



Decarbonization of the Saudi Power Grid: A Techno-Economic and Environmental Assessment of Advanced Conductors

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Abstract: - In response to Saudi Arabia's commitment to achieving net-zero emissions by 2060, this paper explores the role of advanced overhead line conductor technologies in decarbonizing the nation's power grid. Recognizing the urgent need to reduce greenhouse gas (GHG) emissions in the electrical sector, a detailed techno-economic and environmental analysis is carried out. The research develops a practical assessment framework that combines analytical methods with statistical tools to compare the performance of conventional conductors with newer, more efficient alternatives. Particular emphasis is placed on the ability of advanced conductors to cut line losses, improve energy efficiency, and lower the environmental impact of transmission networks. To ground the analysis in real-world conditions, the study features a case investigation of an existing 380 kV transmission line in Saudi Arabia. Here, ACSR, ACAR, ACCC, and AAAC conductor types are evaluated using a custom-developed calculation tool, which has been validated against recognized industry standards. Through this work, the study aims not only to assess the technical and economic viability of adopting greener transmission solutions but also to support broader sustainable energy practices across the Kingdom.

Keywords: Decarbonization, Power Grid, Transmission Lines, Overhead Conductors, Energy Efficiency, Greenhouse Gas Emissions, Techno-Economic Analysis.

1. Introduction

In the global pursuit of decarbonization, efforts have predominantly centred on shifting energy generation toward renewable sources and improving efficiency on the demand side. Yet, a critical component of the energy system, the transmission infrastructure, has often been overlooked. Modernizing transmission networks presents a significant opportunity to reduce carbon emissions, enhance the integration of renewable resources, and increase overall grid resilience [1]. Despite its potential, the decarbonization of transmission systems remains a



relatively underexplored pathway in achieving deep, systemic reductions in greenhouse gas emissions.

Addressing the causes of climate change remains an urgent global imperative, with the power and energy sectors acknowledged as major contributors. Saudi Arabia, as a leading energy producer in the Middle East, has pledged to achieve net-zero emissions by 2060 [2]. Realizing this ambition will require extensive reforms, particularly within the power sector, which continues to rely heavily on fossil fuels. The escalating concentration of greenhouse gases (GHGs), especially carbon dioxide (CO₂) from the combustion of fossil fuels, is a primary driver of global warming, necessitating prompt and sustained action from all nations [3]. The integration of advanced transmission lines plays a critical role in decarbonizing the grid by enabling the efficient delivery of renewable energy across regions. As the power sector transitions towards renewable energy sources, the modernization of transmission infrastructure becomes essential for optimizing grid stability and minimizing carbon emissions. High-efficiency transmission systems, such as those utilizing advanced conductors and flexible AC transmission systems (FACTS), facilitate the integration of intermittent renewable sources like wind and solar, thereby improving grid resilience and reducing the reliance on fossil-fuel-based backup power. The ongoing development of smart grids, equipped with high-performance transmission lines, supports real-time monitoring and dynamic control, ensuring optimal energy flow and minimized losses, a practice crucial for reducing the carbon footprint of power systems [4].

This study explores the challenges and opportunities associated with decarbonizing Saudi Arabia's power grid, with particular emphasis on the transmission sector and the role that advanced transmission technologies can play. It further aims to address the existing gap in emission reduction strategies specific to the Kingdom's electricity transmission system, offering insights into pathways toward a more sustainable and resilient energy future.

The presented paper is structured sequentially to guide the reader through the research outcomes. Section 2 offers a comprehensive review of the literature, highlighting both local and global decarbonization strategies. Section 3 presents the technical framework, economic assessments, and CO₂ emission calculation models developed for the study. Sections 4 and 5 discuss the results and analysis, with a focus on evaluating different conductor types and their implications for decarbonization. Finally, Section 6 summarizes the principal findings and provides recommendations to support future efforts in advancing decarbonization strategies within the power industry.

2. Literature Review

The global framework for managing greenhouse gas (GHG) emissions traces its origins to the 1992 Earth Summit, a pivotal moment in the evolution of international environmental



governance. This summit led to the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), which laid the foundation for subsequent landmark agreements, including the Kyoto Protocol and the Paris Agreement [5-7]. These international instruments underscore the necessity of coordinated global action to address climate change and its far-reaching impacts. Since the mid-19th century, atmospheric carbon dioxide (CO₂) concentrations have increased by more than 40%, primarily driven by the combustion of fossil fuels and widespread deforestation. These anthropogenic activities have profoundly disrupted the planet's climatic balance, contributing to severe environmental consequences.

In the context of Saudi Arabia, the close interlinkage between CO₂ emissions and economic growth presents unique challenges. Developing effective and sustainable mitigation strategies is therefore essential to balance environmental stewardship with economic development goals. The Kingdom's Nationally Determined Contributions (NDCs) under the Paris Agreement offer a structured framework for emissions reduction, emphasizing energy diversification and enhanced energy efficiency [8-10]. This strategy reflects Saudi Arabia's commitment to sustainable development while navigating the complexities inherent in decarbonizing an economy traditionally reliant on fossil fuels.

2.1. Decarbonization Strategies: Global Contributions

Across the globe, nations and regions are undertaking transformative initiatives within their power sectors to achieve substantial decarbonization. The European Union has emerged as a leader in this effort, advancing a comprehensive strategy aimed at significantly reducing greenhouse gas emissions while simultaneously decreasing reliance on imported energy [11]. Similarly, the United States has set an ambitious target of achieving 100% carbon-free electricity by 2035, with a broader goal of attaining a net-zero economy by 2050. This approach leverages a diverse array of energy sources, including hydropower and nuclear energy, while utilizing existing natural gas infrastructure and promoting the development of advanced battery storage technologies [12].

