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# Carbon emission and energy risk management in mega sporting events: challenges, strategies, and pathways

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Carbon emissions from mega sporting events pose a serious challenge to the sustainable development of the global environment, and the management of carbon emissions and energy efficiency in sporting events has become a focus of attention for both countries and international organizations. However, most existing research focuses on carbon emissions in sporting events is limited by a narrow focus on individual cases, limited attention to indirect emissions, insufficient integration of socioeconomic dimensions, a lack of broader data coverage, the adoption of interdisciplinary methodologies, and an emphasis on lifecycle energy risk management to provide robust support for sustainable event practices and policy development. To remedy these deficiencies, this study systematically compiles the current situation of carbon emissions in sports activities, analyzes the carbon emission characteristics and energy-saving potential of different types of sporting events, and summarizes the excellent cases of carbon emission and energy efficiency management in sports activities. The study reveals that large-scale sporting events generate substantial carbon emissions and energy consumption in transportation, venue construction, and event operation. However, carbon emissions and energy usage can be significantly reduced by optimizing venue locations, promoting green transportation, and implementing energy-saving measures at all stages. This study not only provides empirical data and theoretical support for the management of carbon emissions and energy efficiency in sporting events but also proposes practical and feasible suggestions that are highly important for the sustainable development of future sporting events. The findings have reference value for policymakers and event organizers in planning and implementing energy-saving and low-carbon events, helping promote environmental governance and sustainable development in the sports sector.

KEYWORDS

**carbon emissions, energy risk management, energy savings, mega sporting events, sports participants**

# 1 Introduction

Carbon emission governance and energy efficiency improvements have become global concerns, as climate change and energy consumption pose unprecedented challenges to the survival and development of human societies. Carbon dioxide, a major greenhouse gas (GHG), accounts for the vast majority of anthropogenic GHG emissions (Triantafyllidis and Davakos, 2019; Xu and Chen, 2020). In addition to carbon emissions, inefficient energy use exacerbates the environmental crisis, as the growing energy demand for large-scale activities leads to increasing GHG emissions and resource depletion. Global warming and energy inefficiency not only threaten the stability of ecosystems but also pose serious threats to the economy, society, and human health (Sovacool et al., 2022). To address these interrelated problems, countries worldwide have cooperated extensively under multilateral frameworks, such as the Paris Agreement, which aims to limit global average temperature increases to within 2°C above preindustrial levels. Countries have formulated and implemented policies to reduce emissions and improve energy efficiency, such as the Climate Change Act in the United Kingdom, the Global Warming Countermeasures Advancement Act in Japan, and the Clean Energy and Security Act in the United States (Nejat et al., 2015). These efforts focus not only on reducing carbon emissions but also on enhancing energy-saving measures in various sectors.

As the world's largest emitter of carbon dioxide, China faces a significant challenge in reducing emissions and improving energy efficiency. In the context of global carbon emission governance, China has actively participated in international cooperation and taken strong measures to control GHG emissions while promoting energy-efficient technologies and practices (Lin and Sun, 2010; Deng et al., 2025). Scholars have outlined a six-pronged strategy to drive low-carbon transformation in Chinese cities, aiming to support sustainable development and foster global low-carbon urbanization. This strategy encompasses the establishment of carbon emission monitoring systems, the promotion of enterprise digitalization, the advancement of renewable energy technologies, the enhancement of carbon trading markets and regulatory frameworks, and the widespread adoption of low-carbon principles (Zhao and You, 2020; Xinfa and Jinglin, 2022; Xinfa et al., 2023). Since 2009, China has pushed forward a green and low-carbon economy by establishing carbon emission trading markets and launching pilot programs aimed at both reducing carbon emissions and improving energy savings in industries and urban planning (Pan and Guo, 2024; Liu et al., 2024a). China's "dual carbon" goals, to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, also prioritize energy efficiency as a key component in meeting these targets (Liu et al., 2022; Xu et al., 2023). Shifting focus to large-scale sporting events shows that the energy demand of large-scale sporting events has significant environmental and economic implications, accompanied by risks such as supply uncertainties, price fluctuations, and potential challenges arising from policy or environmental changes. Adopting systematic energy risk management strategies can help mitigate disruptions and stabilize costs, ensuring the successful achievement of sustainability goals.

Under the overall framework of global carbon emission governance, the carbon emissions of sporting events, as activities with wide-ranging social influence, are receiving increasing attention. Large-scale sporting events are important sources of carbon emissions because of their wide participation and large flow of people and logistics. In particular, a large amount of carbon emissions are generated in the construction of event venues, the operation of events, and the transportation of spectators and athletes (Zhang et al., 2022). Therefore, the study of carbon emission governance in the field of sporting events is not only of academic importance but also plays an important guiding role in practical emission reduction.

International sports organizations have also attached great importance to this issue (Wicker and Thormann, 2022). In 1992, the International Olympic Committee (IOC) incorporated environmental protection into the Olympic Charter for the first time at the Barcelona Olympic Games, proposing that environmental protection is an important part of the modern Olympic movement. Since then, the IOC and the United Nations Environment Programme (UNEP) have jointly established the Sport and Environment Commission, which has further promoted the sustainable development of sporting events (Wicker, 2019). In this context, several major international sporting events, such as the Olympic Games and the World Cup, have begun to implement carbon emission management measures, gradually integrating the green concept into all aspects of these events (Herold et al., 2022). These initiatives not only enhance the sustainability of these events but also provide examples and practical experience for the realization of global carbon emission reduction targets and energy-efficient improvements.

In the field of academic research, studies on the carbon emission management of sporting events have made some progress, but many urgent problems remain to be solved. Studies have shown that the carbon footprint measurement methods for sporting events are being improved (Pedauga et al., 2022; Müller et al., 2021), and many scholars have proposed different carbon emission measurement models and methods to quantify the environmental impacts of sporting activities (Herold et al., 2022). However, most existing studies focus on case studies and lack systematic and comparative studies across event types (McCullough et al., 2020). In addition, how can carbon emissions be effectively reduced while ensuring the quality of the event? How to incorporate low-carbon and energy-efficient concepts at the planning stage of an event still needs to be explored in depth (Cooper, 2020).

Despite increasing attention being paid to carbon emissions and energy efficiency in sports events, existing research remains largely limited to case-specific analyses, restricting the generalizability of the findings across diverse event types and contexts. Moreover, indirect carbon emissions and lifecycle energy consumption are often overlooked, with studies predominantly focusing on direct emissions during events. The socioeconomic implications of carbon governance in sports also remain underexplored, leaving a critical gap in understanding the broader impacts of sustainability initiatives. Additionally, while quantitative methods have advanced, they often lack integration with the qualitative insights necessary for effective planning and decision-making in carbon management. This study addresses these gaps by systematically analyzing carbon emission characteristics and energy-saving potential, including lifecycle impacts, across various types of sporting events. Drawing on exemplary case studies and comparative insights, this study provides a comprehensive framework from which to understand and manage carbon emissions in sports. The findings contribute both to theoretical advancements and practical applications, offering actionable strategies for policymakers and event organizers to implement sustainable, low-carbon practices, particularly in alignment with China's dual carbon goals.

The advantage of these studies is that they provide a large amount of data support, which provides a theoretical basis on which decision-makers can formulate relevant policies. However, the limitations of the studies are also obvious; first, the limitations of the research object lead to the poor generalizability of the results; second, the research methodology lacks a comprehensive consideration of indirect emissions, energy consumption, and lifecycle emissions; and finally, most existing studies are quantitative analyses, which lack a comprehensive consideration of the impacts of the social and economic aspects in the process of carbon emission and energy efficiency governance. To address the limitations of existing studies, this work employs sustainability and energy efficiency theories to provide a structured analysis of carbon emissions and energy governance in mega sporting events. Sustainability theory focuses on balancing economic, environmental, and social objectives, making it a critical lens through which to evaluate the long-term impacts of sporting events. Integrating renewable energy, waste reduction measures, and sustainable transportation practices into event operations can significantly reduce carbon emissions. Energy efficiency theory highlights the importance of optimizing energy usage to achieve maximum efficiency with minimal environmental impact. Mega sporting events, characterized by high energy demands for venue operations, lighting, and transportation, offer unique opportunities for implementing innovative energy-saving technologies and practices. This framework is applied to explore three core dimensions. The first dimension includes lifecycle carbon emissions, which involves identifying critical intervention points across the planning, execution, and decommissioning stages of events. The second dimension includes technological innovation, which focuses on renewable energy systems and smart technologies to increase resource efficiency. Finally, the third dimension involves socioeconomic impacts, which are examined to understand how low-carbon initiatives can foster community engagement and sustainable economic development. By incorporating these theoretical perspectives, this study contributes to addressing the environmental challenges associated with mega sporting events and provides actionable insights for policymakers and organizers. Therefore, an overview study of carbon emissions and energy efficiency governance in sporting events can not only systematically address the current research progress but also highlight directions for future research, which has important academic value.

To overcome the shortcomings of the existing research, this study adopts a combination of systematic combing and case study analysis. First, this work combines the current situation of carbon emissions in sporting activities in detail and analyzes the carbon emission characteristics and energy consumption patterns of different types of sporting events and their influencing factors. Second, this study summarizes excellent cases of carbon emission and energy efficiency management in sports activities, such as the Olympic Games and the World Cup, and discusses the successes and shortcomings of these cases in terms of carbon emission and energy-saving management. In addition, this work provides thoughts and suggestions on carbon emission and energy efficiency management for sports activities in China and proposes a management path suitable for China's national conditions to provide theoretical support and practical guidance for the sustainable development of sports activities in the future.

