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Original Article

Influence of Cabling on Photovoltaic System Performance: Wire Length, Diameter, and Material

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Abstract: Despite advancements in solar photovoltaic (PV) technology, significant challenges remain in the Global South, including financial, human resource, environmental, and technological constraints. System losses—caused by reflection, temperature effects, inverter inefficiency, cabling losses, shading, and degradation—are a major concern. This study examines how cabling parameters—wire length, diameter, and material—affect PV system performance and energy losses. Using a computational model, it evaluates a 3 kWp PV system in Durban, South Africa, analyzing efficiency, specific annual yield, and avoidable CO_2 emissions across various cabling configurations. The study's key findings include: at a constant wire diameter of 4 mm, specific annual yield decreases as wire length increases, dropping from 977.36 kWh/kW at 5 m to 966.32 kWh/kW at 50 m, reflecting efficiency losses; at a constant wire length of 20 m, yield improves with increasing diameter, rising from 970.71 kWh/kWp at 2.5 mm to 977.81 kWh/kWp at 20 mm. Beyond 25 mm, yield gains diminish, stabilizing around 978.39 kWh/kW at 90 mm; at a fixed wire length of 20 m, avoided CO_2 emissions increase with wire diameter up to 25 mm, after which gains level off from 30 mm to 90 mm; at a constant diameter of 4 mm, avoided CO_2 emissions increase from 1,378 kg/year at a wire length of 5 m to 1,363 kg/year at 50 m. These findings highlight the importance of optimizing cable parameters to minimize system losses and enhance the overall efficiency and sustainability of PV systems.

1. Introduction

The transition to a net-zero carbon emissions economy is crucial for mitigating climate change and reducing the environmental impact of fossil fuel dependence. Solar photovoltaic (PV) systems are essential for achieving this goal by providing clean and renewable energy, decentralizing energy generation, enhancing energy security, reducing carbon emissions in energy-intensive sectors, and promoting economic growth and job creation [1, 2]. Solar PV systems convert sunlight into electricity without emitting greenhouse gases during operation. They can be installed at various scales, from large utility-scale farms to small rooftop installations, enhancing energy security by reducing dependency on centralized fossil-fuel-based power plants. This decentralized nature increases the resilience of the energy grid and empowers individuals, businesses, and communities to produce their clean energy. By increasing the share of solar PV in the energy mix, economies can significantly reduce their reliance on carbon-intensive sources like coal, oil, and natural gas. According to the International Renewable Energy Agency (IRENA), transitioning to a low-carbon energy system with solar PV playing a major role could reduce global energy-related CO_2 emissions by up to 70% by 2050 [3].

Solar PV systems are vital for delivering sustainable energy and achieving climate goals, including the Paris Agreement's target to limit global temperature rise below 2 °C [4, 5]. The International Energy

Agency highlights that distributed solar PV could meet nearly half of the global energy demand growth through 2040, with rooftop solar contributing significantly to reducing emissions in residential, commercial, and industrial sectors [6]. Solar PV systems also offer significant economic benefits, particularly regarding job creation. The solar industry is labour-intensive, requiring skilled workers for manufacturing, installation, maintenance, and operation. According to IRENA, the renewable energy sector employed over 11.5 million people globally in 2019, with solar PV accounting for approximately 3.8 million jobs [7].

While solar PV systems are widely recognized as a critical solution in combating climate change, concerns about their environmental impact and equity issues have also been raised [8, 9]. The growing demand for metals, driven by the need for technology and infrastructure in renewable energy production, could spark new mining activities, potentially leading to further environmental degradation [10]. Additionally, there are concerns about equitable access to the benefits of renewable energy, particularly in developing regions [11]. However, advances in design, sustainability, and recycling are expected to mitigate these concerns [12, 13]. Overall, the benefits of transitioning to renewable energy, particularly solar PV, far outweigh the costs. Ensuring equitable distribution of renewable energy benefits is crucial to avoid marginalizing low-income households and to promote fair access for all [14]. Despite significant advancements in solar PV technology over the decades, many challenges persist, particularly in the Global South. These challenges span financial, human resource, environmental, and technological constraints, all of which impact the widespread adoption and efficiency of solar energy systems [3, 15, 16]. Among the technological challenges, system losses pose a significant barrier, reducing the overall effectiveness of solar PV installations. These losses arise from various factors, including reflection, temperature effects, inverter inefficiency, cabling losses, shading, and long-term system degradation.

The absence of comprehensive localised standards results in cost increases and delays in implementing new PV projects [17]. While conventional electrical system standards can be adapted for PV industry use, modifications are necessary due to PV systems' unique characteristics, such as environmental dependencies and distinctive I-V curve behaviours. Issues like current fluctuations due to temperature changes or faults impact the sizing of wiring systems, fuses, blocking diodes, and other components. Improper selection or installation of cables, diodes, PV modules, and other components have led to failures in PV systems [18], with potential fire hazards from device malfunctions. Therefore, standards related to the wiring and protection of PV systems, which were not fully addressed in the referenced paper [19], may require adjustments or additional clauses. Figure 1 illustrates the typical components of a standalone PV system supplying a battery as a direct current (DC) load. Power generated by modules is distributed through electrical wiring and protective devices (e.g., fuses) to a DC-DC converter, which optimizes and transfers maximum power from PV modules to the battery. Combiner boxes consolidate wiring by combining power from multiple modules into a single interconnection while blocking diodes prevent reverse currents that could damage PV modules [20, 21].

Photovoltaic systems face several wiring and cabling challenges that can affect their performance, safety, longevity, and connector compatibility [22-25]. Using connectors from different manufacturers, known as cross-mating, can lead to poor connections, increased resistance, and potential failures. Ensuring all connectors are compatible and preferably from the same manufacturer is essential for system integrity; inadequate wire management: Neglecting proper wire management can expose cables to environmental damage, leading to insulation degradation and safety hazards. Implementing structured wire management practices, such as securing cables at appropriate intervals and using suitable clips or trays, is crucial for system reliability; misapplication of components: selecting inappropriate components, like non-ultraviolent (UV)-rated cable ties or improper fasteners, can compromise system durability. It's vital to choose components specifically designed for PV applications and environmental conditions to prevent premature failures. Others are environmental damage: cables are susceptible to damage from factors like UV radiation, moisture, and temperature fluctuations, which can degrade insulation and performance over time. Utilizing cables with appropriate insulation and protective measures can mitigate these risks of overheating. For example, improper cable sizing or bundling can lead to overheating, reducing efficiency, and potentially damaging the system. Ensuring correct cable sizing and adequate ventilation is essential to prevent overheating. Addressing these challenges through careful design, appropriate component selection, and regular maintenance can significantly enhance the performance and safety of PV systems.

