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CONCERNS ABOUT THE SUSTAINABILITY OF COPPER BASED LIGHTNING PROTECTION

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ABSTRACT

The direct lightning protection industry is highly dependent on the use of copper. Indeed, direct lightning protection installations use a lot of copper. Gradually over the past few years, the copper market has been under tension for several reasons: reduced production during the Covid19 crisis, declining mining yields, prices increasing following the economic recovery, more expensive production due to the increase in energy prices and its supply following the Russia-Ukraine war, the strong growth in demand for copper required by new technological uses. In the medium/long term, the main threat lies in the fact that the shortage is in focus. In addition, global warming, which imposes restrictions on CO_2 emissions and tensions on the electricity market (limited supply and high price per MWh) forces us to think about alternatives. The direct lightning protection industry is therefore also concerned. Alternatives are possible to delay the shortage of copper by using alternative materials, or by using less demanding installation techniques. However, the carbon and energy footprints must be considered depending on the solutions chosen, in particular with a view to social responsibility. In this paper, we will look at the reduction of materials in the design of the ELPS, and in the use of alternative materials. Substantial gains are possible.

1 - INTRODUCTION

It has already been shown that copper [1], which is an excellent metal for direct lightning protection, is increasingly used globally in the world economy and that its exploitation requires a lot of energy and produces pollution. The impact of the increased exploitation of this metal has shown that the shortage could occur as early as 2024 [2] because the mine supply growth will peak, leading to an increase in prices.

Recently, with the liberalization of the electricity market in Europe and the upheaval of the hydrocarbon market in the world due to the ongoing conflict in Eastern Europe since February 2022, the energy necessary for the production and transformation of copper is a preponderant criterion. Also, nuclear power plants in working order are in short supply due to the aging of the fleet, and gas-fired power plants need to be supplied following the blockade of Russian gas on which Europe in particular depends heavily.

Also, the strong environmental pressure, particularly in developed countries or through Western societies, requires reducing or containing greenhouse gas emissions (CO_2 in particular).

These four factors: - increasingly high demand, - future shortage, - cost and instability of the energy market, - environmental concerns, mean that the economic sectors dependent on copper will be increasingly impacted in the near future. One could speak of a serious and long crisis [2].

In this context, the lightning protection microcosm that extensively uses copper as a primary material, will inevitably suffer from this situation.

2 - MACRO-ECONOMICAL BACKGROUND

2.1 - GROWING COPPER NEEDS

New technologies and the acceleration of the all-electric future (electric vehicles, solar power generation equipment, batteries for storage, expansion of distribution and charging infrastructures) will require more and more copper (figure 1). It is estimated that copper demand will double by 2035, i.e. 50 million tons, or 86 to 102 Mt with so-called “Business As Usual” (BAU) mobility by 2050 [3], which also refers to the necessary levers of sobriety in this area. These technological trends are more copper-intensive than conventional technologies. For example, an electric vehicle needs 2.5 times more copper than a combustion vehicle [3], offshore solar and wind installations need 3 to 5 times more copper per MW produced than generators running on fossil fuels [2]. Mining companies Teck Resources and Wood Mackenzie predict that copper demand for the electrified vehicle sector alone will increase by 7.5Mt by 2040, more than a third of global production [8].

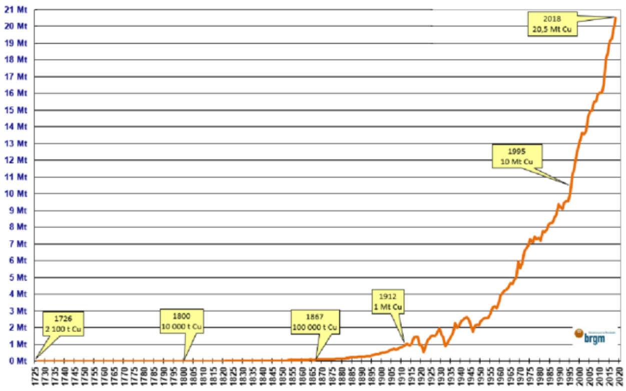

Figure 1 – Evolution of the worldwide copper mining production from 1726 to 2020 (Mt)

2.2 - AVAILABLE RESERVES AND PRODUCTION

It is estimated a deficit of 10 million tons of copper per year according to forecasts [2]. The commissioning of new copper mines, if any, takes an average of 16 years [2]. Although the location of mines and resources is relatively diversified in the world, geopolitical issues will therefore come into play to appropriate supply flows. For example, China already controls nearly 40% of global copper refining to ensure its economic growth [3]; which can be a problem because of the growing political tensions between China and the West and neighboring countries. In addition, China is securing its imports by strengthening its presence in Asia, Africa and Latin America, challenging the existing geopolitical balance, as most of the reserves and extraction are located in these areas, see Table 1 [9].

