Environmental Science and Ecotechnology 16 (2023) 100263

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

News

Powering green and low-carbon Olympics

The 2022 Winter Olympic and Paralympic Games (hereafter "Beijing 2022 Olympic Games") were held in Beijing and Zhangjiakou, Hebei Province, respectively, from February to March 2022. By committing to the mission of hosting a "green, sharing, open, and clean" Winter Olympics, Beijing 2022 has integrated sustainability principles throughout all stages of the Games preparations, aiming to reduce the negative impacts of the games while maximizing their positive impacts. It was the first time in the history of the Olympics that all venues were 100% powered by green energy, fully implemented the sustainability requirements of Olympic Agenda 2020 from preparation to delivery, and were the most digitally engaged Olympic Winter Games. After the Beijing 2022 Olympic Games, quite a few great green-and-low-carbon practices were summarized and announced. Here are some exceptional cases of the winners (see Figs. 1–2).

First carbon-neutral Olympic ever

The major challenges in achieving carbon-neutral games were to reduce carbon emissions of venue constructions and renovations, transport infrastructure and logistics, and venue operations which occupied majority of the total emissions. The Beijing 2022 Olympic Games integrated the low-carbon concept into all relevant aspects of the Games' preparations through a low-carbon management plan. The plan includes four types of carbon reduction measures: low-carbon energy, venues, transport, and actions. Three types of carbon offset measures were adopted considering the following aspects: forest carbon sinks, corporate sponsorship, and public participation. As a guideline for low-carbon management, the plan carried out 18 carbon reduction, four carbon-neutral, and four safeguard tasks. The units responsible for each task were defined, and some tasks were included in the list of the Beijing Municipal Working Group.

A Low-Carbon Management Report of the Beijing 2022 Olympic Games (pre-Games) was introduced to describe the management of carbon emissions in order to determine the carbon emissions related to the Games. This report focuses on the methodology of carbon neutralization, Greenhouse Gas (GHG) emission baseline data, and actual emissions determined during the preparatory stage. According to the carbon emission accounting, total GHG baseline emissions for the Beijing 2022 Olympic Games were 71.4×10^4 t-CO_2e (carbon dioxide equivalent) from 2016 to June 2022, among which the construction of transport infrastructure and venues contributed the largest amount of carbon emissions, while venue operation contributed the most in 2022. The construction and renovation of venues, transportation infrastructure, logistics services, and spectator activities are the three primary sources of carbon emission. Low-carbon management measures have led to a reduction in carbon emissions to 31.46×10^4 t-CO_2e. The local governments of Beijing and Zhangjiakou donated 110×10^4 t-CO_2e of forest carbon sinks to neutralise GHG emissions. The partners of the games contributed 60×10^4 t-CO_2e.

The Beijing 2022 Olympic Games have successfully met their commitment to carbon neutrality through a variety of innovative measures. As Lionel Kambeitz,[1] the Executive Chairman of Delta CleanTech, shares, "Beijing 2022 Olympic Games was the first Winter Olympics to be carbon neutral, which may change the world we know today and pave the way for a carbon-neutral future." Carbon management mechanisms, such as carbon emission trading, carbon emission assessment and management, and carbon emission compensation, have been explored and established. These could be adopted to achieve carbon neutral of other large-scale events or campaigns worldwide.

A sustainability management system

Sustainability was highlighted as one of the three ideas in the 2020 Olympic Agenda.[2,3] Attainment of the 28 bid commitments is based on the Sustainability Management System, which is underpinned by three international standards, including the ISO 20121 Event Sustainability Management System, the ISO 14001 Environmental Management System, and the ISO 26000 Guidance on Social Responsibility. The system defines the sustainability management of events, the performance of tasks for sustainability, and reflection on requirements pertaining to sustainability with respect to all aspects and stages of preparation for the event. The Beijing 2022 Post-Games Sustainability Report was published on February 1, 2023, to comprehensively summarise the achievements made in the area of sustainability before and during the Games.

With the principle of fueling the energy of functional departments without extra burden, the risks and opportunities associated with sustainability management were identified, integrated into the work, and combined with the main business of Olympics preparation. In May 2020, the Sustainability Plan for the Beijing Winter Olympics and Paralympics was released. The plan focuses on improving the environment, developing regions, and improving lives, including 12 missions, 37 measures, and 119 works.

