Volume 6, Issue 2, 2022 ISSN: 2617-4553
DOI: https://doi.org/10.31058/j.er.2022.62003

ITS

The Declining Cost of Solar Enables Carbon-Neutral Sports Stadium: a Case Study in Wuhan, China

Wei Guo[1], Rui Shan[2,3]*

[1] School of Physical Education, Jianghan University, Wuhan, China
[2] Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, United States
[3] Carbon Baseline Inc. Shanghai, China

Email Address

rui.shan@unc.edu (Rui Shan)
*Correspondence: rui.shan@unc.edu

Received: 29 August 2022**; Accepted:** 8 September 2022**; Published:** 25 October 2022

Abstract:

Climate change is threatening the world, including the sports industry. Sports industry, although not the big emitter of greenhouse gas, could play a critical role in climate change mitigation because it could unite people and form a consensus. The low emission from the sports industry makes it possible to hold carbon neutral sports events. However, these carbon neutral events are usually limited to those mega international ones with sufficient budgets. In this paper, through real-world data of a stadium with moderate solar resources, we pointed out that even a local medium-scale stadium could achieve net zero-emission operation through solar PV retrofits. The carbon cap and trade market in China provides an additional revenue stream, making the financial status of the project more reliable under the changes in cost and electricity price. The carbon credit revenue also extends such feasibility to a wider range of stadiums spreading across China.

Keywords:

Stadium Management, Sport Ecology, Rooftop Solar PV

1. Introduction

Climate change as a global issue is receiving more and more attention not only from the science society but also from various industries. The sports industry, although not the major carbon emitter nor the ones affected most by climate change, has engaged in environmental and sustainability initiatives as early as 1930s [1]. Early actions from industries are limited to the reporting and monitoring with some emphasis on sustainability in the sports-related communication, but few mitigation measures are taken [2,3]. Most of the related research focuses on how climate change affects sports events and the assessment of carbon footprints of sports activities [4]. Wicker collected data from more than six thousand sports participants of 20 different sports events and estimated the average annual carbon footprint of a participant is about 844 kg CO2-eq [5]. Other researchers have also examined carbon footprints of some specific sports events[6,7,8], all resulting in a relatively small number compared with other manufacturing industries. The low impact from the sports industry, if excluding the sports-related manufacturing, makes the sports organizations or events easier to achieve a carbon neutrality target.

On the other hand, the sports industry has incentives to achieve a carbon neutrality target. Snow sports are directly impacted by global warming by changing the quality and availability of snow and ice [9,10]. The increasing occurrence of extreme weather due to climate change also causes event cancellations and declining interests from spectators, bringing more complexity to stadium management [4,11]. Climate change, especially the heat will affect the health and performance of athletes[12,13,14]. In the long term, climate change will also make many stadiums not suitable to host sports events, leaving considerable stranded assets [15].

Besides the negative impacts of climate change, for a sports organization achieving a carbon neutrality goal would also help to promote both themselves and sustainable behavior. Previous research showed that a pro-environmental strategy can effectively improve the reputation of the sports team [16], enhance the loyalty of existing fans, and attract new consumers [17]. Climate change is usually politically charged and hard to communicate [18,19]. Sports events by their nature can easily unite people and contribute to the development of sustainability and environmental awareness [20]. Previous surveys indicate that sustainability campaigns can affect the behavior of fans not only in the events but also at home [21,22].

There are several approaches to achieving the carbon neutrality goals. From a perspective of life cycle, the highest share of emissions of a sports event comes from transportation, and adjusting the transport method [7,23] or the location of the event [24] could help to reduce the emission. Another common practice is to renovate the sport stadium [25,26]. However, the renovation often faces high capital cost, imposing challenge on the implementation [25,26,27]. Only some large stadiums, usually built for international mega-events, have the budget for eco-design and other renewable technologies to reduce the emissions. Additionally, there is a lack of quantitative analysis to evaluate the financial viability of such retrofits especially not considering the declining cost of solar [28], increasing willingness to pay [29], and various climate policies [30].

In short, the sports industry has the potential to achieve carbon neutrality at a low cost due to its low emission. Professional sports organizations achieving the carbon neutrality target could bring positive impacts on public reputation and community environmental awareness. However, there is a lack of quantitative understanding about how much emission could be economically reduced through the stadium renovation with a limited budget. In this paper, the energy usage and sports events data from a stadium in Wuhan, China are collected to conduct a feasibility analysis, demonstrating the carbon reduction potential for thousands of medium-size sports stadiums.