This study aims to examine the role of cabling in the discrepancies between the amount of solar energy captured and the energy ultimately delivered by the system. By analysing how different cabling parameters contribute to these losses, the research aims to highlight the importance of optimising wiring configurations to improve overall system efficiency and performance. The research questions include:

- How do different cabling parameters, specifically wire length, diameter, and material, impact energy losses in a PV system?
- To what extent do variations in wire size and material contribute to the difference between the energy received from sunlight and the energy ultimately delivered by a PV system?
- What insights can computational modelling provide into optimizing wire sizes and materials for improved PV system performance?
- How can findings on cabling influences inform technical standards and policy frameworks to support the growth of efficient, safe PV installations?

The findings will offer insights into the performance of PV systems with different wire sizes and materials, providing valuable technical guidance for investors and installers. Furthermore, the study will supply crucial data to help regulatory and standard agencies establish frameworks that support the growth and provision of safe, clean electricity.

The paper is systematically structured to address the identified gaps as follows: section 1 provides an introduction, while section 2 outlines the methodology used to achieve the study’s objectives. sections 3 and 4 focus on extraction and discussion, respectively, of information from the study's report regarding the impacts of wire length, diameter, and material on PV system performance. Section 5 is the paper’s conclusion.

2. Materials and Methods

This study examines key factors contributing to energy losses in solar PV systems, focusing on cable losses. It uses published research and credible reports within the solar energy domain. Three scenarios—cable length, diameter, and material—are analysed to evaluate their impact on PV system performance through computational modelling. A hypothetical 3 kWp PV system is simulated using PV*SOL software to assess how wire size (length and diameter) affects performance. The scenarios consider a range of wire lengths (5 m–50 m), diameters (2.5 mm–90 mm), and two materials. The system's performance metrics, including system losses, specific annual yield, and performance ratio (PR), are analyzed. The process of evaluation of the cabling effect is depicted in figure 1.

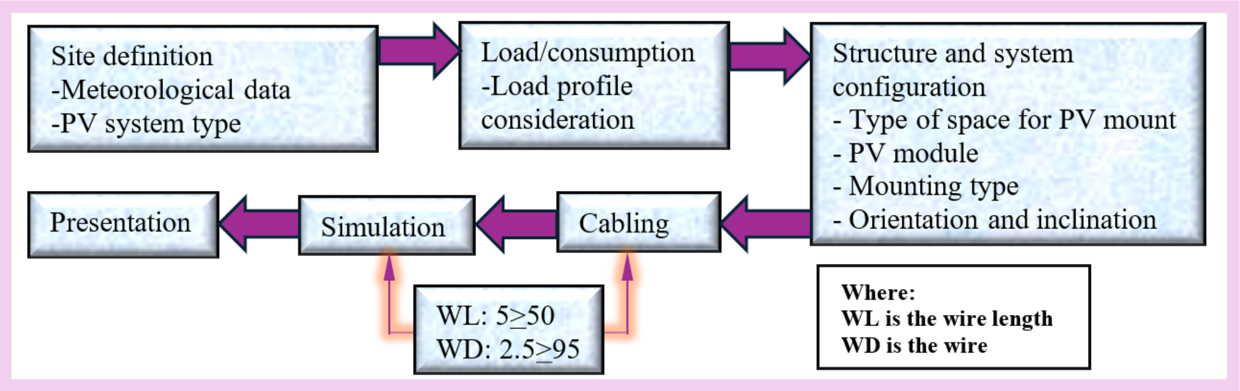

Figure 1: Block diagram of a process of evaluation of cabling effect.

2.1. Material Structure and Efficiency Variation

The efficiency of PV panels varies significantly with changes in their material structure, particularly in how charge carriers (electrons and holes) move through the material. This varying efficiency is seen between crystalline silicon and thin-film panels, and this has been attributed to some factors, including material thickness, light absorption, and manufacturing process. The crystalline silicon panels are made of silicon crystals arranged in a regular lattice structure. Their panels typically have high efficiency (around 15-20%) due to the high charge carrier mobility within the crystalline structure. Electrons can move easily through the ordered lattice, leading to the effective conversion of sunlight into electricity. The thin-film panels use layers of different semiconductor materials, such as amorphous silicon, cadmium telluride, and copper indium gallium selenide deposited in thin layers onto a substrate. Thin-film panels generally have lower efficiency (around 10-15%) compared to crystalline silicon panels. This is partly due to lower charge carrier mobility in the less ordered structure of thin films. However, they offer advantages like flexibility, lower manufacturing costs, and better performance in low-light conditions.

While the material structure significantly influences the efficiency of PV panels, advancements in both crystalline silicon and thin-film technologies continue to push the boundaries of solar energy efficiency and cost-effectiveness. Each type of panel has its strengths, making them suitable for different applications depending on factors like cost constraints, space availability, and environmental conditions.

2.2. Energy Losses in Solar PV Systems

Energy losses in solar PV systems, ranging from 30% to 50%, occur at various stages, influenced by design, component quality, and environmental factors [26]. Modern PV panels, with efficiencies ranging from 15% to 25%, are classified into three main types as follows - monocrystalline panels, which achieve 20%–22% efficiency using single-crystal silicon [27]; polycrystalline panels, offering 15%–18% efficiency and composed of multiple silicon crystals [28]; and thin-film panels, which are lightweight, flexible, and operate at 10%–12% efficiency [29, 30].

System losses beyond panel efficiency include reflection, temperature effects, inverter inefficiency, cabling losses, shading, and degradation. A breakdown of these losses is presented in table 1.

