 times larger than the standard cross-sections.

It is clear that practical considerations also come into play. Often there is limited space for electrical installations in homes, buildings, electricity networks or substations, restricting the extent of feasible upsizing.

However, considering the wide scope for greater optimisation demonstrated above, we can safely say that 'one-size-up' from the standard is a no-regrets policy in most cases, irrespective of the conductor material used.

	Economic cross-section (mm2)		Standard cross-section (mm2)
I_{rated}	F = 2.43 (office)	F = 7.62 (iron, paper)	
20	10	16	1.5
30	16	25	2.5
40	35	35	4
50	35	50	4
60	35	50	6
75	35	70	10
100	50	95	25
150	70	120	35
200	95	150	50
250	120	185	70
300	150	240	95

Table 9

MAINTENANCE AND RELIABILITY FACTORS (OPEX)

Degradation and failures of electrical connections can have an impact on the life cycle cost of the installation in a number of ways:

- Degradation can increase electrical resistance and lead to additional energy losses;
- Degradation can increase maintenance costs, in an effort to reduce the risk of (unexpected) failures;
- A failure can reduce conductor service life;
- An unexpected failure can lead to a power outage with high secondary costs, such as lost production, idle personnel during outage, material waste, process restart costs and equipment damage.

Conductor failure is connection or insulation malfunction resulting from hot spots inside the conductor. Such hot spots can have many root causes, such as mechanical deformation, corrosion, galvanic corrosion, thermal cycling and surface contamination (see Chapter 5 – Design and operational properties). As with energy losses, the costs related to degradation and failure can be avoided by specifying sufficiently durable conductors and connections at the design stage. Such an investment can pay itself back several times over the life time of the conductor.

Since energy losses result in temperature rise and a higher risk of hot spots, poor energy efficiency compromises the durability and reliability of the connection. This, in turn, leads to higher costs for maintenance actions aimed at detecting and avoiding degradation and failure.

7. Mitigation of carbon footprint

Opting for a larger conductor cross-section to reduce the life-cycle cost of an application comes with the additional advantage of mitigating the carbon footprint. The carbon emission savings, associated with the energy savings, compensate many times over for the emissions inherent in the production of the extra conductor material. The environmental pay-back factor for additional copper used to improve the energy efficiency of electrical applications ranges roughly between 8 and 1,000.

Calculating the environmental optimum

The environmental impact of an electrical conductor can be assessed through a life cycle analysis (LCA), which is standardised by ISO. The five major impact categories taken into account are:

- Global warming potential
- Acidification potential
- Ozone depletion potential
- Ground level ozone creation (smog)
- Eutrophication potential

Other impact categories also play a role, such as:

- Toxicity (see Chapter 9 – *Environmental and social concerns*)
- Fossil fuel depletion (which largely runs parallel with the global warming potential)
- Mineral extraction (see Chapter 8 – *Copper in the circular economy*)
- Waste disposal (see Chapters 8 and 9)

The disadvantage of a full LCA is that it can often become highly complex, and for some impact categories, such as toxicity, mineral extraction or waste disposal, no scientifically validated assessment methodology is yet available.

For most electrical conductors in use, energy losses have the greatest environmental impact. For electricity production, the five major impact categories together with fossil fuel depletion largely run parallel, since they are mainly related to the environmental footprint of fossil fuel power stations. Consequently, if global warming potential is minimised, the other relavant impact categories will also be close to their minimum. A useful alternative method is therefore to calculate carbon footprint, also known as carbon profile, which is an LCA limited to global warming potential (including carbon dioxide and methane emissions, among other factors). This limitation makes it easier to apply the calculation to integrated systems.

The three remaining impact categories (toxicity, minerals extraction and waste disposal), for which the LCA methodology is less suitable, are discussed in chapters 8 and 9 of this document.

CARBON FOOTPRINT

As discussed in Chapter 5, the energy losses in an electrical conductor are inversely proportional to the conductor cross-section. In Chapter 6 we demonstrated how to calculate the economically optimal cross-section. In most cases, the optimal cable is at least one size up (and often several sizes) from that prescribed by the technical standards. An additional benefit of the larger cross-section is the reduction in carbon emissions associated with the energy savings, which easily compensates for the carbon emissions inherent in the production of the additional conductor material.

The following are the main figures used to calculate carbon emission savings related to a greater conductor cross-section:

- The average global warming potential of copper cathode is **4.10 kgCO_{2eq} /kg Cu** (2017) [22]. Through energy efficiency improvements in the copper production process and a reduction of the GHG emissions related to the electricity used for electrolysis, this figure is expected to continue its downward trend in coming years.
- The average carbon intensity of EU power generation was 447 g CO_{2eq}/kWh in 2013 [23]. This figure declined 17% between 2009 and 2013. If it continued to decline at the same rate between 2013 and 2017, the figure for 2017 can be estimated at **371 g CO_{2eq}/kWh**. In any case, this figure is expected to go down further in the next few years, as electric power production is increasingly decarbonised. Note that the figures differ greatly from country to country. France, for example, has acarbon intensity close to 100 g CO_{2eq}/kWh while Poland and Latvia still have figures close to 1,000 g CO_{2eq}/kWh [23].