2. Materials and Methods

China is the largest carbon emission producer and also proposed an ambitious target for achieving carbon neutrality by 2060. China is also one of the most populated countries in the world with 637 sports stadiums across the country [31]. Wuhan Sports Center is adopted for a case study. Since its opening in 2002, it has hosted some international events like the 2015 Asian Athletics Championships and 7th

 ITS

International Military Sports Council (CISM) Military World Games, but most of its usage is for regional events, similar to many other stadiums in China. The seating capacity is around 50,000, almost half of the national stadium in Beijing. The rooftop area is 12,230 m2. The total energy usage data for the stadiums from 2019 to 2021 are collected, including both the normal operation and some large events (Figure 1). In the analysis, two demand scenarios are taken into account: back-to-normal (BTN) and under-COVID (UC). The average energy consumption in 2020 and 2021 is adopted as a benchmark for the energy consumption of under-COVID times. The energy consumption in 2019 is used to compute the back-to-normal monthly energy consumption and then the annual energy consumption.

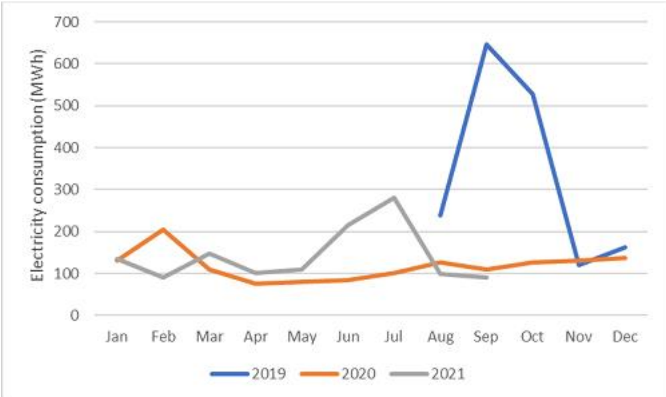

Figure 1. *Monthly electricity consumption of Wuhan Sports Center from August 2019 to September 2021.*

The solar generation potential in Wuhan is retrieved from previous research estimating the hourly generation in China with high spatial and temporal resolution [32]. The solar resource in Wuhan is not outstanding with an annual capacity factor of about 10.43%-12.55% and the average of the lower and upper bound is adopted in this analysis. The emission factor of electricity in Wuhan, as in the Central China Grid, is 0.8587tCO2/MWh according to the 2020 estimation from the Ministry of Ecology and Environment [33]. To account for the decarbonization process, it is assumed the emission factor decrease linearly to zero in 2060 when the Chinese government aims to achieve carbon neutrality.

The cost and performance of rooftop solar PV are assumed to be three scenarios, the high scenario is benchmarked with the cost from NREL annual technology baseline [34], the medium scenario is based on a recent study about China's distributed solar PV development [35], and the low scenario is designed based on the recent lowest public bidding result of a few real projects in China. Based on the bidding results, the Engineering, Procurement, and Construction (EPC) cost ranges from 5.07-3.12 CNY/W [36].The exchange rate is assumed as 1USD=6.5CNY. The loan ratio, interest rate and degradation rate are all assumed to be the same as the ones in a previous study[35]. The project lifetime is assumed as 20 years and the project is assumed to be installed in 2021. The loan payback period is set as 15 years. The discount rate is 3%. The tax rate for small business owners is 3% and 17% for a normal business owner. Solar projects in the grid operated by the State Grid of China can enjoy a 50% tax rate discount. The national feed-in tariff in China is 0.42CNY/kWh (0.06$/kWh), lower than the retail price in Hubei 0.55-0.85 CNY/kWh[37]. To make the case more representative, the local supportive policies are not considered.