# 2 Current status of carbon emissions and energy saving from sports activities

## 2.1 Carbon emissions and energy saving from mega sporting events

Mega sporting events are the main focus of carbon emission research in the field of sports. While showcasing the socioeconomic development of venues, large-scale sporting events inevitably generate carbon emissions due to rigid energy consumption. The reason for this is that the expansion of the scale of sporting events attracts many spectators from all over the world, and corresponding facilities must keep up with these growing crowds, leading to an increase in carbon emissions. The construction of event infrastructure and the field of transportation during an event are the main sources of carbon emissions from large-scale sporting events (Ito and Higham, 2023).

In addition to carbon emissions, energy consumption is a significant concern (Xu et al., 2019; Xu et al., 2020). Mega sporting events require enormous amounts of energy for lighting, heating, cooling, and venue operation, making energy risk management critical for reducing the overall environmental impact of such events (Cerezo-Esteve et al., 2022). Energy-saving measures and energy efficiency improvements have become key objectives for host cities aiming to minimize the carbon footprint of these events.

The international community has a long history of concern for green Olympics, with the IOC and the UNEP working together to protect the environment. At recent Olympic Games, environmental protection has become one of the key concerns of host countries. Under the leadership of the Olympic Committee, the organizers of the Olympic Games have made efforts to reduce carbon emissions and have taken various measures to achieve the goal of greening the Olympics.

A significant part of these efforts has been improving energy efficiency in venue operations and promoting energy-saving technologies (Elnour et al., 2022). For example, the use of renewable energy sources, such as solar and wind energy, has helped reduce the degree of reliance on traditional, carbon-intensive energy sources. The integration of clean energy solutions, including hydrogen, wind, and solar power, has accelerated the shift away from carbon-intensive energy systems. In venue construction, low-carbon technologies such as carbon capture and storage, electrolytic metal production, and process optimization have been advanced to increase energy efficiency and resource utilization levels, whereas advanced energy risk management systems have optimized energy use in real time to ensure minimal waste (Xinfa and Xue, 2022; Tang et al., 2024).

The Beijing Olympics made great achievements in implementing the concept of green Olympics, with only 1.18 million tons of carbon emissions being released during the games, which is much lower than that of the London Olympics in 2012 (3.4 million tons), the Rio Olympics in 2016 (4.5 million tons), and the Tokyo Olympics in 2020 (3.01 million tons) (Cooper, 2020). The reduction in carbon emissions during the Beijing Olympics was largely due to the incorporation of energy-efficient technologies (Wu and Zhang, 2008), such as LED lighting in stadiums, energy-efficient cooling systems, and the widespread use of electric vehicles for transportation. These technologies significantly reduced energy consumption and carbon emission levels, setting a new standard for energy efficiency in mega sporting events.

The 2024 Paris Olympics also committed to hosting a green and sustainable sporting event by setting a "carbon budget" that limited carbon emissions to 1.58 million tons of carbon dioxide equivalent for the entire event (Heynen and Vanaraja Ambeth, 2023). Organizers actively promoted energy-saving initiatives, such as through the use of public transportation and encouraging athletes to travel by train to reduce carbon emissions from transportation. Moreover, the Paris Olympics focused on improving energy efficiency across all venues by incorporating smart energy risk management systems and energy-saving technologies in infrastructure design, which included the use of sustainable building materials and energy-efficient heating, ventilation, and air conditioning (HVAC) systems and the integration of renewable energy sources, such as solar panels, to meet part of the energy demand during the event. In addition to these measures, the Paris Olympics in 2024 faced significant climate risks, including projections of extreme heatwaves exceeding historical records by up to 4°C under severe scenarios. To address these risks, organizers implemented adaptive strategies such as modifying event schedules, installing cooling systems in key areas, and leveraging advanced climate models such as CMIP6 to predict and manage extreme weather conditions. These efforts exemplify how proactive planning and technological innovation can mitigate the dual challenges of climate adaptation and carbon reduction.

In contrast, the 2010 Winter Olympics in Vancouver focused on the following two aspects: first, the implementation of public transportation and the increased use of hydrogen power, and second, the construction of low-carbon projects worldwide through cooperation with green energy agencies (Scott et al., 2015). The 2014 Winter Olympics in Sochi constructed specially designed venues using transparent glass structures to save energy (Prudnikova, 2012). Energy-saving designs, such as the transparent glass structures used in Sochi, not only reduce the need for artificial lighting but also improve the energy efficiency of the venues by maximizing the amount of natural light. This approach, combined with the use of renewable energy sources, helped lower the overall energy consumption of the event.

In addition to the use of green buildings and clean energy, the 2018 Pyeongchang Winter Olympics constructed a GHG monitoring system and issued a carbon management report (Kim and Chung, 2018). However, all three of the abovementioned Winter Olympics suffered problems such as venues being quickly deserted after the games, some of the energy being nonrenewable, and the large-scale use of smart technology having yet to be realized. To address these issues, energy efficiency planning must extend beyond the event itself to include designing venues that can be repurposed or used sustainably after the games and ensuring that the energy systems in place, such as solar panels or wind turbines, continue to generate renewable energy for the local grid long after the event has concluded.

The 2022 Beijing Winter Olympics is a more typical example. The green essence of the 2008 Beijing Olympics continued to develop, and moreover, carbon emissions were minimized through the implementation of a series of low-carbon management measures (Wang et al., 2022). For unavoidable and unmitigated emissions, carbon credits or other means were used to offset the remaining carbon emissions. Energy risk management played a crucial role in achieving carbon neutrality at the 2022 Beijing Winter Olympics. During these Olympics, a combination of renewable energy sources, such as wind and solar energy, was utilized, and advanced energy-saving technologies were implemented across venues. Furthermore, smart energy risk management systems were employed to monitor and optimize energy usage in real time, ensuring maximum energy efficiency during the event.

Starting from four aspects—energy, buildings, transportation, and carbon sinks—and through cutting-edge technologies such as artificial intelligence and 5G, all carbon emissions were neutralized. As Juan Antonio Samaranch Jr., President of the IOC Beijing Winter Olympics Coordination Commission, stated, "Even in the difficult times of the pandemic, the Beijing Winter Olympics Organizing Committee will host an extraordinary Winter Olympics." The incorporation of AI and 5G technologies into energy risk management marked a significant step forward in improving energy efficiency. These technologies enabled the real-time monitoring and optimization of energy use across venues, reducing energy waste and ensuring that the event operated as efficiently as possible.

Overall, the carbon emissions of the Summer Olympics, Winter Olympics, and World Cup show that there is still a long way to go to reduce carbon emissions from mega sporting events, as shown in Table 1.

In view of the above findings, academics have resorted to the carbon footprint to quantify the carbon emissions of mega sporting events (Zhang et al., 2022; Wilby et al., 2023; Edwards et al., 2016). Factors such as the level, scale, number of spectators, and number of sports programs of large-scale sporting events determine the total amount of carbon emissions from these events. Although existing studies are still fragmented, transportation travel still accounts for a large proportion of the carbon footprint of all types of large-scale sporting events. In addition to carbon emissions, energy consumption plays a significant role in the overall environmental impact of these events. The high energy demands for the lighting, cooling, heating, and powering of various event infrastructures, particularly during peak times, further exacerbate the carbon footprint of such events. Energy efficiency improvements and energy-saving initiatives are essential to complement carbon footprint reduction efforts, ensuring that overall energy use is optimized and reduced.

On a different scale, the challenges of energy consumption and carbon emissions in large-scale sporting events involve several key risks. First, the increased energy demand during events may disrupt operations due to power outages or fuel shortages, raising concerns

TABLE 1 Carbon emissions from selected mega sporting events.

| Race name | Venue | Year of organization | Carbon emissions (tons) |
|---|---|---|---|
| Summer Olympic Games | Beijing, People's Republic of China | 2008 | 118 |
| | London, United Kingdom | 2012 | 340 |
| | Rio de Janeiro, Brazil | 2016 | 450 |
| | Tokyo, Japan | 2020 | 301 |
| | Paris, France | 2024 | 158 |
| Winter Olympic Games | Vancouver, Canada | 2010 | 25 |
| | Sochi, The Soviet Union | 2014 | 52 |
| | Pyeongchang, Korea | 2018 | 159 |
| | Beijing, People's Republic of China | 2022 | 130.6 |
| World Cup | German | 2006 | 25 |
| | South African | 2010 | 275 |
| | Brazil | 2014 | 227 |
| | Russia | 2018 | 216 |
| | Qatar | 2022 | 363 |

Note: Data from the author's compilation of the Sustainability Report and Carbon Management Report for previous tournaments.

over supply reliability. Second, volatile energy prices can lead to budget overruns, undermining the execution of sustainability plans. Third, unexpected changes in energy policies or regulations by the host region may necessitate adjustments to management strategies. Finally, extreme weather events, such as storms or heatwaves, can strain the energy infrastructure. These risks not only complicate energy risk management but also threaten event sustainability objectives. Thus, effectively addressing these issues requires embedding risk management within the broader framework of event energy planning.

Dolf and Teehan (2015) counted the travel modes of approximately 40,000 spectators hosted by 10 varsity teams of the University of British Columbia in a single season from 2011 to 2012. The 4% of spectators who chose to travel by air produced 52% of the total carbon footprint of all spectators. It is evident that air travel has extremely high carbon emissions and that the choice of transportation mode of event participants is a key determinant of the total carbon emissions of the event at hand. The energy consumption associated with various transportation modes, particularly air travel, further underscores the need to integrate energy-saving transportation options into carbon reduction strategies. For example, encouraging the use of energy-efficient public transport or electric vehicles can significantly reduce both carbon emissions and energy consumption.

