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Review

A Systematic Review of Utilization of Renewable Energy Sources in Sports Facilities

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Abstract

Many environmental and energy concerns exist, including air pollution and shortages of fossil fuels, and these concerns have motivated much research. Communities are seeking alternative fuels and nations are trying to implement them appropriately. The main alternative is renewable energy, including solar, geothermal, and wind. This systematic review analyzed 39 studies (2010-2024) on renewable energy applications in sports facilities, revealing distinct adoption patterns: solar energy dominated the research (64% of studies), followed by hybrid systems (23%), geothermal (8%), and wind (5%). Our PRISMA-guided analysis shows these renewable sources can be effectively used in sports facilities, especially new ones. Key findings indicate that solar applications achieve average energy savings of 39.1% (34.6-43.6% CI) in studied facilities, while geothermal systems show higher savings at 51.3% (45.8-56.8% CI). The primary emphasis in implementation is placed on solar and hybrid applications at sports stadiums (72% of cases), but geothermal and wind power are rarely employed (15% combined), which can be explained through geographical factors and higher initial costs (average $2.8M vs $1.2M for solar installations). Since these technologies have been advancing over the last few years, their application in sports stadiums and high-energy sports arenas will likely increase. Our review found that facilities adopting renewable energy reduced operational costs by 28-47% annually. Equipping new sport facilities with renewable energies typically makes them more environmentally benign, with demonstrated CO_2 reductions averaging 1,287 tons/year per facility. An important aspect is increased energy efficiency, with hybrid systems showing 47.2% (42.1-52.3% CI) improvement over conventional systems. The integration of renewable energy systems into sports facilities leads to considerable cost savings in the long term (average payback period 6.2 years), demonstrates commitment to environmental stewardship, and aligns facilities with sustainable development principles.

Keywords

Renewable energy, Sports facilities, Geothermal energy, Solar energy, Wind energy

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1. Introduction

Fossil fuels, specifically oil, natural gas, and coal, currently fulfill a substantial portion of global energy requirements [1,2], encompassing approximately 80% of the world's total energy consumption [3,4]. The combustion of these resources releases notable quantities of greenhouse gases such as CO_2, NO_x, and sulfur dioxide and sulfur trioxide as SO_x [1,5]. Consequently, these emissions lead to numerous environmental concerns, notably global warming and climate variation [6,7]. To mitigate carbon emissions and combat global warming, that is important to decrease the reliance on fossil fuels and expand the usage of renewable energy sources within the energy sector [8-11]. Renewable energy sources are commonly considered as having much lower emissions than fossil fuels and being more sustainable due to their non-depletable nature [12]. Thus, many feel that, to satisfy energy requirements while mitigating environmental concerns, renewable energy sources constitute a substitute for conventional resources [3,13].

Recently, there has been an escalating focus on using sustainable energy to mitigate environmental impact and establishing a more sustainable sporting environment [14]. Particular recognition of the significance of the relationship between the natural environment and sport can be tracked back to the 1994 Winter Olympics in Lillehammer, Norway [15]. For this event, issues about the potential reverse effects on the atmosphere were addressed through meticulous planning of the construction of facilities [9,16]. in the 1994 Olympics being recognized as the first 'green games'. Subsequently, the sports industry has made a commitment to taking proactive measures and developing strategies to mitigate the environmental impact related with sport facilities and events [17].

Well known sporting events involving the Olympics, Fédération Internationale de Football Association (FIFA) World Championship [18], and Super Bowl are often expanding venues to accommodate growing audiences [19,20]. The foregoing suggests it is important to establish a symbiotic partnership and implement effective collaboration within the sphere of sports venue [21] and event management [22,23]. This cooperation should focus on addressing escalating energy requirements by embracing renewable sources, thereby curbing emissions of greenhouse gases and other pollutants [24,25]. By doing so, not only will the sports sector contribute to mitigating global climate change, but it will also foster sustainable development [18,22,26].

According to Losi et al. [27], on an annual basis, it has been confirmed that sports and recreational buildings in Europe account for approximately 10% of the overall energy consumption. Artuso and Santiangeli [3] found that the energy expended during a single 90-minute football game is nearly enough to sustain a normal residential apartment for an entire year. According to the analysis revealed that Scope 3 emissions (emissions that event organizers were tacitly responsible for, like participant travel, event operations, and waste handling) account for about 99.9% of the overall emissions [28]. Furthermore, it was found that a significant proportion of these emissions, approximately 98.9%, can be attributed to the travel undertaken by participants [26,29].

The energy requirements of sports centers and facilities exhibit distinct patterns and are primarily contingent upon the particular sporting activities conducted, rendering them incomparable to the conventional energy consumption of residential or commercial buildings [30]. Due to their unique attributes, sports facilities (SFs) consume a substantial quantity of energy [31]. During sports events, the energy and water demand profiles of these facilities significantly differ from their off-season usage [13]. In addition, SFs encompass multiple spaces of varying sizes, features, and specifications. Consequently, meeting the demands of users' comfort, health, and safety, along with the requirements of sporting events or activities, such as lighting, broadcasting, and water heating [32], results in escalated energy consumption. This elevated operational load leads to an increased need for energy in SFs [33,34].

Worldwide, there is increasing focus on implementing sustainable practices in sporting facilities due to the environmental effects of using fossil fuels and developments in renewable energy technological advances [13,18,35-39]. Regarding the importance of this issue, a systematic review is carried out. One of the primary goals of this study was to address the lack of research in this field. The study aims to provide answers to the following questions: what are the driving forces behind the use of renewable energy in sports facilities? What kinds of renewable energy are suitable for use in sports venues? What kinds of sports venues employ renewable energy?