China, meanwhile, is rapidly expanding its renewable energy capacity and diversifying its portfolio of flexible low-carbon resources. The country has established a formidable objective of achieving an 80% share of renewables in its energy mix by 2060, while simultaneously working to reduce its dependence on coal as a primary energy source [13]. This dual strategy reflects a comprehensive approach to enhancing both energy security and environmental sustainability.

2.2. Power Grid Challenges and Opportunities in Saudi Arabia

Saudi Arabia is embarking on a transformative journey toward a sustainable energy future, driven by a firm commitment to reducing greenhouse gas emissions while meeting rising



electricity demand. At the heart of this effort is the Saudi Vision 2030 initiative, which outlines ambitious targets for emissions reduction, including a 35% decrease through a balanced energy mix composed of 50% renewable sources and 50% natural gas [14]. In addition, the Kingdom has pledged to achieve net-zero emissions by 2060, reflecting its determination to fundamentally reshape its energy portfolio [15].

A central actor in this transition is the Saudi Electricity Company (SEC), which has established its own target of achieving net-zero emissions by 2050 [16]. In the generation sector, SEC is increasingly deploying combined-cycle power plants, recognized for their superior thermal efficiency, typically around 60%, and their significantly lower emissions compared to traditional single-cycle gas plants. By 2019, approximately 31% of SEC's electricity generation was derived from these advanced facilities [16]. Moreover, SEC is also making substantial investments in renewable energy, with plans for solar and wind projects designed to contribute to a generation profile comprising 50% renewables and 50% natural gas by 2030 [17-19]. Furthermore, in collaboration with King Abdullah University of Science and Technology (KAUST), SEC has launched a carbon capture research project at the Rabigh Power Plant [19]. This initiative seeks to reduce emissions from fuel combustion, including carbon dioxide, sulfur oxides, and nitrogen oxides, through the deployment of cryogenic carbon capture technology.

In the transmission sector, SEC is actively modernizing its infrastructure to enhance the efficiency and reliability of electricity delivery. Key strategies include the adoption of high-voltage direct current (HVDC) technology, which enables long-distance electricity transmission with minimal losses, typically less than 3% [20-21]. Initiatives to increase power ampacity across the grid are also critical, facilitating higher transmission capacities and significantly reducing energy losses [22]. In parallel, supported by the Ministry of Energy, SEC has installed nearly 11 million smart meters over the past three years, which is deemed a major milestone in the automation of the distribution network. This technological advancement empowers consumers to monitor and manage their energy consumption more effectively, contributing to improved energy efficiency and further reductions in emissions [22].

2.3. Transmission Line Decarbonization Strategies

Enhancing the power capacity of existing transmission lines is a critical strategy for advancing grid decarbonization. This effort can be divided into several key components as follows:

- *Upgrading*: involves increasing the power transfer capacity of transmission lines through various methods; Voltage upgrading raises the operational voltage to enable greater energy transport, while current upgrading permits higher electric current flow within safety limits. Additionally, conductor upgrades involve replacing or reinforcing existing conductors with materials offering superior conductivity and tensile strength [23, 24]. Implementing enhanced



conductivity technologies mitigates power losses and reduces carbon emissions, allowing transmission lines to accommodate higher loads in a more environmentally sustainable manner.

- *Upgrading*: focuses on improving the mechanical integrity of transmission infrastructure components to ensure resilience against severe weather events and operational stresses. Strengthening these elements reduces the risk of equipment failure, which can lead to costly outages and safety hazards [25]. A related strategy is refurbishment, which entails comprehensive assessments and extensive repairs to restore equipment to optimal operational condition. Refurbishment not only extends the lifespan of assets but also enhances grid reliability and safety [25].

- *Life extension strategies*: involve significant renovations or repairs that extend equipment functionality without necessarily restoring it to its original operational lifespan. If full operational lifespan restoration is achieved, the intervention is classified as refurbishment [26]. Life extension reduces the probability of failure without altering the consequences associated with potential failures.

- *Network Expansion*: refers to augmenting the capabilities of transmission line components. In this context, uprating overhead lines increases their megavolt-ampere (MVA) capacity without requiring substantial structural modifications, reconstruction, or the replacement of existing infrastructure [27].

Implementing these strategies to enhance transmission capacity is crucial for minimizing energy losses, improving thermal stability, and strengthening overall grid reliability. By reducing resistive losses and bolstering system efficiency, these enhancements play a pivotal role in lowering carbon emissions and supporting the transition toward more sustainable energy systems.

2.4. Advanced Conductor Technologies

Recent advancements in conductor technologies have been instrumental in enhancing the capacity and performance of overhead line (OHL) systems. A significant innovation is the adoption of Aluminium Trapezoidal (TW) Stranding Patterns, which optimize electrical efficiency by increasing the volume of conductive material within a defined cross-sectional area. This advancement improves performance under a variety of operational conditions. Another important development is the use of non-steel conductor cores. By eliminating traditional steel cores, these alternative materials not only improve transmission efficiency but also reduce the environmental impact associated with conventional power transmission systems, thereby contributing to more sustainable electrical infrastructure. High-Temperature Low-Sag (HTLS) Conductors represent another substantial leap in conductor technology. These conductors are designed to operate at elevated temperatures, reducing sag and enhancing ampacity. This enables them to carry higher currents without performance degradation, even



under challenging thermal conditions [28]. Table 1 provides a detailed comparison of various conductor structures, highlighting their material compositions.

