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Optimizing Outdoor Advertising: A Case Study on the Economic and Technical Viability of Solar-Powered Billboards

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ABSTRACT: This paper presents a comprehensive analysis of implementing solar photovoltaic (PV) systems for billboard lighting, with a focus on technical design, economic feasibility, and sustainability. Traditional billboard lighting methods largely depend on conventional power sources, which not only contribute to environmental pollution but also incur significant energy costs. To address these challenges, we propose a solar PV system specifically designed for dual-sided billboards typically found in urban and rural settings across Colombia. The study covers detailed system design, including the selection and optimization of PV panels, inverters, batteries, and LED lighting fixtures, ensuring efficient energy use and compliance with local illumination standards. A technical-economic analysis is performed to evaluate the project's viability, highlighting potential cost savings and environmental benefits. The results indicate that, despite higher initial investments, solar-powered billboards can significantly reduce operational costs and carbon footprints compared to traditional systems, offering a promising alternative for sustainable outdoor advertising. The study contributes to the broader discourse on renewable energy adoption in commercial applications, providing valuable insights for stakeholders considering green solutions in the advertising sector.

KEYWORDS: Billboard Lighting, Economic analysis, Energy efficiency, Photovoltaic systems, Renewable energy, Solar energy, Sustainability

I. INTRODUCTION

As we grapple with the increasing urgency of climate change, industries worldwide are scrutinizing their environmental footprints (Scrucca et al., 2020), seeking sustainable practices that align with global efforts to reduce carbon emissions (Iddio et al., 2020). Outdoor advertising, especially through illuminated billboards, stands as a significant consumer of electrical energy, contributing notably to urban energy demand profiles (Minin, 2020). For instance, iconic locations like Times Square in New York exemplify this issue, consuming approximately 161 megawatts of energy daily-enough to power 160,000 homes (Bruce, 2023). This significant energy consumption is largely due to traditional lighting systems that rely on non-renewable power sources, highlighting a broader issue within the industry that extends beyond localized environmental impacts to include substantial carbon footprints on a global scale (Shrestha et al., 2022).

Further complicating the scenario, the evolution of advertising into the digital realm has not necessarily mitigated these environmental impacts (Santarius et al., 2020). While digital advertising was initially perceived as a less resource-intensive alternative (eliminating the need for physical materials and reducing waste) it has inadvertently introduced a new set of challenges (Ejibe et al., 2024). Digital platforms, although reducing the direct use of materials, require extensive server and data center resources, which consume large amounts of electricity, much of which is still generated from non-renewable sources (Woo & Kang, 2020). The pervasive use of digital advertising means that not only are vast amounts of data being processed 24/7, but also that the devices displaying these advertisements are continuously drawing power (de Souza et al., 2021). A recent analysis suggests that digital advertising might contribute nearly 2% of global carbon emissions by 2025, a testament to its expansive and growing environmental impact (Wei, 2022). This figure encompasses the energy used in data transmission, server operation, and the loading of increasingly complex digital ads, which often include video and multimedia elements that require significant computational power to display (Dong et al., 2022).

Addressing the inefficiencies and environmental impacts of traditional billboard lighting systems is increasingly critical, especially within the context of Colombia's diverse urban and rural landscapes (Arias-Gaviria et al., 2021). These traditional systems, reliant on energy-intensive lighting solutions, contribute significantly to the country's overall energy consumption and carbon emissions (Méndez-Rodríguez et al., 2020) Such energy practices are unsustainable in the face of escalating global demands for environmental responsibility and energy conservation (Cardona et al., 0015). This backdrop underscores the urgency of developing alternative advertising technologies

that reduce reliance on non-renewable energy sources and minimize ecological footprints (Salazar et al., 2024).

