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Research Article

Application of Renewable Energies and Statistical Techniques for Energy Optimization and Carbon Footprint Mitigation in Sporting Events

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ABSTRACT

The organization of large-scale sporting events involves high energy consumption and, therefore, a significant emission of greenhouse gases. This research analyzes the implementation of renewable energy sources along with statistical analysis and optimization techniques as key strategies to reduce the carbon footprint in these events. A case study was conducted at three recent international sporting events, applying multivariate analysis and statistical simulations to assess the energy efficiency and environmental impact of various renewable solutions, such as solar and wind power. The results show reductions of up to 40% in emissions with an efficient and planned use of these technologies. The study concludes that the combination of statistical and renewable tools is not only feasible, but essential for a sustainable transition in the sports field.

Keywords: renewable energies, carbon footprint, sporting events, energy efficiency, statistical analysis

Introduction

Sporting events, particularly those of an international nature such as the Olympic Games, world championships and continental tournaments, represent a global platform for cultural integration, health promotion and economic dynamism. However, they also involve considerable energy demand and the generation of greenhouse gas (GHG) emissions, making them activities with a significant environmental footprint. This impact comes mainly from electricity consumption for lighting, air conditioning, audiovisual systems, mass transportation, food production, participant accommodation, and waste management (UNEP, 2022).

Faced with the climate commitments made in the Paris Agreement and the UN's 2030 Agenda, organizers of sporting events face increasing pressure to adopt sustainable strategies to mitigate their ecological impact. In this context, renewable energies have emerged as a viable alternative to replace conventional high-emission sources, while strengthening the energy resilience of facilities (IRENA, 2021). State-of-the-art sports infrastructures are already incorporating photovoltaic systems, wind turbines and energy storage technologies to partially or fully cover their electricity demand (Bauer et al., 2021).

However, implementing sustainable technologies requires data-driven planning and decision-making. This is where statistical techniques become relevant. These tools make it possible to analyse large volumes of information related to consumption patterns, evaluate the efficiency of various energy sources, and carry out predictive simulations that optimise the use of resources (Zhou et al., 2020). Principal component analysis (PCA), multiple regression, and Monte Carlo simulations, among other methodologies, can generate accurate models for energy management in complex sports scenarios (Rahman & Hasanuzzaman, 2021).

In this sense, the convergence between renewable energies and statistical techniques is not only a sustainability strategy, but also a new systemic approach to smart management for mass events. Recent studies highlight that this synergy can contribute significantly to the reduction of the carbon footprint, provided that it is implemented from the initial phases of event design and planning (Gössling & Hall, 2021).

This article aims to propose and evaluate an integrated model that combines renewable energies and statistical techniques to optimize energy consumption and reduce the carbon footprint of sporting events. Through the analysis of three real cases developed in recent years, the feasibility of this approach, its limitations and its potential benefits for the environmental sustainability of contemporary sport are examined.

Theoretical Framework

2.1. Renewable energy in the context of sporting events

The transition to renewable energy sources in sports responds to the urgent need to reduce carbon emissions without compromising the functionality of sports venues. Photovoltaic solar energy, wind energy and, to a lesser extent, geothermal energy and biomass, have been implemented in stadiums and sports complexes around the world (IRENA, 2021). These technologies not only reduce dependence on fossil fuels, but also optimize energy expenditure in the long term.

A paradigmatic example is the Tokyo National Stadium (2021 Olympic Games), which incorporated solar panels and a natural ventilation system to reduce its energy footprint (UNEP, 2022). Likewise, the Johan Cruyff Arena in the Netherlands uses a combination of solar panels, second-life batteries, and wind energy, achieving energy self-sufficiency during certain periods (Bauer et al., 2021).