EXAMPLES OF CARBON FOOTPRINT SAVINGS THROUGH ADDITIONAL CONDUCTOR MATERIAL

15 KW INDUCTION MOTOR [23, 24, 25]

A 15 kW low-voltage induction motor is frequently used to pump water or compressed air, and in ventilation systems. Upgrading this motor from 89.4% to 91.8% efficiency involves 2 kg of additional copper conductor material (rising from 8.3 kg to 10.3 kg). Assuming that the motor has a lifetime of 20 years and an average loading of 50% over 6,000 hours per year, the efficiency upgrade reduces carbon emissions by 8,013 kg of CO_{2e} over the lifetime of the motor, using an average EU electricity mix of 371 g CO_{2eq}/kWh. The net carbon emission reduction per additional kg of Cu is consequently 4,006.5 kg CO_{2eq} /kg Cu (= (8,013/2) kgCO_{2eq} /kg Cu – 4.1 kgCO_{2eq} /kg Cu).

1.6 MVA TRANSFORMER [23, 26 , 27]

A 1.6 MVA oil-cooled transformer is frequently used to connect industrial plants to the high- or medium-voltage public grid. Upgrading this transformer to higher efficiency, or even to an amorphous iron core transformer, results in an increase in copper material of 220 kg and 720 kg respectively. Assuming the transformer has a lifetime of 30 years and an average loading of 50% over 8,760 hours per year, net emissions are reduced by 531 kg CO_{2e} per kg of copper in the first scenario and by 284 kg of CO_{2e} per kg of copper for the amorphous core transformer, using an EU electricity mix of 371 g CO_{2eq}/kWh.

ELECTRICAL WIRING IN A SMALL OFFICE BUILDING [23, 28]

Electrical wiring in a small office building designed in accordance with data from widely-used cable design software contains a total of 32.5 kg of copper. Upsizing the cables by one standard calibre would increase copper content to 52.2 kg and decrease carbon emissions by 3,137 kg over the lifetime of the cables, still using a EU electricity mix of 371 g CO_{2eq}/kWh. This leads to a net lifetime reduction of 155 kg CO_{2e} per kilogramme of additional copper. These figures come from the 'Modified cable sizing strategies' study by Agidens [27].

Cable cross-sections sized according to the lowest life cycle cost of the system would be even greater and copper usage would increase to 114 kg. Lifetime carbon savings compared to the base case would be 5,804 kg, or 67 kg CO_{2e} per additional kilogramme of copper.

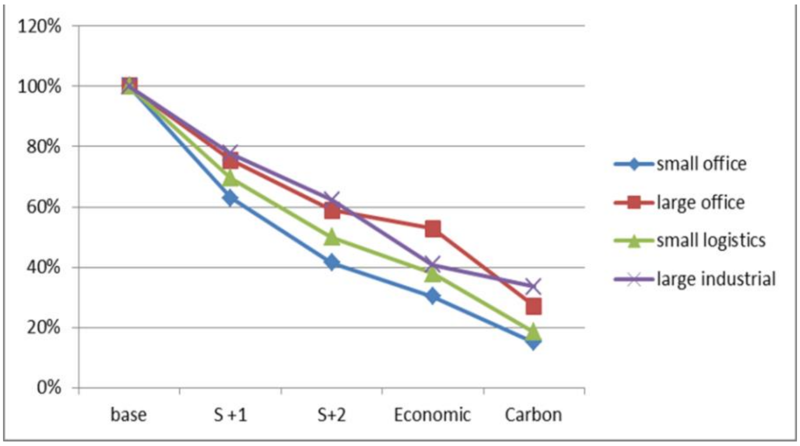

Figure 9 – Comparing the carbon footprint of different cable sizes in various types of buildings. The base case is the international standard. S+1 and S+2 are cables upsized respectively by one and two standard calibres. 'Economic' means designed for the lowest life cycle cost. 'Carbon' means designed for the lowest carbon footprint. [28]

DC RAILWAY OVERHEAD LINES

[23, 29, 30]

The Dutch railway system uses 1.5 kV DC for its traction. Upgrading the cross-section of their overhead lines from 500 mm^2 to 800 mm^2 results in 2,670 kg additional copper per kilometre of track. This upgrade would reduce overhead line energy losses by 488 MWh over the life-time of the system, calculated based on the average daily train schedule of the Dutch railways. The eco-design tool calculates the net carbon emission reduction to be 64 kg of CO_{2e} per additional kilogram of copper over the life-time of the system, assuming an EU electricity mix of 371 g CO_{2eq}/kWh.