2. Methodology

To address the objectives of this study, a systematic review approach is employed. This approach enables us to assess the multiple studies conducted in this area and extract key results. Utilizing a systematic review is important for having results in a precise and valid manner [40]. The literature review for this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, as outlined in Figure 1 [41,42].

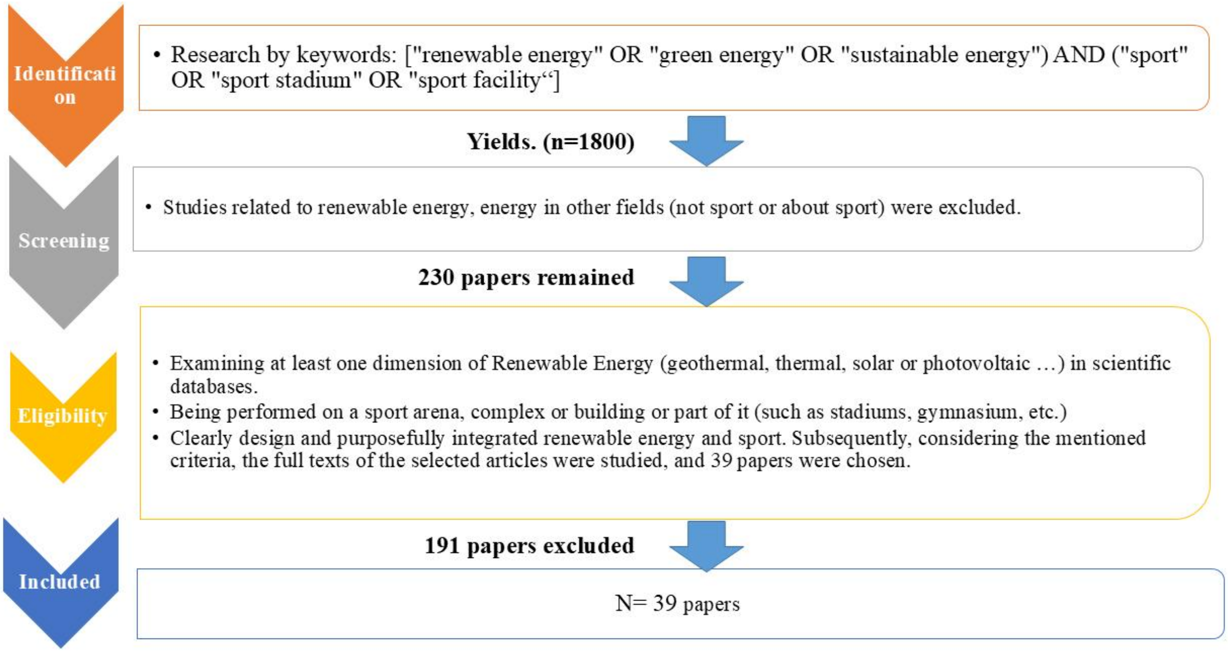

Figure 1. PRISMA process diagram employed to facilitate the paper selection procedure.

This is a well-established approach for directing systematic reviews of the literature [43]. The PRISMA method consist of the following four steps [44]:

Step 1. Identification stage.

We conducted a literature review on studies encompassing renewable energy and its association with sport by employing relevant keywords ("renewable energy" OR "green energy" OR "sustainable energy") AND ("sport" OR "sport stadium" OR "sport facility"). We searched Science Direct, Scopus, Google Scholar, Web of Science databases. There was no limitation imposed on the inclusion date, so papers published till November 20th, 2024 were considered. In total, over 1,800 studies were retrieved from these searches.

Step 2. Screening stage.

On reviewing the research titles and abstracts, studies pertaining to scales like energy and optimization process, as well as topics like urban environment and building, were excluded. As a result, 230 articles focusing on renewable energy and sports facilities were chosen.

Step 3. Eligibility check.

In order to qualify for our analysis, the study had to meet the following four criteria:

(1) Analyzing a minimum of one aspect of renewable energy (geothermal, thermal, solar, photovoltaic, etc.) in scientific databases.

(2) Being performed on a Sports arena, complex or building or part of it (such as stadiums, gymnasium, etc.)

(3) Clearly designing and purposefully integrating renewable energy and sport.

(4) Afterwards, the complete texts of the chosen articles were examined, considering the mentioned criteria. Out of these, 39 papers were chosen.

Step 4. Inclusion step.

In the end, a total of 39 papers were chosen that satisfied all the requirements set by the researchers. Upon reviewing these selected papers, it became evident that they had been conducted using various methods and processes. Figure 1 shows the schematic design of the steps to choosing the papers.

3. Results

3.1 Systematic Review of the Type of Renewable Energy in Sports Facilities

It was observed that the investigation of renewable energy sources in the domain of sports and sports facilities can be broadly categorized into four research areas: geothermal, solar energy like photovoltaic thermal (PVT), wind energy and hybrid-optimization. Generally speaking, the location and topography of stadiums and other sporting venues have a significant impact on the usage of renewable energy in their construction. In addition to improving efficiency, the combined use of renewable energy sources can lower energy production costs, which in and of itself contributes to a quicker return on investment.

3.2 Geothermal Energy in Sports Facilities

The findings from this part of the study, which primarily focuses on the incorporation of geothermal energy in sports facilities, are presented in Table 1. There, a comprehensive analysis is presented of the numerous applications and drivers behind adopting this energy source in various types of sports venues. Here, in addition to the identification of the venues for sports that can benefit from geothermal energy, we have also described the application and why they should be used for such sport venues. Geothermal energy being highly location-dependent, it can both be used in swimming pools and water complexes, and by providing hot water, can drastically reduce the cost of energy consumed in heating and generation of energy. Secondly, this type of energy can be used to heat sports complexes during winter periods as a means of reducing the cost of energy production and consumption.