Edwards et al. (2016) conducted a 2-year follow-up study at the University of Arizona, and through the combined efforts of the researchers and event organizers, the total impact of the back-to-school event in 2013 (1,900 t $CO_2$-eq) was 19% lower than that in 2012 (2,400 t $CO_2$-eq). These efforts are reflected in the following: in terms of transportation, initiatives to reduce carbon emissions from transportation trips, including encouraging carpooling trips and providing bus services, were implemented in 2013. Researchers continue to attribute the reduction in carbon emissions to participants traveling closer together. In addition to these transportation-related initiatives, energy-saving strategies played a role in reducing the overall environmental impact of the event. By implementing energy-efficient lighting systems and minimizing energy use during nonpeak hours, event organizers were able to further reduce energy consumption while maintaining event quality.

Tóffano Pereira et al. (2019) calculated the carbon footprint of Premier League clubs during the 2016–2017 season and reported that infrastructure and travel modes were the main sources of carbon emissions. The largest share of GHG emissions at mega sporting events is caused by spectator travel (Musgrave et al., 2021) and the severe impact of spectators' choice of transportation mode to the stadium (Dosumu et al., 2017). For example, the VfL Wolfsburg sustainability report shows that over 60% of GHG emissions come from spectator travel (Herold et al., 2024). Spectators may come to the stadium on foot, by bicycle, by car, by bus, or by public transport, and their choice of transportation may depend on a variety of intrinsic and environmental factors. Unfortunately, to date, few studies have investigated the environmental impacts of spectator mobility in the context of events, especially considering the carbon footprint of various spectator mode choices (Orr and Inoue, 2019). Moreover, the energy consumption associated with different transportation modes has not been sufficiently explored. Energy-intensive modes of travel, such as private cars or air travel, increase not only the carbon footprint but also overall energy demand. Studies should aim to examine energy-efficient transportation alternatives, such as electric buses or cycling, to provide lower-energy-consuming options for event participants.

In particular, the literature lacks insights into which transportation modes are chosen by different groups of spectators to reach sporting event venues and into the contributions of these different groups to total GHG emissions.

On the basis of data measurement, scholars have also proposed corresponding carbon reduction measures, such as reducing long-distance air travel, increasing vehicle usage, and encouraging the choice of low-emission transportation, on the basis of the results of data analysis. These carbon reduction measures can be further enhanced by focusing on energy efficiency improvements. For example, increasing the availability of energy-efficient electric vehicles and optimizing energy use in public transportation systems through smart grids and renewable energy sources can reduce both carbon emissions and energy consumption.

## 2.2 Carbon emissions and energy risk management of stadiums

The importance of the construction of many stadiums is self-evident given the environmental impacts generated by large sporting events. For the construction of large-scale stadiums and ancillary facilities, event organizers raise a large amount of money through various channels to build stadiums to meet the needs of such events, and a large amount of carbon dioxide is emitted during the planning, design, construction, operation, and dismantling of the whole process. For the 2008 Beijing Olympic Games, Beijing, as the host city, built 12 new venues, covering a total area of 1.4 million square meters and an area of 2.49 million square meters of ancillary infrastructure. This scale of construction also had great ecological impacts on Beijing because of the large area covered by the stadiums (Worden et al., 2012). In addition to carbon emissions, energy consumption during the construction and operation of these stadiums is another critical factor. Energy-efficient improvements, such as the use of energy-saving construction materials and energy-efficient systems for lighting, heating, and cooling, are essential to reduce the overall environmental impact.

The Qatar World Cup invested 6.5 billion dollars in seven world-class stadiums while renovating and expanding one old stadium. Over the past 10 years, Qatar has spent approximately $300 billion on preparing for the World Cup, which is approximately 26 times greater than the 2014 World Cup in Brazil and 21 times greater than the 2018 World Cup in Russia (Al-Jabir and Isaifan, 2023). The Qatar World Cup has made efforts and innovations in several areas, such as clean energy, green transportation, and resource recycling, but as a whole, the carbon emissions consumed by the tournament should still not be underestimated, with 3.63 million tons of carbon emissions during the period. According to the Building Design According to the Greenhouse Gas Accounting Report (GGA Report) for the Qatar World Cup released by FIFA in 2021, the carbon emissions caused by the construction of stadiums for this World Cup event accounted for approximately 24.6% of the total carbon emissions of the event (Ito and Higham, 2023). Energy efficiency measures, such as the use of renewable energy sources and the implementation of smart energy risk management systems, have also been integrated into stadium operations. These measures help reduce energy demand during games, increasing the energy efficiency of such stadiums.

In addition, the transportation of raw materials during the construction of stadiums also increases local transportation carbon emissions (Daddi et al., 2021). The scheduled hosting of the 2022 Beijing Winter Olympics marked Beijing as the world's first "Double Olympic City." At the Beijing Winter Olympics, all the newly built venues adhered to the three-star green building certification and the renovated venues adhered to the two-star green building certification through energy-saving renovation, which perfectly interprets the sustainable development bidding concept put forward by the Organizing Committee for the Winter Olympic Games (OCOG). For example, the "Ice Ribbon" of the National Speed Skating Arena adopted a series of green building materials and energy-saving technologies, and its use of air to heat venue management rooms was able to reduce GHG emissions by up to 160 tons per year (Liu et al., 2023). These energy-saving technologies not only reduce carbon emissions but also significantly lower the energy consumption required for venue operations, setting a new standard for energy-efficient sports facilities.

To reduce the carbon emissions brought about by sports stadiums, more than 10 different specifications have been established globally to assess the carbon emission sources of large buildings, such as sports stadiums, like PAS2050 issued by the British Standards Institution (BSI), ISO14067 issued by the International Organization for Standardization (ISO), by the joint efforts of the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI), the Greenhouse Gas Protocol, etc. The more authoritative international assessment systems are as follows. 1) The Leadership in Energy and Environmental Design (LEED) certification was established by the U.S. Green Building Council in 1998 and is considered the most systematic, authoritative, and widely applied assessment standard for sustainable, green, and low-carbon buildings in the existing assessment systems worldwide (Germain and Penfield, 2010). LEED certification emphasizes energy-efficient improvements by requiring the use of energy-efficient materials, systems, and designs that minimize energy consumption and promote sustainable energy use. 2) The United Kingdom established the Building Research Establishment Environmental Assessment Method (BREEAM) system in 1990 with the core concept of "adapting to local aspects and balancing benefits," which has provided a practical direction for the construction of buildings that can not only follow the concept of sustainability but also satisfy local requirements (Awadh, 2017). Both the LEED and BREEAM systems advocate reducing energy consumption in buildings through energy-efficient design and smart energy risk management systems. Building information modeling (BIM) information technology, which is currently more widely used in the field of construction than in other fields, has the advantages of improving carbon emissions and energy consumption throughout the lifecycle of sports stadiums.

Scholars in various countries are also making efforts in this area. For example, Rhee and Kim (2021) argued that the public's concern for environmental protectionism must be greater than the performance of the games played in the stadiums because of the large amount of raw materials used in the construction of sports stadiums and the aggravation of local traffic emissions caused by the construction and operation of these stadiums. Pereira et al. (2017) proposed a stadium facility location problem (FLP), which analyzed the international travel distances and associated carbon footprints of participating sports teams on the basis of quantitative data and explored, via 11 simulation scenarios, how the host country with the closest overall average travel distances for all sports teams can be selected in the planning phase of the event to reduce its negative effects on the environment. Moreover, Triantafyllidis et al. (2018) investigated on-campus venues (high-density areas in cities) versus off-campus venues (low-density areas in suburbs) on the basis of the different areas in which university intercollegiate competition venues are located and concluded that the environmental impact can be reduced by altering the public transportation system in high-density areas; this study revealed that energy-efficient public transportation options, such as electric buses and trains, could further reduce both the carbon emissions and energy consumption associated with spectator and team travel.

Manni et al. (2018) argued that green behaviors in the planning and construction stages of stadiums can be achieved by sourcing locally produced raw materials for the venues; constructing types of "movable venues" such as air-film venues; and using recyclable and environmentally friendly materials as much as possible in the construction of these venues. The use of locally sourced materials also helps reduce the energy consumption associated with transportation during the construction process. Additionally, Dong et al. (2020) proposed that carbon emission accounting research on stadiums can be divided into two dimensions. One dimension considers the macro perspective of the overall accounting of national, regional, provincial, and municipal buildings; the other dimension considers the micro perspective of the accounting of individual buildings. Moreover, Onat and Kucukvar (2020) studied an evaluation model of green stadiums and suggested that the existing lifecycle assessment (LCA) model should be extended by using an advanced lifecycle sustainability assessment framework, in which the impacts of green stadiums on three aspects—society, the economy, and the environment—can be analyzed. Through this evaluation model, not only the reduction potential of the carbon footprint but also the lifecycle cost, economic value added, and impact on human health can be assessed. Energy-efficient improvements are an integral part of LCA, as reducing energy consumption across the entire stadium lifecycle—from construction to operations—directly contributes to decreasing the carbon footprint.

Academics both at home and abroad have begun to explore the scientific site selection, low-carbon construction, sustainable evaluation, and public awareness of environmental protection based on venues.

