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# Feasibility study on the replacement of copper conductors with copper-clad steel conductors in photovoltaic plants

## *Estudo de viabilidade na substituição de condutores de cobre por condutores de aço cobreado em usinas fotovoltaicas*

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**Abstract:** This study examines the technical and economic feasibility of replacing copper conductors with copper-clad steel conductors in the grounding systems of a commercial-scale photovoltaic plant. A literature review was conducted to identify existing applications, followed by an analysis of data from a photovoltaic complex where copper grounding conductors and rods were replaced by copper-clad steel. Results show that the substitution is feasible, maintaining grounding efficiency within regulatory standards, despite higher electrical resistivity. The change also results in cost reduction, increased mechanical strength, and lower risk of material theft, factors that support sustainability and operational safety. Further research is recommended on long-term performance and durability in different soil conditions. The findings suggest that copper-clad steel conductors are a promising alternative for large-scale photovoltaic applications, contributing to sustainable and cost-effective energy solutions.
Keywords: copper-clad steel conductor; sustainability; photovoltaic power plant; electrical conductivity.

***Resumo**: Este estudo analisa a viabilidade técnica e econômica da substituição de condutores de cobre por condutores de aço cobreado nos sistemas de aterramento de uma usina fotovoltaica em escala comercial. Inicialmente, realizou-se uma revisão de literatura sobre aplicações existentes. Em seguida, foram analisados dados de um complexo fotovoltaico no qual condutores e hastes de aterramento de cobre foram substituídos por equivalentes em aço cobreado. Os resultados apontam que a substituição é viável, mantendo a eficiência do aterramento dentro dos padrões normativos, mesmo com maior resistividade elétrica. Além disso, observou-se redução de custos, maior resistência mecânica e menor risco de furto de materiais, aspectos relevantes para a sustentabilidade e segurança operacional. Recomenda-se a continuidade das pesquisas, com foco na durabilidade e no desempenho a longo prazo em diferentes condições de solo. Conclui-se que a utilização de condutores de aço cobreado é uma alternativa promissora para aplicações fotovoltaicas de grande porte, contribuindo para soluções energéticas sustentáveis e economicamente eficientes.*
*Palavras-chave: condutor de aço cobreado; sustentabilidade; usina fotovoltaica; condutividade elétrica.*

## 1 Introduction

Photovoltaic (PV) energy production technologies have been extensively studied, aiming to promote technological education and contribute to a more sustainable world. Bibliometric analysis shows that the main themes in the literature are related to global energy, forecasting of photovoltaic energy production, and electricity consumption. Advances in photovoltaic (PV) technology have significantly enhanced material efficiency, reinforcing the importance of solar energy in global sustainability efforts (Velasco et al., 2017; Ahmed, Habib and Javaid, 2015).

Consequently, investments in renewable energy sources, particularly solar power, have increased substantially in recent years. Large-scale photovoltaic plants can contribute to sustainability by integrating technological and ecological systems, reducing environmental impact, and enhancing energy security (Hernandez et al., 2019). Solar energy could provide a majority of global energy by 2030 and 30 to 70 TW by 2050, requiring complementary technologies and research in performance, reliability, manufacturing, and recycling (Haegel et al., 2019).

In engineering, electricity plays a fundamental role in power generation and transmission from plants to residential and industrial users. Ensuring system safety, particularly in grounding systems, is a key responsibility of electrical engineers. In power plants, grounding systems are essential to mitigate hazards to people and equipment caused by dangerous voltages and high potential gradients during system faults. Design parameters such as soil resistivity, and the number of groundings meshes and rods significantly impact the quality and efficiency of substation grounding systems.

A reliable grounding system dissipates electrical current safely into the earth, protecting structures and internal systems from damage caused by atmospheric discharges (Associação Brasileira de Normas Técnicas (ABNT), 2015). Regulations indicate that lightning strikes generate current impulses lasting approximately 50 milliseconds, though, in complex systems, this can vary between 10 and 250 milliseconds. Without an effective grounding system, lightning can damage equipment, compromise safety, and disrupt operations.