MITIGATION OF CARBON FOOTPRINT – CONCLUSION

As the above examples demonstrate, carbon emission savings associated with conductor cross-section upsizing are greater for devices with a high utilization rate, but are also substantial in other circumstances. Carbon emissions reductions per additional kg of copper over the lifetime of the installation are typically:

- 35-65 kg CO_{2e} for traction overhead lines
- 50-200 kg CO_{2e} for office building wiring
- 250-600 kg CO_{2e} for transformers
- 1,500-4,100 kg CO_{2e} for electric motors

The mining and manufacturing of 1 kilogramme of copper emits 4.1 kg of CO_{2e}. Consequently, the environmental pay-back factor for any copper used to improve the energy efficiency of electrical applications ranges roughly from 8 to 1,000, with an average pay-back factor of around 30.

Moreover, those figures relate to first use of copper material after manufacture from ore. Bulk copper conductors can be recycled at the end of life, saving 85% of the energy required for copper production starting from ore.

8. Copper in the Circular Economy

Copper has a high degree of recyclability and is therefore ideal as electrical conductor material in a circular economy.

The energy transition and material use

The technologies currently available to help decarbonise the economy make greater overall mineral demands than conventional energy technologies:

- Renewable energy systems have a lesser power density, a more decentralised character and a more variable output than fossil fuel or nuclear power plants, resulting in greater material use in the systems themselves, as well as in their connection to the grid, and the interconnection between different European climate zones.
- The energy efficiency of electrical systems is enhanced by enlarging the cross-section of conductors and thus increasing the material use.
- The expected mass markets in electrical vehicles and heat pumps will lead to an estimated increase in electric motor sales of 6 million units per year by 2040.

Such a transition will be sustainable only if these minerals can be incorporated into a circular economy that anticipates future mineral scarcity. In a circular economy, end-of-life waste is minimised by creating a path from *grave to cradle* that complements the traditional *cradle to grave* trajectory.

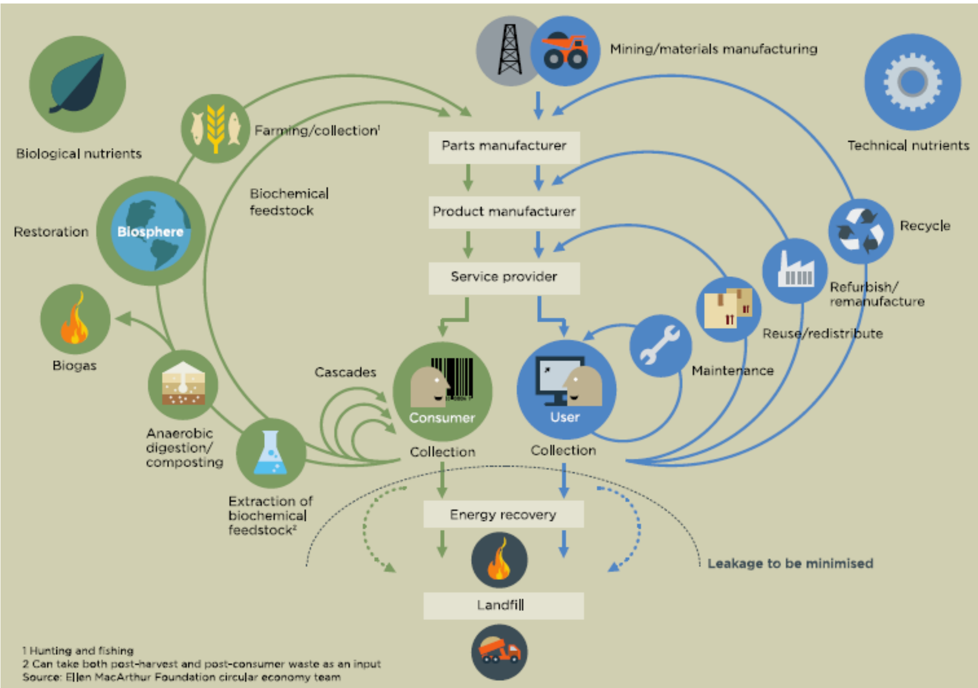

Figure 10 – The circular economy (reproduced with permission; copyright 2013 Ellen MacArthur Foundation) [31]

The circular economy, as defined by the *Ellen MacArthur Foundation*, has a biochemical and a mineral side.

On the mineral side, a crucial aspect is the recovery of scrap at product end-of-life, as well as preparing the product for re-use. The success of the circular economy depends largely on the efficiency with which this can be achieved. Equally important is at which stage of the production process the recycled material is re-used, and how.

- Is there any loss in the applicability of the recycled material compared to the same metal originating from mining?
- How much energy is still required to manufacture the end product?
- What is the maximum share of recycled material that can be used in the production process?

The EU is developing a regulatory framework for the circular economy, starting with the adoption of the Circular Economy Package by the European Commission on 2 December 2015. The package includes legislative proposals on waste, with long-term targets to reduce landfilling and increase recycling and re-use. It also includes an action plan to support the circular economy at each step of the value chain – production, usage, repair, waste management, and re-use as secondary raw material [32]. The regulatory package will lead to robust end-of-life requirements and strengthened materials management systems.