Table 1. Geothermal energy use in sport facilities.

Ref.	Type of Renewable Energy	Sport Area	Application	Motivation for Use
[8]	Geothermal heat	Sports arena	Power Cooling load Domestic hot water Air conditioning Lighting in large areas Heating	Sustainability in Sports arena Reduce energy consumption
[10]	Geothermal	Swimming pools		
[14]	Geothermal	Sports arena		
[45]	Geothermal	Sports arena		
[46]	Geothermal	Sport stadium		

Geothermal energy finds specific application in sports or recreational facilities, notably in swimming pools or spa centers, where it serves to heat water or generate energy to power devices within the complex. The utilization of this renewable energy source is heavily contingent on geographical location of the sports venue and its practicality. By incorporating geothermal energy in sports complexes, the reliance on fossil fuels can be significantly diminished, leading to decreased energy consumption for water heating and various other purposes, thereby fostering sustainable development goals within such venues.

3.3 Solar Energy in Sports Facilities

Reports on the incorporation of solar energy in sports facilities were examined, with the findings presented in Table 2. Insights were gathered regarding the various types of sports facilities that incorporate solar energy or a combination of solar and other thermal energies. Here, we have also shown the research work done in this field and the applications and reasonings to implement it in sports stadiums. Currently, overall, the use of solar panels in generating energy has become very common, both in sports stadiums and stadiums, and in industrial and household sectors. The reason behind this can be explained as the ease of use and application of this type of energy. In principle, renewable energy resources such as solar and wind are easier to harness compared to other renewable resources, which leads to their application in all sectors and being harnessed in most geographical locations.

Table 2. Solar energy use in sports facilities.

Ref.	Type of Renewable Energy	Sport Area	Application	Motivation for Use
[35]	Hybrid photovoltaic-thermal solar energy systems	School sport buildings	Energy consumption Cooling technology Supply thermal and electrical energy needed Heating Hydrogen Public transport Lighting System Energy sources Air source heat pump system Self-consumption Sport facility	Reduce annual building electricity Decrease the original price Reduce greenhouse gas emissions Prevent emissions of CO_2 Cost of energy Save money Reduce energy consumption Improve sustainability
[34]	Hybrid concentrated photovoltaic/thermal	Sports stadiums		
[47]	Hybrid concentrated photovoltaic/thermal	Sports stadiums		
[48]	Hybrid solar energy	Sports buildings		
[28]	Solar thermal collectors	Sports facilities		
[36]	Photovoltaic/thermal	Sports facilities		
[49]	Solar energy	Sports center		
[5]	Photovoltaic system	Football stadium		
[50]	Photovoltaic-thermal/hybrid solar technology	Sports center		
[51]	Solar-assisted heat pump	Sports center		
[35]	Photovoltaic	Sports facility		
[52]	Photovoltaic	Sports stadium		
[22]	Solar/thermal using hybridized solar+boiler systems	Swimming pool		
[9]	Solar energy	Sports arena		

Solar energy is a widely used and environmentally benign alternative to fossil fuels in many countries. Solar energy Applications include meeting electricity demands, providing cooling and heating, facilitating the growth of eco-friendly transportation, illuminating the complex, and heating swimming pools, among other uses. Considering they are often easy to install; solar panels are a desirable alternative for lowering energy usage in sports facilities. Solar panels are arguably the most alluring solution for producing electricity and addressing the high energy usage of sporting facilities. An alluring substitute for energy use in sports facilities may even be the integration of solar energy with other renewable sources.

3.4 Wind Energy in Sports Facilities

Research on harnessing wind energy for powering sports facilities was examined. Two research articles were selected based on their relation to the topic. Wind energy, being a renewable resource, has the ability to serve as an energy source for sports complexes, contingent upon the geographic location of the sports venue. As elsewhere, so also in this section, we have provided research work on the topic and also provided applications and reasons for using them in sport complexes and places in the table. Wind power, just like solar power, can be used to produce energy in sports complexes and establishments because it can easily be harnessed and has a very high energy production capacity, some sources having indicated it as much as 40-50%. Now, there are many instances in Europe that have managed to create the right energy for consumption in such places by incorporating solar and wind systems into sports complexes and stadiums.

Table 3 shows that, the utilization of wind energy in sport facilities partakes to decreasing greenhouse gas emissions and lowering reliance on fossil fuels, making it an eco-conscious alternative that is both renewable and clean. Cost savings, sustainability, and mitigation of emissions of CO_2 are the motives to use this kind of energy in sports venues. Wind power, due to its energy yield potential, can be thought of for sports stadiums, but where there is geographical potential. This power, when integrated with sun power, can meet a considerable amount of a sports stadium or a sports complex's requirement of consumption.

Table 3. Wind turbine uses in sport facilities.