## 2.3 Carbon emissions and energy risk management of sports participants

A sports participant is a general term for a person who is involved in sports or sports communication activities (Beaton et al., 2011). Both athletes directly involved in the competition and spectators of sporting events leave a carbon footprint of varying degrees. The carbon footprint of a sport is the total amount of GHG emissions caused by an individual, event, organization, service, or product in the process of sports participation, which is included in energy consumption, raw materials and goods, food, services, transportation, travel, waste management, and equipment. Energy consumption plays a significant role in the carbon footprint of sports participants, particularly in terms of transportation and accommodation. Implementing energy-saving measures, such as using energy-efficient modes of transportation or opting for accommodations with energy-efficient systems, can significantly reduce the overall environmental impact. For example, travel by athletes and spectator tourists accounted for 67% of carbon emissions at the 2010 FIFA World Cup in South Africa (Cartwright et al., 2012). The entire 2005–2012 London Olympics cycle generated approximately 3.4 million tons of carbon emissions, with onsite spectator-related emissions accounting for 20% of total emission (Gold and Gold, 2013), and the carbon emissions from the 2014 Brazilian World Cup amounted to 83% of total emissions. Carbon emissions from spectator tourists at the 2016 Rio Olympics accounted for 55.33% of carbon emissions during the hosting phase and 74% of carbon emissions from the 2018 FIFA World Cup in Russia (Pereira et al., 2017). The carbon equivalents contributed by spectator tourists during the preparation and hosting of the 2018 PyeongChang Winter Olympics accounted for 62% of total carbon emissions in the hosting stage. According to the Qatar World Cup 2022 Carbon Emissions Report, 1.2 million fans arrived in Qatar during the event, which resulted in an average increase of 100,000 tons of carbon emissions per day (Kucukvar et al., 2021).

The study of sports participants focuses on the carbon emissions produced by sports participants during sports activities, which is the latest achievement of applying carbon footprint analysis to sports. Blake (1999) reported that highly educated sports participants may have more environmental knowledge than may less educated sports participants but that this knowledge does not directly trigger "pro-environmental behaviors" among sports participants. The above study confirmed the asymmetry between environmental awareness and behavior, suggesting that there is an "environmental value action gap" in sports activities. Diekmann and Preisendörfer (2003) argued that this gap can be explained by the low-cost hypothesis, whereby sport participants perceive the "higher cost" of using public transportation (because of the loss of convenience) for the trips required for them to participate in sports and are reluctant to forego the use of more convenient modes of travel, such as private automobiles, thus resulting in a greater carbon footprint. Encouraging participants to adopt energy-efficient behaviors, such as using low-carbon transportation options such as electric vehicles or public transport, can help bridge the gap between environmental awareness and action. Promoting energy efficiency and energy-saving measures across all aspects of participation is key to reducing overall emissions.

Wicker et al. (2020) estimated that the average annual carbon footprint of active snow sports participants due to transportation was approximately 431.6 kgCO2-e in 2015 via an online survey of German skiers; he then further analyzed the relationship between individual differences in sport participants and carbon footprint emissions. The regression analyses revealed that there is a significant positive correlation among income level, the actual number of skiing days, and the annual carbon footprint of snow sports participants, whereas there is no significant relationship between the awareness of environmental protection and the carbon footprint. This finding suggests that environmental protection attitudes are not related to behavior, as far as individually generated carbon emissions are concerned. Moreover, Wicker (2019) analyzed the annual carbon footprint of individual sports and its influencing factors, as

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generated by the transportation trips of active participants in 20 sports (12 individual sports and 8 team sports) in Germany. The results revealed that the annual carbon footprint *per capita* of team sports (514.0 kgCO2-e) is significantly lower than that of individual sports (1,006.5 kgCO2-e). Three sports—diving, golf, and surfing—have the highest carbon footprints, all exceeding 2,000 kgCO2-e. It is evident that those sports with a greater carbon footprint are tourism- or vacation-driven sports activities, which are highly dependent on natural resources.

In these cases, the energy consumption associated with long-distance travel and accommodation is a significant contributor to the high carbon footprint. Implementing energy-efficient measures, such as promoting sustainable tourism practices or using energy-efficient accommodations, can reduce the carbon and energy impacts of these activities. Similarly, the income effect is likewise mostly positive in 20 summer sports, and the variables related to education are not significant. Additionally, Castaignède et al. (2021) constructed a formula to account for the carbon footprint of marathon participants and conducted an empirical study. The marathon was analyzed, and the key carbon emission sources of participation include mainly transportation carbon emissions, catering carbon emission, accommodation carbon emissions, and solid waste emissions, whereas offsite participants are the core contributors to the carbon emissions of marathon participation. Through empirical investigation, Castaignède et al. (2021) reported that the average carbon footprint of the whole sample of participants in the 2021 Zhengkai International Marathon is 94.57 kg of carbon equivalent, the average transportation carbon footprint is 81.56 kg of carbon equivalent, the average lodging carbon footprint is 3.21 kg of carbon equivalent, the average food and beverage carbon footprint is 8.96 kg of carbon equivalent, and the average solid waste carbon footprint is 0.84 kg of carbon equivalent. The total carbon footprint of the 2021 Zhengkai International Marathon is estimated to be 3,484,904 kg of carbon equivalent, of which the total transportation carbon footprint is 3,005,486 kg of carbon equivalent, the total lodging footprint is 118,289 kg of carbon equivalent, the total food and beverage footprint is 330,176 kg of carbon equivalent, and the total solid waste footprint is 30,970 kg of carbon equivalent.

In addition to carbon footprint measurements, energy efficiency improvements in transportation and accommodation services can further enhance the level of reduction in environmental impact (Si et al., 2020; Liu et al., 2024b). By adopting energy-efficient technologies and services, such as electric buses for transport and energy-saving technologies in hotels, the carbon and energy footprints of participants can be further minimized. In addition to carbon footprint measurement helping improve the public's understanding of environmental impacts, it also provides information for decision-makers to formulate policies and set priorities in terms if which measures to undertake. For this reason, many companies have developed web-based carbon footprint calculators for public use (Benjaafar et al., 2013). As Collins et al. (2009) suggested, the carbon footprint not only provides a local perspective on measuring the environmental impact of sports but also, importantly, links the environmental impact of sports to the global ecosystem. Although there are subtle differences in the calculation methods of these approaches, they play a catalytic role in promoting individual perceptions of environmental impacts (Blanchard et al., 2011). Although there are few studies on the application of carbon footprint analysis in the field of physical activity, several commonalities can still be found in existing studies; there is no correlation between environmental awareness and an individual's total annual carbon footprint, and most of the carbon footprint is reflected in the transportation travel of participants, especially the carbon emissions generated by air travel. Moreover, energy-saving behaviors, such as carpooling, the use of public transportation, or low-carbon transportation options such as bicycles, can significantly reduce both carbon emission and energy consumption levels. When sports participants use these energy-efficient modes of travel, the overall carbon and energy footprints of the event are greatly reduced.

# 3 Excellent cases of carbon emission and energy risk management in sports activities

## 3.1 Excellent cases of carbon emission and energy risk management for mega sporting events

As shown in Table 2, the IOC was the first international sports organization to propose sustainable development and introduce the carbon footprint to measure the environmental impact of sporting events. This study takes milestone events as the nodes to sort out the IOC's efforts for the carbon reduction issue and provides a broad historical staging for it, which is summarized into the budding period (1984–1999), the preparatory period (2000–2010), the trial period (2011–2020), and the improvement period (2021-present).

### 3.1.1 Budding period (1984–1999)

After the 1984 Los Angeles Olympic Games, the environmental costs of noise, pollution, energy consumption, and resource consumption caused by crowds generated by large-scale sporting events received a great deal of attention, thus triggering reflection by the IOC. In 1992, the IOC sent representatives to attend the United Nations Conference on Environment and Development (UNCED) and subsequently made efforts to publicize the concept of controlling climate change in the sports world. In February 1994, the Lillehammer Winter Olympics, for the first time, included environmental protection assessment and measures as the main content of the Olympic Games preparation and hosting stage. The organizing committee set five green goals, which included addressing energy consumption and improving energy efficiency in venue operations. These Olympic Games were the first to incorporate environmental protection into their management, marking the first specific response to the climate issue through programs and measures included in the event hosting process. In August of the same year, the Olympic Centennial Congress held in Paris specifically discussed the issue of sports and the environment and decided to take the environment as one of the three pillars of Olympism, emphasizing that the Olympic Movement must take responsibility for environmental protection. In 1995, the IOC established the Sport and Environment Commission, which included climate and environmental indicators in the bidding criteria and observed them in all Olympic-related activities. In 1996, provisions on the environment and sustainable

TABLE 2 IOC's "carbon reduction" actions.