Table 1: Sources of losses in PV solar system.

S/N	Source	Percentage	Description of impact
i	PV Panel efficiency	15–22	Modern PV panels convert only 15%-22% of sunlight into electricity, losing 78%-85% due to material limitations and light reflection or absorption by non-active components [28].
ii	Reflection and absorption losses	2-3	Typically, 2% to 3% of sunlight is lost due to these effects.
iii	Temperature losses	5-15	Panel efficiency drops by 0.4%-0.5% for every °C above 25°C, causing 5%-15% losses in hot climates [31].
i.	Inverter efficiency	2-5	Inverters are 95%-98% efficient, with 2%-5% energy lost during DC-to-AC conversion.
ii.	Cabling and resistive losses	1-5	Electrical resistance in wires and connections leads to 1%-5% energy loss, especially with longer or undersized wires [32].
iii.	Soiling (dirt, dust, and debris)		Dirt, dust, and debris can reduce energy output by 2%-5% or more if uncleaned.
iv.	Shading	5-20	Partial shading can cause 5%-20% energy losses, especially in series-connected panels.
v.	Mismatch losses	2-5	Variations in panel performance or exposure led to 2%-5% energy losses in arrays.
vi.	Degradation over time	0.5-1	Panels lose 0.5%-1% efficiency annually, totalling 10%-20% over 25 years.
vii.	Other losses	1-5	Factors like inverter startup/shutdown, suboptimal orientation, and tilt add 1%-5% additional energy losses.

2.3. PV System Cable Losses

Cable losses, often overlooked, significantly affect system performance. Factors such as corrosion, overheating, and resistance lead to energy dissipation. While cables account for only 4%–5% of total project costs, they can greatly influence power output [32]. Properly designed systems aim to keep cable losses below 2% [27], but real-world conditions often result in losses up to 3% [33]. Improper cable sizing leads to voltage drops - reducing inverter efficiency; inverter overheating: Caused by excessive resistance; power loss - lowering system energy yield; and safety risks - increased fire hazards due to electrical arcing. A well-designed PV system ensures optimal cabling to minimize losses and enhance longevity.

To minimize energy losses and optimize solar PV system performance, proper component sizing and effective operation and maintenance (O&M) strategies are essential [34]. While system design should follow relevant standards for safe operation, it often overlooks long-term Joule losses in cables. Research has mainly focused on improving solar cell efficiency, maximum power point tracking, and inverter topologies, with limited attention to optimal DC cable selection. Neglecting cable losses during design can compromise system efficiency and longevity, impacting key components like inverters, as outlined in Table 2.

Table 2: Effects of improper cable sizing in a PV system.

Increased voltage drops	Undersized or poor-quality cables can cause excessive voltage to drop, leading to lower voltage levels reaching the inverter. This forces the inverter to work harder to convert the available power, reducing its efficiency and possibly causing it to operate outside its optimal voltage range, which can lead to frequent shutdowns or reduced output.
Inverter overheating	Poor cabling can result in higher resistance, leading to greater energy dissipation as heat. This can cause components like the inverter to overheat, which not only reduces efficiency but can also lead to premature failure of the inverter or require derating (operating at reduced capacity).
Power loss	Poorly designed cables can cause substantial power losses due to increased resistance. The energy lost as heat reduces the overall energy yield of the PV system, directly affecting the amount of electricity the inverter converts and the system's return on investment.
System imbalance	Poor-quality cabling can create imbalances between different parts of the PV array, causing unequal power distribution. This can result in the inverter receiving mismatched voltages or current levels, which can lead to inefficient power conversion and potential damage to the inverter's components.
Safety risks	Undersized or damaged cables can cause electrical arcing, which poses serious safety hazards such as fires. This not only jeopardizes the inverter but can damage other PV system components and put the entire installation at risk.

2.3.1. Transmitting Power through Electrical Wiring

A PV system comprises multiple modules or module strings, with power transmitted through wiring and protective devices, such as fuses, to an inverter. Combiner boxes consolidate power from multiple modules, reducing wiring needs. Wires, typically made of copper or aluminium, have electrical resistance (R), causing voltage drops (V_d) and hindering current flow (I). Temperature variations impact the current and voltage of PV cells, affecting their efficiency and overall system performance [35], as outlined in Table 3.

Table 3: Wire resistance and current flow relation [21].

Wire voltage drops (Vd)	$V_d = I * R$ $= \frac{2*I*L*R}{A}$
Transmission power losses (Ptpl)	$P_{tpl} = I^2 R$ $= V_d * I$
Operating voltage of module strings (Vm)	$V_m = V_d + V_c$ $= I_m * R_m + V_c$
Maximum power output (Pmax)	$P_{\max} = V_{\max} * I_{\max}$ $=(FF) * V_{OC} * I_{SC}$

Where Vc is the voltage of the corresponding combiner box; Vinv is the inverter DC voltage; Ic is the combiner box transmitting current; Rc is the resistance of the wiring connecting a combiner to the inverter; Im is the current produced by Vm; Rm is the resistance of the wiring connecting module-strings to combiner boxes; FF is the fill factor; Voc and Isc are the open circuit voltage and short circuit current, respectively; subscript, max, is the maximum power point (MPP) in the I–V curve of the module; A is the cross-sectional area of the conductor (in mm^2)

2.3.2. R-Square (Coefficient of Determination)

R-Square or coefficient of determination (COD) indicates how well a model explains data variability. A value of 1 signifies a perfect fit, while lower values indicate unexplained variability. It measures how effectively an independent variable, like wire length, explains variation in a dependent variable, such as wattage loss.

2.3.3. Residual Sum of Squares

Residual sum of squares (RSS) quantifies the difference between observed and predicted data points in a model, such as linear regression. Lower RSS values indicate better model accuracy, while higher values suggest significant discrepancies between predictions and observations.

2.3.4. Pearson's Correlation Coefficient

Pearson's coefficient (r) measures the linear relationship between two variables. Values range from -1 to 1, where 1 indicates a perfect positive relationship, -1 is a perfect negative relationship, and 0 no linear relationship.