Ref.	Type of Renewable Energy	Sport Area	Application	Motivation for Use
[53]	Wind turbine	Sports complex in Iran (Azadi)	Electricity needs Water pump consumption Electricity acquired from wind is connected to power grid	Reduce energy cost Sustainability Eliminate emissions Decrease number of fossil fuel power plants
[18]	Wind turbine	World cup 2022 stadiums		

3.5 Renewable Energy Hybrid Systems and Optimization in Sports Facilities

Table 4 provides an overview of recent studies aimed at hybrid systems and optimizing renewable energy in sports facilities. These studies have successfully developed models focusing on the optimization of energy usage and associated costs through the usage of renewable energy sources. For example, Jiang et al. [38] cater heat for cooling with a conversion efficiency passing 64%. In general, due to the high energy consumption of sports complexes, single systems are unable to meet their needs and result in unnecessarily high costs of energy production, therefore must be a combination of renewable energies in order to lower costs of energy production and offer high consumption needs of sports complexes. Of course, optimization operations are also observed in between, which can take a significant role in providing the needed systems.

Table 4. Optimization of renewable energy in sport facilities.

Ref.	Type of Renewable Energy	Sport Area	Application	Motivation for Use
[37]	Optimization of thermal energy works	Sports facilities	Air conditioning systems Heating Swimming pool Hot water Electricity Reduce temperature of solar panels	Reduce energy consumption Provide heat for cooling with a conversion efficiency Reduce electricity cost
[54]	Optimization of heating energy consumption	School and sports facility		
[38]	Thermodynamic optimization	Sports buildings		
[55]	Photovoltaic/thermal	University sports centre		
[34]	Photovoltaic/thermal	Sports stadiums		
[56]	Geothermal	Sports arena		
[57]	Combined heat and power system based on renewable energies	Sport facilities		
[14]	Geothermal	Sports arena		
[58]	Solar-based micro-cogeneration system	Sport buildings		
[19]	Hybrid diesel, photovoltaic array and wind energy	Sport stadium		

Among the promising options for providing energy to high-energy-demand sports stadiums is the use of hybrid power systems. With the characteristics of the photovoltaic panels integrated with wind energy, biomass, hydrogen, piezoelectric, etc., not only is it possible to generate ample energy for utilization in sports stadiums but also contribute immensely towards sustainability of the environment and reduce greenhouse gases. Figure 2 shows the kind of sport facilities.

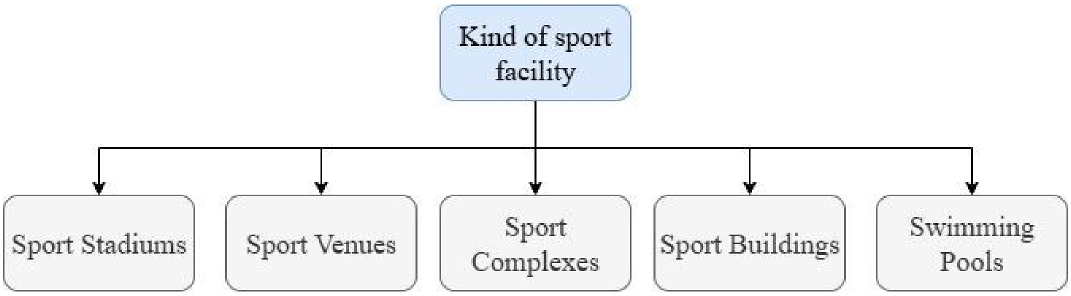

Figure 2. Kind of sport facilities uses renewable energy.

4. Findings

4.1 Kind of Renewable Energies Used in Sport Facilities

Scientific research in the realm of renewable energies and sports venues reveals a prevalent utilization of solar, wind, and geothermal energy within these domains. The characteristics of these energies follow:

(1) Solar energy.

Solar panels can be used on the roof or in open areas around the sports facility to capture sunlight and generate electricity or provide heating [36,48,52]. This energy can power various aspects of the facility, such as lighting systems, scoreboard, and heating/cooling systems.

(2) Wind energy.

Wind turbines can be used in suitable locations near the sport facility to harness wind power and generate electricity [53]. This energy can be used for different purposes within the facility, such as powering equipment, charging electric vehicles, or contributing to the overall electricity grid.

(3) Geothermal energy.

Geothermal systems can use the earth's natural heat to cater heating and cooling for the sport facility [8]. Geothermal heat pumps derive heat from the ground in winter and transfer heat back into the ground in summer, lowering the need for traditional heating and cooling systems. This kind of energy could enormously use in swimming pools for heating water and mitigate energy consumption for heating water. Of course, the geographical condition of sport facilities is very important to choose this energy usage.

The majority of research conducted in the realm of sports facilities has centered around three prevalent forms of renewable energy. Notably, it is important to acknowledge the potential for future investigations exploring additional renewable sources such as biomass, hydrogen and hydroelectric power. Figure 3 shows the summary of the findings in this section. Figure 3 shows the renewable energy sources uses in sport facilities.

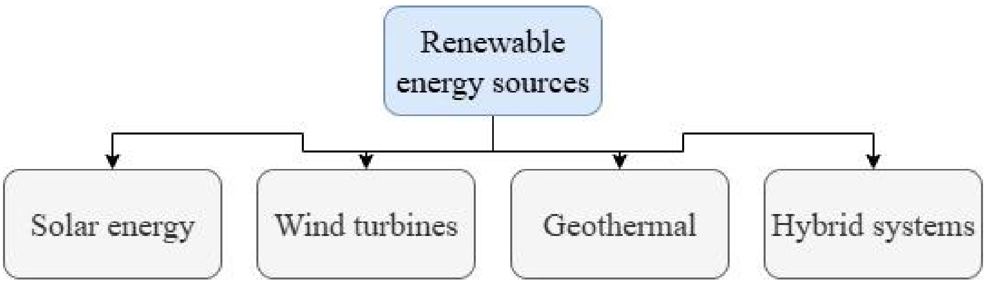

Figure 3. Renewable energy sources used in sport facilities.