Table1. Comparison of Various Conductor Designs Based on Material.

Conductor Design	Electrical Conductivity	Thermal Expansion	Weight	Tensile Strength	Thermal Capacity
Round Wire (RW)	Medium	Medium	Medium	Medium	75-100°C
	Consists of circular aluminium wires arranged around a steel or composite core. It is the traditional and most common design in transmission networks.				
Trapezoidal Wire (TW)	High	Medium	Medium	Medium	90-150°C
	Uses trapezoidal cross-section wires to improve packing and reduce air gaps between wires, increasing electrical efficiency.				
High-Temp. Low-Sag (HTLS)	Very High	Very Low	Light	High	150-250°C
	Uses advanced materials such as aluminium-zirconium or carbon composites to reduce thermal expansion and withstand very high temperatures.				
Gap Conductors	Medium	Low	Very Light	Medium	90-200°C
	Features a hollow structure to enhance cooling and reduce weight while maintaining high current carrying capacity. Typically used in high-voltage stations.				
Compact Conductors	Very High	Medium	Medium	Medium	90-150°C
	A compact design that reduces gaps between wires, increasing the aluminium-to-diameter ratio, and improving electrical and mechanical performance.				
Composite Core (ACCC, ACFR)	Very High	Very Low	Very Light	High	200-250°C
	Has a composite core made of fiberglass or carbon instead of steel, making it lighter and more resistant to thermal expansion.				
Gap-Type Conductors	Very High	Very Low	Medium	High	150-250°C
	Includes an internal gap filled with oil or another material that reduces thermal expansion and enhances conductor thermal and mechanical performance.				



3. Description of the Developed Evaluation Model

This research employs a mixed-methods approach, combining qualitative analysis of literature with quantitative analysis of power system data. The study framework centres on modelling power transmission systems and evaluating their performance using a developed calculation tool. The study will use analytical techniques and statistical tools as illustrated in Fig.1 and 2 to process and interpret the collected data. The developed evaluation model is depicted in Figure 1 which entails three main stages: data collection, evaluation process, and obtaining the optimal conductor type. In fact, the evaluation process involves technical, economic, and environmental evaluation (i.e. CO₂ emissions). Moreover, Fig. 2 below shows the details of the evaluation process, which includes: input data, processing calculations, and output results.