Copper in the circular economy

Copper recycling: the "urban mine"

One of the major advantages of copper is its excellent recyclability. The pure copper used for most electrical conductors becomes high grade scrap at its end of life, which means that it can be recycled without downgrading. Even for copper that is micro-alloyed, alloyed or contains impurities, recycling is still possible and efficient. Unlike with some other metals, the foreign elements can be removed to recover the copper in its pure state, ready to be re-used in any kind of application.

Three paths can be followed for copper recycling, depending on the purity of the scrap and the type of installation in which it is processed (see "The copper production process" on page 15).

1. Low grade scrap can be mixed with copper concentrate to be subjected to a pyro-metallurgical process, followed by electrolysis. The copper cathode plates are then used to manufacture the copper semi end products (wires, tubes or strips).
2. Medium grade scrap can be subjected to a pyro-metallurgical process and then directly melted to manufacture copper wires, tubes or strips, without the intermediate purification step of electrolysis.
3. High grade scrap can be melted directly, together with copper cathode plates coming from electrolysis, to manufacture copper wires, tubes or strips.

Because of its high degree of recyclability, the stock of copper in use in electrical applications is not lost, but can be seen as a copper reserve of lower entropy than that in the copper ore in the earth's crust. Since 1900, an estimated two-thirds of the 550 million tonnes of copper produced is still in productive use [33]. This enormous stock of copper in its diverse range of end uses is often referred to as society's "urban mine". It is equivalent to around 20 to 25 years of copper mining output.

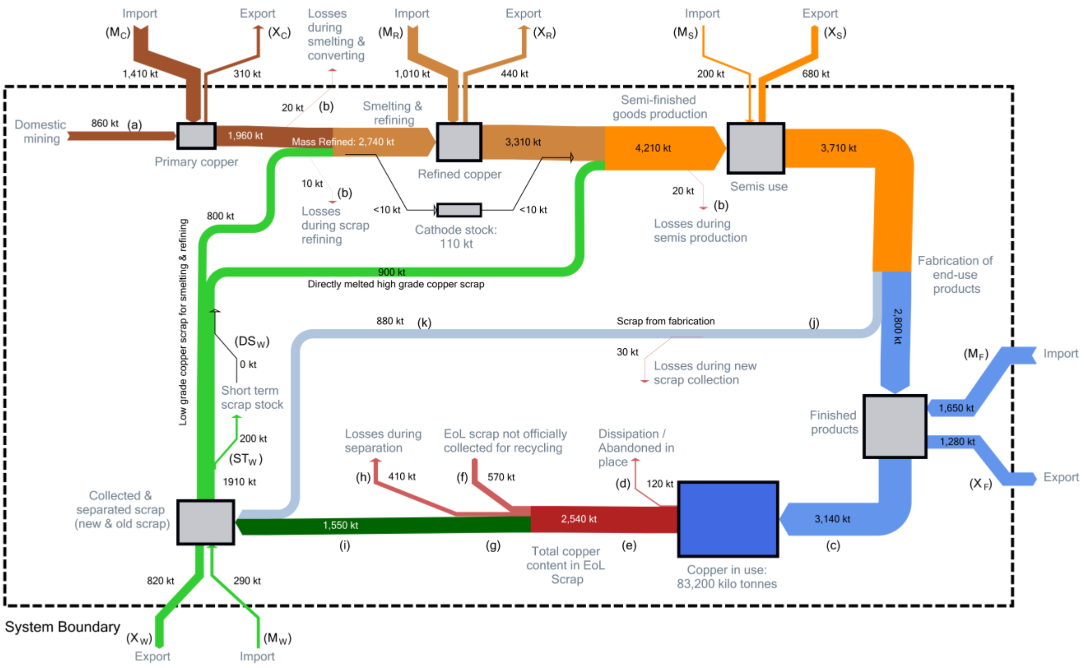

Figure 11 – Copper stocks and flows in EU28 in 2015 (ECI and Fraunhofer ISI).

The EU is a world leader in copper recycling. In 2015, 61% of end-of-life European copper was recycled, while copper scrap made up 47% of the source material to produce new copper. The disparity can be explained by the fact that the demand for new copper is greater than the amount of copper at the end of its life cycle. This disparity will become even greater because of the need for copper conductors to fulfil the needs of the energy transition.

Copper reserves

Because the demand for conductor material is growing and conductors have a long service life, there is a limited supply of used metals available for recycling into new products. Primary metal production (the mining of copper ore) fills the gap between the availability of secondary material and total demand. [34]

According to the US Geological Survey, since 1950 reports have regularly shown that there have always been an average of 40 years of copper reserves and over 200 years of resources available. According to the latest data (USGS, 2013), known copper reserves are around 680 million tonnes. Actual resources are much greater than this and short term supply limitations, often resulting in upward price trends, are an incentive to explore new deposits. [35]

Reserves are deposits that have been discovered, evaluated and assessed as profitable. Resources are far greater and, in addition to reserves, include discovered and potentially profitable deposits, as well as undiscovered deposits predicted from preliminary geological surveys. Total copper resources are estimated to exceed 3,000 million tonnes (USGS, 2013), which does not include vast copper deposits found in deep sea nodules and seafloor massive sulphide deposits.