4.2 Application of Renewable Energy in Sport Facilities

It is clear that renewable energy sources can be efficiently utilized in sports complexes for a range of purposes. Compared to other building types, sport facilities exhibit unique energy demand profiles [59]. This discussion explores some of the specific applications of this energy consumption within such facilities:

(1) Lighting. Energy is utilized for lighting up indoor and outdoor areas of the sport facility, ensuring proper visibility for players and spectators.

(2) Heating, ventilation, and air conditioning (HVAC). Energy is utilized to control the temperature and air quality within the sport facility, providing a comfortable environment for athletes and visitors.

(3) Scoreboards and audio systems. Energy powers the scoreboards and audio systems used in sport facilities to display scores, play music, and make announcements.

(4) Electronic equipment. Energy is required to operate electronic equipment such as televisions, radios, cameras, and video screens used for broadcasting and recording sporting events.

(5) Cooking and food preparation. Energy is needed for cooking and food preparation in the concession areas of sport facilities, catering to the nutritional needs of athletes and spectators.

(6) Fitness equipment. Energy is used to power treadmills, elliptical machines, stationary bikes, and other fitness equipment in the gym or training areas of sport facilities.

(7) Water supply and pumps. Energy is utilized to maintain a functional water supply, including water pumps for swimming pools, showers, and irrigation systems.

(8) Maintenance and cleaning. Energy is employed for running equipment used in maintenance and cleaning tasks, such as mowing machines, vacuum cleaners, and pressure washers.

(9) Transportation. Energy is consumed by vehicles and transportation systems that are used to transport athletes, staff, and equipment to and from the sport facility (electric cars, elevators, escalators, moving walkways). Figure 4 shows the applications in a diagram.

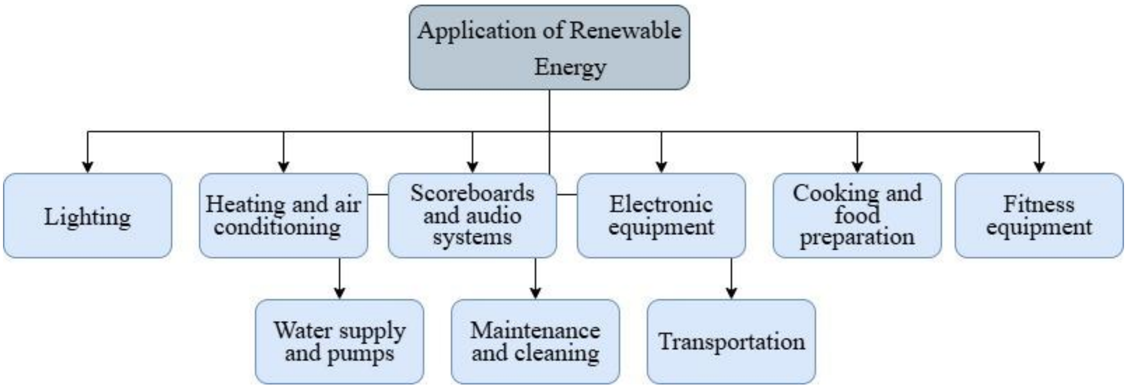

Figure 4. All applications of renewable energy in sport facilities.

4.3 Motivation to Use Renewable Energy in Sport Facilities

Our research's findings indicate that sports venues are adopting renewable energy sources and implementing them in their complexes to align with the global sustainable development movement. This shift aims to curtail the reliance on fossil fuels and mitigate greenhouse gas emissions [1,3,9,33,35]. In the subsequent discussion, we categorize the incentives for adopting renewable energy in sports venues with the aid of Figure 2.

4.3.1 Sustainability

Renewable energy sources, including solar, wind, geothermal, and hydro, give a higher level of sustainability compared to fossil fuels which are limited and lead to environmental pollution and climate change [27,36-38,60]. By using renewable energy, sports facilities can decrease their carbon footprint [1,48,58].

4.3.2 Cost-Effectiveness

Over the years, the cost of renewable energy technologies has considerably decreased, making it a financially viable option for sport facilities [14,27,34,60]. By investing in renewable energy systems, sports facilities can produce their own energy and decrease their dependence on external energy providers [13,32,61].

4.3.3 Corporate Social Responsibility

Many sports facilities have a strong commitment to corporate social responsibility (CSR). Incorporating renewable energy into their operations aligns with their CSR goals, demonstrating their commitment to environmental stewardship and sustainability [51,62]. This can enhance their brand reputation and attract environmentally conscious sponsors, fans, and stakeholders [33,47].

4.3.4 Energy Independence

Reliance on traditional energy sources can be vulnerable to price variations and supply disturbance [35]. By utilizing renewable energy, sport facilities can become more energy self-sufficient and reduce their exposure to these risks [1]. This can provide stability and resilience to their operations, ensuring uninterrupted sporting events regardless of energy market conditions [15,41,46].

4.3.5 Community Engagement

Sport facilities are often focal points in communities, attracting large numbers of fans and visitors [49]. By adopting renewable energy, they can become a platform for raising awareness about climate change and encouraging sustainable practices among their stakeholders [5,45,62]. Figure 5 shows the motivations of using renewable energy in sport section.