[1] Lionel Kambeitz: Beijing 2022 Winter Olympics paves the way for a carbon neutral future. February 19, 2022. https://deltacleantech.ca/news-articles/.
[2] IOC, Olympic Agenda 2020, 2014.
[3] IOC, Olympic Agenda 2020 + 5 Recommendations, vols. 1e27, 2021.

https://doi.org/10.1016/j.ese.2023.100263
2666-4984

High standards and requirements for sustainability management in venue construction have also been suggested considering the preservation of the ecological environment. The Sustainability Management Rules of Venue for the Beijing Winter Olympics and Paralympics, Guidance for Sustainability of Venues and Facilities, and Guidance for Sustainability of Temporary Venues and Facilities were formulated for 2017–2021. Full-time personnel at key positions were appointed to ensure effective and sustainable management of the venues. Additionally, environmental impact assessment reports for the construction of competition zones were compiled, and other institutions were hired for environmental supervision. A series of responsibility requirements for environmental protection were implemented, and 54 and 44 works were assigned to the Yanqing and Zhangjiakou competition zones, respectively.

A leading group, expert panel, and work team for the sustainability management system were formed during the games. Measures were undertaken to achieve the agreed sustainable development goals, e.g., scheduled meetings for sustainability management, on-site inspections for venue sustainability management, and third-party reviews. The Guidance for Event Sustainability Evaluation was formulated and released as a Beijing local standard by the end of 2021, in which thirty-five indicators were proposed to assess the sustainability performance of events in terms of technology, management, and comprehensive benefits. It also provides a reference for the scientific evaluation of event sustainability worldwide.

The Beijing 2022 Olympic Games successfully met all of its bid commitments regarding sustainability. It pioneered all-encompassing sustainability management in Olympic history, resulting in a workable, practicable, and standardised Beijing scheme for sustainability management pertaining to the overall management of large-scale events.

The greenest snow Olympic venues

The construction of low-carbon venues is necessary to enhance the concept of the Green Olympics. Comprehensive consideration of resource conservation, environmental protection and cultural protection goals, a series of measures of resource conservation and carbon reduction were conducted. Then, seven snow venues were rated with three stars as per the Evaluation Standards for Green Snow Sports Venues that were released at the end of 2018.

Snow venues usually located in mountains need to consider ecological and environmental protection before planning and construction, compared to those in urban built-up areas. Most venues were constructed to be adaptive to local conditions, considering the goal of the environmentally friendly Olympics. The National Sliding Centre has used cantilevered awnings and matching sunshades to turn the sunny slope into a shady slope to reduce energy consumption. Genting Snow Park was designed to adhere to the original path in order to minimise the invasion and destruction of nature. The National Ski Jumping Centre utilises wind power and renewable building materials to create green venues. The National Biathlon centre was built near the mountains to conserve local trees and recycle debris. Furthermore, the Xiaozhuanghu village site in Yanqing competition zone was fully protected and displayed by compiling the conservation and utilization plan of cultural relics, and implementing protection projects.

The use of venues postgame had been considered during their construction. The expansion of venue service functions allows for the availability of physical and cultural services, including national fitness, sports events, professional training, and commercial and cultural activities. Snow venues can be fully utilized all year round, not just in winter. At the Yanqing competition zone, visitors can take a cable car directly to the top of the Haituo Mountain to enjoy the summer scenery, and also visit the National Sliding Centre along a 1.9-km roof-top sightseeing road. At the Zhangjiakou competition zone, the National Ski Jumping Centre features artificial grass that allows for activities such as grass skiing and soccer. The National Cross-Country Skiing Centre integrates the surrounding natural resources to create a mountain outdoor sports park that includes mountain climbing, mountain biking, hiking, grass skiing, sledding, and rock climbing. In addition, more than 100 types of temporary facilities have been deployed for the Beijing 2022 Olympic Games, including athletic and spectator service systems, broadcast systems, health and epidemic prevention facilities, and safety facilities that could be reused after the Games.

Accelerated use of green energy

Green energy is essential for carbon neutral. Electricity usage in all the venues for the Beijing 2022 Olympic Games was 100% generated by wind and solar power in Zhangbei, as a result of the renewable energy flexible DC power grid project and the cross-regional green power trading mechanism in the host cities. A trading mechanism was created through which green energy was made available for trade and use. Since the launch of green power trading at the venues in June 2019, ten batches of transactions involving 780 million kWh of electricity have been conducted.