Historically, copper and aluminum were the primary materials used in electrical conductivity and grounding applications. However, recent advancements have introduced composite conductors, such as steel-reinforced aluminum (ACSR), which improve mechanical strength while maintaining conductivity (Riba, Liu, Moreno-Eguilaz and Sanllehí 2022; Wang, Zhu, Niu and Mao 2021). The transmission of electricity at high voltages (above 110 kV) minimizes energy loss over long distances, making ACSR conductors widely used in overhead power lines (Verhoeven et al., 2022; Lv et al., 2019).

In photovoltaic plants, grounding materials play a crucial role in both conductivity and electrostatic discharge protection. Copper-clad steel has demonstrated performance equivalent to pure copper in large-scale renewable energy projects, such as wind and hydroelectric power plants. Studies suggest that by 2050, the demand for metals in the wind and solar PV power systems will increase significantly, with solar PV leading to this demand (Chen, Kleijn and Lin, 2023). Copper-clad steel electrodes offer advantages such as corrosion resistance, theft reduction, and lower costs, making them suitable for power system grounding (Southey, Jordan and Dawalibi, 2022).

Copper-clad steel (CCS) conductors have emerged as an alternative to pure copper in grounding applications, particularly for economic and system safety reasons. These bimetallic conductors combine the mechanical strength of steel with the high conductivity and corrosion resistance of copper (Knych et al., 2022). Studies show that CCS grounding rods can provide similar or even superior performance to copper rods while significantly reducing material costs (Zhang et al., 2017).

The electrical properties of CCS conductors depend on factors such as resistivity, thermal coefficient, and ambient conditions. Their conductivity typically ranges between 15% and 40% IACS (International Annealed Copper Standard), which must be considered when designing grounding systems (Eduful and Atanga, 2020). For effective current dissipation, the copper layer thickness should be equal to the skin depth of the current, ensuring optimal performance in high-frequency discharge events.

In Brazil, the COVID-19 pandemic disrupted global supply chains, leading to a shortage of copper conductors (Nakamura and Managi, 2020). This scenario accelerated the search for alternative materials in the energy sector, highlighting the importance of resilient supply chains and sustainable resources. This research investigates the technical and economic feasibility of replacing pure copper conductors with copper-clad steel conductors in grounding systems of a commercial photovoltaic solar plant (UFV).

## 2 Methodology

Installing large-scale photovoltaic (PV) plants in rural areas in Brazil and around the world has become increasingly frequent, but there is little knowledge about the implementation and installation of lightning and discharge protection in large-scale PV plants and it is still premature (Charalambous, Kokkinos and Christofides, 2014).

The study monitored the installation of a photovoltaic power plant. Data collected from the participating companies underwent thorough qualitative and quantitative analyses, emphasizing the implementation of conductor cables and grounding rods within the comprehensive solar complex system. In reference to the attributes of the conductors utilized in the installation, bare copper cables with a cross-section of 50 mm² have been substituted with IACS copper-clad steel cables of the same cross-section, as well as 40% IACS copper-clad steel cables with a cross-section of 70 mm². The technical data for these materials were obtained from the NBR 5419 standard (Associação Brasileira de Normas Técnicas (ABNT), 2015) and the supplier's specifications. The 40% IACS copper-clad steel wires consist of 65% steel and 35% copper. To assess copper savings in the installation of the entire solar complex, the volume of each material was calculated and compared.

The grounding rods used in the project can have diameters of either 3/4" inches (19,05 mm) or 5/8" inches (15,87 mm), which influences the mechanical strength of the grounding system. A study on a solar power plant in Bangli suggests that for the grounding system, it is recommended to install two electrodes with a length of 3 meters and a diameter of 5/8 inches. In large-scale grounding systems, 3/4 rods are the most suitable for grounding, as they are more efficient and durable.

The study includes data from eight solar farms with different power generation capacities, allowing the use of both diameters according to the project specifications. In terms of durability, the difference between copper and copper-clad steel grounding rods is minimal. Regardless of the rod diameter, the minimum copper layer thickness for a high-layer copper-clad steel rod is 254 μm (0.254 mm). These rods are coated with electrolytic copper through the anodic electrodeposition process, ensuring an inseparable and homogeneous bond between the metals.