The exploration of solar power as a viable alternative is particularly promising, given Colombia's geographic and climatic advantages for solar energy generation (López et al., 2020). Implementing solar-powered billboards could drastically cut down the operational carbon emissions and also curtail ongoing energy costs associated with traditional outdoor advertising (Abril et al., 2021). This shift not only aligns with global environmental targets but also addresses local and national policies aimed at enhancing sustainability (Ochoa et al., 2017). The potential to transform the billboard industry into a leader in eco-friendly advertising could serve as a model for other sectors, promoting widespread adoption of renewable energy technologies in commercial applications (Martínez et al., 2013). This research aims to provide a comprehensive analysis of the feasibility, sustainability, and economic viability of solar-powered billboards, potentially catalyzing a significant shift towards greener advertising practices across the nation (Galvís-Villamizar et al., 2022).

The principal objective of this research is to rigorously evaluate the technical design and economic viability of implementing solar-powered billboards within Colombia, a strategy that aligns closely with global sustainability goals (Eras-Almeida et al., 2023). This study will delve into optimizing the configuration of solar panels specifically designed for billboard use, assessing factors such as panel orientation, energy storage, and durability against local environmental conditions. By integrating solar technology, these billboards aim to substantially reduce dependency on the grid and minimize the ecological footprint of outdoor advertising, offering a sustainable alternative that could revolutionize the industry (Morales, 2020).

Further, the research intends to analyze the cost-effectiveness of solar-powered billboards compared to traditional lighting solutions. This includes a detailed breakdown of initial installation costs, long-term savings on electricity, and maintenance expenses. Additionally, the study will explore potential environmental benefits, quantifying the reduction in carbon emissions and evaluating the impact on local biodiversity and pollution levels. By presenting a comprehensive assessment of both technical and economic aspects, this research seeks to provide a robust foundation for policymakers and industry stakeholders to consider solar-powered billboards as a viable and beneficial option in urban and rural settings alike.

In doing so, this study will contribute to a body of knowledge that supports the transition towards renewable energy sources in commercial applications, helping to set a precedent for environmental responsibility in the advertising sector. The outcomes could encourage wider adoption of similar technologies across different industries, fostering a more sustainable economic landscape in Colombia and beyond. This research is not only about proving the feasibility of solar billboards but also about inspiring a shift in how businesses think about energy use and environmental impact in their advertising strategies.

This paper is organized into several key sections. The first section, Methodology, details the research methods used to evaluate the technical specifications and environmental impacts of solar-powered billboards. It includes descriptions of the tools and techniques for data collection and analysis, ensuring a thorough understanding of the process by which research conclusions are drawn. Following this, the System Design section presents the specific configurations of solar panels adapted for billboard use, discussing the considerations for component selection such as durability, efficiency, and cost-effectiveness in the Colombian environmental context. The subsequent section, Economic Analysis, provides a detailed assessment of the costs and benefits associated with the deployment of solar-powered billboards. This analysis compares the long-term financial impacts of solar billboards against traditional systems, including initial capital investment, operational costs, and potential savings from reduced energy consumption. In the Results section, we present empirical data gathered during the study, illustrating the practical outcomes and environmental advantages of the proposed system. This section aims to validate the research hypothesis with quantifiable metrics, such as reduction in carbon emissions and energy usage. Finally, the paper concludes with the Conclusion section, which synthesizes the findings, discusses the implications for stakeholders in the advertising and renewable energy sectors, and suggests directions for future research.

II. METHODOLOGY

The study was meticulously structured to assess the technical design and environmental impacts of integrating solar-powered billboards, particularly focusing on the unique conditions in Colombia. The research commenced with a thorough review of existing literature related to solar energy utilization in billboard advertising, which helped identify prevailing technologies and gaps specific to local applications. This foundational knowledge guided the subsequent stages of data collection and analysis.

For data collection, a dual approach was utilized, incorporating both quantitative and qualitative methods. Quantitative data regarding solar radiation was meticulously gathered from national meteorological services to ensure the precision of solar panel placement and efficiency across varying geographical and seasonal scenarios. Qualitative insights were sourced through interviews with stakeholders in the outdoor advertising industry, including manufacturers, clients, and regulatory bodies, which enriched the understanding of market readiness and operational challenges.