In addition to wind and solar power, hydrogen energy has also been used as fuel for torches and vehicles to minimise carbon dioxide emissions. The act of ignition was replaced by a fire created using hydrogen instead of natural gas or propane for the first time in the history of the Olympics at the opening ceremony of the Beijing 2022 Olympic Games. The first high-pressure hydrogen storage scheme for the Olympic cauldron was introduced in the opening ceremony of the Games, which proved that carbon emissions were curtailed to a 1/5000 level compared to those in the Beijing 2008 Games.

In addition, distributed renewable energy has been utilized to build venues, considering the local climate and natural resource conditions, to ensure proper usage. Crystalline silicon PV modules are installed on the roof of the Wukesong Ice Hockey Training Hall, which generates approximately 700,000 kWh of electricity annually. A rooftop PV power station with an annual capacity of 140,000 kWh was established at Yanqing Mountain Press Centre. These measures have not only helped to meet the energy needs of the venue's operations during the Games, but have also facilitated the production of green energy. According to Lionel Kambeitz, “future Olympics will not only be forced to follow suit with the Beijing 2022 Olympics and do even more to protect our precious planet in the process, but other major events and organisations can learn from this example how to use renewable energy and procure planning and logistics for a more conscious footprint."

Low-carbon transportation systems

Public transport, new-energy vehicles, and intelligent query systems are necessary for Olympics to provide safe, efficient, and punctual transport services during large-scale events. The Beijing-Zhangjiakou high-speed railway connecting the three competition zones was completed by the end of 2019. Passengers can reach Zhangjiakou from Beijing within 1 h. Martin Jacques, a well-known British scholar, points out that China has promoted rural development through its advanced transportation infrastructure by organizing the Olympics. Furthermore, traveling via public transport was encouraged during the games. The host cities used existing electric and hydrogen buses and rail transit vehicles to provide environmentally friendly transportation services while also

encouraging the development of charging stations and hydrogen refueling stations. According to statistics, energy-saving and clean-energy vehicles accounted for 100% of minibuses and 85.8% of all vehicles in the games, establishing a new record in the history of the Olympics.

By integrating information about traffic, weather, and the flow of people and materials into an intelligent traffic system, traffic information is provided via dynamic query systems and guidance systems via the internet and mobile terminals. Athletes and spectators can access real-time analysis results of traffic conditions. Some dedicated lanes have been set up between the three competition zones to facilitate efficient car driving. Additionally, a green and intensive supply chain system was built that linked upstream and downstream suppliers in the games. Adopting a series of measures pertaining to logistics transportation has the effect of reducing carbon emissions, including paperless operation in the warehouse, the application of intelligent equipment, the use of new energy logistics vehicles, and recyclable boxes. In addition to these measures, the carbon emissions resulting from transportation have been curtailed, and the process of green and low-carbon transportation has accelerated.

Ecological protection v.s. engineered construction

In the entire process of venue planning, construction, operations, and post-game use, ecological protection has been prioritized and placed in a more prominent position. In addition, near-to-natural restoration has been promoted and practiced in competition zones. The Yanqing competition zone is characterized by subalpine meadows with rich species, excellent topsoil seed banks, and many animals. Minimizing encroachment of the ecological environment due to construction is a key concern that poses challenges in venue construction. The Zhangjiakou competition area has features such as high altitude, high slope, dry climate, low green coverage rate, and fragile ecological environment. Ecological restoration has been difficult owing to climate and topography, and controlling soil erosion is also challenging.

Before the Yanqing competition zone was constructed, a baseline survey of ecological resources was conducted as the reference to protect important habitats, and ancient and valuable trees. Several measures were undertaken in designing and planning of competition area to reduce the environmental impact, including minimizing land-use area, regulating construction range, and reasonably arranging roads. Several measures have been planned to protect the ecological environment, including the launch of the environmental impact assessment plan and the formulation of the responsibility matrix pertaining to environmental protection in the competition area. To develop a first-class water-saving competition zone in the Zhangjiakou competition zone, a water resource assessment report was compiled based on a comprehensive investigation and water resource capacity.