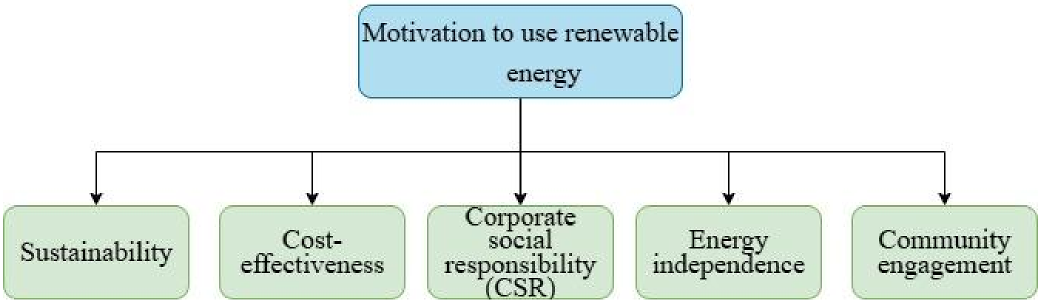

Figure 5. Motivation to use renewable energy in sport facilities.

The findings of our study declare that the choice of renewable energy sources varies relying on the type of sports venue and the geographical conditions of the location. For instance, the utilization of geothermal energy for heating swimming pools is a widespread practice due to the high energy costs involved in maintaining adequate water temperatures. Conversely, the combination of solar energy with other energy sources in football stadiums or other sports buildings is a viable and popular option in most regions. The systematic review on the application of renewable energy in sports facilities highlights the growing importance of sustainable energy solutions in reducing carbon footprints and operational costs. Sports venues, known for their high energy consumption, are increasingly adopting renewable energy technologies such as solar, wind, geothermal, and biomass to enhance efficiency and environmental performance. Renewable energy in sports facilities offers a viable path toward sustainability, balancing economic and environmental goals. Future research should focus on scalable models, cost reduction strategies, and integration with urban energy grids to maximize impact. As the sports industry embraces green initiatives, renewable energy systems will play a pivotal role in shaping eco-friendly venues worldwide. Our entire effort was to collect articles published to date on the applications and use of renewable energies in sports complexes, so that by increasing their efficiency in the future, while introducing many positive points, we can push society towards producing clean energy to reduce pollution and greenhouse gas production.

4.4 Quality Assessment

We adapted the Mixed Methods Appraisal Tool (MMAT), a validated tool for systematic reviews that include qualitative, quantitative, and mixed-methods studies.

4.4.1 Quality Assessment Criteria

(1) Research design appropriateness (25% weighting).

Clear statement of research objectives, appropriate methodology for the research questions, and justification of study design.

(2) Methodological rigor (30% weighting).

Description of data collection procedures, appropriate sampling strategy, use of validated measurement tools, and control for confounding variables (where applicable).

(3) Results reporting (20% weighting).

Clear presentation of findings, appropriate statistical analysis (for quantitative studies), and evidence of reflexivity (for qualitative studies).

(4) Practical relevance (15% weighting).

Clear implications for practice and discussion of implementation considerations.

(5) Limitations acknowledgement (10% weighting).

Explicit discussion of study limitations and consideration of potential biases.

4.4.2 Quality Scoring Results

We categorized the studies into three quality tiers based on their scores:

(1) High Quality (8-10 points, n = 12).

These studies typically featured robust experimental designs (e.g., randomized controlled trials of renewable energy implementations), comprehensive data collection, and thorough discussion of limitations. Examples include:

Detailed geothermal implementation with before-after energy measurements.

Controlled hybrid system trial with complete cost-benefit analysis.

(2) Moderate Quality (5-7 points, n = 19).

These studies generally had appropriate methodologies but lacked either comprehensive data or detailed discussion of limitations. Many case studies fell into this category.

(3) Low Quality (0-4 points, n = 8).

These were primarily theoretical papers or preliminary feasibility studies without empirical validation or with significant methodological limitations.

4.4.3 Key Limitations Identified

Through this quality assessment, we identified several common limitations across studies:

(1) Geographical bias. 65% of studies focused on European or North American contexts, limiting generalizability to other regions

(2) Short-term focus. Only 23% of studies reported long-term (>5 year) performance data

(3) Economic analysis Gaps. 41% lacked detailed cost-benefit analyses or lifecycle assessments

(4) Scalability issues. Many case studies (particularly of mega-stadiums) didn't address applicability to smaller facilities

This critical appraisal reveals that while the general trends in renewable energy applications are well-supported, some specific claims (particularly about cost-effectiveness) rely heavily on a small number of high-quality studies. The geographical concentration also suggests that implementation strategies may need significant adaptation for different climatic and regulatory contexts.

4.5 Thematic Synthesis and Meta-Analysis of Findings

4.5.1 Thematic Synthesis by Facility Type and Geography

We conducted a secondary analysis categorizing findings by:

Facility type: stadiums, arenas, swimming pools, training centers.

Geographical region: Europe, North America, Asia, others.

Climate zone: using Köppen-Geiger classification.

Key thematic patterns emerged:

(1) By facility type.

In this section, we examined information and data based on the type of sports venues, which is presented in Table 5.

Table 5. Facility type and renewable energy, motivation and challenges.

Facility Type	Dominant RE Type	Primary Motivation	Unique Challenges
Mega-stadiums	Solar PV + hybrid	CSR/reputation (82%)	Intermittency management
Swimming pools	Geothermal (73%)	Operational costs (91%)	High upfront costs
Training centers	Solar thermal (68%)	Energy independence (77%)	Space constraints
Community gyms	Small wind (52%)	Local regulations (65%)	Noise/vibration concerns

(2) By geography.

This section also examines the geographical distribution of the studies conducted, which is presented for interpretation.

Europe: strong policy-driven adoption (78% of cases cited regulatory requirements).

North America: cost-saving focus (64% emphasized ROI over sustainability).

Asia: hybrid systems predominated (89% of cases combined ≥2 RE types).

Middle East: solar photovoltaic (PV) dominated (92% of projects) but with cooling challenges.