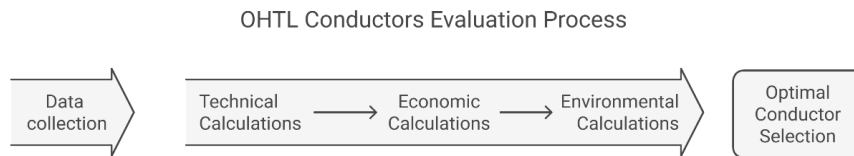


Fig. 1. OHTL Conductors Evaluation Process

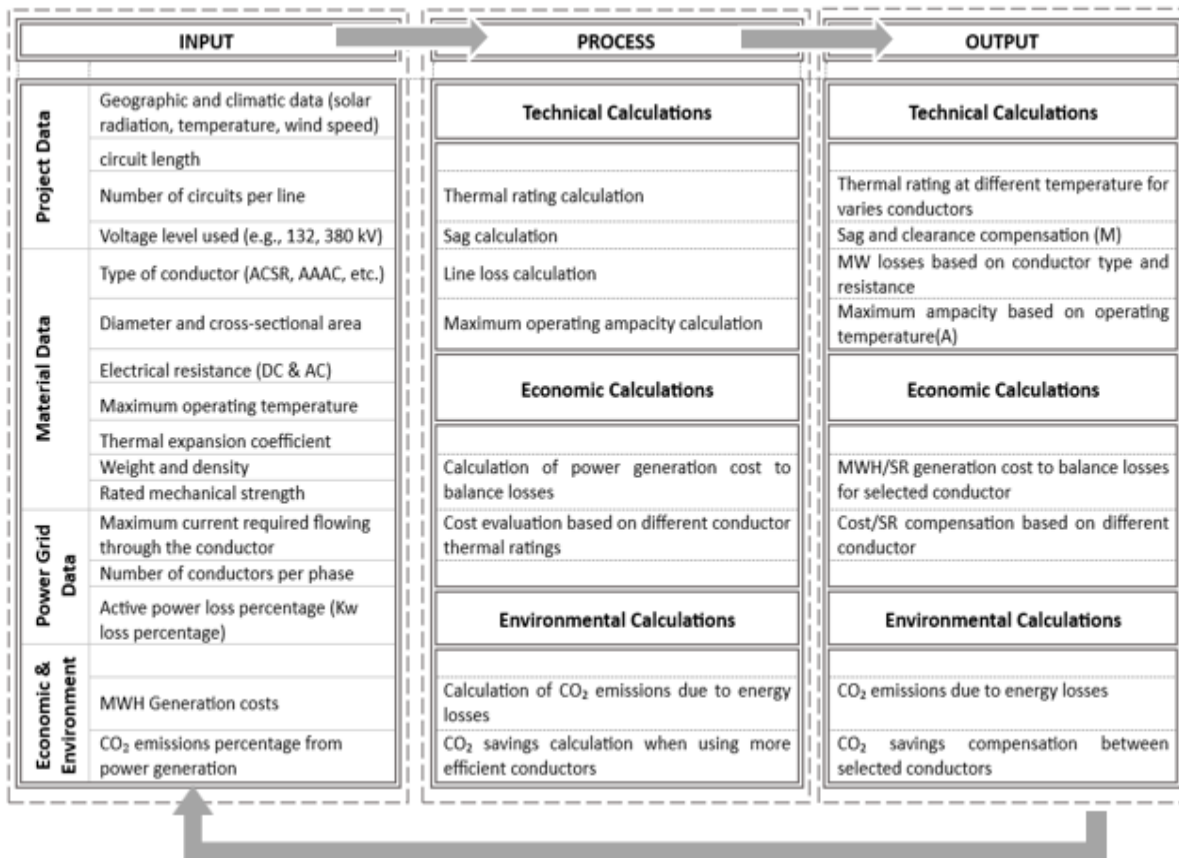


Fig. 2. Details of OHTL Conductors Evaluation Process



3.1. Mathematical Technical Calculations

The technical analysis includes Transmission Line Ampacity and Heat Balance Equations. The temperature of overhead conductors can rise when electricity flows through them, affecting their performance and safety. The IEEE 738 standard is used to calculate the steady-state temperature of conductors. The heat balance equation is given by Equation (1) [29].

$$q_c + q_r = q_s + I^2 \cdot R(T_c) \quad (1)$$

Where, q_c is heat loss through convection (watts per linear length of conductor), q_r is heat loss through radiation (watts per linear length of conductor), T_c is conductor temperature (degrees centigrade), q_s is heat gain from the sun (watts per linear length of conductor), I conductor current (dc amps), and R resistance per linear foot of conductor at T_c (ohms per meter).

From Equation (1), the current in the conductor is calculated using Equation (2), whereas the conductor sag is crucial for ensuring safe operation and is influenced by conductor temperature and tension. The state change equation, as shown in Equation (3), is used to calculate conductor temperature by sag.

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad (2)$$

$$S = \frac{mgL^2}{8 \cdot \text{Sag}} \quad (3)$$

Where, m is Mass per unit length of the conductor (kg/m), g is Gravitational acceleration (m/s^2), L is Span length of the conductor (m), and Sag is the vertical distance between the highest and lowest points of the conductor (m).

3.2. Economic and CO₂ Emission Calculation

The economic analysis in this paper is based on the assessment of energy losses, which are crucial for evaluating the performance of power transmission lines. These losses are typically quantified using analytical equations that account for key parameters such as conductor resistance, voltage, and load. A commonly used equation for estimating energy losses is the Annual Energy Loss (AEL) equation, which calculates the yearly energy lost due to the resistance of conductors carrying electric current. The AEL equation incorporates essential variables, including peak load, resistance per meter, loss factor, total annual operating hours, voltage, and power factor. The equation for estimating the Annual Energy Loss (AEL) is as follows [30]:



$$AEL = \frac{(Peak\ kW)^2 * \frac{Resistance}{phase * length} * Loss\ Factor * \frac{8760\ hours}{year}}{(Voltage\ KV)^2 * (Power\ Factor)^2 * no.\ of\ Phases * \frac{1000k\Omega}{\Omega}} \quad (4)$$

Where the *Load Factor* is (Average Demand) / (Peak Demand), Peak kW is the maximum electrical load in kilowatts, Resistance/(phase×length) is the conductor resistance per kilometre per phase, and Loss Factor is the loss factor, which represents the relationship between energy loss and peak demand = $(0.84)^2 \times (Load\ Factor) + (0.16) \times (Load\ Factor)$.

The calculated energy loss is then used to determine the additional power generation required to compensate for these losses. This is achieved by multiplying the lost energy by the cost of energy generation to estimate the economic impact of transmission inefficiencies. According to the Saudi Electricity Company (SEC), it is reported that the cost of energy generation for the summer of 2024 was 0.101 SR per megawatt-hour (MWh). This value serves as a critical parameter in evaluating the financial implications of transmission losses and emphasizes the importance of optimizing conductor selection and improving transmission efficiency to reduce both economic costs and environmental impact. The following formula in (5) estimates the economic impact.

$$CostLoss = AEL \times CostGen \quad (5)$$

Where, Cost Loss is the Total cost of energy losses (SR), AEL is the Annual Energy Loss (MWh), the Cost Gen is the Cost of energy generation (SR/MWh).

In addition to calculating energy losses, this equation can be used to estimate CO₂ emissions associated with the lost energy in conductors. This is done by multiplying the annual energy loss (AEL) by the emission factor, which represents the emissions produced per MW-hour of generated electricity. According to the Saudi Electricity Company, the emission factor for electricity generation is 0.55 metric tons of CO₂ per megawatt-hour of energy produced [31]. Thus, the emissions associated with transmission losses can be calculated using Equation (6).

$$Emissions = AEL + Emission\ Factor \quad (6)$$

Where, Emissions is the total annual carbon dioxide emissions in metric tons, AEL is the annual energy loss in megawatt-hours, Emission Factor is the emission factor (0.55 metric tons per megawatt-hour).

This analysis is essential for assessing the environmental impact resulting from energy losses, helping to develop effective strategies to minimize losses and reduce carbon emissions, thereby promoting the sustainability of the power sector.



3.3. Utilization of the Development Calculation Tool

The Power Transmission Decarbonization Tool (PTDT) is a calculation tool developed to provide a comprehensive framework for the mathematical operations necessary for the analysis of power transmission lines, as outlined in Fig.1 and 2. This tool facilitates the quantification of emissions from power transmission systems and enables comparative evaluations of different conductor types. The PTDT is built on a foundation of reliable scientific references, drawing from previous studies and experiments to ensure an accurate technical framework for calculating the current-carrying capacity of power transmission conductors, as per standards.