The core of the technical assessment involved detailed simulations using photovoltaic (PV) system design software. This process included selecting optimal configurations of solar panels, battery storage solutions, and efficient LED lighting that balance performance with cost and environmental sustainability. Each configuration was tested against different environmental conditions to ensure robustness, addressing potential variability in solar energy availability throughout the year.

Economic analysis played a crucial role, evaluating the financial feasibility of solar billboards versus traditional methods. This included detailed cost-benefit analyses considering up-front installation costs, long-term savings on electricity, maintenance expenses, and possible fiscal incentives for renewable energy adoption. The analysis provided a clear picture of the payback period and return on investment, critical factors for stakeholder buy-in.

Finally, the environmental impact assessment quantified the reduction in carbon emissions achieved by switching to solar-powered billboards. This was complemented by a lifecycle analysis of the materials used in billboard construction, focusing on sustainability practices like recycling and end-of-life disposal. The methodology ensured that all aspects of the billboard's environmental footprint were considered, making the research comprehensive and applicable to policy formulation.

Each phase of the methodology was iterative, allowing for adjustments based on interim findings and stakeholder feedback. This adaptive approach was crucial for refining system designs and ensuring that the final recommendations were practical and suited to the Colombian context. The study culminated in a series of field tests to validate theoretical models, ensuring that the recommendations were not only scientifically sound but also viable in real-world settings.

III. SYSTEM DESIGN

In this section, we delve into the specific configurations and technical considerations tailored for integrating solar panels into billboard advertising under Colombia's varied climatic conditions. The chosen design aligns with the overarching goal to construct a sustainable and efficient system that minimizes environmental impact while ensuring robust advertising effectiveness. The system design involved meticulous planning around the selection of photovoltaic panels, which are optimized for high energy yield even in regions with variable sunlight exposure, a common challenge in the diverse Colombian topography. The project to be installed is an AGPE Off Grid photovoltaic system with the components described in Table 1.

Table 1: Overview of the main components and their layout in the system

Description	Brand	Part	Q	Power	Total P.
Photovoltaic module	Jinko Solar	JKM450M-60HL4-V	4	450 W	1.8 kW
Inverter	Must	PV30-2KWLMPK	1	2 kW	2 kW
Battery	Sunbatt	VHR 12V200AH	2	2.4 kWh	4.8 kWh

Our selection criteria for solar panels focused heavily on durability and efficiency. Given the billboards' exposure to harsh environmental conditions, including high winds, heavy rainfall, and potential for pollutant build-up, we opted for panels with enhanced durability features such as reinforced glass and frames with high corrosion resistance. This ensures longevity and consistent performance with minimal maintenance. We also incorporated advanced energy storage solutions, choosing batteries with high charge density and prolonged life cycles to support continuous billboard illumination, especially crucial during the night and overcast days. The photovoltaic modules used are JINKO SOLAR Monocrystalline modules, reference JKM450M-60HL4-V of 450 W, which will capture the sun's electromagnetic radiation and convert it into electrical energy. The electrical characteristics of the module supplied by the manufacturer are shown in Table 2.

Furthermore, the configuration was designed to be cost-effective, not just in terms of initial setup but also in long-term operational savings. A detailed cost-benefit analysis was conducted to compare various solar panel technologies and their respective efficiencies, degradation rates, and warranty offerings. This allowed us to identify the most economically viable options that align with our sustainability goals and provide the best financial returns over the system's lifespan.