| Years | Events | Actions |
|---|---|---|
| 1984 | Los Angeles Olympics | People have been raised concern about the environmental costs, prompting a rethink by the International Olympic Committee |
| 1992 | United Nations Conference on Environment and Development | The International Olympic Committee (IOC) was represented at the conference and focused on promoting the concept of climate change control in the sports world |
| 1994 | Lillehammer Winter Olympics | For the first time, environmental protection assessment and measures were made a major part of the preparation and hosting of the Olympic Games |
| 1994 | The Centennial Olympic Congress in Pairs | The IOC has specifically discussed the issue of sport and the environment |
| 1995 | Establishment of the Committee on Sport and the Environment | The inclusion of climate and environmental indicators in the bidding criteria signals the transition of sport's sustainable development model |
| 1996 | Revision of the Olympic Charter | Environment and sustainable development provisions were included in the Charter |
| 1997 | Kyoto Protocol | Called for future Olympic Games to fulfill their responsibility to alleviate the pressure of global greenhouse gas emissions |
| 1999 | Olympic Movement Agenda 21 | Proposed the "Bid City Contract" standard requirements, marking the normalization of Olympic Games carbon emission management |
| 2000 | Sydney Olympics | The Green Olympic Games was the theme for this event |
| 2004 | London's Olympic bid | Identifying environmental quality and sustainability was a key component of the London Olympic Games |
| 2006 | Turin Winter Olympics | The Turin Olympic organizing committee has initiated the purchase of equivalent carbon offsets to achieve carbon neutrality during the Olympic Games for the first time |
| 2008 | Beijing Olympics | Formed the prototype of China's carbon neutrality strategy for large-scale sports events |
| 2009 | London 2012 Sustainable Development Plan | Developed and used advanced carbon footprint technologies and methods |
| 2010 | Vancouver Winter Olympics | The Vancouver Organizing Committee has chosen to use a variety of new energy sources and technologies to minimize the carbon footprint of the games |
| 2012 | London Olympics | It's the first-ever to accurately calculate and measure carbon emissions for a single Olympic Game's full cycle |
| 2015 | UN Sustainable Development Goals Paris Agreement on climate change | It served as a blueprint for global development strategies for the next "15 years" (2015–2030) |
| 2015 | The Paris Agreement | The decision, which took effect in November 2016, showed the urgency of carbon emissions |
| 2017 | IOC strategy of sustainable development | The planning of sports facilities and the organization of events should take into account the net-zero emissions of greenhouse gases |
| 2017 | Climate-friendly organization | Authorized Dow Chemical Company as the official carbon partner to develop a comprehensive carbon reduction plan |
| 2018 | The Olympic agenda: New Standard | Set the goal of achieving a climate-friendly Olympic Games by no later than 2030 |
| 2018 | Host City Contract-Operational Requirements | Host cities were explicitly required to submit a Carbon Management Plan |
| 2018 | Sports for Climate Action Framework | Commit to fulfilling the standards of the United Nations Framework Convention on Climate Change, using sports as a means to promote climate protection awareness and action among global citizens |
| 2018 | IOC Carbon Footprint Methodology for the Olympic Game | Providing guidelines for carbon neutrality management in the Olympic Games |
| 2020 | Tokyo Olympics | the Tokyo Olympics were made "carbon neutrality" through emissions quotas donated by over 210 companies |
| 2020 | Beijing 2022 Olympic and Paralympic Winter Games Sustainability Plan | Including "Low-Carbon Winter Olympics to Address Climate Change" as a major initiative, which promoted the realization of the "carbon neutrality" commitments |
| 2021 | Olympic Agenda 2020 + 5 | Establish a new strategic roadmap for the International Olympic Committee for the next 5 years |
| 2022 | Beijing Winter Olympics | The carbon offset program covers 93.7% of emissions not directly related to the Olympic Games, fully achieving carbon neutrality |
| 2024 | Paris Olympics | Strive for negative carbon emissions, becoming the first Olympic Games to make a positive contribution to the climate |

(Continued on following page)

TABLE 2 (*Continued*) IOC's "carbon reduction" actions.

| Years | Events | Actions |
|---|---|---|
| 2026 | Milano Cortina Winter Olympics | Sign the Host City Contract, committing to achieve carbon neutrality |
| 2028 | Los Angeles Olympics | Develop the "Zero Emissions 2028 Roadmap 2.0" plan |
| After 2030 | The Future Olympics | Require all Organizing Committees and host cities to achieve "carbon neutrality" throughout the entire lifecycle of the events |

Note: Data compiled from the authors.

development were included in the Olympic Charter, which also added provisions related to environmental protection and the fight against climate change, including energy-saving initiatives. The Charter listed the environment, sports, and culture as the three pillars of the modern Olympic Movement (Cantelon and Letters, 2000).

In December 1997, after the Kyoto Protocol was enacted, GHG emissions became the key to measuring global climate control, and the IOC quickly followed up by deciding to comprehensively request the bidding cities for future Olympic Games to focus on improving energy efficiency and reducing energy consumption during the events. In October 1999, the Olympic Movement's Agenda 21 was signed and adopted at the Third World Conference on Sport and the Environment, drafted with the support of the UNEP. The Agenda set out specific requirements for the Olympic Games in terms of venues, transportation, energy, accommodations, food, and waste. Energy-saving technologies and renewable energy sources were included as energy-related requirements. The IOC took control of event-related climate change as a compliance requirement of bidding city contracts, stipulating that bidding cities must meet the standards of environmental health, nature conservation, climate protection, resource management, and energy risk management, marking the entry of the carbon emission and energy efficiency management of the Olympic Games into the normalized preparatory and hosting work.

### 3.1.2 Preparatory period (2000–2010)

The IOC's concern for sustainable development directly promoted that attention be paid to environmental issues by the bidding countries and the organizing committees of the host countries. In 2000, the Sydney Olympic Games took green Olympic Games as their theme, and the OCOG implemented standards for energy conservation, water resources, waste disposal, pollution control, and cultural and environmental protection in the process of planning and organizing the games. Energy conservation measures were particularly emphasized, with a focus on energy efficiency in venue operations and the use of renewable energy sources.

In 2004, when bidding for the 2012 Summer Olympics, London emphasized that environmental quality and sustainability were key elements in its bid. In the 2006 Winter Olympics in Turin, a precedent in Olympic history was set for climate response, with the core goal of being "climate friendly." With the core objective of "no harm to the climate" and with the support of the UNEP, the Turin Organizing Committee initiated the purchase of equivalent carbon emission offsets. The local government invested approximately 3 million euros to purchase approximately 200,000 tons of carbon emission-reduction credits from Italian domestic enterprises and energy-saving and emission-reduction projects. These credits were used to compensate for the carbon dioxide generated via transportation and the operation of the competition venues during the Olympic Games. In addition to compensating through reforestation and energy-saving projects, the games achieved carbon neutrality for the first time. The integration of energy efficiency technologies in venue construction and the adoption of clean energy sources were pivotal to minimizing the carbon and energy impacts of this event.

The Beijing OCOG (BOCOG) for the 2008 Olympic Games actively took measures to save energy and reduce emissions, thus fulfilling its obligations to protect the environment. These measures included incorporating energy consumption index requirements into construction standards, widely adopting green energy sources such as solar and wind power, and adopting new environmentally friendly building materials. This approach can be considered the embryo of the Chinese strategy of "carbon neutrality" for large-scale sporting events. The IOC, especially the OCOGs, began to experiment with how to formulate a unified carbon footprint methodology in a professional, accurate, open, and transparent manner to monitor the climate response situation related to Olympic events and ensure that mega sporting events are "carbon neutral." In December 2009, after several years of research and development, the OCOG released the London 2012 Sustainability Plan, which abandons the traditional method of estimating carbon footprints on the basis of the average value of the construction of other venues.

Instead of the traditional estimation based on the average value of other venues and construction data, the LOCOG developed and used advanced carbon footprint techniques and methodologies to estimate the carbon emissions generated during the entire London Olympic cycle (2005–2012). The carbon emissions of the entire Olympic Games was approximately 3.4 million tons of carbon dioxide equivalents, with the development and construction of the venues accounting for 50%, transportation infrastructure accounting for 17%, operations accounting for 13%, and onsite spectator-related emissions accounting for 20% (Ito et al., 2022). The use of advanced carbon footprint analysis was combined with energy-efficient strategies to minimize energy consumption and emission levels across all aspects of the event. On the basis of this result, the LOCOG then determined and planned for the reduction, abatement, and offsetting of carbon credits. Moreover, the Organizing Committee of the 2010 Vancouver Winter Olympics chose to minimize the carbon impact of the event by choosing to use cleaner energy sources and technologies, enriching the city's public transportation system, energy-efficient green buildings of Olympic venues, and the purchase of offsets to offset the direct carbon emissions of the Olympic Games, among other commitments.

### 3.1.3 Trial period (2011–2020)

The London 2012 Olympic Games were the first Olympic Games in history to accurately calculate and measure the full cycle of carbon emissions from a single Olympic Games and to achieve "future-proof" carbon-neutral management (Tallec Marston et al., 2015). The LOCOG accurately realized the carbon footprint detection and management of the whole cycle of the event, which provided a more solid basis for the IOC to adopt "net-zero emissions" as the key concept in the event field to address the global climate problem. In addition to carbon neutrality, significant emphasis was placed on energy efficiency in the construction and operation of venues. Furthermore, energy-saving technologies were implemented to reduce energy consumption levels throughout the event lifecycle.

In 2015, the United Nations Sustainable Development Goals (SDGs) were adopted as the blueprint for the world's development strategy for the next 15 years (2015–2030). As a leader of the global sports order change, the IOC has been paying more attention to sustainability issues in sports and actively leading the new global sports order as a "global governance actor." In December of the same year, the Paris Climate Change Agreement was adopted and quickly came into force in November 2016, demonstrating the urgency of carbon emission reduction in controlling the global climate problem.

In October 2017, the IOC issued the IOC Sustainability Strategy, which listed the "climate" as one of the five focus areas, requiring that in the planning of sports facilities and organizing events, energy efficiency and energy-saving measures be prioritized to achieve net-zero GHG emissions. In the same year, to establish itself as a "climate-friendly organization," the IOC reached an agreement with Dow Chemical Company, authorizing it to serve as its official carbon partner. Dow developed the IOC's overall carbon emission-reduction program and offset the carbon footprint of the IOC's operations. Through Dow's innovative energy-saving and carbon reduction technologies, approximately 250,000 tons of carbon emissions generated by the IOC's operations from 2017 to 2020 were offset, further improving energy efficiency and contributing to the IOC's status as a "carbon-neutral organization."

Regarding, the Olympic Agenda, the New Norms, launched in February 2018, state that "By no later than the end of the year, the IOC will be in a position to reduce its carbon footprint." In June 2018, the IOC issued its Host City Contract-Operational Requirements, which explicitly require host cities to submit a carbon management plan (CMP). This plan must ensure carbon-neutral management and include energy-saving strategies to reduce those GHG emissions generated by the activities of the event organizing committee. Host cities were encouraged to adopt clean energy sources and energy-efficient technologies for transportation, venue construction, and operations to minimize both carbon emission and energy consumption levels.