4. Case Study: New OHTL Al-Omran to Salwa 380 kV Overhead Transmission Line

This case study evaluates a proposed 380 kV transmission line project in Eastern Saudi Arabia, primarily aimed at linking the AL-OMRAN and SALWA substations. The analysis includes several conductor types approved by the Saudi Electricity Company, specifically ACSR (Aluminium Conductor Steel Reinforced), AAAC (All Aluminium Alloy Conductor), ACAR (Aluminium Conductor Alloy Reinforced), and various models of ACCC (Aluminium Conductor Composite Core) as proposed conductor. A thorough investigation was conducted into the thermal performance of each conductor type under critical conditions: a load of 650A, an ambient temperature of 50°C, and a wind speed of 0.61 m/s. This detailed assessment ensures that the selected conductor will fulfil the necessary performance criteria for the transmission line infrastructure.

4.1. Thermal Rating Calculation

The thermal rating analysis presented in Fig. 3 reveals a clear distinction in performance among the evaluated conductor types, highlighting the superior thermal characteristics of ACCC conductors. These conductors demonstrated remarkable thermal stability, consistently operating well below their maximum allowable temperature limits, even under critical loading and ambient conditions. In contrast, the traditional ACSR, ACAR, and AAAC conductors, which are typically rated for a maximum operating temperature of 93°C, exhibited a more constrained thermal margin.

ACCC conductors, designed to withstand temperatures up to 200°C, offer a significant operational advantage. This substantial increase in thermal tolerance not only enhances the conductors' ability to maintain mechanical integrity under high-temperature scenarios but also significantly mitigates the risks associated with sagging, thermal degradation, and mechanical fatigue. Such characteristics are crucial in regions like Eastern Saudi Arabia, where extreme ambient temperatures and high load demands are common.

The enhanced thermal resilience of ACCC conductors translates into greater system reliability and flexibility, enabling operators to defer costly transmission infrastructure upgrades by accommodating higher power flows over existing rights-of-way. Moreover, the ability to



operate safely at elevated temperatures provides an additional layer of contingency management during peak demand periods or emergency conditions, contributing to overall grid stability.

From a strategic perspective, the deployment of ACCC conductors aligns with broader decarbonization efforts. Their reduced sag and higher ampacity not only improve system efficiency but also indirectly support the integration of renewable energy sources by enhancing transmission capacity without necessitating new corridors. Therefore, the findings underscore that, while the initial investment in ACCC technology may be higher compared to conventional conductors, the long-term operational, environmental, and reliability benefits present a compelling case for their adoption in modern transmission systems.

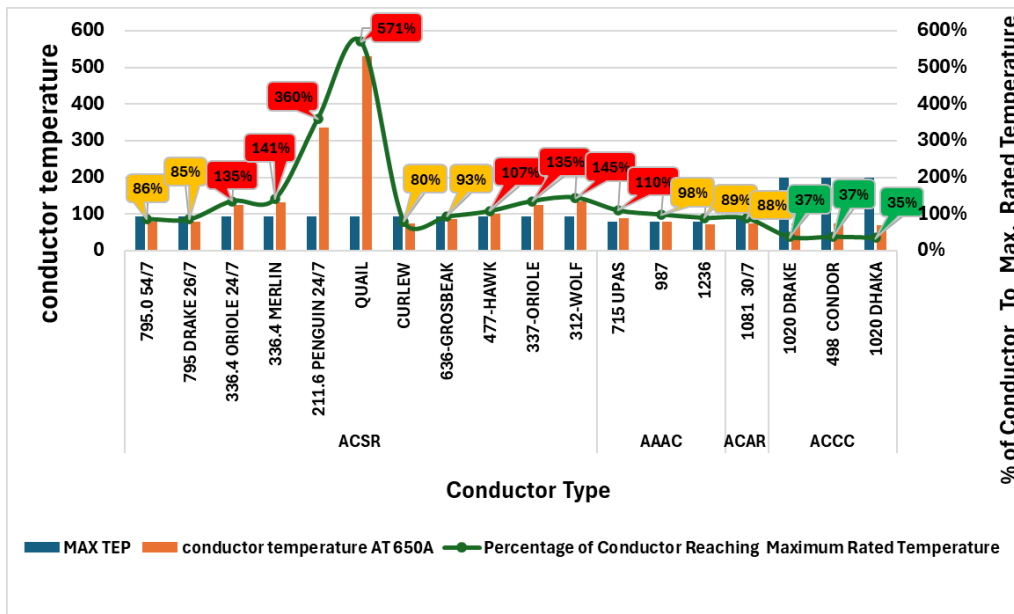


Fig. 3. Thermal Comparison Between the Different Types of Conductors.

4.2. Energy Losses Calculations

A critical criterion in evaluating the candidate conductors for energy efficiency was their thermal output relative to their maximum temperature limits. Conductors that exceeded these thresholds under the specified operating conditions were systematically excluded from further analysis to ensure the reliability and stability of transmission performance. The remaining conductors, which satisfied the thermal stability requirements, were subsequently subjected to a detailed comparative assessment focused on their annual energy losses — a key metric that significantly influences the overall operational efficiency and environmental footprint of power transmission systems. The comparative results are illustrated in Fig. 4.