It is estimated that 78.3% to 89.4% of known copper resources in 2010 will be extracted in 2050 according to the “4D” and “2D” global warming scenarios [3]. The energy transition therefore has a significant effect.

Refined copper world production, see Table 2 [8], is largely dominated by China. Chili on its own still significantly contributes to the refining, on the contrary to most of the industrialized countries, especially Europe countries which are therefore very dependent.

2.3 - COST AND INSTABILITY OF THE ENERGY MARKET

In 2021, Europe (mainly Germany, Poland, Spain, Belgium) produced 2,681 Mt of refined copper, i.e. 10.8% of world production. World production consists of 83% of primary origin (from ore) and 17% of secondary origin (recycling). In 2014, Europe is the geographical entity that recycles the most copper with 45% of secondary production. These primary and secondary production activities require the use of fossil energy for the pyrometallurgical treatment of the ore (natural gas furnace, coke, fuel oil, even electricity) and electrical energy for the final refining by electrolysis (also for hydrometallurgical process). These processes consume a lot of energy, see Table 3 [3].

At European level, the opening up of energy markets to competition began in 1996 with a first European directive concerning electricity and in 1998 for gas. The latest directives are respectively the following: 2009/72/CE [5] and 2009/73/CE [6]. This opening of the market has gradually been deployed by liberalizing the production and supply of energy within a certain framework. The costs are more related to supply and demand as well as speculation. Moreover, the means of nuclear production were impacted by the periodic maintenance and necessary repairs, which reduced nuclear production capacity by 25% in 2022 compared to the previous year, which weighs for 31.3% in the European energy mix in 2021 [10]. Because of these factors for several years and the Russo-Ukrainian context since February 2022, the sale prices of energy have soared in recent years, see figures 2 and 3 [11;12]. These energy costs weigh on copper production, in addition to strong demand pressure. Copper prices therefore follow the law of supply and demand, and energy costs, see Figure 4. The increases and variations are very significant.

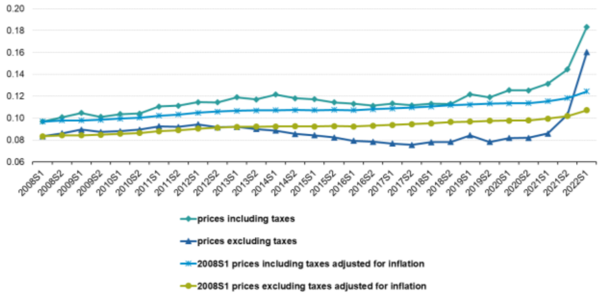

Figure 2 – Development of electricity prices for non-household, EU, 2008-2022 (€/kWh)

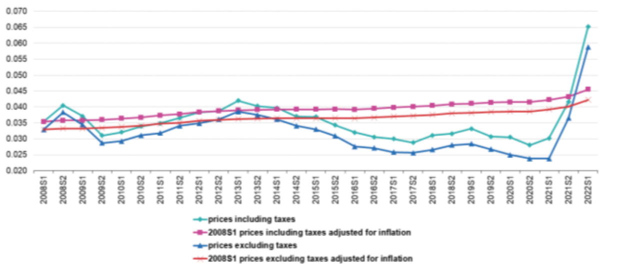

Figure 3 – Development of natural gas prices for non-household, EU, 2008-2022 (€/kWh)

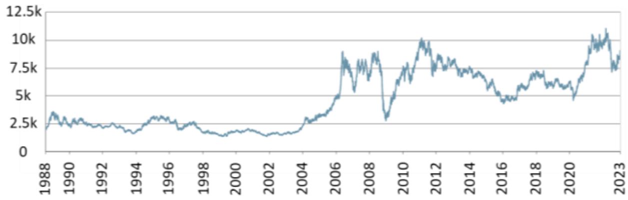

Figure 4 – Evolution of copper price (USD/t) from 1988 to 2023

2.4 - ENVIRONMENTAL CONCERNS

This production of copper, which is the key material for the ecological energy transition, paradoxically gives rise to greater pollution in the form of mining waste, foundry slag, heavy metal fumes, and harmful or greenhouse gases, or even chemical waste, as well as energy consumption (hydrocarbons or electricity) and water.