Initially, product suppliers were requested to provide data on the physical characteristics (such as material specifications, resistivity, conductivity, weight, and length) and economic values of their products. The data collected was systematically recorded in tables and utilized to conduct technical and economic feasibility analyses.

## 3 Results and discussions

This section presents the main findings derived from the application of the methodology previously described. The analyses focused on evaluating the network's resilience under different failure scenarios, using predefined performance metrics. The data obtained enabled a comparison of the simulated models' performance and helped identify critical points affecting the robustness of the studied topology. Figure 1 provides a visual summary of the context and key outcomes of this study.

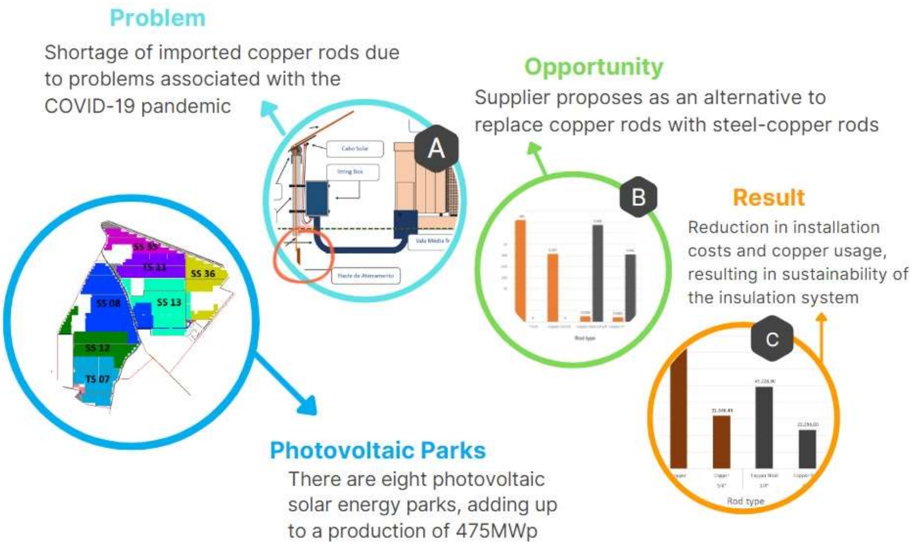


Figure 1. Overview of the study context and outcomes.

The diagram illustrates the shortage of imported copper conductors due to the COVID-19 pandemic (Problem), the supplier's proposal to replace copper rods with copper-clad steel alternatives (Opportunity), and the observed benefits in terms of cost reduction and improved sustainability of the grounding system (Result). The map also displays the layout of the eight photovoltaic parks that comprise the studied plant, totaling 475 MWp of installed capacity.

### 3.1 Characteristics of the studied photovoltaic solar plant

The study was conducted in a photovoltaic solar plant (*UFV Sol do Sertão*), located in the city of Oliveira dos Brejinhos, in the state of Bahia (Figure 2). The project received R$1.4 billion in investment and has 475 MW of installation capacity. The general scope for service involves all components of a photovoltaic system, this includes conductors, photovoltaic panels, switches, mounting system, string box (protection devices), and inverters. Services include soil testing, construction site management, project execution, earthworks, access routes, drainage, electromechanical assembly, underground low and medium voltage network setup, commissioning, and complete project documentation.