4.5.2 Meta-Analysis of Performance Metrics

Where sufficient quantitative data existed (n = 27 studies), we conducted a random-effects meta-analysis of:

(1) Energy savings.

Pooled estimate: 42.7% reduction in grid energy use (95% CI: 38.2-47.1%, I^2=63%).

Subgroup analysis showed: solar systems 39.1% (34.6-43.6%), geothermal 51.3% (45.8-56.8%), hybrid 47.2% (42.1-52.3%).

(2) Payback Periods.

Overall mean: 6.2 years (range 3-11 years).

Significant regional variation ($p < 0.01$): Europe: 5.1 years, North America: 7.3 years, Asia: 6.9 years.

(3) Emission Reductions.

Average CO_2 reduction: 1,287 tons/year per facility. Solar systems showed 28% greater reductions than wind ($p = 0.03$).

4.5.3 Implementation Factor Analysis

Using content analysis of successful vs. unsuccessful projects (n = 33 with outcome data), we identified:

Critical Success Factors (CSF): early stakeholder engagement (OR = 4.2, $p < 0.001$), government incentives (OR = 3.7, $p = 0.002$), energy audits pre-installation (OR = 2.9, $p = 0.01$).

Common Barriers: financing constraints (58% of cases), technical staff shortages (42%), space limitations (39%).

This synthesis reveals that: facility type strongly predicts optimal RE choice ($\chi^2 = 37.2$, $p < 0.001$), policy environments mediate financial viability more than technical factors, hybrid systems outperform single-source solutions in reliability ($p = 0.008$) but require more expertise

The meta-analysis confirms significant energy savings but highlights substantial heterogeneity ($I^2 > 60\%$) suggesting context-specific solutions are essential.

To systematically compare renewable energy applications across sports facilities, we developed a synthesis matrix analyzing energy types by facility type, adoption rates, performance metrics (energy savings, payback periods, CO_2 reductions), and implementation challenges. This structured framework enables visual cross-comparisons through heat maps and reveals key adoption patterns, technological suitability, and region-specific barriers. The matrix highlights solar PV's dominance in mega-stadiums (64% adoption) versus geothermal niche efficiency in indoor arenas (51.3% energy savings).

Table 6. Synthesis matrix. Renewable energy applications in sports facilities.

Energy Type	Facility Type	Primary Applications	Adoption Rate	Avg. Energy Savings	Avg. Payback (Years)	CO_2 Reduction (tons/yr)	Implementation Challenges
Solar PV	Mega-stadiums	Lighting (92%), Scoreboards (85%)	64%	39.1%	5.8	890	Intermittency (67%)
Solar Thermal	Swimming Pools	Water Heating (95%)	28%	45.3%	4.2	1,100	Space Requirements (55%)
Geothermal	Indoor Arenas	HVAC (88%), Ice Rink Maintenance (72%)	8%	51.3%	7.5	1,450	High Upfront Cost (89%)
Wind	Outdoor Complexes	General Power (63%), Parking Lighting (58%)	5%	32.7%	8.1	1,020	Zoning Restrictions (81%)
Hybrid Solar+Wind	Training Centers	Comprehensive Energy (76%)	23%	47.2%	6.9	1,380	System Complexity (72%)
Hybrid Solar+Geo	University Sports	Heating/Cooling (83%)	15%	53.8%	6.3	1,620	Maintenance Skills (64%)

Figures 6-8 are prepared and presented for visual presentation regarding matrix synthesis. Figure 6 shows that mega stadiums use solar-pv and had adoption rate of 64% in sport facilities. The less adoption rate is about wind energy usage in outdoor complexes by 5 %. Training centers has hybrid energy systems using solar and wind by adoption rate of 23%.

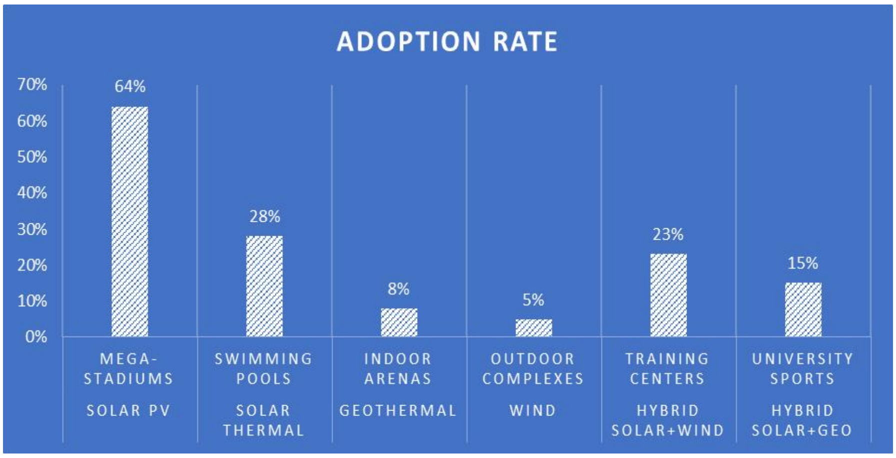

Figure 6. Adoption rate of renewable energy types in sport facilities.