Secondary production of refined copper (copper recycling) is growing steadily from 2 Mt in 1998 to 4.6 Mt in 2015 [3]. This secondary production requires much less waste and energy than primary production (see Table 3). This is therefore in line with the ecological energy transition and partly ensures the security of supply, and this in short circuits. However, recycling is still insufficient due to the increasingly dispersive use of copper in a multitude of consumer goods, which represents an increased difficulty for this secondary production sector.

Mines have seen their yield drop in recent years. In the 1930s, the extraction of one ton of copper required 55 tons of ore, nowadays it takes 125 tons (2010) [7]. The average grade of exploited deposits fell by 41% between 1990 and 2017 [8].

Country/ Year	2018	2019	2020	2021	2022
World (total)	830	870	870	870	880
Chili	170	200	200	200	200
Australia	88	87	88	88	93
Peru	83	87	92	92	77
Russian Federation	61	61	61	61	62
Mexico	50	53	53	53	53
USA	48	51	48	48	48
Indonesia	51	28	32	32	31
Democratic Republic of Congo	20	19	19	19	31
China	26	26	26	26	26
Zambia	19	19	21	21	21
Other countries	210	220	200	200	180

Table 1 – World copper reserves by country (in Mt)

Country	Production
World (total)	**24.1Mt**
China	38.5%
Chili	10.2%
Japan	6.6%
USA	4.6%
Russian Federation	4.2%
Democratic Republic of Congo	4.1%
South Korea	2.8%
Germany	2.8%
India	2.3%
Poland	2.1%
Other countries	21.7%

Table 2 – Refined copper production in 2018

Energy (MJ/kg)		Water (m^3/t)	
Secondary production	Primary production	Secondary production	Primary production
14	31-2040	15	40-200

Table 3 - Amount of water and energy used for the extraction of copper ore or the reuse of waste from the mining industry (world averaging)

Metal	Copper	Aluminium	Steel
Total production (t)	21 000 000	60 000 000	1 800 000
Production energy cost (GJ/t)	64	212	23
CO_2 emissions (tCO_2/t)	4	17	2
Total CO_2 emissions ($MtCO_2$)	82	1025	3346

Table 4 – Estimation of the worldwide metal production energy cost and CO_2 emissions per ton of metal produced

3 – LIGHTNING PROTECTION BACKGROUND

3.1 - INTRODUCTION

There is a remarkable unbalance between the amounts of attention that the research community has devoted to each of the types of lightning protection systems. Single rods have been subject of intense research during the last half century. Part of this activity has focused on the (still ongoing) assessment of the performance of evolved forms of the single rods. Another significant part of this activity has been devoted to developing the so-called electro-geometrical model and its derived engineering methodology (the most relevant one being the “Rolling Sphere” method), which allows designing consistent protection structures [13;14]. This contrasts with the background behind mesh cages, whose installation still relies in the meshwork method, largely based on accumulated experience, rather than theoretical deduction [15].

At present, two types of protection systems dominate the direct lightning protection market (ELPS) and therefore are employed massively. So far there is no scientific evidence that one of these types of protection performs better than the other, although it is commonly agreed that poor installation design dramatically decreases the efficiency of the protection system [16]. Nevertheless, there is no discussion around the fact that scientific research is the only way that will allow developing more efficient lightning protection systems through a better understanding of the amazingly complex subject of physics of lightning.

The acceleration of consumption has made obvious that it is impossible to conceive a highly developed society at a global scale without focusing into industrial production schemes that are sustainable. However, this is not the case of some of the models proposed by the lightning protection industry.

Both types of protection systems, single rods and mesh cages, are mainly composed of metal, particularly copper, in the form of large cross-section conductors.