In addition, the IOC is further transforming itself into a climate-change-positive organization by planting an Olympic Forest and contributing to the UN-supported Great Green Wall project in Africa. On 13 December 2018, the IOC and the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) jointly released the Sports for Climate Action Framework, which emphasizes that sports are uniquely positioned to help drive global climate action because of their influence on billions of sports fans and their inspirational power. The framework encourages sports organizations to implement energy-saving and energy-efficient measures in their operations, further aligning the sports sector with global climate protection efforts.

Through these two overarching objectives, the IOC and UN Climate clearly have "sponsor" profiles as policy advocacy coalitions, and the inclusion of more than 270 sports nongovernmental organizations (NGOs) signals a comprehensive response to the IOC's initiative. In December 2018, the IOC released its Carbon Footprint Methodology for the Olympic Games to provide application guidelines for the carbon-neutral management of the Olympic Games in terms of methodology, organization, and implementation procedures. The methodology emphasizes energy efficiency and the reduction in energy consumption as core elements in achieving carbon neutrality during the Olympics.

On 4 March 2020, the IOC's executive board passed a resolution to ensure that all upcoming Olympic Games are carbon neutral and committed to significantly reducing the carbon footprint. The Tokyo 2020 Olympic Games undertook significant efforts to reduce emissions, with a carbon footprint of 3.01 million tons of $CO_2$ equivalent. Despite these efforts, these games were made "carbon neutral" through the granting of emission allowances by more than 210 companies in the Tokyo Metropolitan Government and Saitama Prefecture. The integration of energy-saving technologies in venue operations and public transportation helped Tokyo maintain zero growth in $CO_2$ emissions during the hosting period, demonstrating the positive impact of energy efficiency on reducing the environmental impact of large-scale events.

On 15 May 2020, the IOC, the Intergovernmental Panel on Climate Change (IPCC), and the BOCOG jointly released the Sustainability Plan for the Beijing 2022 Winter Olympics and Paralympics, which includes "Low-Carbon Winter Olympics to Combat Climate Change" as a key action and promotes the realization of the commitment to carbon neutrality. Energy-saving measures, such as the use of renewable energy sources and energy-efficient technologies, were central to achieving carbon neutrality during the Beijing Winter Olympics, further cementing the importance of energy efficiency in combating climate change.

### 3.1.4 Improvement period (2021 to present)

On 13 March 2021, the 137th IOC Plenary Session adopted the 2020 + 5 Olympic Agenda as the IOC's new strategic roadmap for the next 5 years, in which Routes 2 and 13 clearly set out specific pathways for participation in climate action. The new agenda emphasizes reducing carbon emissions by 50%, demonstrating the IOC's determination to lead by example. Energy efficiency improvements and energy-saving measures are integral components of this strategy, particularly in terms of reducing energy consumption levels in venues and transportation systems.

Moreover, the IOC's strategy to address the issue of climate change has begun to expand to the micro level. On the basis of the concept of the strategy, the IOC has clarified the total amount of carbon emissions; established low-carbon and green requirements; and designed a framework for monitoring, reduction, and compensation on the basis of the management of the event cycle. These efforts include optimizing energy use in operations, integrating renewable energy sources, and adopting energy-efficient technologies to minimize energy consumption levels throughout the entire event lifecycle.

In the 2022 Beijing Winter Olympics, the carbon offset program covered 93.7% of the non-directly related credits for the Olympic Games. The greening of public transportation models with green electric energy further contributed to energy savings, as well as carbon offset through the Beijing–Hebei Forestry Sequestration Project, leading to full carbon neutrality. The use of green electricity and energy-efficient public transportation reduced the overall energy demand and enhanced the sustainability of the games.

For the 2024 Paris Olympics, 95% of the existing and temporary venues were low-carbon buildings, reducing emissions by more than 50% compared with the London Olympics standard. Paris aimed to achieve negative carbon emissions, with an estimated 1.65 million tons of $CO_2$-equivalent emissions, making it the first Olympics to make a positive contribution to the climate. Energy efficiency in building design and the implementation of energy-saving technologies were key strategies for reducing the carbon footprint of the Paris Games.

For the 2026 Milan Cortina Olympic Games, the Host City Contract, which committed to carbon neutrality, was signed. Similarly, the 2028 Los Angeles Olympic Games introduced the "Zero Emissions 2028 Roadmap 2.0" to promote zero carbon emissions from transportation in the greater Los Angeles area, reducing total GHGs and air pollution by 25%. The focus on energy-efficient transportation systems, such as electric vehicles and public transport powered by renewable energy, is expected to significantly reduce both energy consumption and emission levels in the region.

After 2030, direct and indirect GHG emissions will be reduced by an additional 50%, demonstrating the IOC's determination to lead by example, which ensures that the positive impacts of the Olympic Games on the climate will outweigh the negative impacts (Wilby et al., 2023). At the same time, the IOC's strategy to address climate issues has deepened at the micro level. On the basis of the strategy's concept, the IOC has clarified the total amount of carbon emissions; set low-carbon and green environmental protection requirements; and designed a framework for monitoring, reduction, and compensation on the basis of event cycle management. Given the efforts of the IOC and the host countries of the Olympic Games, the environmental externalities of large-scale sporting events are not entirely negative. Many positive environmental effects have been generated through the improvement in hardware facilities and the promotion of energy-efficient green buildings, leaving a sustainable Olympic legacy for the local community.

## 3.2 Excellent cases of carbon emission and energy risk management in sports stadiums

The new and renovated venues of the Beijing Winter Olympic Games embraced the concept of green Olympics and sustainability, leveraging emerging technologies to construct smart and low-carbon venues. A notable feature of the Beijing Winter Olympics was its focus on science and technology, which supported the sustainable development of venues through innovative solutions. These efforts maximized the long-term benefits of Winter Olympic venues. Energy-saving technologies played a key role in reducing the carbon footprint of these venues, with innovative systems focused on energy efficiency. For example, the use of carbon dioxide transcritical refrigeration technology and cadmium telluride power generation glass as energy-efficient construction materials contributed significantly to energy savings.

The Zhangbei flexible DC grid provided renewable energy to competition areas, further enhancing the energy efficiency of the entire Olympic event by reducing the degree of reliance on fossil fuels. These green and low-carbon initiatives were implemented throughout the construction and operation of the venues, emphasizing energy conservation and carbon reduction in every aspect. These measures not only demonstrated China's technological advancements but also highlighted the long-term sustainability of the Olympic legacy. By focusing on energy efficiency and sustainable technology, the Winter Olympics promoted a shift toward greener production methods and lifestyles, fostering harmonious development among people, cities, and the environment.

### 3.2.1 Smart venue

In terms of refined event viewing services, the National Speedskating Arena, the only newly built Olympic stadium in Beijing, used thousands of sensors to accurately control the air temperature and humidity on the ice surface, creating a comfortable environment for athletes and improving the quality of viewing services. In addition, these sensors helped optimize energy consumption by ensuring efficient climate control and reducing unnecessary energy use.

The venue applied BIM technology and robotics to solve the construction challenges of the ice-making system, ensuring that the hardware facilities were energy efficient and low carbon. The venue was equipped with various Internet of Things (IoT) sensors to capture operation data both indoors and outdoors. The rooftop meteorological station could autonomously adjust air intake on the basis of outdoor air quality, further contributing to energy savings.

A key innovation was the "Super Brain" system, which promoted the automatic control of the air supply, ice-making, and dehumidification. This system optimized energy use in real time, significantly lowering energy consumption levels across various operations, including epidemic prevention, roof electric windows, and air quality management.

### 3.2.2 Low-carbon buildings

During the Beijing Winter Olympics, the "Water Cube" was transformed into the "Ice Cube" for curling events. Its green development practices were reflected in the following three key areas. 1) Advanced construction materials: the exterior of the Water Cube was made from environmentally friendly and energy-saving ethylene tetrafluoroethylene (ETFE) membrane material, which is light, strong, durable, and recyclable. The membrane's high degree of light transmittance (up to 95%) allowed natural light to illuminate the interior, reducing the degree of reliance on artificial lighting and supporting energy efficiency. 2) Multifunctional design: the Water Cube can be converted from an ice rink to a summer sports venue, maximizing its post-Olympics utilization. By enabling easy switching between ice and water functions, the venue ensures long-term use, thus enhancing its sustainability. 3) Energy-saving and emission-reduction measures: from structural design to material selection and technological innovation, energy-saving practices were incorporated throughout the building process. All the venues of the Beijing Winter Olympics were required to meet low-carbon and energy-efficient standards, supporting China's dual carbon goals by reducing the carbon footprint of large-scale sporting events.

These measures offer a model of green sports building design, providing valuable insights into sustainable venue construction and postevent utilization.

## 3.3 Excellent examples of carbon governance and energy risk management by sports participants

Increasing the level of construction of open and outdoor green sports spaces, such as green health runways and sports parks, effectively increases residents' participation in sports while promoting low-carbon lifestyles. This approach helps reduce the carbon emissions of sports participants. Typical examples of transitioning to low-carbon sports participation include the popularization of smart outdoor gyms and the promotion of eco-fitness sports clubs. These efforts also focus on providing free, energy-efficient, low-carbon facilities for bottom-level sports participants.

### 3.3.1 Smart outdoor gyms

In recent years, with the promotion of 15-minute fitness circles in urban communities and 10-minute fitness circles in certain areas, smart outdoor gyms have become popular venues for public sports activities. A major feature of these gyms is their focus on energy savings and environmental protection. Their power generation comes from the following three sources: the energy generated by participants exercising on the equipment, solar power panels installed on the gym roof, and stored solar energy in internal batteries. This energy-efficient initiative ensures low-carbon fitness options for the general public (Skea and Nishioka, 2008).