During construction, the ecological restoration in Yanqing's competition zone implemented four measures: subalpine meadow stripping, topsoil stripping, slope ecological restoration, and snow-road vegetation restoration. Nine protected communities were identified in this study. In addition, *in situ*, *near situ*, and *ex situ* conservation measures have been implemented for plant protection, including 11,027 shrubs on *near situ* conservation measures and 24,272 trees on *ex situ* conservation measures. 3500 square meters of subalpine meadows were restored. 81,848 cubic meters of topsoil resources were stripped and reused. A total of 2.16 and 0.45 million square meters were eco-restored, respectively, in Yanqing and Zhangjiakou competition zones.

Eco-friendly technologies are widely used to conserve and recycle water resources. To intensify the internal circulation of snow-making water, ski resorts have built ponds and reservoirs to collect, store, and reuse rainwater and snowmelt water in multiple ways. The Zhangjiakou competition zone had been built as a “sponge competition zone” by means of permeable sidewalks, near-track grass ditches, water storage tanks, water-saving equipment, and the use of reclaimed water to harvest and utilize the rainwater and snowmelt water in multiple ways. All snow sports venues have adopted efficient, water-saving smart snowmaking systems and equipment to dynamically maintain the best

Fig. 1. Located in an ecologically fragile area, the Yanqing competition zone has implemented a range of measures to protect and restore the environment. These include conducting a baseline survey, planning construction land in a rational manner, formulating a responsibility matrix, and reusing surface soil. Thanks to these efforts, ecological protection and restoration work is carried out before and after venue construction. Furthermore, the competition zone minimizes the impact of Olympic facility construction on the ecological environment while maintaining the stability of the ecological security pattern. The result is a harmonious coordination between nature protection and engineering construction that is truly impressive. (Photo by Visual China Group).

snowmaking efficiency according to changes in the external environment. In addition, the Yanqing and Zhangjiakou zones have built both decentralized and centralized sewage treatment facilities, achieving full collection and treatment of domestic sewage.

Guided by the concept of "ecological Olympics amid mountains and forests", ecological protection, ecological restoration, resource conservation, and venue construction have all been coordinated, aiming to minimise the impact of the event on animals and habitats, consumption of water resources, disturbance, and reduction of the ecological footprint, thus making extremely strong efforts to restore the natural ecology. The Beijing 2022 Olympic Games created a green project model of harmonious coexistence between humans and nature under complex mountain conditions.

Blue skies

The Beijing 2022 Olympic Games coincided with the winter heating period in northern China, during which heavy pollution weather frequently occurred. Nevertheless, after great efforts to fight air pollution in the past decade, the air quality in Beijing and Zhangjiakou met the standard every day during the Games. The average concentrations of fine particulate matter ($PM_{2.5}$) in Beijing and Zhangjiakou were 36 and 20 μg m^{-3}, respectively, which decreased by 63% and 59%, respectively, from the 2015 levels. Beijing has created a world miracle of air pollution control in megacities to solve the contradiction between ensuring smooth operation of the economy, a warm winter for the masses, and achieving the goal of air quality assurance.

The Ministry of Ecology and Environment (MEE) has made unremitting efforts to control air pollution in the Beijing-Tianjin-Hebei region. A leading group that breaks the restrictions of administrative regions has been established in three regions and surrounding areas. Measures have been taken to continuously optimize the energy structure, carry out industrial pollution source control, and strictly control motor vehicle pollutant emissions through coordinated planning, unified standards, joint emergency response, and information sharing. The Winter Olympics Air Quality Assurance Command Platform was built to provide daily real-time satellite monitoring data and analysis results of particulate matter and air pollutants in the area of joint prevention and control around competition zones to facilitate macro-research on the overall situation and transmission process of air pollution.

Taking full account of the impact of pollution transmission on competition zones, the MEE carried out zonal, classified, and graded control measures so that cities in the assurance scope were divided into core areas, key areas, and general areas, which are subject to successively decreasing control requirements. Depending on changes in weather conditions, control measures have been dynamically adjusted and optimized to ensure reductions in both the scope of industries and the number of companies under control in joint prevention and control cities. During the Games, no control measures were applied to companies, projects, and vehicle types on the whitelist to effectively ensure a warm winter for the masses, such as companies involved in energy supply, livelihood assurance, epidemic prevention and control, event services, foreign trade exports, and strategic emerging industries. A series of measures have provided an optimal solution to ensure people's livelihoods and air quality. From 2015 to 2021, the concentration of $PM_{2.5}$, declined at an annual rate of approximately 7 μg m^{-3} in Beijing.