2.4. PV System Design and Simulation

This study uses PVSOL software for PV design and simulation, which involves these key steps include - defining the location, orientation, tilt angle, and meteorological parameters; configuring the PV system layout, selecting modules and inverters, and optionally adding battery storage; inputting electrical parameters like wire lengths and cross-sections to optimize efficiency; simulating to calculate metrics like specific annual yield and performance ratio (PR); and exporting detailed reports for documentation. While the study excludes financial analysis, PVSOL also supports advanced features, such as shading analysis and economic evaluations.

3. Results

In this section, information regarding the impacts of wire length and diameter on PV systems will be extracted from the study's report and discussed. Understanding and optimising the operational parameters of PV systems will facilitate the efficiency and output of PV systems, leading to higher energy yields and better performance. The input parameters and description of the system’s circuit for this study are presented in table 3 and figure 2, respectively.

Table 3: PV generators 1 and 2.

Module Area - Bay 1-Roof Area East	
Name	Bay 1-roof area east
Location (Steve Biko Campus)	-29.852922926731402, 31.005967931251714
PV Modules	5 x 300 Wp - Si monocrystalline (v2)
Inclination (°)	51
Orientation (°)	East 90
Installation Type	Roof parallel
PV Generator Surface (m^2)	8.4
Module Area - Bay 1-Roof Area West	
Name	Bay 1-roof area west
PV Modules	5 x 300 Wp - Si monocrystalline (v2)
Inclination (°)	51
Orientation (°)	West 270
Installation Type	Roof parallel
PV Generator Surface (m^2)	8.4
Ambient conditions	
Annual average temperature outside (°C)	20.8
Module annual average temperature at Bay-1 roof (°C)	25.2
Module annual average temperature at Bay-2 roof (°C)	25.3
Annual average windspeed (m/s)	6.3

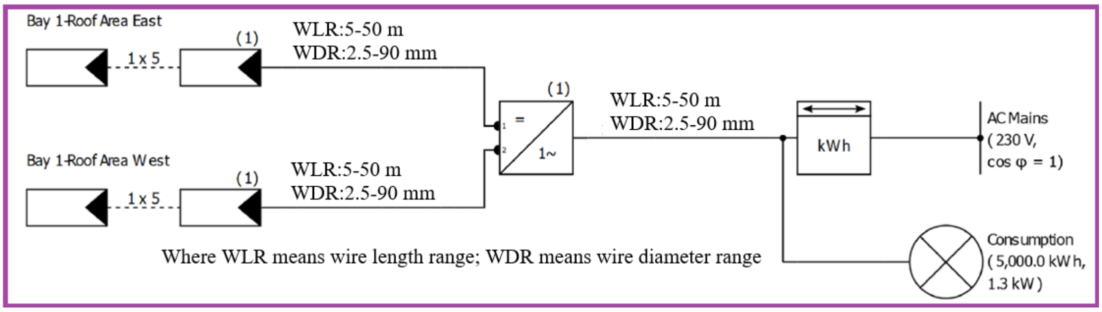

Figure 2: A description of the system's circuit.

3.1. Impact of Wire Length and Diameter on PV System

The effects of different wire lengths and diameters of copper and aluminium on PV system performance were examined using computational modelling and the results obtained are presented graphically and analysed, as presented in figure 3. The wire length shows direct proportionality with power loss for both copper and aluminium wires, as depicted in figure 3 (a). In the case of wire diameter, a polynomial relationship was observed with a straight-line relation from 1 mm to 15 mm diameter. The relation tends to unity as the diameter increases for both copper and aluminium wires, as seen in figure 3(b).

The linear relationship observed between wire diameter and resistance from 1 mm to 15 mm indicates that within this range, resistance decreases predictably as diameter increases, which conforms with the resistivity relation, as in equation (1).

$$R = (\rho * L)/A \qquad (1)$$

Where R is the electrical resistance of the wire; ρ is the resistivity of the material; L is the length of the wire; A is the cross-sectional area of the wire.

The convergence of the resistance ratio between copper and aluminium wires toward unity for larger diameters is due to the diminishing effect of resistivity differences as the cross-sectional area (and thus the diameter) increases, leading to proportionally similar resistances despite the inherent material differences.

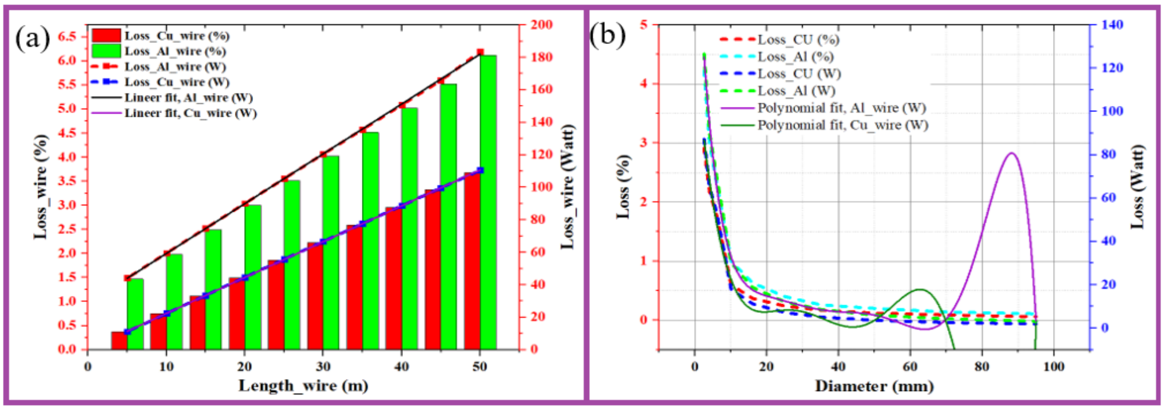

Figure 3: Wire size against power loss (a) the graph of wire length and power loss; (b) the profile of wire diameter and power loss.

3.1.1. Length of Wire and Power Loss

Analysis was conducted on the graphs to establish the curve's equations and statistical parameters, such as a residual sum of squares, Pearson's ratio, r-square, and adj. r-square and these are presented in figure 4 and table 4. Figure 4 (a and b) presents information about the length of the wire about PV system power loss.