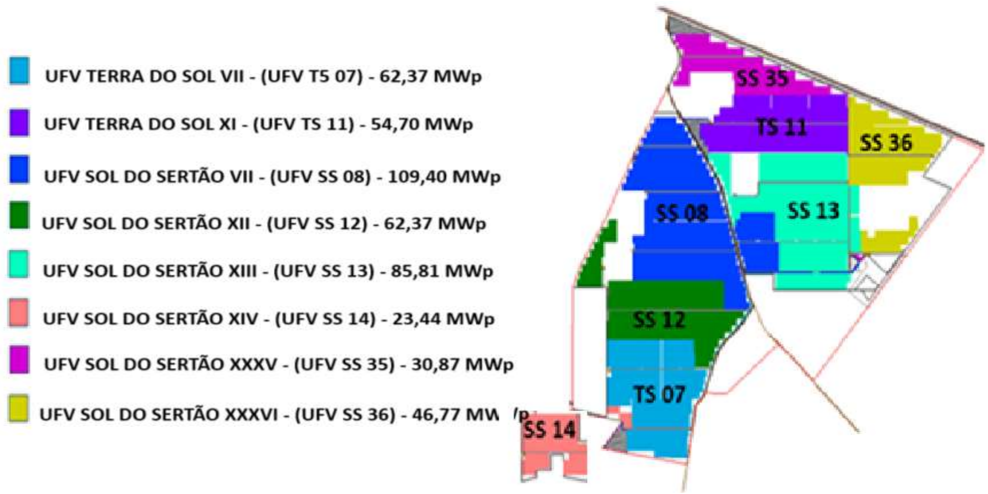


Figure 1. List of commercial-scale photovoltaic parks.

This plant will have a total installed power of 475 MWp, distributed in 8 commissioned parks, with a total area of 977 ha (9.77 km²), there will be 800 ha (8 km²) for the installation of the modules, a suppression of 752 ha (7.52 km²), 135,251m of low voltage trenches (low voltage conductor), 24,274m of medium voltage trenches (medium voltage conductor), 61 ITS bases (solar voltage inverter), 170,240un of driven piles, 1,075,200 modules, 70% of 35W and 30% of trackers and 2,318un of String box (command box) SB. Each module will be grounded with rods installed as shown in the grounding system installation method (Figure 3).

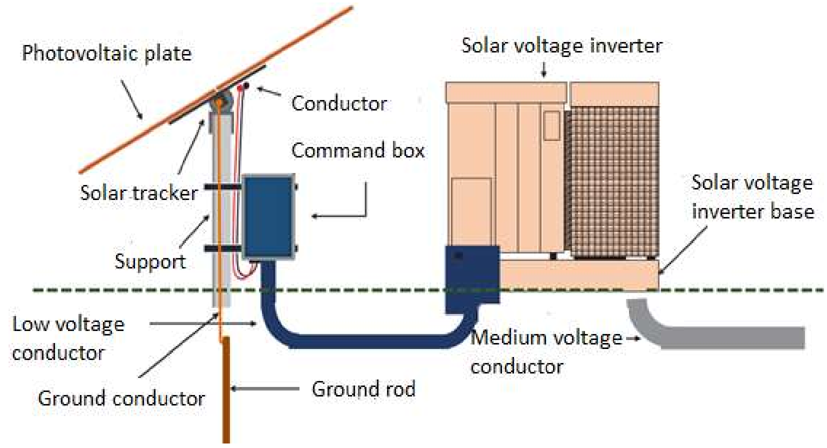


Figure 2. Grounding system installation method.

Comprising all these services, we arrived at the conductor cables for grounding under study with a total of 280 km and 512 units of grounding rods, all for the complete system, composed of these 8 units. The power of each plant varies from 23.44 MW to 109.85 MW.

### 3.2 Characteristics of conductor cables

The data collected on the conductors used in the installation of the solar complex are presented below. The raw data used to generate these results is available online. The data were obtained from and from conductor suppliers.

The analysis of the collected data showed that the amount of copper for copper-clad steel conductors is significantly lower for these conductors. For replacing the 50 mm$^2$ (13.85 m$^3$) section copper cable for system installation. When replacing it with a 50 mm$^2$ (4.61 m$^3$) copper-clad steel conductor for the installation of the same system. If the conductors are replaced with 70 mm$^2$ (7.32 m$^3$) copper-clad steel for system installation. In other words, replacing it with 50 mm$^2$ cables (steel copper) generates a reduction of 66.71% in copper. For replacement by 70 mm$^2$ cables (steel-copper), it decreases 47.14% of copper about solid copper conductors (Figure 4).