The recycling limitations of copper-clad aluminium

Copper-clad aluminium (CCA) is a material sometimes used in data transmission (coaxial) cables (see Chapter 4). Apart from its technical and safety limitations, this type of cable is also difficult to recycle. It is a complex and energy intensive process to separate the two metals, resulting in a less efficient recycling process and lower quality scrap compared to pure copper or aluminium conductor recycling.

9. ENVIRONMENTAL AND SOCIAL CONCERNS

Copper is an essential micronutrient for the human body.

A risk assessment carried out by the European Commission showed that with the existing legislative framework, copper does not pose a risk to the environment or the health of workers or the general public.

All major copper mining companies are members of ICMM, which is dedicated to safe, fair and sustainable mining.

TOXICITY

COPPER IS NATURALLY PRESENT AND ESSENTIAL TO LIFE

Copper and the environment go hand in hand. It can be found naturally in all waters, sediments and soils and is essential to life – plants, fish, animals and humans all need copper to function properly. Consequently, if a soil contains insufficient levels of copper, it cannot sustain productive arable farming.

Along with iron and zinc, copper makes up the mineral trio essential to human well-being. It is vital to the health of the body, from foetal development to old age. Without copper our brains, nervous systems and cardiovascular systems could not function normally. Humans have developed built-in mechanisms to manage copper intake levels. Copper is not formed naturally in the body and so must be obtained from food and drinking water each day as part of a balanced diet and if required through the use of dietary supplements. Our digestive systems assimilate the amount necessary for good health through a system of uptake called homeostasis. Excess copper is excreted.

COPPER IS NOT TOXIC

The use of copper products is generally safe for Europe's environment and for the health of its citizens. This was demonstrated by a voluntary risk assessment (VRA), carried out by the copper industry and published in April 2008 [36], an example of the proactive steps taken by the copper industry to meet its duty of care.

The risk assessment dossier was agreed by the EU Technical Committee for New and Existing Substances. The EU Scientific Committee on Health and Environmental Risk (SCHER) carried out a final evaluation and further endorsed the conclusions on the environmental and human health risk characterisations. The assessment covers the production, use, and end-of-life aspects of the copper value chain. It confirms that the existing legislative framework safeguards Europe's environment, the health of industry workers, and the health of the general public. More specifically, the VRA clearly demonstrates that copper is not a CMR or a PBT material, meaning that it is **NONE** of the following:

- Carcinogenic (causing cancer)
- Mutagenic (changing genetic material)
- Reprotoxic (interfering with normal reproduction)
- Persistent (not degradable)
- Bio-accumulative (not excreted by living organisms)
- Toxic (directly harmful to life in any form)

The maximum threshold value in the environment

Despite the fact that copper is not a toxic material, exposure to high concentrations can be detrimental for humans and other living organisms. Copper used as a conductor is unlikely to cause such concentrations. In most conductivity applications the copper material is covered with insulation. Only in a few minor applications (e.g. thin film PV, busbars) might small dilute quantities of copper be released into the environment.

The threshold value for acute effects in drinking water is 4.0 mg/l of copper, while the World Health Organization (WHO) advises a maximum of 2.0 mg/l. In the EU, the general public is typically exposed to 0.7 mg/l, which is well below the WHO threshold. [36]

The European-wide safe levels for copper in freshwater and marine waters are respectively 7.8 and 2.6 µg Cu/L. The safe level for copper in soil is 79 mg/kg dry weight. The safe levels for copper in freshwater, estuarine and marine sediments are respectively 87, 144, and 338 mg Cu/kg dry weight. Copper levels measured in European waters, sediments and soils are usually well below these safe threshold levels. [36]

The lower and upper threshold values of dietary intake

For adults, the minimum daily dietary intake is 1 mg, with a maximum threshold of 11 mg. Actual intakes range between 0.6 and 2 mg. This suggests that copper deficiency could be a greater concern than excessive intake levels. [36]

Risk environments

There are two possible situations where poor management might lead to copper concentrations above the threshold value with a potentially detrimental effect on human health:

1) Copper production or copper processing sites with insufficient on-site water treatment or where the effluent is discharged into a water body with low dilution [36];

2) When copper cables are overheated, e.g. because of a short circuit, bringing the risk of exposure to excessive concentrations of copper vapour.

The European Copper Institute’s voluntary risk assessment [37] outlines the required management action to be taken by copper producers and users to avoid these situations.

The social and environmental impact of mining

The copper mining industry is conscious of the impact of open-pit mining and its associated activities. Mining projects are therefore approached with a coordinated longer-term vision taking special account of sustainability. [38]

The International Copper Association (ICA) and all the major companies involved in copper mining around the world are members of the International Council on Mining and Metals (ICMM), which is dedicated to a safe, fair and sustainable mining industry. Members commit to a set of principles, position statements and reporting practices which have been benchmarked against leading international standards. Substantial progress has been made over the past 15 years, and the ICMM and its members continually strive for further improvement.