In the case of single rods, two conductors are used to guide the discharge from the rod itself towards the ground, so the amount of conductor used is roughly equivalent to twice the height at which the rod is placed. In the case of mesh cages, a much larger amount of copper wire is needed in order to build the grid which wraps around the whole structure to be protected. Figure 5 shows a comparison of the amount of copper needed to protect a medium-size basement following current standards [17]. This example illustrates how a protection based in a mesh cage type of system does not fall at all into a sustainable logic.

The schematic representations illustrated in figure 5 correspond to lightning protection systems of single rod type and mesh cage type, designed to protect a basement measuring 40 meters long, 20 meters wide and 10 meters high. This represents a typical average building in western Europe. It is assumed that the building has a poor conducting structure, as wood. The systems have been designed following the specifications of standard EN 62305-3, to achieve protection of level II. The red lines represent the copper wiring with section of 50 mm². For the simple rod ELPS, there are 4 type A earthing systems (50mm² copper 3m triangle), as for the mesh cage ELPS, there is a type B loop earthing system (50mm²). Considering the lengths of wire and the density of copper (8920 kg/m^3) we can estimate the amount of copper used in these installations, which is approximately 48.8 and 190.4 kg respectively (equivalent to about 3 electric vehicles). The impracticality of the mesh cage approach becomes evident as soon as calculation is applied to a group of basements, or industrial area that will require tons of copper. As it has been already discussed, there is no proof that the mesh cages will perform better than a consistently constructed single rods structure, which will be much less consuming of natural resources.

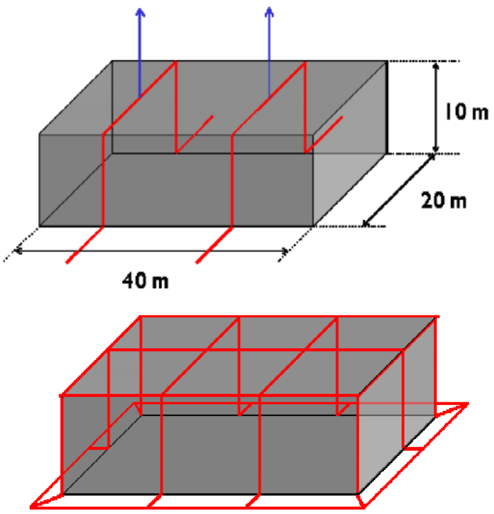

Figure 5 – Single Rod (top) and Cage protection (bottom) methods

3.2 – COPPER CONSUMPTION EXAMPLE

In this paragraph, we will assess the metal consumption involved in installing ELPS by a company leading the lightning protection market in France (INDELEC). In 2022, the total copper consumption including downconductors, rods, and components was 19.95 tons (French and export market). However, this value is lower than the real amount of metal used. The export share does not always represent the image of complete lightning protection installations, as many components could be sourced directly from the local industry by customers (mainly downconductors). On the contrary, the French national market sales are more representing complete installations (rods, downconductors, components, etc.) but a substantial quantity of downconductors are directly purchased by the installation companies. So the real total quantity of installed copper is difficult to trace, as well as for the aluminium downconductors. The estimated copper downconductor mass shown in Table 5 is based on the parameters on figure 5 (top) to give an order of magnitude. The aluminium mass is given in Table 6. The amount of aluminium downconductors are much lower than reality as per explained above.

Items / Market	Export	France (estimation)
Downconductors	5.75	25.93 (estimated) 5.95 (non-estimated)
Various components	0.18	1.23
Rods	4.48	2.34
TOTAL	39.91	

Table 5 – Copper used or sold for ELPS in tons of copper in 2022

Items / Market	Export	France
Downconductors	0.057	0.156 (non-estimated)
Various components	0.73	0.854
Rods	0	0
TOTAL	1.8	

Table 6 – Aluminium used or sold for ELPS in tons of copper in 2022

4 - ALTERNATIVE PROPOSALS

The proposed solutions are: - the recycling of copper (see §2.4), - the use of aluminum which remains cheaper than copper and is less in tension because the shortage is not expected before a hundred years, and – use less metal by using more responsible ELPS designs.

Recycling can be greatly improved as Europe is able to produce 45% of secondary copper as the world averages at 17%. This means that the shortage could be postponed much further to a date that is yet to be estimated. However large investments must be made to modernize copper treatment facilities under the political impetus.