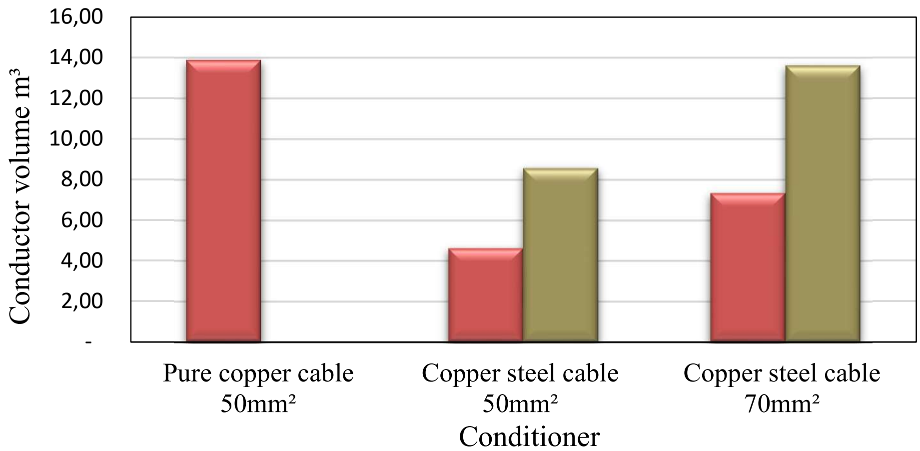


Figure 3. Volume of copper and steel in the cables are used as conductors of the grounding system.

Electrical resistivity is an intrinsic property of materials that quantifies their opposition to electric current flow, measured in ohmmeter (Ω·m). Materials with lower electrical resistivity allow better electron flow and greater current conduction (Halliday, Resnick and Walker, 2011). Copper-clad steel cables exhibit higher electrical resistance than pure copper conductors due to the higher resistivity of steel.

To mitigate resistance differences, 70 mm² cables were used, reducing discrepancies in electrical resistance. However, the increased resistivity of the cables does not significantly affect the expected grounding resistance of the system (Gall et al., 2021), as soil resistivity remains the dominant factor in grounding performance. Studies show that copper-clad steel significantly improves electrical conductivity compared to uncoated steel (Mandal and Mondal, 2018). (Figure 5).

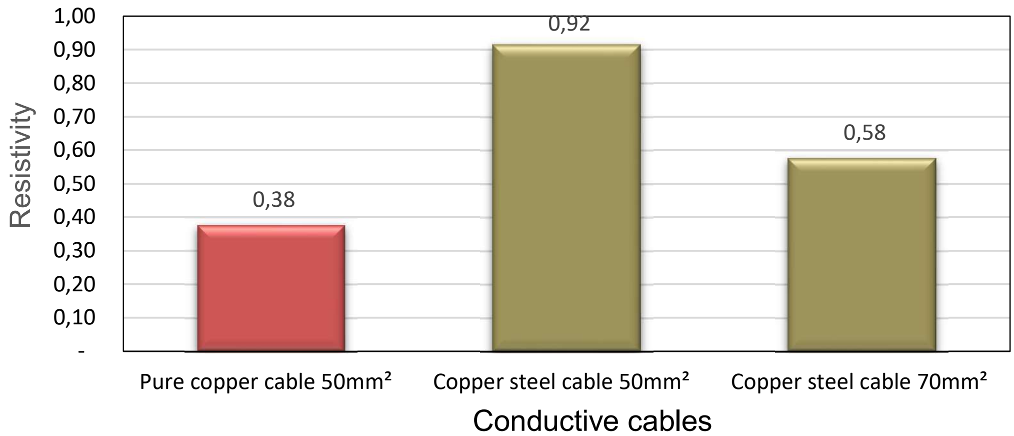


Figure 4. Comparison of resistivity of pure copper / copper-clad steel in the conductor cables for the system.

The most important parameter to be observed is admissible short-circuit current for an event of 50ms (in kA), necessary for the proper functioning of the system and the passage of electrical current above normal. When the analysis was carried out, the results showed that of the three cable options, all have a capacity greater than the value provided in the regulations (Figure 6).