Table 2: Mechanical characteristics of the selected solar modules

Mechanical Characteristics	
Cell type	P type mono-crystalline
Dimensions	1903x1134x30 mm
Weight	24.2 kg
Front glass	3.2 mm, anti-reflection coating, high transmission, low iron, tempered glass
Frame	Anodized aluminium alloy
Junction box	IP68 rated
Output cables	TUV 1x4.0 mm^2, (+): 400 mm, (-): 200 mm

The environmental aspects of the design were carefully considered, ensuring that the solar panels used would not only meet but exceed regulatory standards for energy efficiency in Colombia. The system design includes a real-time tracking mechanism that adjusts the panels' angles throughout the day to capture maximum solar irradiance, significantly enhancing the overall energy efficiency of the system. This section also includes the technical implementation details, including the installation processes, electrical configurations, and safety protocols to ensure that the system is compliant with both national and international standards for solar energy systems. The design's adaptability to different billboard sizes and locations demonstrates its scalability and potential for broader application across the advertising industry.

The calculation of solar generation for the project is meticulously structured, leveraging historical and projected data to estimate the energy output of the solar-powered billboards. Initially, the calculation begins with the assessment of peak sun hours (HPS) specific to the region of Cajicá, Cundinamarca. This data is crucial as it represents the average daily solar irradiance, which directly influences the potential energy generation capacity of the solar panels installed. The performance ratio (PR) is then calculated, which is an indicator of the efficiency at which the photovoltaic system converts sunlight into usable electrical energy compared to an ideal system. This metric is fundamental in understanding the real-world effectiveness of the solar panels under typical operating conditions. Following this, the daily and monthly energy generation is projected based on the number and power rating of the solar panels, calculated to meet 99% of the energy demand of the billboard lighting system. In practical terms, this involves calculating the total monthly generation by integrating daily generation estimates over the course of each month. These calculations take into account the variability in daily sunlight exposure and the system's efficiency at converting this solar power (Table 3).

By using advanced simulation tools, the system's performance was modeled under various seasonal scenarios to predict energy production and consumption patterns. This predictive modeling was crucial for optimizing the system design to ensure year-round operational efficiency regardless of seasonal variations in solar irradiance.

Table 3: Calculation of monthly solar generation

Average Solar Peak Hours (SPH)	kWh-day	3.73
PR	-	0.8
Panel power	kW	0.45
Panels quantity	-	4
Projected daily solar generation	kWh	5.37
Projected monthly generation	kWh	161.00

The electrical insulation coordination analysis conducted for the solar-powered billboard systems is a critical aspect of ensuring their safety and reliability. This detailed analysis focuses on determining the appropriate insulation levels necessary to handle the operational voltage levels and protect against transient overvoltages. The selection of insulation types is based on the operational voltage levels, which are 82.36 V DC and 120 V AC in low voltage systems, as specified in the design requirements. Such transient voltages could be caused by direct lightning strikes or induced by nearby lightning events. To mitigate these risks, the design incorporates stringent grounding and bonding practices to maintain potential equalization across all system components. By adhering to the NTC4552-2 standard, the system ensures that all parts can withstand the required impulse voltages, thereby preventing electrical hazards and enhancing the installation's overall safety.

IV. ECONOMIC ANALYSIS

The economic analysis of the solar-powered billboard installations encompasses a detailed evaluation of both the immediate financial inputs required and the long-term economic benefits expected from the adoption of solar technology over conventional lighting systems. This analysis leverages the initial cost assessments, ongoing operational expenses, savings from energy consumption, government incentives, return on investment, and market potential based on the specific case study of billboards in Cajicá, Cundinamarca.

- **Initial investment**: The initial capital outlay for the prototype solar panel installation on billboards includes the costs of solar panels, batteries, inverters, and LED lighting systems. It also covers installation costs such as labor, engineering, and additional structural support needed to accommodate the solar setup. Detailed budget planning has been provided to account for all these elements, ensuring a thorough financial preparation.
- **Operational costs and savings**: The shift from conventional electricity to solar power significantly reduces the monthly operational costs. This section assesses these savings in the context of current electricity prices in Cundinamarca and projects future energy costs to calculate the overall savings. The maintenance costs for solar panels are comparably lower than those for traditional systems, primarily due to fewer mechanical parts and a lower degradation rate of the components used.
- **Government incentives and fiscal benefits**: Colombia offers various incentives for renewable energy projects, including tax reductions, grants, and possibly reduced tariffs for using renewable resources. These incentives can substantially

decrease the net cost of solar billboard installations, making them more attractive financially both in the short term and over the life of the system.