China opened its national emission trading scheme in 2021 with the price ranging from 30CNY/ton CO2eq to 60 CNY/ton CO2eq, much lower than the price in the European market at the same period ~50euro/ton (1USD=1.06EUR). In this study, It is assumed the carbon price in China takes a 20-year linear growth to reach this level. The solar PV project can apply and earn carbon emission reduction credit, which is also another revenue stream from the project. Despite various ways that consulting companies charge the project development cost, 10% of the revenue from selling the carbon credit could be an estimation for the cost of project development, monitoring, reporting and verification (MRV), and this cost lasts for 5 years. The net present value (NPV) is adopted as the main metric to evaluate the project. Some assumptions are summarized in Table 1.

Table 1. *Solar PV financial model assumption.*

	High	Medium	Low
Capital Cost ($/kW)	2743[34]	1000[35]	311[36]
O&M cost ($/kW)	29[34]	2[35]	8[38]
Loan ratio	70%[35]		
Loan interest rate	5%[35]		
Degradation	3% in the first year, 0.7% per year thereafter[35]		
Feed-in tariff ($/kWh)	0.06		
Tax	17%		
Tax reduction	50%		

3. Results and Discussion

The carbon emissions from the stadium operation almost all come from electricity consumption. The maximum installed solar PV capacity in the stadium is about 2.39MW if only the constraint of rooftop area is taken into consideration. Other constraints like the capacity of the converter are not considered. Despite the slight degradation of solar PV, the generated electricity could cover the electricity consumption of the stadium in the UC scenario, as shown in Figure 1. It means the emission generated from electricity consumption could be entirely offset by the electricity generated from solar PV. If only to offset the emission from stadium operation under the COVID scenario, the required solar PV capacity is about 1.57MW, leaving some room for other constraints. Therefore, technically speaking, the solar PV could help the stadium to achieve a carbon neutral operation in similar activity levels as in COVID. It should be noted that the electricity generated from the solar PV could not perfectly meet the demand due to its intermittency and unavailability at night. The stadium still needs to connect with the grid and still consumes electricity with carbon emissions when no green electricity is available. If the whole roof is covered with solar PV, it will generate additional 9,362 ton CO_2eq carbon reduction credits across its lifetime. These credits could be used to offset the emission from travel and other scope 3 emissions induced by the sports events.

In the following analysis, the capacity is set as 1.57MW, which is the minimal capacity required for offsetting the carbon emissions in the UC scenario. Figure 3 displays the net present value (NPV) of the solar PV project under three cost assumptions and with or without carbon credits. If the cost of solar PV is as expensive as in the United States, it does not make economic sense to install such a project. Even if the import tariff and cost of transportation are not taken into account, the soft cost such as license fee, labor cost and overhead fee still make the solar roof system much more expensive in the United States [39]. When the cost drops to almost one-third of the cost in the U.S., the revenue from the carbon market becomes important. Without sales of carbon credits, the NPV is $-401,190 and with carbon credits, the NPV grows to $-37,802. Although it is still negative, the loss is not impossible to address. One potential option is to charge a higher price on the ticket as a green premium in one or two large events. A survey in the U.S. indicates the audience's willingness to pay for sustainability efforts is about $6.5 per ticket [29]. It is likely that audience in China may have a lower willingness to pay but even if it is assumed half of the price, ten thousand tickets with a green premium can cover the loss. In 2020 and 2021, as the representative of the COVID scenario, the stadium rarely hosted events with more than ten thousand persons but several events hosted had spectators ranging from 5000 to 7500 persons. In the low-cost scenario or the real-world scenario, it can be found that the NPVs are positive with or without the carbon credits, $0.70 million and $0.35 million respectively.

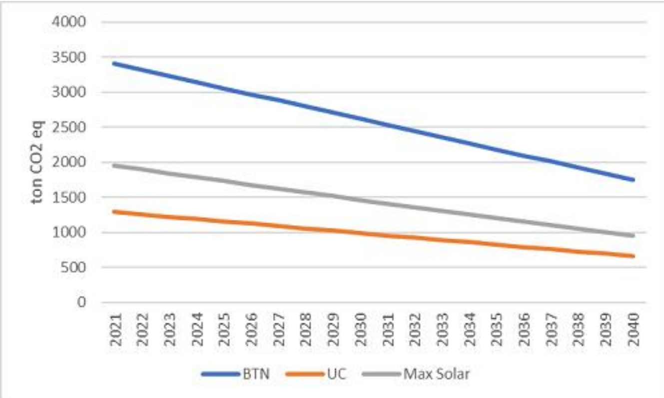

Figure 2. *Emission generated from electricity consumption under two scenarios (BTN: Back-to-normal, UC: Under COVID) and emission reduced from maximum solar PV capacity installed (Max Solar).*