Among the evaluated options, the ACCC DHAKA 1020 conductor emerged as the most effective in minimizing energy losses, achieving an impressive 47% reduction relative to the conventional ACSR baseline. This substantial improvement can be attributed to the conductor's innovative design, which integrates a high-strength aluminium alloy with a lightweight carbon-fibre-reinforced composite core. This advanced construction not only enhances thermal performance but also significantly increases tensile strength and minimizes conductor sag under high loads, ensuring superior mechanical stability alongside improved electrical efficiency.

The ACCC CONDOR conductor, while exhibiting slightly lower efficiency gains compared to the DHAKA variant, still demonstrated noteworthy reductions in resistive losses. Its incorporation of a high-conductivity aluminium core improves current-carrying capacity and enhances thermal management, positioning it as a strong alternative where a balance between performance enhancement and cost-effectiveness is critical.

In comparison, ACAR conductors provided moderate improvements in energy efficiency. By combining aluminium and steel components, ACAR conductors offer optimized mechanical strength and conductivity; however, their energy loss reduction capabilities were not as pronounced as those observed in the ACCC variants. Finally, the AAAC conductors exhibited the least reduction in energy losses among the studied options. Despite their advantages of lower weight and high corrosion resistance, their limited impact on resistive loss reduction rendered them less favourable for applications where maximizing transmission efficiency is a priority.

These findings underscore the pivotal role of advanced conductor technologies in optimizing the performance of modern transmission systems. By substantially reducing operational losses and enhancing energy efficiency, high-performance conductors like the ACCC variants contribute directly to grid reliability, economic savings, and the broader objectives of power sector decarbonization.

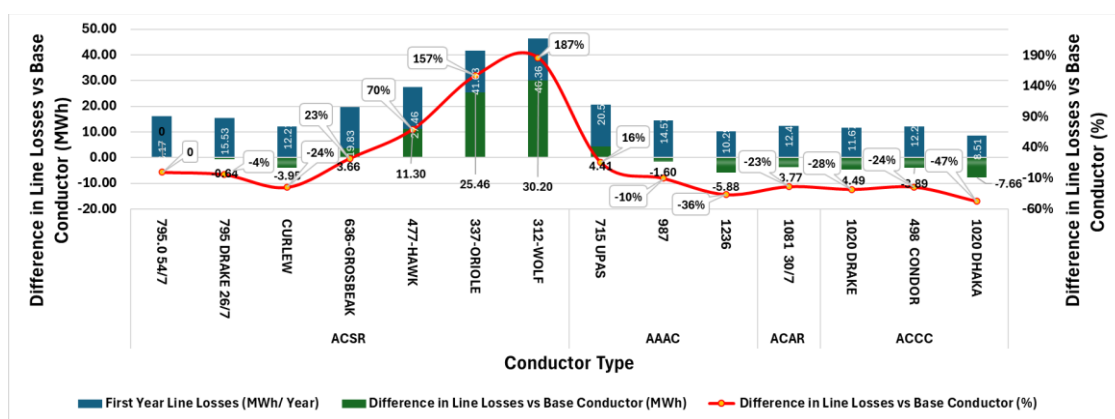


Fig. 4. Comparison of Annual Conductor Losses Relative to the Base Conductor



The results of this study provide clear guidance for strategic decision-making in transmission line projects aimed at enhancing grid efficiency and sustainability. The superior performance of ACCC conductors, particularly the DHAKA 1020 model, highlights their value in projects where minimizing energy losses and improving thermal stability are critical objectives. By adopting advanced composite-core conductors, utilities can achieve significant operational cost savings, extend asset lifespan, and contribute meaningfully to national and global decarbonization targets. Furthermore, careful selection of conductor types tailored to project-specific conditions can optimize the balance between capital investment and long-term environmental and financial benefits, supporting the broader energy transition strategies outlined in initiatives like Saudi Vision 2030.

4.3. CO₂ Emissions Evaluation and Environmental Impact Discussion

Evaluating the CO₂ emissions associated with different conductor types is a critical step in understanding their environmental footprint and operational efficiency within modern electrical transmission systems. The analysis presented in Fig. 5 offers important insights, particularly regarding the performance of the ACCC DHAKA 1020, ACCC CONDOR, ACAR, and ACSR conductors.