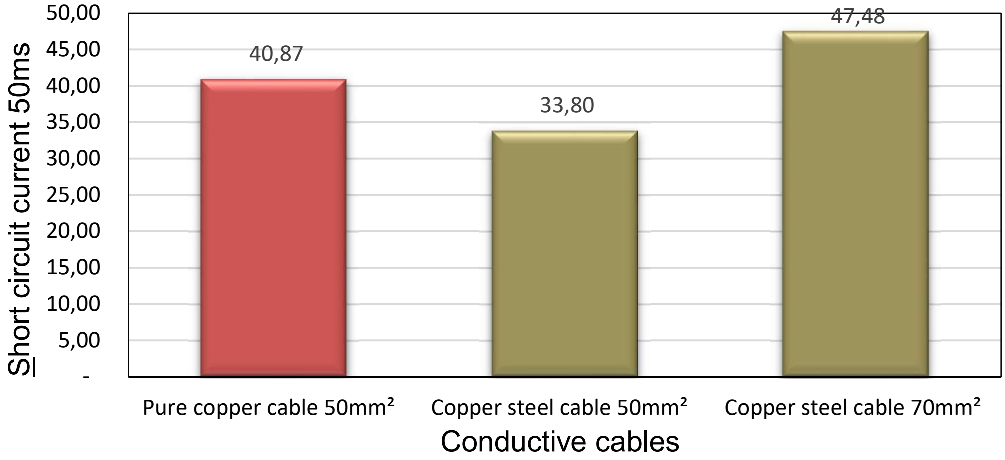


Figure 5. Comparison of the short-circuit current limits in the system conductors.

In summary, replacing the 50 $mm^2$ copper conductor cable with a 70 $mm^2$ copper-clad steel conductor cable resulted in greater resistivity and greater current in the system. This situation represents the possibility of substitution. However, the customer chose to use the solid copper cable as the conductor. The economic analysis, which will be presented later, demonstrates an economic advantage of the use of copper-clad steel cables.

### 3.3 Characteristics of conductor rods

After analyzing the electrical cables for the solar complex, an additional assessment was conducted to evaluate the replacement of 3/4” and 5/8” copper rods used in the grounding system. As shown in figure 7, the total volume of copper required for installation, considering 3/4” and 5/8” solid copper rods, is 0.460 $m^3$ and 0.307 $m^3$, respectively.

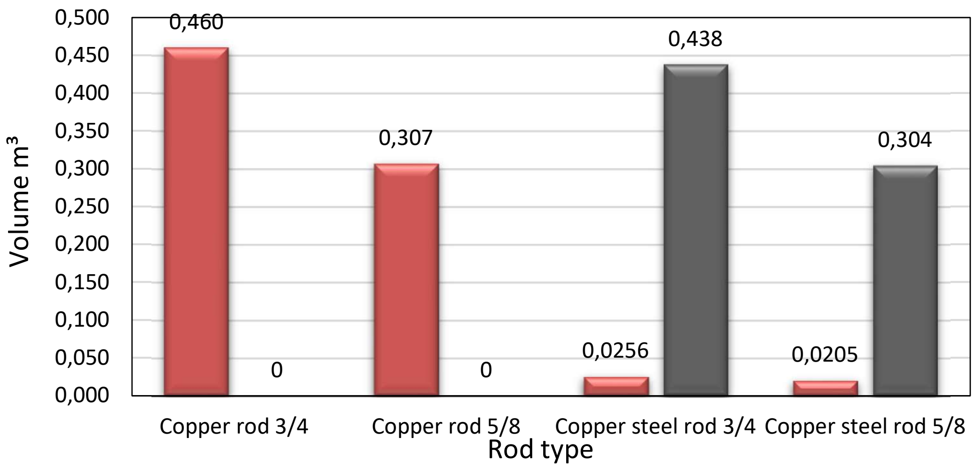


Figure 6. Volume of copper and steel rods for the power plant grounding system.

If copper-clad steel rods are used instead, the required copper volume decreases to 0.0256 $m^3$ for 3/4” rods and 0.0205 $m^3$ for 5/8” rods, while the corresponding steel volume in the rods increases to 0.438 $m^3$ and 0.304 $m^3$, respectively. The reduction in copper usage achieved by switching to copper-clad steel rods is 94.43% for 3/4” rods (0.434 $m^3$ less copper) and 93.32% for 5/8” rods (0.286 $m^3$ less copper) compared to solid copper rods. Additionally, copper-clad steel offers improved corrosion resistance in non-saline and slightly saline soils. Its resistance increases over time with immersion and stabilizes in higher soil salinity conditions (Zhang et al., 2017).