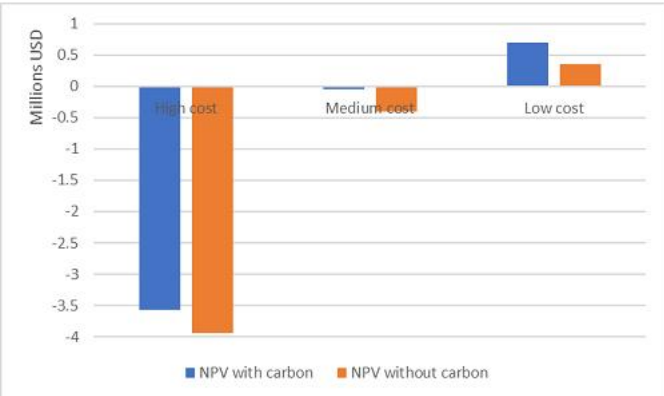

Figure 3. *Net present value of the solar project with different cost assumptions.*

Based on the low-cost scenario setting, a sensitivity analysis is conducted, as shown in Figure 4 and Figure 5. The revenue tax reduction is trivial. Even if there is no such policy, the NPV decreases 12% with carbon credits and 15% without carbon credits, but still positive. The feed-in tariff has a significant impact on the project revenue. When the tariff decreases by 22%, the project could not be economically viable without a carbon credit revenue. When the tariff drops 49%, even if the carbon credits are taken into account, the NPV will shrink to zero. From the perspective of policy design, it is certainly more important to maintain the feed-in tariff rather than the tax reduction. The O&M cost has a minimal impact on the project's economic feasibility while the capital cost is crucial. Even when the O&M cost increases by 50%, the NPV only drops by 12% with carbon revenue and by 23% without carbon revenue. When the capital cost increases by 46%, the NPV drops to zero without carbon credit revenue. If the carbon revenue is taken into consideration, the NPV could stay positive until the capital cost increases to 923$/kW, almost doubling the current price.