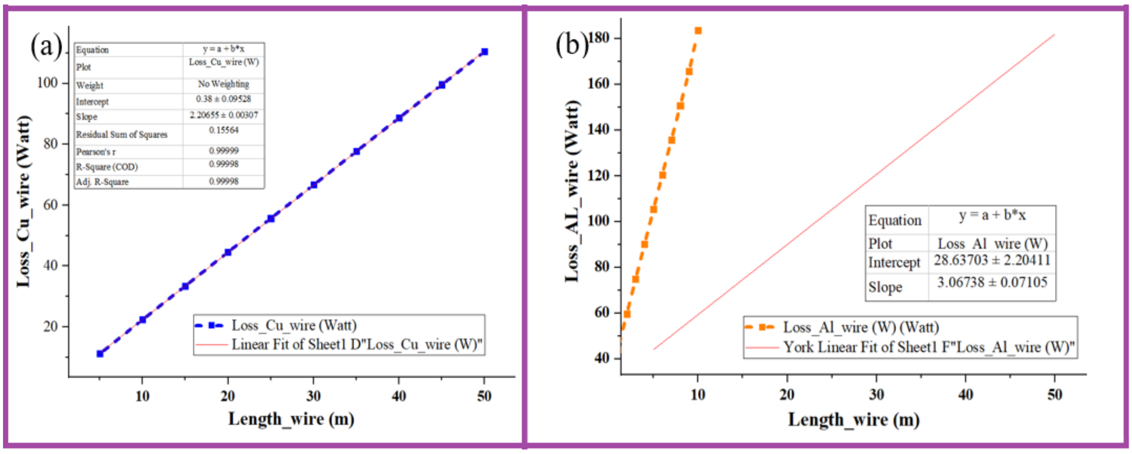

Figure 4: Statistics information (a) linear fit Copper wire length vs power loss; (b) linear fit Aluminium wire length vs power loss.

Table 4: Statistical information on wire length and power loss in PV system.

Plot	Loss Copper wire (W)	Loss Aluminium wire (W)
Intercept	0.38 ± 0.09528	28.65333 ± 0.49196
Slope	2.20655 ± 0.00307	3.06679 ± 0.01586
Residual sum of squares	0.15564	4.14897
Pearson's r	0.99999	0.99989
R-Square (COD)	0.99998	0.99979
Adj. R-Square	0.99998	0.99976
Equation ($y = a + b*x$)	$y = 0.38+2.20655*x$	$y = 28.65+3.07*x$

Where y is the dependent variable (output); x is the independent variable (input); a is the y-intercept, indicating the value of y when $x = 0$; b is the Slope, representing the rate of change in y for a unit change in x

3.1.2. Wire Diameter and Power Loss

Analysis of wire diameter and its impact on power loss, including statistical metrics like RSS, Pearson's ratio, R^2, and adjusted R^2, is presented in figure 5 and table 3. Figure 5 (a and b) illustrate the relationship between wire length and PV system power loss.

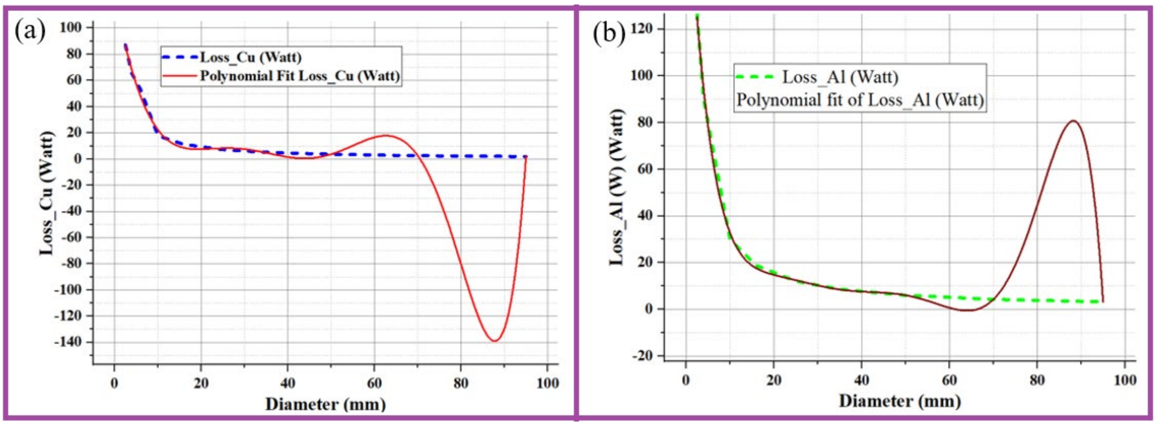

Figure 5: Statistics information (a) polynomial fit of wire Copper dia vs power loss curve; (b) polynomial fit of wire Aluminium dia vs power loss curve.

The comparison between the impact of copper and aluminium wire diameter curves on performance will be discussed based on their curve fitting equations, RSS, R-Square (COD), and Adjusted R-Square values presented in table 5.

Table 5: Relation between wire diameter (mm) and power loss (Watt) in PV system.

Plot	Loss Copper wire (W)	Loss Aluminium wire (W)
Intercept	126.04441 ± 21.71225	28.65333 ± 0.49196
Slope	2.20655 ± 0.00307	3.06679 ± 0.01586
Residual sum of squares	62.16624	51.90965
R-Square (COD)	0.99288	0.99692
Adj. R-Square	0.96794	0.98616

3.1.3. Copper Wire Diameter Equation

$$y = 126.04441 - 17.75235 * x^1 + 0.84801 * x^2 - 0.00605 * x^3 - 6.74275E - 4 * x^4 + 2.11267E - 5 * x^5 - 2.38101E - 7 * x^6 + 9.38875E - 10 * x^7 \qquad (2)$$

Aluminium wire diameter equation:

$$y = 28.65333 - 36.32572 * x^1 + 3.0271 * x^2 - 0.1358 * x^3 + 0.00348 * x^4 - 5.06486E - 5 * x^5 + 3.87706E - 7 * x^6 - 1.20351E - 9 * x^7) \qquad (3)$$

3.1.4. Impact of Wire Size on Power Generation

Figure 6 illustrates the effect of wire length and diameter on a PV system's specific annual yield and PR:

Figure 6 (a): At a constant diameter of 4 mm, specific annual yield decreases as wire length increases from 5 m (977.36 kWh/kW) to 50 m (966.32 kWh/kW), reflecting efficiency losses due to increased resistance.