### 3.4 Economic feasibility analysis of the replacement of conductors for the system

The analyzed comparison of the grounding cables refers to 3 in budgets of the materials to be used in the system, the material specifications refer to the data presented in the data collection instrument (Comparative and data of the grounding cables) at the beginning of these results (Section 4.2), total values are described for the proposed system installation, which is estimated at 280 km of cables.

The analysis of the values of copper-plated steel (proposal C) for the proposal of supplier "A" for solid copper cable, represents a difference greater than 65%, and the proposal of supplier "B" for solid copper cable represents a difference greater than 95%. Therefore, the use of copper cables represents an increase in the value for all the cabling of the analyzed work from R$2,648,800.00 for supplier "A" to R$ 3,850,000.00 for supplier "B" (Figure 8).

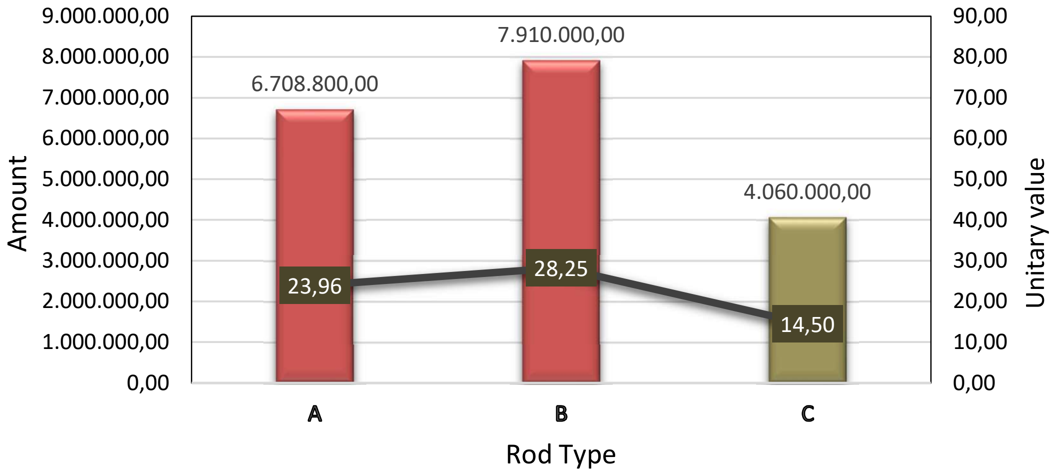


Figure 7. Graphical representation of comparative cable cost data (in Reais).

The analysis of the ground rod values is based on four material budgets, each with the potential to be used in the project. The material specifications are referenced in the comparative study data and the ground rod data (Section 4.3), where the values are representative of the proposed system, totaling 512 units. The comparative analysis of the two proposals from supplier "A" for rods with diameters of 3/4" and 5/8" revealed a price difference of R$ 43,913.60, representing 59.475%. Similarly, the budget analysis for supplier "B" showed a difference of R$ 25,942.80 and a percentage difference of 52.83% for rods of the same diameters (3/4" and 5/8").