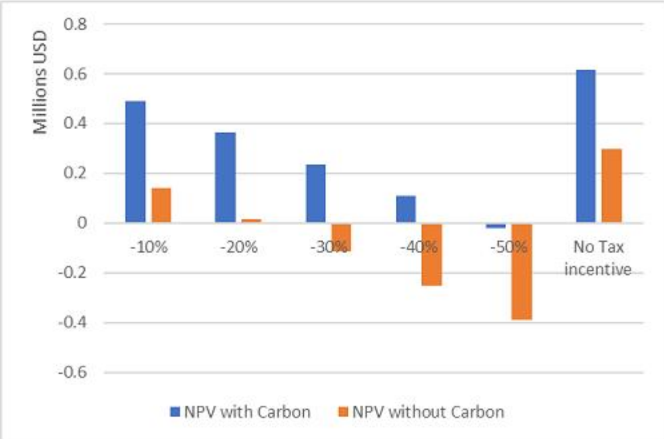

Figure 4 *NPV when feed-in tariff change and no tax incentive.*

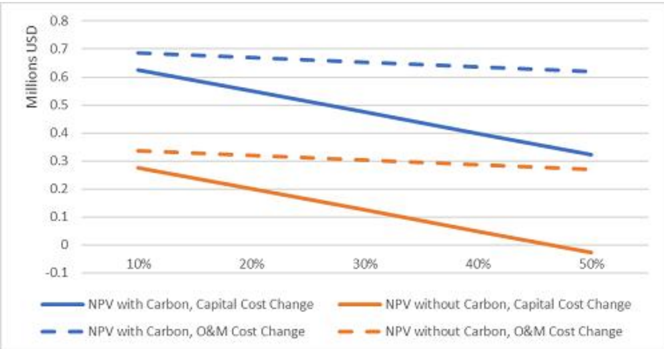

Figure 5 *NPV when cost assumption changes.*

4. Conclusions

Sports events could generate a considerable positive impact on spectators' perception of climate change, inspiring more climate-friendly activities. The emission, if only Scope 1 and 2 emission of the event is considered, mostly comes from the stadium operation, much lower than the emission of manufacturing factories. Due to the low emission, many mega international sports events like the Olympics could offset the emission at a relatively low cost even when the scope 3 emissions like emission from traveling are accounted. However, such budgets for emission offset and reduction are usually limited to these mega events and large stadiums. The regional medium sports stadiums, supporting rarely mega events and more often, the ordinary physical exercise of the residents, also have a positive impact on the climate change awareness of local communities but do not have the extra budgets. Through an analysis of a stadium in Wuhan, with real-world operation data and cost data, it reveals that even with moderate solar resources like Wuhan, the sports stadium could achieve carbon neutrality by installing the solar PV under a low activity level similar to the level during the pandemic. Since COVID-19 may permanently change the lifestyle and the frequency of the large sports events held in a stadium, this finding could be encouraging and informative to the stadium managers and all the people caring about sports and climate change. The financial feasibility of the solar PV project relies on both the low capital cost of solar PV in China and the feed-in tariff policy. However, the revenue from the carbon market could make the project more financially robust against the change in cost and tariff. With the carbon credits revenue, the results from the case study in Wuhan could be applied to places where the solar resources are more abundant but with a higher grid emission factor like Shanxi Province [40].

This research is a starting point to encourage the industry to conduct similar analysis across the country or the world and potentially form a feasible standard practice in the stadium operation. Currently this research still faces several limitations to be addressed in the future studies. Climate change, as the objective of the renovation, could also affect performance of the solar PV and stadium. The generating efficiency of solar PV is subjected to the temperature and solar radiation resources which will change with the climate change. As described above, the frequency and attendance of outdoor sports events will be affected by weather. We also notice the demand of air conditioner in the stadium management, which will bring uncertainties in the feasibility of carbon neutral operation. Additionally, the energy storage system which is usually paired with solar PV is not considered in this study and could potentially increase the capacity factor of the solar PV and boost the emission reduction from the renovation.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Author Contributions:

Conceptualization, R.S.; methodology, R.S.; formal analysis, W.G.; data curation, W.G..; writing—original draft preparation, W.G.; writing—review and editing, R.S.; funding acquisition, W.G. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Wuhan Committee of China National Democratic Construction Association.

Data Availability Statement

Data used in this analysis is available in the supplementary material.

Acknowledgments

The authors would like to express the gratitude to Wuhan Sport Center for their kind support in providing the energy consumption data and the activity data.

References

[1] del Fiacco, A.G.; Orr, M. A Review and Synthesis of Environmentalism within the Olympic Movement. *International Journal of Event and Festival Management,* 2019, 10, 67-80, DOI: 10.1108/IJEFM-05-2018-0038/FULL/XML.

[2] McCullough, B.P.; Pfahl, M.E.; Nguyen, S.N. The Green Waves of Environmental Sustainability in Sport. *Sport in Society,* 2016, 19, 1040-1065, DOI: 10.1080/17430437.2015.1096251.

[3] McCullough, B.P.; Orr, M.; Kellison, T. Sport Ecology: Conceptualizing an Emerging Subdiscipline Within Sport Management. *Journal of Sport Management,* 2020, 34, 509-520, DOI: 10.1123/JSM.2019-0294.

[4] Orr, M.; Inoue, Y. Sport versus Climate: Introducing the Climate Vulnerability of Sport Organizations Framework. *Sport Management Review,* 2019, 22, 452-463, DOI: 10.1016/j.smr.2018.09.007.

[5] Wicker, P. The Carbon Footprint of Active Sport Participants. *Sport Management Review,* 2019, 22, 513-526, doi:10.1016/J.SMR.2018.07.001.

[6] Chard, C.; Mallen, C. Examining the Linkages between Automobile Use and Carbon Impacts of Community-Based Ice Hockey. *Sport Management Review,* 2012, 15, 476-484, DOI: 10.1016/j.smr.2012.02.002.

[7] Dolf, M.; Teehan, P. Reducing the Carbon Footprint of Spectator and Team Travel at the University of British Columbia's Varsity Sports Events. *Sport Management Review,* 2015, 18, 244-255, DOI: 10.1016/J.SMR.2014.06.003.

[8] Collins, A.; Roberts, A. Assessing the Environmental Impact of Economic Activity Surrounding Major Sport Events. *Routledge Handbook of Sport and the Environment,* 2017, 207-219, DOI: 10.4324/9781315619514-15.