Key commitments include:

Human rights

As a member of the ICMM, the copper mining industry respects the following commitments:

1) Ensuring **fair remuneration for all employees**, as well as good working conditions. Forced, compulsory and child labour are excluded under all circumstances.

2) **Minimizing involuntary resettlement** using all reasonable means. If resettlement cannot be avoided, the community will be compensated fairly.

3) Respecting the **culture, customs and heritage of local communities**, including those of indigenous peoples.

Where mining projects are located on lands that are traditionally owned by indigenous people, or which they have customarily used, their special connection to land and water is recognised. A consultation process has been adopted that ensures the meaningful participation of indigenous communities in decision making. This means that they are (i) able to freely make decisions without coercion, intimidation or manipulation; (ii) given sufficient time to be involved in the project before key decisions are made; and (iii) fully informed about the project and its potential impacts and benefits.

Risk management

ICMM members commit to implementing effective risk-management systems based on sound science. These systems are dedicated to minimizing any social, health, safety, environmental and economic risks associated with the companies' activities.

The ECI carried out a voluntary risk assessment in 2008 [37], covering the production, use and end-of-life phases of the copper value chain. In March 2009, the conclusions of the assessment were endorsed by the EU authorities and published online.

Occupational health & safety

As demonstrated by the ECI's voluntary risk assessment [37], the copper mining industry pursues continuous improvement with regard to the health and safety of employees and contractors. All practical and reasonable measures to eliminate workplace fatalities, injuries and disease are being taken, with zero-harm as the ultimate goal.

Environmental performance

As an ICMM member, the copper mining industry pursues continuous improvement in environmental performance, with an emphasis on responsible water management (see below), minimising energy use, and mitigating climate change.

For each new project, the direct and indirect environmental impact over the entire life cycle is assessed.

Once a project is in operation, an environmental management system is implemented. Special attention goes to residual waste and process residues, for which safe storage and disposal is assured.

The closure requirements at the end-of-life of a project are appropriately designed and planned. This minimises adverse impacts and maximises beneficial outcomes for all stakeholders. Copper mining companies and governments pool resources to rehabilitate former mining sites and return them to a stable condition. In doing so, full advantage is taken of the restoration process to enhance the biodiversity of the affected area. [38]

Land-use planning

As an ICMM member, the copper industry follows an integrated approach to land-use. This includes respect for legally-designated protected areas and efforts to conserve biodiversity. Actions as well as communications are based on scientific data and follow inclusive and transparent procedures.

An example of this in practice is the financial support granted by the copper industry to The Nature Conservancy in Mongolia. The South Gobi region is rich in natural resources, making it increasingly attractive for mineral development projects. This is creating new opportunities and supports economic development, but places significant pressure on the natural environment and traditional communities living off the land. The Nature Conservancy was initiated by the Mongolian government to develop a landscape vision that takes into account the full scope of potential mineral development projects and their cumulative impact. It works in close co-operation with communities, NGOs, academics and interested corporations. By applying an innovative, science-based process known as Development by Design (DbD), it aims to reduce conflicts between development and conservation goals, avoid or offset the impacts of development, and support win-win solutions for the region. [39]

Water management

Access to water has been recognised as a fundamental right for all humans and indispensable for the healthy functioning of ecosystems. Water is also a vital input for all mining and metals operations, a truly precious and shared resource with high social, environmental and economic value.

As an ICMM member, the copper industry commits to effective and sustainable water management, following proactive and holistic strategies.

The European copper industry has invested significantly in processes to minimise wastewater, such as rainwater collection and storage facilities. It has also made substantial investment in on-site water treatment facilities to ensure that discharges meet required quality standards before being redirected to streams, rivers and coastal waters. [40]

Tailings management

Mining and minerals processing inherently produces residue material, also called “tailings”. These materials require engineered solutions known as tailings storage facilities (TSFs). As an ICMM member, the copper mining industry ensures that all existing technical guidance to minimise the risk of catastrophic TSF failures is being followed. It continually seeks to improve TSF engineering and management techniques.

10. STRATEGIC CONCERNS

Copper and innovation have gone hand-in-hand for more than 6000 years. Today, copper production processes are fine-tuned to maximise energy efficiency and minimise environmental impact.

Copper theft can be particularly disruptive if it concerns working infrastructure. Examples from France and South-Africa show how effective and feasible measures can counter copper theft.

INNOVATION

Copper processing technology dates back more than 6000 years and is still evolving today. Production processes are continuously fine-tuned to maximise energy efficiency and minimise environmental impact. Fundamental innovation takes place 1. in extraction and manufacturing processes, 2. in the development of new copper materials, and 3. in co-operations downstream in the copper value chain.

A following are a few examples of ongoing or recently concluded innovation projects:

1. **Innovation in extraction and manufacturing**

    a. Manufacturing plants have to adapt increasingly to new material feeds. To cope with this, new processes are being developed to recover materials such as nickel, bismuth and antimony from the copper electrolyte. Recuperating those materials improves the economic balance of the copper refining process and serves the circular economy objectives.
    b. At various mining sites of different copper companies in Europe, mining vehicles have been electrified recently, resulting in substantial savings of fuel and carbon emissions.