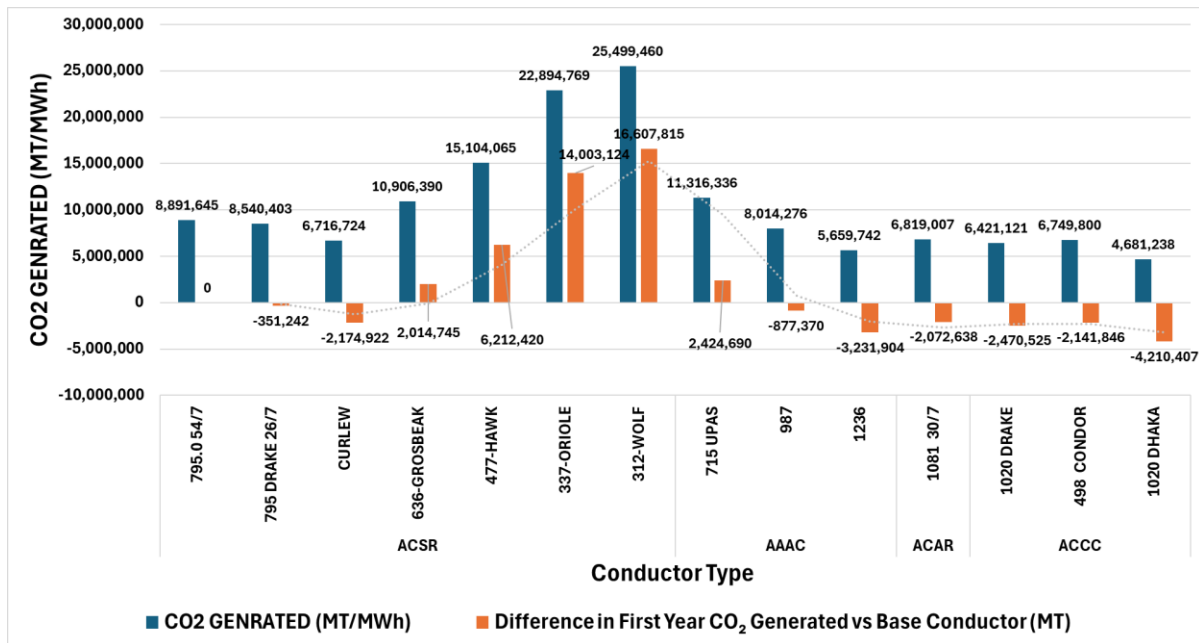


Fig. 5. Environmental Analysis: CO₂ Emissions Comparison vs Base Conductor.

Among the conductors analysed, the ACCC DHAKA 1020 emerged as the most effective in minimizing environmental impact, achieving an impressive reduction of approximately 1,814,686 metric tons of CO₂ compared to the baseline scenario. This substantial emissions reduction is primarily attributed to its advanced composite-core design, which integrates high-



strength carbon fibres and highly conductive aluminium strands. The combination of lightweight construction and enhanced current-carrying capacity not only improves installation efficiency but also reduces structural loads on towers, ultimately contributing to lower energy losses and, by extension, a smaller carbon footprint. The operational efficiencies realized with ACCC DHAKA 1020 reinforce its potential as a transformative technology for sustainable transmission infrastructure.

Similarly, the ACCC CONDOR conductor demonstrated notable environmental benefits, achieving a reduction of approximately 1,064,796 metric tons of CO₂. Featuring similar composite technologies, the CONDOR conductor offers superior conductivity and reduced thermal sag, particularly under high-load and high-temperature conditions. These characteristics make it highly suitable for long-span applications and projects requiring elevated current levels, where minimizing line losses and enhancing system resilience are paramount goals. The environmental advantages of ACCC conductors as a class suggest a strategic value in adopting composite-core technologies for modern grid development initiatives.

In comparison, the ACAR conductors, while providing moderate emissions reductions, were less effective than their ACCC counterparts. The combination of aluminium and reinforcing steel offers reasonable mechanical robustness; however, the heavier construction and higher resistive losses during operation limit their ability to achieve significant environmental performance improvements. Consequently, while ACAR may serve specific engineering needs, its overall contribution to decarbonization objectives remains limited.

Of particular concern, the ACSR conductors exhibited higher CO₂ emissions relative to other alternatives, with some models surpassing baseline emissions levels. The reliance on a steel-reinforced core combined with relatively lower conductivity results in increased transmission losses, higher thermal output, and greater environmental impacts. These findings underscore the urgent need to phase out older ACSR designs, especially as global and national energy policies pivot towards carbon neutrality and enhanced grid efficiency.

Overall, the evaluation highlights the environmental superiority of advanced conductor technologies such as the ACCC DHAKA 1020 and ACCC CONDOR. Their adoption not only aligns with broader sustainability and decarbonization targets but also ensures improved operational efficiency, making them indispensable assets in future-proofing the electrical transmission sector.

4.4. Economic Evaluation and Strategic Implications for Conductor Selection

This study conducted a comprehensive analysis of annual line losses, measured in Saudi Riyals per megawatt per year (SR/MW/Year), to determine the most economically advantageous conductor options for transmission and distribution networks. The findings clearly establish



that the ACCC DHAKA 1020 conductor demonstrated the lowest cost impact associated with line losses, thereby setting a critical benchmark for economic performance and cost-effectiveness in future grid developments.

As illustrated in Fig. 6, the comparative analysis highlights that while ACAR conductors offered a commendable balance between cost efficiency and operational performance, they are best suited for projects where moderate technical requirements coexist with budgetary constraints. In contrast, for projects prioritizing sustainability, energy efficiency, and long-term operational excellence, the ACCC conductor family proved superior. Their engineered composite designs significantly enhance thermal stability, increase current-carrying capacity, and minimize resistive energy losses, making them highly effective for optimizing utility performance under the demanding environmental conditions typical of the region.