Figure 6 (b): At a constant length of 20 m, yield improves with diameter, rising from 970.71 kWh/kWp at 2.5 mm to 977.81 kWh/kWp at 20 mm. Beyond 25 mm, yield gains diminish, stabilizing around 978.39 kWh/kW at 90 mm.

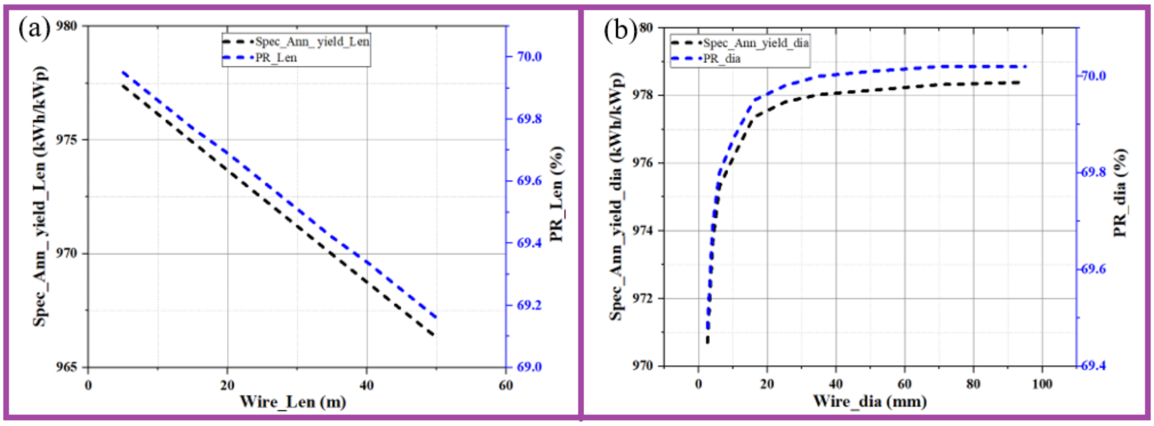

Figure 6: Performance PV system (a) influence of wire length; (b) influence of wire diameter.

3.1.5. Influence of Wire Size on Avoidable CO_2 Emissions

In the scenario of a constant wire diameter (4 mm), the 3 kWp installed capacity PV system avoided CO_2 emissions of 1378 kg/year at a wire length of 5 m and 1363 kg/year at 50 m, as presented in figure 7(a). The decrease in avoidable emissions is due to the increased energy losses in longer cables as the wire length increases, which results in lower overall system efficiency. In figure 7(b), it was observed that at a constant wire length of 20 m, the avoided CO_2 emissions of a 3 kWp PV system increase as the wire diameter grows from 2.5 mm to about 25 mm, and then remain almost constant from 30 mm to 90 mm.

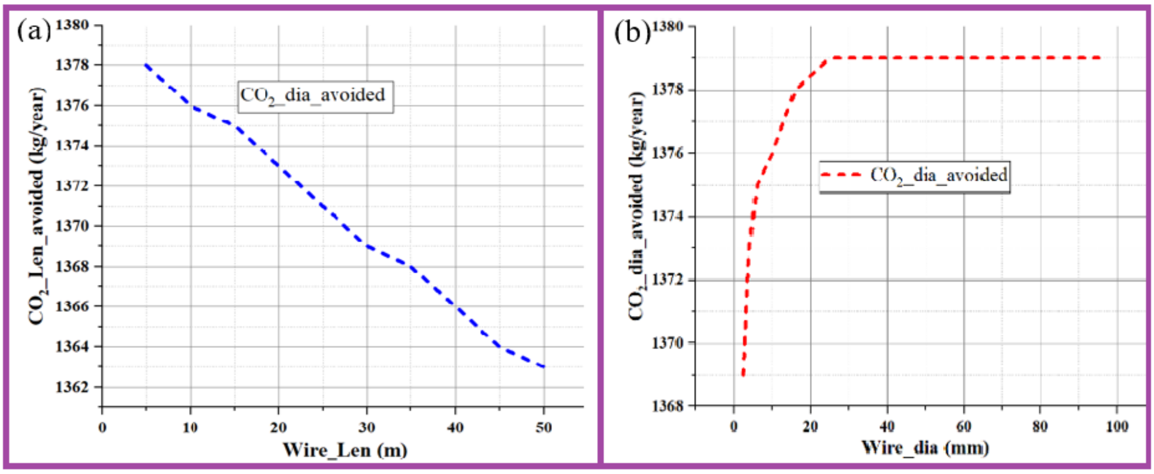

Figure 7: Influence of wire size on avoidable CO2 emissions (a) wire length impact; (b) wire diameter impact.

3.2. *Optimising the Hypothetical 3 kW PV System*

The most commonly used sizes for DC cables in PV systems are 2.5 mm², 4 mm², and 6 mm². However, 4 mm² PV cables are the standard choice for the majority of installations due to their balance between current-carrying capacity, voltage drop mitigation, and cost-effectiveness [36]. Determining the optimal wire diameter and length for a 3 kW PV system requires knowing the system's voltage, current, type, and allowable voltage drop [37, 38]. The allowable range of voltage and current for the different types of PV systems is presented in table 6.

Table 6: Voltage and current ranges for the different PV system types [39, 40].

System type	Voltage range (V_{max})	Current range (I_{max})	System type	Voltage range	Current Range
Small off-grid (<3 kW)	12V–48V	10A–100A	Grid-tied	200V–600V	5A–20A
Large off-grid (3–10 kW)	48V	50A–200A	Utility-scale	1000V–1500V	2A–10A

In this case study, the following design considerations were used to calculate the optimal wire lengths for a 3 kW PV system - 4 mm wire diameter, V_{max} and I_{max}, the allowable voltage drop of 1% and 2%, copper and aluminium, and off-grid and grid-tie PV systems [41]. Details of design consideration parameters and the corresponding wire lengths are presented in Table 7.