Europe	World average	China
7	18	20

Table 7 – Aluminium primary production footprint in 2022 in tCO_2/t

Metal / Alloy	Resistivity Ω.m	Thermal conductivity W/(m.K)	Density
Copper	$17.8\ 10^{-9}$	390	8.96
Aluminium	$26\ 10^{-9}$	237	2.7
Stainless Steel	$7000\ 10^{-9}$	26	7.9

Table 8 – Electrical and thermal characteristics of some metals

Cross-section	Material								
	Aluminium			Copper			Stainless Steel		
	Level of Protection			Level of Protection			Level of Protection		
	III-IV 100kA	II 150kA	I 200kA	III-IV 100kA	II 150kA	I 200kA	III-IV 100kA	II 150kA	I 200kA
10 mm²	564	-	-	169	542	-	-	-	-
16 mm²	146	454	-	56	143	309	-	-	-
25 mm²	52	132	283	22	51	98	940	-	-
50 mm²	12	28	52	5	12	22	190	460	940
100 mm²	3	7	12	1	3	5	45	100	190

Table 9 – Temperature rise in °C of downconductors according to cross-section and Level of Protection (lightning current)

Country	Reserve
World (total)	**31 000**
Guinea	7 400
Vietnam	5 800
Australia	5 100
Brazil	2 700
Jamaica	2 000
Indonesia	1 000
Guyana	850
China	710
India	660
Russian Federation	500
Other countries	4 280

Table 10 – World bauxite reserves by country in 2022 (in Mt)

4.1 – USING ALUMINIUM

The use of aluminium instead of copper is already a reality in some industries, for example distribution power lines, solar panels, batteries, etc. This substitution may go farther. The demand for this metal has increased sharply since the 1990s, see Table 11.

However, in ELPS, as Table 5 and Table 6 would suggest that the aluminium could be used more widely.

1886	1949	1973	1995	2012	2020
13 t	1.3 Mt	13 Mt	20 Mt	45 Mt	67 Mt

Table 11 – Evolution of the worldwide aluminium production

Country	Production
World (total)	**69**
China	40
India	4
Russian Federation	3.7
Canada	3
United Arab Emirates	2.7
Bahrein	1.6
Australia	1.5
Norway	1.4
USA	0.86
Iceland	0.75
Other countries	9.49

Table 12 – Refined aluminium primary production in 2022 in Mt

Energy (MJ/kg)	
Secondary production	Primary production
2.34 (in 2012)	47 – 54 (in 2010)

Table 13 – Energy consumption in Europe for primary and secondary aluminium

Figure 6 – Evolution of aluminium price (USD/t) from 2012 to 2021

However, calculated per ton refined, the worldwide averaged carbon footprint of aluminum compared to copper is 4.25 times more unfavorable and the energy footprint is 3.31 times more unfavorable, see Table 4 [4].

Europe is making huge efforts to reduce its own environmental footprint by increasing the efficiency of the aluminium processing (less energy) and reducing the CO_2 greenhouse gas, as well as water consumption and wastes. The carbon footprint of European aluminium has decreased by over 55% since 1990 [18]. A real breakthrough has been achieved in Europe compared to the world production, led by the European Aluminium industry association members, see Table 7 [18].

Europe is also a leader in the aluminium recycling industry as 50% of the European aluminium industry's output comes from recycled sources (secondary production). Moreover, recycling saves 95% of the needed energy for the primary aluminium production [19].

If we compare Tables 3, 4, 7 and 13, we see that aluminum of primary and secondary European origin has a solid advantage in terms of reducing the energy required and CO_2 emissions compared to copper. Europe is producing 16% of the total worldwide combined primary and secondary aluminium in 2012 [19].

Reserves of bauxite, which is the ore of aluminum, remain vast, see Table 10 [9]. In addition, the content of this ore is high: to produce 1 ton of aluminum, you need 4 to 5 tons of Bauxite. Although China holds only a small reserve of Bauxite, this country dominates the world's primary aluminum production, see Table 12.

The price per ton of aluminium is quite smaller than copper, see figure 6. On April 2023, aluminium is 4.5 cheaper than copper. So the use of this metal has the advantage of cost reduction too.