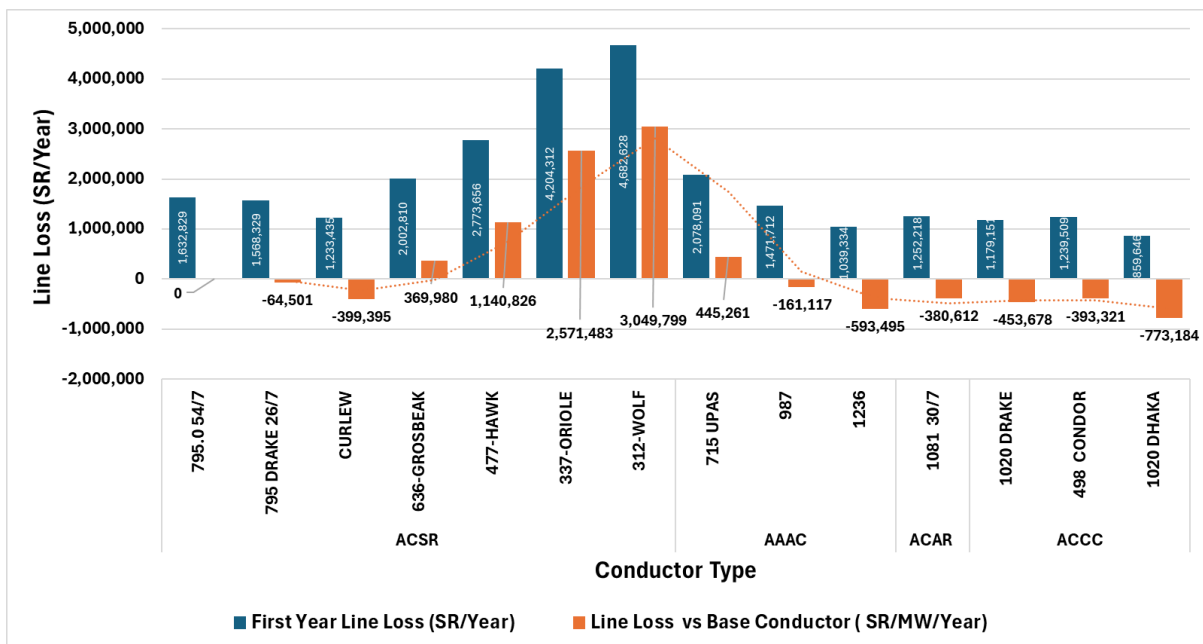


Fig. 6. Economic analysis: Conductor Loss vs Base Conductor in (SR/MW/Year).

The outcomes of this investigation reaffirm the strategic advantages of integrating advanced conductor technologies, particularly the ACCC variants, into Saudi Arabia's evolving power transmission infrastructure. The deployment of such conductors not only delivers measurable reductions in line losses but also directly correlates with significant CO₂ emission reductions. These benefits align strongly with the Kingdom's Vision 2030 initiatives and its broader commitment to achieving net-zero emissions by 2060.

Importantly, the Power Transmission Decarbonization Tool (PTDT) developed in this study consistently demonstrated robust predictive capability across different conductor scenarios, providing a reliable technical foundation for assessing thermal and electrical performance. The



findings further reinforce the case for modernization: ACCC conductors, with their superior ability to operate at temperatures up to 200°C, in contrast to the approximately 93°C limit for traditional ACSR and AAAC conductors, present a clear and compelling choice for future-proofing the grid.

Moreover, the integration of ACCC conductors enables an impressive 47% reduction in annual energy losses relative to baseline ACSR conductors. This improvement translates directly into substantial operational cost savings, enhancing the economic viability of power transmission projects. Additionally, the reduced thermal sag and superior mechanical properties of ACCC conductors lead to lower maintenance requirements and extended service life, further enhancing their attractiveness to stakeholders seeking reliable, sustainable, and economically sound infrastructure solutions. In summary, the results advocate strongly for a strategic shift towards advanced conductor technologies as a cornerstone for Saudi Arabia's transition to a more resilient, efficient, and sustainable energy grid.

5. Conclusion

This study provides compelling evidence for the superior performance of ACCC conductors over traditional options such as ACSR, AAAC, and ACAR across multiple critical performance metrics. The enhanced thermal efficiency of ACCC conductors, coupled with their significant reduction in energy losses and lower associated carbon emissions, positions them as a formidable and future-ready choice for modernizing energy infrastructure. Notably, these advanced conductors demonstrate remarkable resilience under extreme environmental conditions, which is a crucial attribute for regions characterized by harsh climates, such as Saudi Arabia's Eastern Province operating areas.

The ability of ACCC conductors to sustain elevated operating temperatures up to 200°C without significant sag or performance degradation distinctly separates them from conventional conductors, which typically operate around 93°C. Furthermore, the substantial 47% reduction in annual energy losses achieved by ACCC DHAKA 1020 relative to baseline ACSR conductors translates into not only significant economic savings but also contributes to environmental sustainability through reduced CO₂ emissions.

In the context of Saudi Arabia's Vision 2030 and its commitment to achieving net-zero emissions by 2060, the findings of this study strongly support the strategic adoption of advanced conductor technologies. The benefits extend beyond immediate energy and cost efficiencies, offering long-term enhancements in grid reliability, asset longevity, and maintenance reduction, all of which are pivotal for supporting a sustainable, resilient, and high-performance transmission network. Thus, the power sector is recommended to:



- Prioritize the adoption of ACCC conductors, particularly high-efficiency models like ACCC DHAKA 1020, for new transmission line projects and critical grid upgrades, especially in regions with elevated ambient temperatures and high load demands.
- Develop transition plans to systematically phase out outdated ACSR conductors in favour of advanced composite core technologies, targeting installations where operational inefficiencies and carbon emissions are currently highest.
- Integrate comprehensive evaluation tools like the Power Transmission Decarbonization Tool (PTDT) into project planning and feasibility studies to accurately model thermal performance, energy loss, and environmental impact when selecting conductors.
- Invest in training and capacity-building programs for utility engineers and planners, focusing on the technical advantages, installation considerations, and lifecycle management of modern composite conductors.
- Align conductor selection strategies with broader sustainability and decarbonization goals, ensuring that every major transmission project not only meets performance standards but also contributes meaningfully to reducing the nation's carbon footprint.

By proactively adopting these recommendations, power utilities can substantially enhance the economic efficiency, environmental responsibility, and operational resilience of their transmission networks, paving the way for a cleaner and more sustainable energy future.

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