Table 7: 3 kW PV system design parameters considerations.

System type	Wire material	Installed capacity (kW)	Wire diameter (mm)	System current	System voltage	Wire length Voc drop = 1%	Wire length Vmax drop = 2%
Off-grid	Copper	3	4	62.5A	48 V	0.88 m	1.75 m
Grid-tie	Copper	3	4	13.04A	230 V	20.3 m	40.6 m
Off-grid	Aluminium	3	4	62.5A	48 V	8.4 m	16.8
Grid-tie	Aluminium	3	4	13.04A	230 V	0.145 m	0.291

4. Discussion

Considering section 3.1: for aluminium wire, the lower RSS (51.90965) indicates fewer residual errors compared to copper, and the higher R-Square (0.99692) shows the model explains 99.69% of the data variance. The adjusted R-Square (0.98616) further supports the model's accuracy, justifying its complexity. While both models perform well, aluminium wire demonstrates a better fit, suggesting greater accuracy in predicting diameter-related changes. However, practical selection between copper and aluminium wires depends on factors like cost, conductivity, and environmental durability.

The Residual Sum of Squares (RSS) for copper wire is 0.15564, indicating an excellent model fit with minimal deviation between observed and predicted power losses. For aluminium wire, the RSS is significantly higher at 4.14897, suggesting a less accurate fit and potential additional factors affecting aluminium wire losses. This highlights copper wire's more predictable relationship between length and power loss compared to aluminium. A detailed explanation of the results in sections 3.1.1 and 3.1.2, presented in figures 4 and 5 and table 4, are as follows:

Both copper ($R^2 = 0.99998$) and aluminium ($R^2 = 0.99979$) exhibit near-perfect linear relationships between wire length and power loss, confirming wire length as a strong predictor of losses for both. Copper wire has a slightly better model fit, emphasizing its consistency and reliability in minimizing energy losses.

Pearson's correlation coefficients of 0.99999 for copper and 0.99989 for aluminium confirm strong linear relationships between wire length and power loss for both materials. Copper shows slightly less variability, making it a better choice for applications requiring precise control over power losses, while aluminium may require accounting for additional factors.

The result in figure 6, indicates reduced resistance with larger diameters but diminishing returns beyond a certain size. Performance ratio trends the specific annual yield generation patterns, highlighting that increasing wire diameter reduces resistance and power losses, improving overall system efficiency. The result in figure 7 implies that increasing wire diameter reduces resistance and energy losses up to a certain point (around 25 mm diameter), after which further increases in diameter provide minimal additional benefits in terms of avoided CO_2 emissions. Beyond this size, the system's performance stabilizes, indicating that optimizing wire diameter for efficiency has limits, and oversized wires do not offer significant gains.

4.1. Practical Implications

Copper wires provide more predictable energy losses due to tighter model fit. Aluminium wires may require careful consideration of factors like sizing, connection quality, and environmental influences to minimize losses.

The size of the wire (also referred to as cabling) influences the system's voltage, power, safety, longevity, and cost. Therefore, cabling plays a crucial role in the performance, efficiency, and safety of a PV system. Undersized wires can cause significant voltage drops, leading to excessive power losses. Furthermore, inadequate wire sizing increases the risk of overheating, which can potentially result in a fire hazard. A detailed description of these parameters' influence is presented in Table 8.

Table 8: Parameters influenced cabling [42-45].

Parameters	Description
Voltage drops	Small wires cause significant voltage drops, reducing power delivery and system efficiency. Voltage drops should be kept below 2-3% for optimal performance. While larger wires reduce drops, they are more costly and harder to handle
Power losses	Smaller wires have higher resistance, causing more energy to dissipate as heat. Larger wires reduce resistance, minimizing power losses and improving system efficiency.
System Safety	Undersized wires risk overheating, leading to insulation damage or fire hazards. Proper wire sizing ensures safe current handling.
System longevity	Excessive heat from undersized wires accelerates wear, reducing the lifespan of cables and connected components. Correct wire sizing enhances durability and minimizes maintenance.
Cost considerations	Larger wires are costlier upfront but provide long-term savings through improved efficiency, reduced losses, and lower maintenance. Balancing cost with performance and safety is critical, especially for longer cable runs.
Wire length and diameter	Longer distances increase voltage drop. Thicker wires are often necessary for long runs to maintain efficiency and minimize losses.
Material and insulation	Copper is preferred for its low resistance, while high-quality insulation ensures protection against environmental factors.
Regulatory compliance	Compliance with electrical codes and standards is mandatory to ensure the safety, performance, and legal operation of PV systems.

4.2. Photovoltaic Panel Systems General Starting Template

Photovoltaic panel systems have evolved significantly, offering various technologies tailored to different needs. Creating a comprehensive comparison table for PV panel systems based on system size, efficiency, cost-effectiveness, losses, and space availability involves referencing specific models or types of panels. Table 9 serves as a general starting template, though the specifics will depend on the latest data and products available.

Table 9: Photovoltaic panel systems cost and application.

PV Panel Type	System Size (kW)	Efficiency (%) [46, 47]	Cost-effectiveness [48, 49]	Losses (%)	Space Availability
Monocrystalline Silicon	5-500+	15-22	\$3.00–\$3.50	15-20	Moderate
Polycrystalline Silicon	5-500+	13-18	\$2.80–\$3.00	18-22	Moderate
Thin-Film (CdTe)	1-50+	10-15	\$2.00–\$3.00	20-25	High
Thin-Film (CIGS)	1-50+	10-15	\$2.00–\$3.00	15-20	High
Bifacial Panels	5-500+	18-22	Varies; higher due to advanced technology	10-15	High
Multi-Junction Cells	Used in aerospace	Over 40% under concentrated sunlight	High; primarily used in specialized applications	Low degradation; high efficiency	Not used for standard installations due to cost

4.3. Comparison of Copper and Aluminium Wires

When choosing the optimal wire diameter size for long-distance PV system installations (30 m–50 m), the key factors to consider are current-carrying capacity, voltage drop, and cost-effectiveness. In practice, aluminium cables are commonly used for real-life solar systems due to their affordability and lightweight nature, despite their lower conductivity compared to copper cables.