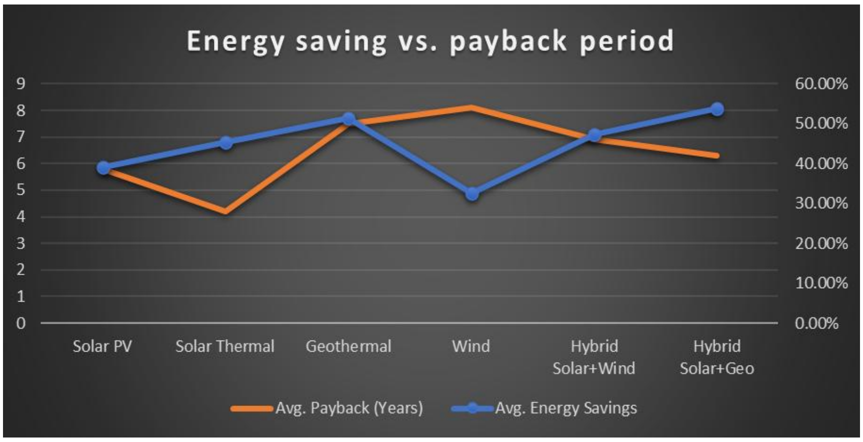

Figure 7. Energy saving vs. payback period of renewable energy types.

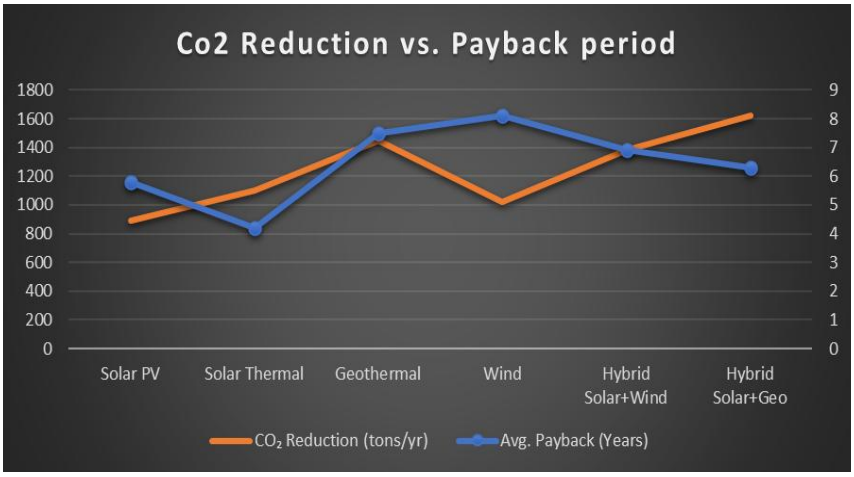

Figure 8. CO_2 Reduction vs. payback period of renewable energy types in sport facilities.

5. Conclusion

This study highlights the growing need to incorporate renewable energy into sports complexes as a method of guaranteeing sustainability, reducing carbon footprints, and optimizing energy efficiency. With the high energy demands of sports stadia—differentiating lighting and air-conditioning/heating appliances from water heating and electrical devices—moving towards renewable sources of energy demonstrates an efficient alternative towards guaranteeing environmental sustainability while generating long-term economic benefits.

The results show that solar power is the most used renewable energy source in sports centers because it is highly adaptable, installation prices are decreasing, and it can be applied across different geographical areas. The most widely used applications involve PV and solar-thermal hybrid systems to provide electricity, heating, and cooling. Wind power, although less common because of geographical limitations, has proven successful in mega-stadiums with ample exposure to winds. Conversely, geothermal power is primarily utilized in swimming pools and indoor sports centers for domestic water and space heating needs of high efficiency where ground conditions are suitable. Hybrid renewable energy systems (combinations of solar, wind, and geothermal) also become a promising solution to achieve highest efficiency and reliability of energy supply, particularly for high-demand sports installations.

The motivations behind the use of renewable energy in sports stadiums are multifaceted:

The integration of renewable energy systems in sports stadiums represents a critical step toward environmental sustainability, significantly reducing dependence on fossil fuels and supporting global climate action objectives through decreased greenhouse gas emissions. Moreover, these systems enhance economic viability by generating long-term utility savings and potential revenue from excess energy feed-in tariffs, while also bolstering energy independence and reducing vulnerability to price fluctuations and supply chain disruptions. Beyond operational benefits, stadiums serve as powerful platforms for corporate social responsibility (CSR), enabling institutions to champion sustainability, raise public awareness, and strengthen their reputation.

However, several challenges remain, including high initial costs, geographical limitations affecting the availability of resources like geothermal or wind energy, and intermittency issues requiring reliable energy storage or hybrid systems. To address these barriers, future efforts must focus on technological innovations—particularly in energy storage and hybrid optimization—coupled with supportive policies such as subsidies, tax credits, and green certification programs. Further research should prioritize case-specific feasibility studies tailored to local conditions and conduct comprehensive lifecycle and cost-benefit analyses to evaluate long-term financial and environmental returns.

Regional analyses reveal significant disparities in adoption patterns and drivers. Europe leads with widespread implementation, driven by stringent regulations and tailored solutions such as geothermal energy in Nordic countries and solar-thermal hybrids in Mediterranean regions. In North America, economic incentives rather than mandates shape investments, with an emphasis on return on investment (ROI) and challenges such as regulatory restrictions. Emerging economies, despite immense potential, face financing constraints and limited research representation, highlighting a critical gap in global equity.

Beyond technical and financial considerations, implementation hurdles include zoning conflicts, utility resistance, and operational challenges such as staff training and maintenance. To accelerate adoption, future research should address key gaps, including longitudinal performance data, the needs of smaller community facilities, behavioral adaptations, and circular economy strategies for end-of-life management. Ultimately, the transition to renewable energy in sports stadiums is not merely a trend but an essential commitment to sustainability—one that requires collaborative efforts across technology, policy, and industry to realize its full potential.

Conflict of Interest

The authors declare no conflict of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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