Speaking of direct lightning protection, it is also possible to use substitute materials of some components. Down conductors and capture conductors for mesh cages, which represent most of the quantity of metal used, can be very advantageously replaced by aluminum, according to the requirements of the EN 62561-2 standard [20]. Indeed, aluminum has very good electrical and thermal characteristics for this application, see Table 8. Its advantageous characteristics make this metal a second place after copper for lightning application. In the past, INDELEC conducted laboratory tests on capture rods using a 200kA current impulse (5.2 MJ/Ω). The results showed the good behavior of the sample under test with very minimal tip meltdown compared to copper. On the contrary, stainless steel showed a significant tip erosion. As downconductors, aluminium bear minimal heating up when lightning current flows through it, see Table 9 [21].

However, the use of aluminium is restricted to the aerial part of the ELPS as the standard forbids to bury aluminium due to corrosion.

Applied to the example exhibited in figure 5, the simple rod ELPS gives 11.65 kg of copper and 11.2 kg of aluminum, as for the mesh cage ELPS involves 56 kg of copper and 40.5 kg of aluminium. Switching to aluminium (case 3) gives us the opportunity to reduce the copper part by respectively 75.7% and 70.6% compared to case 1, see Table 15.

Aluminum can therefore relieve the copper market while being significantly less costly as more environmental friendly European aluminium is available.

4.2 – LESS DEMANDING ELPS DESIGNS

The last solution is to use less metal (copper and/or aluminium), either by modifying the manufacturing processes according to an economical design.

The standard EN 62561-2 allows the reduction of the cross-section of copper downconductors from 50mm² minimum to 28mm² minimum if the mechanical strength is not an essential requirement. The reduction in copper weight is quite substantial (-32.3% and -31.1% respectively), and the resulting heating up is still manageable. The earthing systems cannot be reduced to 28mm² and must still use 50mm² copper conductor. See Table 14 (case 1 and case 2). The cross-section reduction cannot be applied to aluminium downconductors.

Regarding direct protection against lightning, it is possible to apply these two criteria, i.e. reduce the quantity of metals required and use aluminum to replace a large part of the copper. With this in mind, the solution that lends itself most easily to these two criteria is the direct protection by capture rods replacing mesh cages. The number of capture conductors and down conductors is therefore reduced to its simplest expression, as well as the number of earthing systems if type A is selected. In addition, aluminum has a much lower density (2.7 instead of 8.96), which greatly reduces the mass of metal to be installed. Consequently, the negative impact in terms of energy and environment compared to copper is reduced accordingly.

According to Table 14 and Table 15, the ELPS involving the least quantity of copper is by far the Simple Rod one mixing copper and aluminium conductors.

A smaller quantity of metal, as well as the use of aluminum in direct lightning protection is therefore a response to be considered in sustainable development and to significantly reduce the pressure on the copper market, as well as on energy resources and the environment.

in kg	SIMPLE RODS	MESH CAGE
	Cu	Cu
Case 1 (50mm²)	48.8	190.4
Case 2 (28mm² and 50mm²)	33	131.2
Copper reduction	-32.3%	-31.1%

Table 14 – Metal amount involved in figure 5 according to case 1 (50mm² copper conductors) and case 2 (28mm² copper conductors)

in kg	SIMPLE RODS		MESH CAGE	
	Cu	Al	Cu	Al
Case 3 (50mm²)	11.65	11.2	56	40.5
TOTAL of METAL	22.85		96.5	
Copper reduction (Case 3 compared to case 1)	-75.7%		-70.6%	
Copper reduction (Case 3 compared to case 2)	-64.7%		-57.3%	

Table 15 – Metal amount involved in figure 5 according to case 3 (50mm² aluminium downconductors and 50mm² copper earthing systems)

5 - CONCLUSION

In this context of close shortage of copper (scarcity, price), strong demand due to the energy transition (electric vehicles, renewable energies), energy difficulties (availability, price), environmental awareness (greenhouse gas, preservation resources, pollution), actions must be taken to ensure and lead the transition and meet the necessary needs of our societies. One of the solutions is to rely on aluminum to complete all or part of the copper needs. Aluminum can be a reasonably environmentally friendly solution if efforts are made to create a more virtuous sector and increase the share of recycling. Copper is also affected by the imperative of secondary production.

As far as lightning protection is concerned, which has historically relied on copper to produce high-performance and reliable ELPS, it is possible to use recycled copper, aluminum from virtuous sectors and to apply ELPS designs that consume less metal while complying with the standards in force. The metal gains can be substantial as well as the economic gains while participating in sustainable development.

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