Table 10: Cost and application comparison of copper and aluminium wires [50, 51].

Cost of copper vs. aluminium wires

Wire Size (mm^2)	Copper Wire (Cost/m), \$	Aluminium Wire (Cost/m), \$	Savings with Aluminium (%)
4 mm^2	2.0 - 2.50	0.5 - 0.80	68 - 75
6 mm^2	3.0 - 3.50	1.0 - 1.20	66 - 72
10 mm^2	5.0 - 6.00	1.5 - 2.00	67 - 70
16 mm^2	8.0 - 9.00	2.5 - 3.00	67 - 68
35 mm^2	14.0 - 15.00	4.0 - 5.00	67%

Wire size guide for 48V systems (30m–50m Runs) [25]

Current (Amps)	Distance (m)	Copper Wire Size (mm^2)	Aluminium wire Size (mm^2)
20 A	30 m	4 mm^2	6 mm^2
50 A	40 m	10 mm^2	16 mm^2
100 A	50 m	25 mm^2	35 mm^2
150 A	50 m	35 mm^2	50 mm^2

Practically, copper wires should be used for short distances (<30 m) while aluminium wires are used for long distances (≥30 m).

4.4. Recent Wire Material Innovations and Cost Analysis Trends

Recent studies and industry analyses have provided updated insights into the performance, material innovations, and cost considerations of copper versus aluminium wiring in PV systems. The identified recent wire material innovations trends can be categorised into [52-54]:

- Material innovations of Copper-Clad Aluminium (CCA) Conductors: CCA wires feature an aluminium core coated with a layer of copper, combining the conductivity of copper with the lightweight nature and cost-effectiveness of aluminium. This hybrid approach offers a balance between performance and cost, making CCA cables a viable option for solar installations.
- Cost analysis trends: Aluminium is generally less expensive than copper. As of recent data, the average forecasted price for aluminium in 2025 is $2,700 per ton, while copper is expected to be significantly higher at $10,160 per ton. This substantial cost difference makes aluminium an attractive choice for large-scale PV projects requiring extensive wiring.
- Installation considerations: Aluminium wire is lighter and more manageable than copper, which can simplify installation, especially for long-distance runs. However, proper grounding requires the conductor and grounding lugs to be of the same metal type. Since most grounding lugs are made of copper, using aluminium PV wire may incur additional expenses for retrofitting grounding lugs. Additionally, aluminium's higher thermal expansion coefficient necessitates careful installation to prevent loose connections over time.
- Performance and safety considerations: Thermal Expansion and Connection Integrity: Aluminium has a higher thermal expansion coefficient than copper, which means it expands or contracts more when exposed to temperature variations. This can lead to lose connections or cracks over time if not properly installed or maintained. Copper's lower thermal expansion coefficient makes it more stable under temperature fluctuations, reducing the risk of connection issues.
- Corrosion resistance: Aluminium is more susceptible to oxidation, which can increase contact resistance and potentially lead to overheating at connection points. Proper installation techniques, including the use of anti-oxidation compounds and appropriate connectors, are essential to mitigate these risks. Copper is less prone to oxidation, offering more reliable long-term performance in various environmental conditions.

While aluminium wiring offers cost advantages and is lighter, it requires meticulous installation and maintenance to ensure long-term reliability and safety in PV systems. Copper wiring, though more expensive, provides superior conductivity, stability under temperature variations, and lower maintenance requirements. CCA conductors present a middle ground, combining benefits from both materials, but also necessitate careful consideration regarding installation practices and long-term performance. When selecting wiring materials for PV systems, it is crucial to balance cost considerations with performance requirements and long-term reliability, taking into account the specific conditions and demands of each installation.

4.5. Research Gaps on Cabling in PV Systems

Accurately estimating and understanding these factors is crucial for reliable assessments of solar PV potential and for predicting system performance. Inaccurate assumptions regarding solar resources or improper system sizing can result in under or over-sizing, erratic power supply, and increased costs [55]. In this context, undersized wires can lead to significant voltage drops and increased resistive (Joule) losses, thereby reducing the overall energy output of the system. Furthermore, improper wire sizing may cause excessive heat buildup, which can compromise the safety of the installation and even result in fires. Conversely, oversized wires, while reducing energy losses, can increase material costs without proportionate benefits. Research on cabling in PV systems has certain gaps that need to be addressed to optimise performance, efficiency, and safety. These gaps are presented in table 9.

Table 9: Identified research gaps on cabling in PV systems [56, 57].

Optimal cable sizing	Current standards often neglect long-term cable losses from Joule heating. Research is needed to minimize power losses and improve efficiency over the system's lifespan.
Temperature effects	There's limited data on how temperature fluctuations impact cable performance, especially in extreme climates where increased resistance leads to efficiency losses.
Copper vs. aluminium:	More studies are required on the long-term reliability of copper versus aluminium cables, focusing on performance and cost-effectiveness in different climates.
Durability in harsh environments	Data is lacking on how UV radiation, moisture, and other environmental factors degrade cables, affecting longevity.
Economic analysis	Limited research explores the trade-offs between initial costs, efficiency, and long-term energy savings for different cable types
Integration with smart grids	More research is required on how cabling impacts energy flow and losses in smart grids and energy storage systems.

5. Conclusions

The performance of PV systems is significantly influenced by the type, size, and length of wires used to connect system components. This study highlights that copper wires, with better conductivity, result in more predictable and lower energy losses compared to aluminium wires. Findings emphasize that longer and undersized wires increase voltage drops and energy losses, ultimately lowering system efficiency. Additionally, appropriate wire sizing is critical to minimizing losses, enhancing system longevity, and ensuring safety. Poor-quality or undersized cables can cause excessive heating, pose fire risks, reduce system efficiency, and impact key components like inverters.

Optimizing wire selection in terms of material, size, and length is therefore essential to improve PV system performance and reliability, especially in regions with high solar potential. The insights from this study provide valuable guidance for system designers, investors, and regulators to ensure that PV installations operate efficiently with minimal losses over their lifespan.

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