2. **New copper materials**

    a. Special coating products improve the current carrying performance of copper, representing a considerable opportunity in multiple applications, such as electric motors, busbars and transformers.
    b. Newly developed micro-alloyed copper of superior mechanical strength can be used for overhead line conductors. These are traditionally the domain of aluminium because of its lower density. However, the strength of the towers for overhead lines is not so much determined by the weight of the conductor, as by the need to resist forces created by wind and ice. The smaller the conductor cross-section, the lower these forces will be. The newly developed micro-alloyed copper has sufficient mechanical strength of its own to make steel reinforcement obsolete. Combined with the higher electrical conductivity of copper, this results in a smaller conductor section for the same capacity on the line. Moreover, the copper alloy has a higher maximum operating temperature, enabling a higher overload capacity on the line.

3. Co-operations in innovation projects downstream in the value-chain

a. One example is the development of the die-cast copper rotor. Since copper has a higher conductivity than aluminum (58 MS/m compared to 37 MS/m), it is a natural choice for the rotor of an induction motor. However, its high melting point and the resulting high cost of die-casting has for a long time been a major barrier. Several technological breakthroughs in copper die-casting have been achieved over the past twenty years, removing this barrier and clearing the way for industrial production. The main advantage of using copper for the rotor of an induction motor is either cost reduction or efficiency improvement, or both.

b. Participation in the ReFreeDrive project of the European Green Vehicle Initiative. This project is focused on developing the next generation drivetrains for electric vehicles avoiding the use of rare earth magnets. It aims to ensure industrial feasibility for mass production, keeping the cost of the manufacturing technologies in mind.

THEFT

Despite the wide distribution of copper use, often in exterior or public spaces with unprotected access, the problem of copper theft remains limited. It can, however, be particularly disruptive if it concerns theft of working infrastructure. One problem is that thieves often do not know or care about the danger of removing copper in operation. Moreover, it is easy to sell copper for a good price on the scrap market with large quantities being exported from Europe to Asia.

There are technical solutions to counter theft, such as hiding copper under a layer of galvanised steel, attaching cables to a ground anchor, using bimetallic solutions to lower the scrap value, alarm signals to detect damaged cables, forensic marking such as molecular tagging, and surveillance cameras. Given the wide distribution of copper use, however, the cost of these solutions may be prohibitive, while some lower the scrap value when the installation is at end-of-life.

Acting downstream in the copper scrap market has the advantage that efforts can be much more concentrated. In France, wholesalers and recyclers can no longer pay for metals with cash, and need a document with the name, address, annual turnover and vehicle registration of the seller [41]. These measures have proved to be successful and copper thefts have dropped by half in France. Since organised crime is still shipping stolen metals directly to Asia, export controls could further enhance this deterrent.

In South Africa, the *Second Hand Goods Act* makes buying stolen products just as criminal as the theft itself. This legislation is combined with export controls and a discouragement campaign that focuses on the risks of copper theft. This mix of measures has also proved successful. Monthly copper theft fell from 19.8 million rand to 10.5 million rand in just a year, and copper waste exports have also decreased [42].

These two examples from France and South Africa show how effective and feasible measures can counter copper theft, but also that a well-designed programmatic action plan is needed.

11. CONCLUSION

Electrical conductivity is a key characteristic of the high-tech era. With the transition towards a decarbonised energy economy, its importance will only continue to rise. Electricity can be generated from various energy sources including renewables, is easy to transport, and is well suited for control and automation – a basket of advantages that is hard to beat. Conductivity, however, comes in different qualities. It can fluctuate significantly depending on the design of the system and the choice of material. In a good electrical design, the energy losses are minimised down to the economic optimum, safety risks are avoided, and the potential for material recycling is maximised.

Two main conductor materials are used today: copper and aluminium. Both come with variations depending on the production process or with the addition of small quantities of alloy elements. The application area associated with each conductor metal is relatively distinct, and mainly depends on material properties other than conductivity. With a few exceptions, these application areas are already long-established.

ANNEX: CALCULATING THE OPTIMAL CABLE CROSS-SECTION

RECALCULATING THE ENERGY COST TO A PRESENT VALUE

The initial step in this process is recalculating the cost of the energy losses to reveal the cost at the date of installation. **An interest rate (i)** should be set, as well as **the economic lifetime of the cable (n)**. The cost of the losses should then be multiplied by the following capitalisation factor:

$$N_{(i,n)} = ((1 + i)^n – 1) / (i – (1 + i)^n)$$

Moreover, **the average electricity tariff (T)** over the economic lifetime of the cable should be estimated. This leads to the following formula for the cost of the energy losses:

$$C_{losses} = (I^2 \times (\rho/A) \times L) \times t_{econ\ life} \times T_{ariff\ electr}\ (€/kWh) \times N(i,n)$$

TAKING THE ACTUAL LOADING OF THE CABLE INTO ACCOUNT

A second point is that the cable will not be loaded at its rated power continuously. This means the time t is not the complete economic lifetime of the cable, but only the time the cable is under load: $t_{operational\ hours\ econ\ life}$.