[9] Fairley, S.; Ruhanen, L.; Lovegrove, H. On Frozen Ponds: The Impact of Climate Change on Hosting Pond Hockey Tournaments. *Sport Management Review,* 2015, 18, 618-626, DOI: 10.1016/j.smr.2015.03.001.

[10] Orr, M.; Schneider, I. Substitution Interests among Active-Sport Tourists: The Case of a Cross-Country Ski Event. *Journal of Sport & Tourism,* 2018, 22, 315-332, DOI: 10.1080/14775085.2018.1545600.

[11] Dingle, G.W.; Stewart, B. Playing the Climate Game: Climate Change Impacts, Resilience and Adaptation in the Climate-Dependent Sport Sector. *Managing Sport and Leisure,* 2018, 23, 293-314, DOI: 10.1080/23750472.2018.1527715.

[12] Nowak, A.S.; Kennelley, G.E.; Krabak, B.J.; Roberts, W.O.; Tenforde, K.M.; Tenforde, A.S. Endurance Athletes and Climate Change. The Journal of Climate Change and Health 2022, 6, 100118, DOI: 10.1016/J.JOCLIM.2022.100118.

[13] Orr, M.; Inoue, Y.; Seymour, R.; Dingle, G. Impacts of Climate Change on Organized Sport: A Scoping Review. *Wiley Interdisciplinary Reviews: Climate Change,* 2022, 13, e760, DOI: 10.1002/WCC.760.

[14] Ross, W.J.; Orr, M. Predicting Climate Impacts to the Olympic Games and FIFA Men's World Cups from 2022 to 2032. 2021, 25, 867-888, DOI: 10.1080/17430437.2021.1984426.

[15] DeChano-Cook, L.M.; Shelley, F.M. Climate Change and the Future of International Events : A Case of the Olympic and Paralympic Games. *Routledge Handbook of Sport and the Environment,* 2017, 66-78, DOI: 10.4324/9781315619514-5.

[16] Kellison, T.B.; Mondello, M.J. Organisational Perception Management in Sport: The Use of Corporate pro-Environmental Behaviour for Desired Facility Referenda Outcomes. 2012, 15, 500-512, DOI: 10.1016/J.SMR.2012.01.005.

[17] Kellison, T.B.; Kim, Y.K. Marketing Pro-Environmental Venues in Professional Sport: Planting Seeds of Change Among Existing and Prospective Consumers. *Journal of Sport Management,* 2014, 28, 34-48, DOI: 10.1123/JSM.2011-0127.

[18] Bernauer, T. Climate Change Politics. http://dx.doi.org/10.1146/annurev-polisci-062011-154926 2013, 16, 421-448, DOI: 10.1146/ANNUREV-POLISCI-062011-154926.

[19] Paterson, M.; P-Laberge, X. Political Economies of Climate Change. Wiley Interdisciplinary Reviews: Climate Change*,* 2018, 9, e506, DOI: 10.1002/WCC.506.

[20] Triantafyllidis, S.; Darvin, L. Mass-Participant Sport Events and Sustainable Development: Gender, Social Bonding, and Connectedness to Nature as Predictors of Socially and Environmentally Responsible Behavior Intentions. *Sustainability Science,* 2021, 16, 239-253, DOI: 10.1007/S11625-020-00867-X/FIGURES/2.

[21] Casper, J.M.; McCullough, B.P.; Pfahl, M.E. Examining Environmental Fan Engagement Initiatives through Values and Norms with Intercollegiate Sport Fans. *Sport Management Review,* 2020, 23, 348-360, DOI: 10.1016/J.SMR.2019.03.005.

[22] Casper, J.M.; Pfahl, M.E.; Mccullough, B.P.; Casper, J.M.;; Pfahl, M.E.; Is Going Green Worth It? Assessing Fan Engagement and Perceptions of Athletic Department Environmental Efforts. *Journal of Applied Sport Management,* 2017, 9, 11, DOI: https://doi.org/10.18666/JASM-2017-V9-I1-7690.

[23] Chirieleison, C.; Montrone, A.; Scrucca, L. Event Sustainability and Sustainable Transportation: A Positive Reciprocal Influence. 2019, 28, 240-262, DOI: 10.1080/09669582.2019.1607361.