### 3.3.2 Ecological games

Since 2015, Zhejiang Province in China has promoted low-carbon and green fitness activities by organizing ecological games and selecting beautiful ecological leisure and fitness spots. By focusing on natural ecosystems—such as mountains, rivers, lakes, and wetlands—activities such as hiking, mountaineering, cycling, and camping have flourished. These activities take place in environments with excellent air quality, rich in oxygen and negative ions, and with high urban greening and forest coverage rates. These eco-friendly initiatives create sustainable fitness models that meet the energy-saving and low-carbon needs of the public, serving as models for the Yangtze River Delta region and beyond.

### 3.3.3 Low-carbon facility configuration

The sports participation of new-generation migrant workers in Zhuhai city, China, is shaped by cultural and economic constraints. As a result, their participation focuses on low-carbon, minimal-cost sports programs, such as walking, jogging, and the use of open courts and fitness equipment in city squares. These low-cost and energy-efficient facilities contribute to reducing the carbon footprint of these activities.

# 4 Strategies and pathways for carbon emissions and energy governance in sporting events

As shown in Figure 1, to achieve the comprehensive management of carbon emissions, the following paths are derived by considering the management of carbon emissions from sports activities, including the pregame preparation stage, in-game conduct stage, and postgame continuity stage of large-scale sporting events, along with the construction, operation, and postmaintenance stages of sports stadiums and the awareness, attitudes, and behaviors of sports participants.

## 4.1 Strengthening carbon emission regulation

Both international organizations and national institutions have regulated carbon emissions governance from policy, system, and regulation perspectives, which include frameworks such as the UNFCCC, the Paris Agreement, the Sustainable Development Strategy, and the Framework for Action on Sport for Climate. These frameworks serve as high-level policy design concepts and act as conceptual guides for organizations such as the IOC and event-organizing committees. In addition to carbon regulation, energy efficiency and energy-saving practices should be key focus areas in governing sporting events, especially in terms of reducing energy consumption levels in venue operations and transportation systems.

To regulate carbon emissions effectively, the main focus should be on implementing more accurate and reasonable emission calculation tools to better quantify the current situation of carbon emissions. Tracking and monitoring the data on carbon emissions generated by sports and publicly releasing these monitored data can leverage public oversight to regulate carbon emissions from sports activities. Although the IOC has issued its Carbon Footprint Methodology for the Olympic Games, which provides guidance for measuring, evaluating, implementing, and incentivizing improvements in the carbon footprint, this methodology, which is based on LCA, is more conducive to large-scale events. This method assesses the GHG emissions and energy impacts of products, organizations, and services throughout their lifecycle, from raw material extraction to transportation, production, distribution, use, and end-of-life disposal.

For smaller events, energy-saving measures and energy-efficient risk management strategies should be tailored, ensuring that energy consumption levels are minimized while maintaining simplicity in the calculation methods. This approach ensures that energy consumption and carbon emissions are both effectively addressed. Additionally, energy consumption data, particularly those related to energy efficiency improvements, should be a central part of the emission monitoring process, ensuring that energy-saving practices are incorporated. For events with carbon emissions, emissions should be announced in a timely manner, and the organization or institution should be tracked and monitored in the long term to facilitate the better management of its carbon and energy usage.

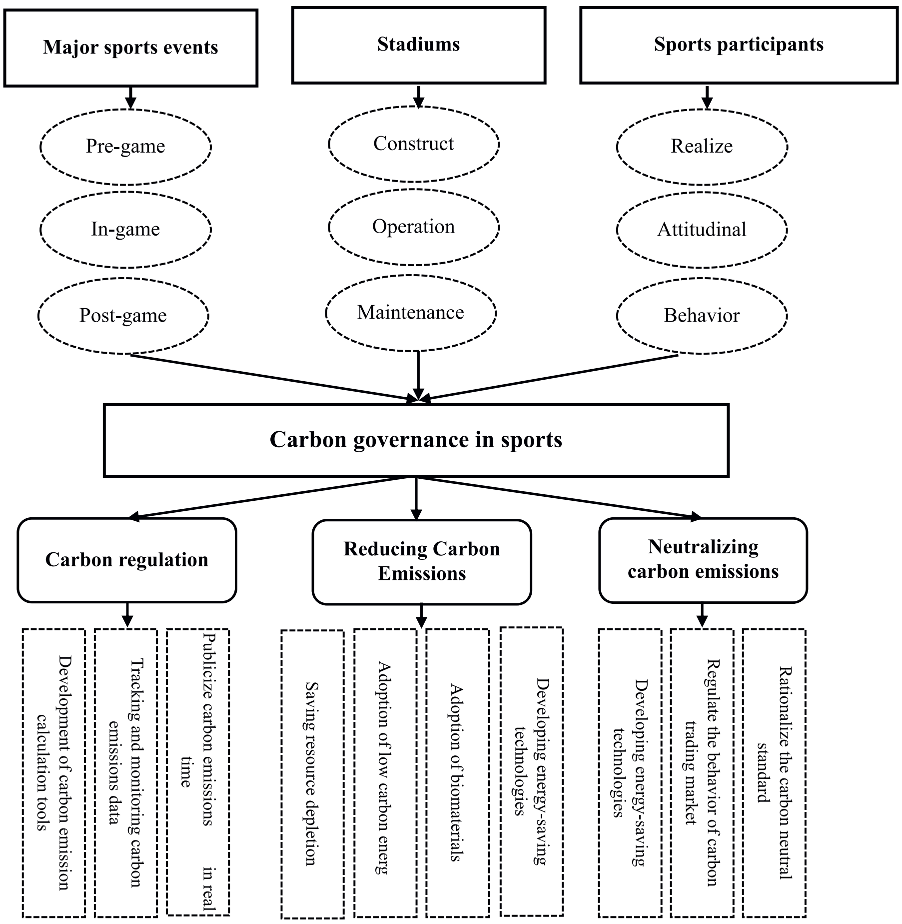


FIGURE 1
Framework for carbon emission governance in sports activities.

## 4.2 Reducing carbon emissions and energy savings

Reducing carbon emissions is a goal that every organization and country is working toward. According to the Host City Contract: Operational Requirements, issued by the IOC in 2018, the host city must submit a Carbon Management Plan (CMP) to promote low-carbon and energy-efficient solutions for the Olympic Games, which also aims to compensate for the GHG emissions generated by the event organizing committee's activities. For example, the Low-Carbon Management Plan for the Beijing 2022 Winter Olympic and Paralympic Winter Games emphasized low-carbon energy substitution, energy-saving venue construction, and energy-efficient transportation upgrades. The OCOG formulated specific emission-reduction measures to ensure that carbon management was implemented from concept to action. Currently, carbon emissions from large-scale sporting events continue to grow, with infrastructure construction and transportation being the primary sources. Thus, these areas are the main focus of carbon emission-reduction management.

Energy-efficient improvements have been crucial in reducing the carbon footprint of transportation and infrastructure. For example, the 2010 Vancouver Winter Olympics used sea ferries, diesel-electric hybrid buses, and high-efficiency aircraft, combined with clean energy sources, to reduce carbon emissions by 18%. The 2018 FIFA World Cup in Russia adopted green building standards and provided public transportation for spectators, encouraging energy-efficient and low-carbon travel. In 2018, for the PyeongChang Winter Olympics, wind power stations were constructed to supply clean electricity, whereas in 2020, for the Tokyo Olympics, the use of existing venues was increased, and fuel cells and electric vehicles were introduced to minimize carbon emission levels.

Energy-saving technologies and the promotion of renewable energy played a significant role in reducing energy consumption during these events. Efforts such as the use of photovoltaic power, wind power, and advanced energy-saving technologies improved energy use efficiency. Low-carbon venue construction, the use of environmentally friendly materials, and recycling practices further minimized energy consumption levels. Furthermore, low-carbon transportation solutions, including new energy vehicles, contributed to reducing the carbon footprint of event logistics.

### 4.3 Neutralizing carbon emissions

Under the global trend of responding to climate change, an increasing number of host cities and organizations have committed to achieving carbon neutrality for sporting events. By collaborating with international sports organizations such as the IOC and FIFA, these cities and organizations are helping advance global climate action. For example, the Turin Organizing Committee initiated the purchase of carbon emission offsets, buying approximately 200,000 tons of carbon credits from domestic enterprises and energy-saving projects. These credits were used to offset the emissions generated by transportation and competition venues during the Olympics. The 2020 Tokyo Olympic Games received emission allowances from more than 210 companies, making these Games a carbon-neutral event.

The role of energy-saving technologies and energy efficiency in achieving carbon neutrality has become increasingly important. By integrating these solutions, event organizers can offset the remaining emissions and reduce the overall carbon footprint. Specific actions to achieve carbon neutrality can include green planting, standardizing energy use in the carbon market, and formulating energy-efficient carbon neutrality standards. These actions reduce the environmental impact of carbon emissions from sports activities and help achieve the ultimate goal of carbon neutrality.

### 4.4 Risk mitigation strategies and pathway planning

To effectively address the abovementioned energy-related risks, the following strategies can be implemented. Diversifying energy sources—combining renewables, storage facilities, and traditional energy—reduces the degree of dependence on single-source supplies. Establishing redundant supply chains for critical equipment and fuel ensures energy availability during emergencies. The incorporation of advanced demand forecasting systems powered by big data and AI enhances the responsiveness to energy fluctuations. Additionally, hedging strategies can mitigate price volatility, insurance mechanisms can transfer supply risks, and emergency reserves can address short-term disruptions. These approaches have been successfully applied, such as during the 2010 Vancouver Winter Olympics, where hybrid transportation and renewable energy minimized supply risks.