Shougang industrial relics rejuvenated

The top ten steel companies in China are located in Shougang Industrial Park, which was established in 1919. This was once the seat for iron and steel production in Beijing. Due to the staging of Beijing in 2008 and the effort to reduce pollution while promoting socio-economic development, the steel plant of the Shougang Group in Beijing was shut down and relocated. Only large-scale industrial land and above-ground buildings were retained. In 2016, the Beijing Organizing Committee for the 2022 Olympic and Paralympic Winter Games (BOCWOG) moved to Shougang Park. Furthermore, in 2018, Shougang Group signed a contract to become the official partner of the urban regeneration service of the Games and simultaneously started the construction of Big Air Shougang. "It has achieved the perfect integration of competition venue, industrial heritage reuse and urban renewal. Over seven years of attention, I

Fig. 2. Shougang Park has a rich history of over 100 years and is considered one of China's earliest and most significant modern steel enterprises. It played a crucial role in the country's industrial and metallurgical development. In 2010, the primary steel production process of Shougang Park was permanently shut down to improve Beijing's clean air after the city won the bid for the Summer Olympics. Despite this, the park was not demolished and remained idle until 2016, when it was repurposed as the first theme cultural park in China to feature steel industry cultural relics. This transformation was based on protection and utilization, and it was made possible by the entry of the Winter Olympics Organizing Committee. Today, visitors can explore and learn about the rich cultural heritage of China's steel industry at Shougang Park. (Photo by Visual China Group).

have witnessed the birth of this great building," says International Olympic Committee (IOC) President Thomas Bach.[4]

The original styles and features of Shougang Park have been preserved, while functional renovation and upgrading of the industrial heritage sites have been carried out in accordance with the principle of maximum preservation and utilization of industrial relics. For example, Big Air Shougang and office buildings of the BOCWOG were built and became landmarks in Beijing. With the transformation of the internal structure, an improvement in the external environment of the park is also required. Eight key ecological conservation projects for Shougang Park have already been initiated in the past several years, such as the river system connectivity project and a waterfront forest park. A post-industrial leisure landscape belt was created to reveal the beautiful skyline of the Western Hills by highlighting mountain-water-industrial landscapes.

After the Games, the optimisation of the layout of Shougang Park was sought through regional development planning to promote the agglomeration and development of sports, cultural, and digital industries. More than 130 companies were established in the park by the end of May 2022, which mainly consisted of green industries such as science-fiction e-sports, cultural experience, digital intelligence, and ice and snow sports. The Big Air Shougang, four ice-training bases, and sports-themed Shougang Extreme Park are open to the public. In close association with the Beijing 2022 Olympic Games and the China International Fair for Trade in Services (CIFTIS), the park has transformed from an industrial heritage park to an international place. Shougang Park has now been converted from an industrial park to a public park and commercial complex, ushering in a new era of green development while also serving as a model for the transformation and upgrade of an old industrial park around the world.

Since 2015, the Beijing 2022 Winter Olympics have engaged 346 million people in winter sports, creating 81,000 job opportunities for residents in areas surrounding competition zones. All venues are enjoyed by public and local athletes, and the winter sports industry in the country is booming. Taking full advantage of the Games promotes the integrated development of the Beijing-Tianjin-Hebei region while promoting transport connectivity, environmental improvement, and coordinated industrial development. The Beijing 2022 Olympic Games are known as the most environmentally friendly and carbon-neutral Olympics, which will provide "China Wisdom" and "China Plan" that can be used as references for the implementation of the sustainability requirements of the Olympic Games in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge financial support from the Environmental Defense Fund Beijing Representative Office. We are extremely thankful for the support provided by the General Planning Department and the Sustainability Advisory Commission of the Beijing 2022 Organizing Committee. We also extend our heartfelt thanks to the Bureau of Ecology and Environment of Beijing Municipality, the Bureau of Ecology and Environment of Yanqing District, relevant enterprises, and experts for their assistance in research, discussion, and data collection.

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28 September 2022

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