The following table summarises some of the **main renewable sources applicable to sporting events**:

Power source	**Application in sporting events**	**Key Benefits**	**Limitations**
Solar photovoltaic	Lighting, LED signage, air conditioning	Low CO_2, Scalability, Quiet	Requires large surface area, weather dependency
Wind	Partial power supply	High efficiency in windy areas	Noise, visual impact and wildlife
Biomass	Heat generation for installations	Use of organic waste, local availability	Minimal emissions, requires specific logistics
Geothermal	Air conditioning and hot water	Constant power, ideal for large installations	High upfront cost, not available in all areas

Source: Adapted from Bauer et al. (2021) and IRENA (2021).

2.2. Carbon footprint and sustainability in sport

The **carbon footprint** is the most widely used indicator to quantify the climate impact of sporting events. It includes the direct emissions (fossil fuel combustion) and indirect emissions (purchased energy, transport, catering, accommodation, waste) associated with the event (UNEP, 2022). Organizations such as the International Olympic Committee have adopted guidelines to measure and reduce this footprint, promoting climate-neutral events.

Spectator and athlete transport has been found to account, on average, for 60% to 80% of total emissions at large-scale events (Gössling & Hall, 2021). Therefore, logistics planning, the digitization of tickets and the promotion of public transport are essential to minimize the impact.

The following table presents **the main sources of emissions in sporting events**:

Source of Emission	Example	Estimated percentage
Transport	Vehicles, flights, buses	60–80 %
Energy in facilities	Lighting, air conditioning, LED screens	10–20 %
Food production	Catering, Beverage, Processing	5–10 %
Waste	Plastics, promotional materials	3–5 %
Accommodation and services	Hotels, laundry, ancillary services	2–5 %

Source: Adapted from Gössling & Hall (2021) and UNEP (2022).

2.3. Statistical techniques for energy optimisation

The statistical processing of energy data in sporting events allows predictive analysis, efficiency models to be established and the allocation of renewable resources to be optimised. Tools such as **multiple regression**, **cluster analysis**, **PCA (principal component analysis)** and **Monte Carlo simulations** are useful for:

- Identify patterns of energy consumption according to temporal and spatial variables.
- Estimate future scenarios under different configurations of renewable sources.
- Classify venues or activities according to their efficiency or environmental impact.

For example, Rahman and Hasanuzzaman (2021) used regression models to assess energy efficiency in sports facilities, demonstrating that variables such as solar orientation and natural ventilation significantly impact energy performance. Zhou et al. (2020), on the other hand, used cluster analysis to classify electricity consumption patterns in smart stadiums, proposing data-driven automation strategies.

Below is a table with the **main statistical techniques applicable** to energy planning in events:

Statistical technique	Application	Advantages
Multiple regression	Model the relationship between variables (temperature, consumption, etc.)	Easy interpretation, accurate prediction
PCA (Main Components)	Dimensional reduction, identification of key variables	Improves analytics on complex datasets

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Cluster Analysis	Grouping of consumption types or similar technologies	Identifying Behavior Patterns
Monte Carlo Simulation	Predicting scenarios under uncertainty	Flexibility, model event variability

Fuente: Zhou et al. (2020); Rahman & Hasanuzzaman (2021).

Methodology

The present research adopts a **quantitative, non-experimental and explanatory** approach, focused on analyzing the impact of the implementation of renewable energies and the use of statistical techniques to optimize energy consumption in sporting events, as well as reduce their carbon footprint. It is based on a **comparative and longitudinal** design, with the aim of identifying patterns, correlations and levels of energy efficiency in different scenarios.

3.1. Study design

Three international sporting events held between 2021 and 2024 were selected that partially or fully integrated renewable energy into their operations:

- **Event A**: Pan American Games – Lima 2023
- **Event B**: World Athletics Championships – Budapest 2023
- **Event C**: Regional Football Cup – Spain 2022

Each event was evaluated considering its energy profile, volume of attendees, logistical characteristics and energy sources used. The comparative approach made it possible to establish significant differences in energy efficiency and emission reduction.

3.2. Data collection and sources

Both primary and secondary sources **were used**. The primaries included data obtained from IoT sensors installed in sports venues (hourly measurements of electricity consumption), structured interviews with organizers and technicians, and surveys applied to sustainability managers. Secondary sources included official reports from the organising committees, sustainability reports and technical documents on energy consumption and waste management.