In this context, carbon reduction plans for large-scale sporting events must integrate energy risk management. First, demand response plans, such as the use of intelligent energy allocation systems to reduce peak demand and optimize distribution efficiency, can be designed. Second, energy storage solutions, such as building battery storage systems and other facilities, can enhance the stability of the energy supply during events. Finally, smart grid technologies can be applied, enabling more flexible and sustainable energy systems to ensure resilience and reliability in event power usage. For example, the Tokyo 2020 Olympics utilized smart grid technology and energy storage solutions to improve energy efficiency during the event while significantly reducing energy supply risk. These practices demonstrate that integrating risk management into energy efficiency is a vital pathway through which to achieve the sustainable development of sporting events.

## 5 Conclusion and implications

### 5.1 Conclusion

In this paper, we systematically analyze the current state of carbon emissions from mega sporting events, examine the primary sources and influencing factors, and highlight both the progress and gaps in current carbon emission governance in sports using data and case studies. The main findings and conclusions from this research are as follows.

(1) Current situation of carbon emissions and energy savings from mega sporting events. Mega sporting events, especially global events such as the Olympic Games and the World Cup, generate substantial carbon emissions. For example, the carbon emissions of the 2014 World Cup in Brazil reached 2.27 million tons, whereas those of the 2022 World Cup in Qatar were 3.63 million tons. These figures illustrate the significant environmental impact of such events, particularly in the transportation, stadium construction, and event operation phases. The incorporation of energy-saving measures and improvements in energy efficiency throughout an event, especially in transportation and venue management, can play a key role in reducing these emissions.

(2) Carbon emissions from sports venues. Stadiums generate a large amount of carbon dioxide throughout their entire lifecycle, from planning, design, and construction to operation and demolition. For example, the construction of new venues and supporting facilities for the 2008 Beijing Olympic Games produced considerable carbon emissions. Studies have shown that the low-carbon and energy-efficient design and construction of sports venues can significantly reduce these emissions. However, existing research in this area needs further exploration and improvement.

(3) Carbon footprint of sports participants. The travel and activities of sports participants are major sources of carbon emissions from mega sporting events. Transport, particularly air travel, is a major contributor to carbon emissions. The carbon footprint of different types of sports activities varies significantly, with team programs generally having a lower carbon footprint than do individual programs. Thus, promoting energy-efficient transportation options, such as electric vehicles or public transport systems, can help reduce the energy consumption and overall carbon footprint of participants.

(4) Carbon emission and energy risk management measures for sporting events. The IOC and other international sports organizations have introduced various measures to reduce carbon emissions from sporting events. For example, the 2022 Beijing Winter Olympics achieved carbon neutrality through the purchase of carbon credits and the adoption of low-carbon and energy-saving technologies. These successful cases provide valuable references for managing carbon emissions in future large-scale sporting events. When social capital theory is applied, carbon management can be refined by leveraging the interplay among relationships, trust,

and norms among stakeholders. Strong relational networks among event organizers, governments, and local communities foster collaboration, enable resource sharing, and enhance the efficiency of energy usage. Institutional and relational trust plays a pivotal role in ensuring compliance with environmental policies and encouraging cooperative behaviors, such as adopting renewable energy and energy-efficient technologies. Moreover, the shared norms within these networks promote collective accountability, motivating stakeholders to align with sustainability objectives and actively contribute to carbon reduction efforts. Furthermore, insights from sustainable tourism governance models underscore the importance of multistakeholder collaboration and the integration of long-term environmental strategies. In parallel with community-based tourism practices, sporting events can achieve sustainability by aligning local development goals with ecological preservation. For example, incorporating community participation in energy-saving initiatives or incentivizing green innovation not only mitigates carbon emissions but also strengthens social cohesion and trust among local populations. These approaches effectively balance economic development, environmental stewardship, and community wellbeing, embedding sustainability into the core operations of sporting events.

(5) Application of carbon footprint and energy efficiency measurement. Carbon footprint measurement is now widely used to assess the environmental impacts of sporting events and has been instrumental in guiding and optimizing emission-reduction strategies. Through scientific carbon footprint analysis, specific data can support policymakers and event organizers in designing more energy-efficient and sustainable practices. Overall, these findings not only demonstrate the substantial environmental impact of mega sporting events but also highlight the urgency and necessity of carbon governance in sports. By integrating energy-saving strategies and improving energy efficiency, the sector can significantly reduce its carbon footprint, paving the way for more in-depth research and action in this area in the future.

## 5.2 Implications

Given the challenges faced by mega sporting events in terms of carbon emissions and the inadequacy of existing governance measures revealed in this study, we believe that more comprehensive and concrete actions should be taken to reduce the environmental impacts of sporting events. To address these challenges and achieve more sustainable sports event management, we propose the below targeted countermeasures, which not only focus on current practical issues but also aim to provide long-term guidance for the planning and implementation of future sports events.

The findings of this study effectively address the challenges and strategies of carbon emissions and energy risk management in mega sporting events. However, they can be further enriched by emphasizing their broader global relevance. Sporting events not only contribute to environmental challenges but also serve as influential platforms for promoting sustainability and climate action. This study highlights practical strategies for reducing carbon emissions and improving energy efficiency, highlighting how sporting events can act as role models for addressing global environmental issues. Events such as the Olympic Games and FIFA World Cup, with their vast global audiences, offer unique opportunities to demonstrate innovative energy-saving technologies and inspire the adoption of sustainable behaviors. These efforts can significantly contribute to advancing the United Nations' SDGs, particularly those focused on climate action and sustainable cities (Xu et al., 2024). This study's emphasis on lifecycle carbon emissions and renewable energy technologies aligns with the global shift toward low-carbon development. These findings underscore the importance of collaboration among event organizers, policymakers, and industry stakeholders to establish frameworks that enhance energy efficiency and long-term sustainability. By bridging the gap between environmental policy and public engagement, sporting events can play a pivotal role in addressing the climate crisis and driving collective action.

### 5.2.1 Strengthening of carbon management in the event planning stage

Carbon emission management should be a critical decision-making factor in the planning stage of sporting events. Specific measures include optimizing the locations of event venues, prioritizing existing energy-efficient and low-carbon venues, and reducing the carbon footprint of newly constructed venues. Additionally, the event schedule should be optimized to minimize unnecessary energy consumption, particularly by considering energy-saving technologies for venue operations.

### 5.2.2 Promotion of green transportation modes

For large-scale sporting events, transportation is one of the primary sources of carbon emissions. Promoting and facilitating energy-efficient and low-carbon transportation modes, such as electric vehicles, public transportation, and carpooling, is recommended to reduce the carbon footprint of spectators and participants. Integrating renewable energy into transportation systems, such as using solar-powered electric buses, can further increase energy efficiency.

### 5.2.3 Optimization of the carbon emission governance of stadiums

To address the carbon emissions from sports venues, it is recommended that energy-saving and low-carbon technologies be integrated into the design phase of venues. This approach can include the use of renewable energy sources such as solar and wind power, as well as the promotion of energy-efficient building materials and equipment, to reduce the energy consumption and carbon emissions of venues. Installing energy-efficient lighting, heating, and cooling systems can significantly lower energy use during events.

### 5.2.4 Enhancement of the environmental awareness of sports participants

Sports participants contribute significantly to carbon emissions, and thus, enhancing their environmental awareness is essential.

Through publicity, education, and incentives, participants should be encouraged to choose low-energy and low-carbon travel modes and reduce unnecessary resource consumption during events. Promoting the use of energy-efficient equipment and practices during sports activities can further reduce the carbon footprint of participants.

### 5.2.5 Promotion of carbon-neutral strategies

Carbon neutrality has been practiced in several mega sporting events. It is recommended that this strategy be promoted to offset unavoidable carbon emissions through the purchase of carbon credits or the implementation of carbon offset projects (e.g., tree planting). Incorporating energy-saving technologies and improving energy efficiency at every stage of the event lifecycle can reduce the need for carbon offsets, thus improving the sustainability of events.

These countermeasures are not only applicable to the current management of sporting events but also provide a practical direction to guide future events. Through effective carbon emission management measures, sports events can minimize their negative impact on the environment and become a positive force for sustainable development. Additionally, these proposed countermeasures highlight the importance of cooperation among all parties—the government, event organizers, stadium operators, and participants—working together to achieve carbon neutrality. Through the implementation of these measures, sporting events can serve as models of energy efficiency and environmental protection, leading society toward a more sustainable future.

## 5.3 Limitations and future prospects

Although this study systematically analyzes the carbon emissions of large sporting events, there are still some shortcomings and directions for future research. Existing research has focused mostly on case studies of specific events, with strong regional limitations and data constraints, making it difficult to obtain universal conclusions. Thus, future research should expand data collection to cover different types and sizes of sporting events to increase the applicability of the findings. Additionally, most studies focus on direct carbon emissions while overlooking the impact of indirect carbon emissions. For example, activities such as advertising, promotion, and product manufacturing by sponsors may also generate significant carbon emissions, yet there is a lack of research in these areas. Future studies should pay more attention to these indirect emissions to comprehensively assess the environmental impact of events. Furthermore, future research should explore energy-saving technologies in areas such as event broadcasting and sponsor operations to minimize the indirect carbon footprint. Finally, the management of carbon emissions from sporting events involves multiple disciplines, including environmental science, economics, and sociology. Future research should deepen interdisciplinary cooperation to explore more effective carbon emission management strategies from multiple dimensions and provide comprehensive support for the sustainable development of sporting events.

## Author contributions

X-zS: Conceptualization, Formal Analysis, Investigation, Validation, Writing–original draft. LC: Conceptualization, Investigation, Validation, Writing–original draft. XX: Conceptualization, Resources, Validation, Writing–review and editing.


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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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