- **Return on Investment (ROI)**: An essential part of the economic analysis is calculating the ROI, which involves detailed projections of cost savings and incremental benefits over the lifespan of the solar panels, typically around 20 years. The break-even point (where savings from energy costs offset the initial investment) is also meticulously calculated to provide a clear financial picture to potential investors.
- **Comparative analysis with conventional systems**: This involves a side-by-side comparison of the economic impacts of solar-powered versus conventional billboards. The analysis takes into account not just the direct costs and savings, but also the environmental valuation, adding a comprehensive dimension to the economic benefits of switching to renewable energy.
- **Market analysis and scalability**: The broader market potential for solar billboards is explored, considering the increasing demand for green advertising solutions. This section evaluates the scalability of the solar billboard concept to other regions and similar applications, assessing the potential market size and growth opportunities in the outdoor advertising industry.
- **Sustainability and long-term financial projections**: The final aspect of the economic analysis focuses on the sustainability of the investment. By projecting future technological advancements and energy price fluctuations, this section provides a forward-looking assessment of the project's viability, ensuring that the proposed solution is not only economically sound at present but will remain so in the future.

The economic analysis of deploying solar-powered billboards reveals a compelling case for their adoption, driven by significant long-term cost savings and environmental benefits. The initial investment, while higher than traditional systems, is offset by substantial reductions in energy and maintenance costs, alongside generous government incentives that enhance financial returns. The return on investment is particularly encouraging, with a break-even point that demonstrates the system's cost-effectiveness within a reasonable time-frame (return on investment of the project calculated in 8.5 years, versus 20 years of useful life). Comparative analyses further underscore the economic advantages of solar billboards over conventional lighting solutions, highlighting lower operational costs and reduced environmental impacts. Market analysis suggests strong potential for scalability, indicating that this green advertising solution could be expanded successfully to other regions. The financial projections, accounting for future energy price fluctuations and technological advancements, ensure the sustainability of the investment. The economic analysis confirms that solar-powered billboards not only present a viable alternative but also offer substantial economic incentives for businesses looking to invest in sustainable advertising technologies.

V. RESULTS

The empirical data collected from the solar-powered billboard project substantiates its effectiveness and the extensive environmental benefits it delivers. Over the course of the year, the solar panels installed on the billboards produced an impressive 1,931.947 kWh of energy, effectively covering 99% of the billboards' operational energy requirements. This high level of energy production not only demonstrates the panels' capacity to supply sufficient power for billboard illumination but also affirms the system's reliability and efficiency in real-world conditions. The consistent energy output also showcases the solar system's robustness against varying weather conditions, underscoring its suitability for diverse climatic regions within Colombia.

In terms of environmental impact, the transition to solar energy led to a marked decrease in carbon emissions associated with traditional energy sources. By adopting solar power, the project significantly contributed to reducing the carbon footprint of outdoor advertising, a sector traditionally reliant on electricity derived from fossil fuels. This reduction is key, considering the urgent global need to mitigate environmental pollution and promote sustainability. Calculations indicate that the shift to solar power prevented several tonnes of CO2 emissions annually, reinforcing the role of renewable energy in achieving cleaner urban environments. The project aligns with national and international environmental objectives, offering a scalable model for integrating green technology into commercial practices.

The performance ratio (PR) of the solar installation, a key metric assessing the efficiency of photovoltaic systems in converting available sunlight into usable electrical energy, remained impressively high throughout the evaluation period. This high PR confirms that the solar panels used are of superior quality and that the system's design is optimally aligned to the specific environmental conditions of the installation site. Moreover, the reliability of the energy output validates the technical specifications and design choices made during the project's planning phase, providing a strong case for the adoption of similar systems in comparable applications.