Moreover, the current I will not be the rated current, but the average of the currents that actually flow through the cable, a figure that depends on the average relative loading:

$$P_{loading} = P_{load}/P_{rated}.$$

$$I_{real} = (I_{real}/I_{rated}) \times I_{rated}$$

$$= (P_{load}/P_{rated}) \times I_{rated}$$

$$= P_{loading} \times I_{rated}$$

with $P_{loading}$ a figure varying between 0 and 1

This leads to the following equation:

$$C_{Losses} = (P_{loading})^2 (I_{rated}^2 \times (\rho/A) \times l) \times t_{hours} \times T_{ariff}\ [€/kWh] \times N_{(i,n)}$$

ISOLATING CABLE CHARACTERISTICS FROM OPERATIONAL AND FINANCIAL VALUES

Now we can put all the factors which are not cable characteristics into one **operational and financial value F**.

$$F = (P_{loading})^2 \times t_{hours} \times T_{ariff}[€/kWh] \times N_{(i,\ n)}$$

The following table gives a few average values for F per industrial or commercial sector.

Industry	Interest	N (year)	Energy price (euro/MWh)	Loading	T (hours)	F (euro/W)
Iron	7.5%	10	100	65%	3700	**7.62**
Non-ferrous	7.5%	10	100	35-45%	2730	**5.62**
Paper	7.5%	10	100	65%	3700	**7.62**
Chemical	7.5%	10	100	40%	1400	**2.88**
Datahotel	7.5%	5	100	25-75%	2735	**3.32**
Office	7.5%	10	100	20-40%	1182	**2.43**

Table 10

In general industrial conditions, F will vary between €0.50 and €20/W. The average value of F across all European industry sectors is €4.24/W. For a long-term investment in a cable that will be constantly loaded close to its rated power, F can be greater than €50/W.

The LCC formula now becomes:

$$C_T = C_I + C_L$$

$$C_T = C_{I[S]} + 1/A \times I_{rated}^2 \times \rho \times l_{ength} \times F$$

Optimal cross-section depending on the cable price

The specific resistance of a copper conductor is 2.059 µΩ*cm at a typical operating temperature of 105 °C (1.724 µΩ*cm for 100% IACS at 20 °C) or 0.02059 mΩ*mm.

Consequently, the equation for 1 m of cable now becomes:

$$C_T = C_c \times A + 1/A \times I_r^2 \times 0.02059 \times F$$

where:

C_c is the cable price in euro per mm² cable cross-section and per meter cable length

A is the cable cross-section expressed in mm²

I_r is the rated current in Ampère

F is the operational and financial value in €/Watt

This equation gives the total life cycle cost of 1 m of cable in euro.

The optimal cross-section A of a cable is the point where the curve of this equation goes through its minimum. It can be proved mathematically that this minimum will always lie at the point where the first part and the second part of the sum are equal.

This occurs when:

$$C_c \times A = 1/A \times I_r^2 \times 0.02059 \times F$$

Or: $$A^2 = I_r^2 \times 0.02059 \times F / C_c$$

We can calculate the optimal cross-section A from:

$$\mathbf{A = I_r \times 0.1435 \times (F/C_c)^{1/2}}$$

where:

I_r is the rated current of the connection

F is a financial and operational value varying per sector

C_c is the cable price per meter and per mm² cross-section.

MINIMUM CONDUCTOR CROSS-SECTION FOR CABLES THAT MUST REMAIN FUNCTIONAL DURING A FIRE [18]

Fire safety cables can be tested by heating them in a furnace with a temperature profile according to the German standard DIN 4102-Part 12, which follows the standard cellulose fire model. Circuit integrity classes are listed in *Table 11 – Circuit integrity classes – according to DIN 4102-12.* They determine the time for which the system remains functional during a test fire, in cases where no short circuit or current interruption occurs.

	Circuit integrity class	Minimum maintenance of functionality
No. 1	**E 30**	≥ 30 minutes
No. 2	**E 60**	≥ 60 minutes
No. 3	**E 90**	≥ 90 minutes

Table 11 – Circuit integrity classes – according to DIN 4102-12.

DIN 4102-12 mentions in the explanatory notes on the last page that there is a “heat-induced increase in conductor resistance”, but does not cover the issue. In other words, it does not provide a way to incorporate this fact into the electrical conductor cross-section calculations. This gap was filled by the Leonardo Energy Application Note *Fire Safety Cables*, which provides the following correction factors *m* on the conductor resistance for the three integrity classes described above:

	E 30	E 60	E 90
m	3.84	4.27	4.52
√*m*	1.96	2.07	2.13

Table 12 – Correction factors for cables at required survival conditions.

The last line of this table indicates the square of the conductor resistance correction factor. This is the figure to be utilised to calculate the minimum conductor cross-section A. So:

$$A = I_r \times 0.1435 \times \sqrt{m} \times (F/C_c)^{1/2}$$

More on this subject can be found in the Application Note *Fire Safety Cables*.

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