[24] Triantafyllidis, S.; Ries, R.J.; (Kiki) Kaplanidou, K. Carbon Dioxide Emissions of Spectators’ Transportation in Collegiate Sporting Events: Comparing On-Campus and Off-Campus Stadium Locations. *Sustainability,* 2018, 10, 241 2018, 10, 241, DOI: 10.3390/SU10010241.

[25] Casper, J.M.; Pfahl, M.E. Building Sport’S Green Houses : Issues in Sustainable Facility Management. 2015, 218-237, DOI: 10.4324/9781315881836-21.

[26] Kellison, T.B.; Hong, S. The Adoption and Diffusion of Pro-Environmental Stadium Design. 2015, 15, 249-269, DOI: 10.1080/16184742.2014.995690.

[27] Ross, W.J.; Mercado, H.U. Barriers to Managing Environmental Sustainability in Public Assembly Venues. *Sustainability,* 2020, 12, 10477 2020, 12, 10477, DOI: 10.3390/SU122410477.

[28] Castrejon-Campos, O.; Aye, L.; Hui, F.K.P. Effects of Learning Curve Models on Onshore Wind and Solar PV Cost Developments in the USA. Renewable and Sustainable Energy Review. 2022, 160, 112278, DOI: 10.1016/J.RSER.2022.112278.

[29] Greenhalgh, G.; Drayer, J. An Assessment of Fans' Willingness to Pay for Team's Environmental Sustainability Initiatives. *Sport Marketing Quarterly,* 2020, 29, 121-133, DOI: 10.32731/SMQ.292.062020.04.

[30] Chen, X.; Lin, B. Towards Carbon Neutrality by Implementing Carbon Emissions Trading Scheme: Policy Evaluation in China. *Energy Policy,* 2021, 157, 112510, , DOI: 10.1016/J.ENPOL.2021.112510.

[31] Li, Y.; Li, B.; Xu, H.; Feng, jun Annual Report On Development Of China'S Sports Venues (2020-2021); 2022.

[32] Li, M.; Virguez, E.; Shan, R.; Tian, J.; Gao, S.; Patiño-Echeverri, D. High-Resolution Data Shows China's Wind and Solar Energy Resources Are Enough to Support a 2050 Decarbonized Electricity System. *Applied Energy,* 2022, 306, 117996, DOI: 10.1016/J.APENERGY.2021.117996.

[33] Ministry of Ecology and Environment of People Republic of China Grid Emission Factor Benchmark for Emission Reduction Project Available online: https://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/202012/t20201229_815386.shtml (accessed on 14 July 2022).

[34] Feldman, D.; Ramasamy, V.; Fu, R.; Ramdas, A.; Desai, J.; Margolis, R. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark (Q1 2020). 2021, doi:10.2172/1764908.

[35] Xin-gang, Z.; Zhen, W. Technology, Cost, Economic Performance of Distributed Photovoltaic Industry in China. *Renewable and Sustainable Energy Reviews,* 2019, 110, 53-64, doi:10.1016/J.RSER.2019.04.061.

[36] More than 4GW Distributed Solar PV EPC Bid Result, Available online: https://guangfu.bjx.com.cn/news/20220524/1227745.shtml (accessed on 24 July 2022).

[37] Qiu, S.; Wang, K.; Lin, B.; Lin, P. Economic Analysis of Residential Solar Photovoltaic Systems in China. *Journal of Cleaner Production,* 2021, 282, 125297, DOI: 10.1016/J.JCLEPRO.2020.125297.

[38] Bid Result of O&M Services for Distributed Solar in Yancheng City, Jiangsu Pro vince Available online: https://guangfu.bjx.com.cn/news/20190510/979596.shtml (accessed on 17 July 2022).

[39] Seel, J.; Barbose, G.L.; Wiser, R.H. An Analysis of Residential PV System Price Differences between the United States and Germany. *Energy Policy,* 2014, 69, 216-7226.

[40] Yan, J.; Yang, Y.; Elia Campana, P.; He, J. City-Level Analysis of Subsidy-Free Solar Photovoltaic Electricity Price, Profits and Grid Parity in China. *Nature Energy,* 2019, 4, 709-717, DOI: 10.1038/s41560-019-0441-z.