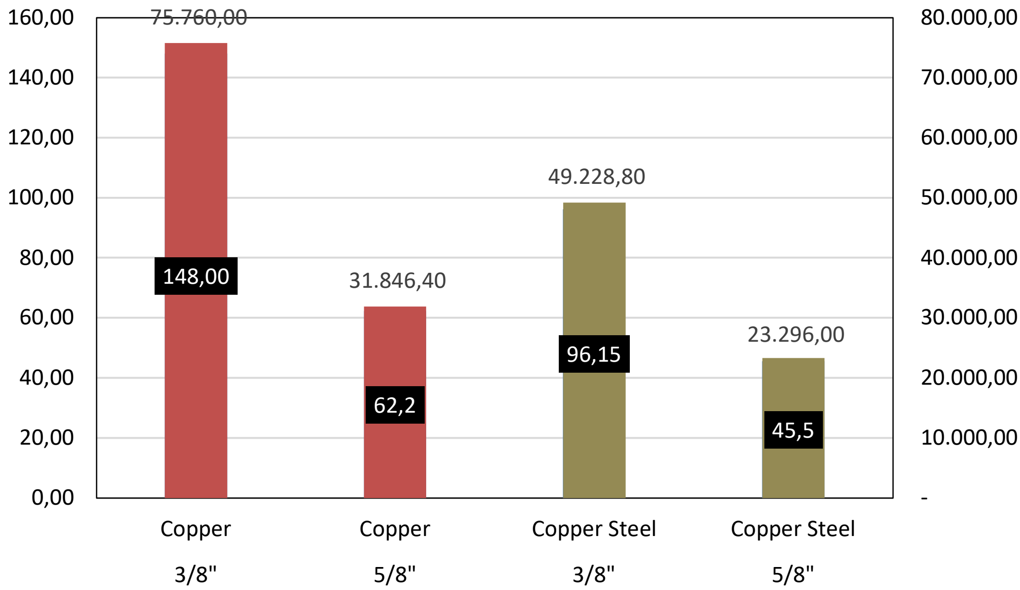


Figure 8. Graphical representation of the comparative data of values in the ground rods.

When comparing suppliers, A and B for 3/4" diameter rods, the price difference is R$ 26,531.20, a 38.482% variation, indicating that supplier B is the better choice. For 5/8" diameter rods, the difference between suppliers amounts to R$ 8,550.40, with a 34.176% variation, again demonstrating that supplier B is the most cost-effective option. Therefore, based on the budget analysis, using copper-clad steel rods in both 3/4" and 5/8" diameters are the most suitable alternative.

The IEC 62305 (IEC, 2010) standard, which is the base standard of NBR 5419 (ABNT, 2015), recommends a diameter of 70mm² for copper-plated steel. NBR 15751 (ABNT, 2013) indicates the substation for diameters smaller than 50mm², due to the mechanical strength of steel. Composite copper-clad steel wire exhibits higher electric conduction properties than copper wire at specific frequencies, due to the reflection of electromagnetic waves at the interface inside the composite wire (Baojun Fei, Mingbing Fei and Zhenghong Chen, 1999). Considering the divergence between the standards, the consultants admit that the requirement of 70mm² of NBR 5419 is not technically justified, despite this being the minimum value tabulated.

However, the standards do allow the application of this material and do not show any damage to the project. In summary, copper-clad steel conductors are efficient, have superior technological properties, and offer economic benefits compared to traditional conductors in substation grounding projects While economic analysis shows clear advantages, market acceptance may still be a challenge. Some customers and industry professionals may hesitate to replace traditional materials such as pure copper with copper-clad steel rods. (Southey, Jordan and Dawalibi, 2022; Zhang et al., 2017).

In contact with the product's commercial representative, the engineer reports that from the point of view of performance for atmospheric discharges, due to the high-frequency components of the lightning and the skin effect, currents of an impulsive nature will circulate only through the copper sheath of the cable and no loss of performance is expected due to the switch from steel cable to copper-steel. The qualitative and quantitative data collected, considering the physical, technical, and financial characteristics of the two materials, showed that copper-clad steel cables and rods presented advantages in technical and economic feasibility, mechanical resistance and, according to representatives, reduced the occurrence of theft and useful life if equal to copper (average 40 years).

## 4 Conclusion

This study aimed to investigate the physical and technical aspects of the replacement of copper conductors with copper-clad steel conductors in grounding systems and conductors in a photovoltaic solar plant built for the commercial production of electricity. The study demonstrated that the replacement of copper conductors with copper-clad steel conductors in grounding systems of photovoltaic plants is technically and economically viable.

The results indicate benefits such as cost reduction, increased mechanical strength, and lower risk of theft, without compromising the expected electrical performance. The technical analysis reinforced that, due to the skin effect, impulsive currents from atmospheric discharges are conducted through the copper layer, ensuring system efficiency.

The research contributes to the search for sustainable solutions in the energy sector, considering the growing demand for alternative conductive materials. More research is needed to study the durability of conductors in different environments and to evaluate their market acceptance.

The adoption of copper-clad steel conductors could represent a significant advance for large-scale renewable energy projects, making solar power generation more affordable and sustainable, in line with the needs of the global energy transition.:

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