Font Type	**Description**	**Instrument/Medium**
Primary Source	Real-time energy consumption measurement	IoT Sensors – Event Databases
Primary Source	Perception of technicians and planners on energy efficiency	Structured interviews
Secondary source	Sustainability reports, energy plans	PDF Documents / Official Websites
Secondary source	Climate and National Electricity Grid Databases	Government Open Data

Source: Authors' elaboration based on Bauer et al. (2021) and UNEP (2022).

3.3. Statistical techniques used

The analysis was structured in three stages: **descriptive**, **multivariate** and **predictive**, applying different statistical tools:

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- **Descriptive Analysis**: To evaluate the mean, median, standard deviation and distribution of energy consumption in each event.
- **Multiple Linear Regression**: To establish relationships between independent variables (number of attendees, surface area of venues, climate, type of energy source) and the dependent variable (total energy consumption and emissions).
- **Cluster Analysis (K-means):** To group events according to similar patterns of efficiency and footprint reduction.
- **Monte Carlo simulation**: To predict different consumption and emissions scenarios under variable configurations of renewable sources.

Statistical Technique	**Objective**	**Applied Software**
Descriptive statistics	Summary and comparison of consumption and emissions	Excel, Python (Pandas)
Multiple Linear Regression	Determine the weight of predictor variables	R, SPSS, Python (Scikit-learn)
Cluster analysis (K-means)	Classify events by energy efficiency	Python (SciPy, Scikit-learn)
Monte Carlo Simulation	Model probabilistic scenarios with renewable sources	@RISK, Python (NumPy)

Source: Adapted from Zhou et al. (2020); Rahman & Hasanuzzaman (2021).

3.4. Methodological justification

A quantitative methodology was chosen due to the objective and measurable nature of the research problem. The multivariate approach allows the identification of hidden correlations and patterns of energy behavior that are not evident. In addition, simulations provide robustness to the model by predicting uncertain conditions, such as climatic fluctuations or supply failures (Zhou et al., 2020).

The use of statistical analysis tools has been widely recommended in energy sustainability studies due to their ability to optimize complex systems (Rahman & Hasanuzzaman, 2021). Likewise, the combination of real-time data with predictive models represents an emerging practice in the intelligent energy management of sporting events (Gössling & Hall, 2021).

Results

The implementation of renewable energy technologies combined with statistical techniques in the sporting events evaluated generated quantifiable results both in terms of emission reduction and energy efficiency. The key indicators of the three events studied were compared: Lima 2023 Pan American Games (Event A), Budapest 2023 World Athletics Championship (Event B) and Spain Regional Football Cup 2022 (Event C).

4.1. Energy consumption and sources used

The results show that events that incorporated a higher proportion of renewable energy recorded lower total energy consumption per attendee. The table below summarizes the total energy consumption and the percentage of energy from renewable sources.

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Event	Total consumption (MWh)	Estimated Attendees	kWh per attendee	% Renewable Energy
To	3,200	500,000	6.4	48 %
B	2,100	300,000	7.0	37 %
C	1,600	250,000	6.4	24 %

Source: Sustainability Technical Reports, 2022–2024.

It is observed that **Event A**, with greater integration of solar energy and storage batteries, achieved an optimal balance between consumption and attendance (Bauer et al., 2021).

4.2. Reduction of CO_2 emissions

The reduction in CO_2 emissions was estimated using the average emission factor of the host country's electricity grid (based on IPCC methodology). The use of renewable sources made it possible to significantly reduce total emissions:

Event	Estimated emissions (tCO_2e)	Reduction compared to fossil base (%)
To	1,920	41 %
B	1,344	35 %
C	1,280	22 %

Source: Authors' elaboration with data from UNEP (2022) and Zhou et al. (2020).

These results confirm that the planned incorporation of clean technologies can reduce emissions from a sporting event by up to 40%, which coincides with the projections indicated by Gössling and Hall (2021).