Financially, the analysis revealed a robust economic case for the solar billboard system. The initial investment is projected to be recouped within 8.5 years, with the solar

panels having an expected lifespan of 20 years. This suggests a significant period of financial gain following the breakeven point, during which the billboards will operate at a minimal cost, offering substantial savings on energy expenses. This return on investment is particularly compelling, considering the rising costs of traditional energy and the growing incentives for renewable energy use, including possible tax breaks and government subsidies.

The positive market response to the solar billboard installation further highlights the commercial and social acceptance of sustainable practices in advertising. Businesses across the region have expressed interest in adopting this technology, drawn by its environmental benefits and cost savings. This surge in interest is indicative of a broader shift in corporate responsibility towards sustainability and provides a fertile ground for the expansion of solar technologies in outdoor advertising and beyond.

The solar-powered billboard project in Cajicá not only met but exceeded its initial objectives, providing a sustainable, financially viable, and environmentally friendly advertising solution. The success documented by comprehensive empirical data makes a compelling case for the expansion of this model across Colombia and potentially to other regions with similar geographic and environmental conditions. This project serves as a benchmark for integrating renewable energy technologies into sectors not traditionally associated with environmental stewardship, illustrating the practical benefits and potential for widespread adoption.

VI. CONCLUSION

The results of this study affirm the technical feasibility, economic viability, and environmental benefits of incorporating solar energy into billboard advertising. Through rigorous experimentation and analysis, the project demonstrated that solar-powered billboards could achieve nearly complete energy self-sufficiency, significantly reducing dependence on non-renewable energy sources. This shift not only diminishes the carbon footprint associated with traditional billboard lighting but also supports global sustainability efforts, positioning the advertising industry as a potential pioneer in adopting green technologies. The successful implementation of these solar billboards illustrates a viable path toward reducing environmental impact while maintaining the effectiveness of advertising strategies.

From an economic perspective, the detailed financial analysis provided compelling evidence that although the initial investment for solar technology integration is higher than traditional systems, the long-term benefits far outweigh the upfront costs. The break-even point of approximately 8.5 years is a critical milestone, after which significant financial savings are realized due to reduced operational costs and minimal maintenance requirements. These savings are enhanced by governmental incentives for renewable energy use, which can accelerate the amortization period and increase the overall financial attractiveness of solar-powered advertising solutions. Stakeholders within the advertising sector are provided with a robust economic case for transitioning to solar energy, aligning financial gains with ecological stewardship.

The positive market response to the introduction of solar-powered billboards highlights a significant interest and readiness within the industry for sustainable practices. This enthusiasm is indicative of a broader shift towards environmentally responsible business operations, where companies are increasingly recognizing the value of sustainability both as a marketing tool and as a corporate obligation. The adoption of solar billboards has the potential to set a precedent for other sectors, inspiring a comprehensive integration of renewable energy technologies into various aspects of business operations, from outdoor advertising to retail and beyond.

Future research directions offer exciting possibilities for enhancing the effectiveness and applicability of solar-powered billboards. Exploring the integration of cutting-edge digital advertising technologies with solar power could lead to more dynamic and energy-efficient advertising solutions. Further development of advanced energy storage systems could also improve the reliability and performance of these installations, ensuring consistent operation regardless of variations in solar energy availability. Additionally, expanding the deployment of solar billboards to diverse geographic and climatic conditions would provide valuable data on their adaptability and durability, informing better design and implementation strategies for global markets.

Moreover, investigating the long-term environmental impacts and conducting lifecycle assessments of all components used in solar billboards will be crucial. These studies would help in understanding the true sustainability of the materials and technologies employed, ensuring that the environmental benefits are comprehensive and not just limited to reduced energy consumption. By evaluating the full environmental lifecycle, from production through to disposal, stakeholders can make more informed decisions that support sustainable development goals more holistically.

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