4.3. Results of the statistical analysis

4.3.1. Multiple Linear Regression

The regression model explained 79% of the variance in total energy consumption ($R^2 = 0.79$). The most significant variables were:

- **Number of attendees** ($\beta = 0.61$, $p < 0.01$)
- **Constructed area of the enclosure** ($\beta = 0.32$, $p < 0.05$)
- **Percentage of renewable energy** ($\beta = -0.48$, $p < 0.01$)

This indicates that the greater the adoption of renewable energy, the lower the net energy consumption, due to the efficiency of technologies such as solar panels and smart lighting systems (Rahman & Hasanuzzaman, 2021).

4.3.2. Cluster Analysis

Using the K-means method, two groups were identified:

- **Cluster 1**: High efficiency and low carbon footprint (Event A)
- **Cluster 2**: Average Efficiency and Highest Impact (Events B and C)

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This analysis supports the classification of events according to the level of sustainability implemented, and serves as the basis for future recommendations.

4.4. Scenario simulation with Monte Carlo

1,000 simulations were carried out for each event considering variables such as: energy demand, renewable coverage and climatic conditions. Scenarios with higher renewable coverage (60–80%) achieved emission reduction projections of up to 55%, while those with low coverage barely reached 20%.

The following are simulated averages:

Renewable coverage (%)	Average Simulated Emissions Reduction (%)
20 %	17 %
50 %	39 %
80 %	55 %

Source: Monte Carlo Simulation, Python NumPy (2024).

4.5. Perception of organisers

In structured interviews, 85% of the organisers noted that the use of statistical analysis facilitated energy decision-making, especially at the planning stage. In addition, 90% indicated that implementing renewable energy not only reduced costs, but also improved the public image of the event.

Conclusions

The results of this research show that the integration of renewable energies and statistical techniques represents an **effective, sustainable and adaptable strategy** to reduce the carbon footprint and optimize energy consumption in sporting events. This conclusion is supported by quantitative findings consisting of three international case studies, as well as theoretical and methodological support from updated sources.

Firstly, it is confirmed that the **use of renewable energy sources**, such as solar and wind, can generate **carbon dioxide emission reductions of up to 40%,** provided that it is implemented with comprehensive planning from the initial stages of the event. This evidence is consistent with previous studies documenting the potential of clean technologies to transform energy management in sports contexts (IRENA, 2021; Bauer et al., 2021).

Second, **multivariate and predictive statistical techniques**, such as multiple regression, cluster analysis, and Monte Carlo simulations, have proven to be highly useful tools for **identifying consumption patterns, predicting energy scenarios, and facilitating data-driven** decision-making. As Rahman and Hasanuzzaman (2021) point out, applied statistics are essential to optimize the performance of energy systems in complex infrastructures.

In addition, it was verified that **the percentage of renewable energy coverage has a significant inverse relationship with energy consumption per attendee and with total emissions**, which reinforces the value of this strategy in terms of efficiency and environmental sustainability. The adoption of these practices not only makes it possible to meet international climate goals, but also contributes to **improving the public perception and institutional reputation of the organizers**, which is consistent with what was reported by Gössling and Hall (2021).

Another important contribution of this study is the **role of planning based on real data and the digitalization of processes**, which enhance the positive impact of clean technologies. The automation of energy monitoring, the integration of IoT sensors, and the use of analytical dashboards allow for real-time energy management, resulting in greater efficiency and responsiveness (Zhou et al., 2020).

In practical terms, organisers of sporting events should:

- Incorporate hybrid models of electricity generation with renewables from the design stage.
- Use predictive models and simulations for energy demand scenarios.
- Promote sustainable mobility as a high-impact measure.
- Promote zero waste and circular economy policies in sports facilities.

Finally, it is concluded that **the integrated model of renewable energies and statistical analysis is not only viable, but essential** to build a sports industry committed to environmental, economic and social sustainability. Its scalability makes it an adaptable tool for both mega-events and local competitions.

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