Circular Economy 2 (2023) 100026

Contents lists available at ScienceDirect

Circular Economy

journal homepage: www.journals.elsevier.com/circular-economy

Original Research

How circular economy can reduce scope 3 carbon footprints: Lessons learned from FIFA world cup Qatar 2022

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A R T I C L E I N F O

Article history:
Received 9 October 2022
Received in revised form
31 December 2022
Accepted 12 January 2023
Available online 23 February 2023

Keywords:
Mega sporting events (MSEs)
Carbon footprint
Scope 3
Circular economy
Carbon neutrality

A B S T R A C T

Mega sporting events (MSEs) such as the FIFA World Cup and the Olympics always attract people around the world to visit the hosting country, boosting its tourism and business, and leaving a positive legacy. However, such events also leave significant negative impacts on the environment such as an increase in greenhouse gas (GHG) emissions in the host and neighboring countries. Considerable research efforts have been devoted to reducing such negative impacts and maintaining the sustainability of infrastructure associated with MSEs. The infrastructure construction in the host country of an MSE is the main and inevitable source of GHG emissions. In particular, the construction work of stadiums. This study presents comprehensive research on scope-based carbon footprint analysis related to two phases, i.e., the construction phase and operation phase of stadiums, by taking the eight world cup stadiums in Qatar as a case study. A life cycle assessment is used to quantify the potential environmental impacts of these stadiums at different stages. The Ecoinvent database is used to quantify the emission factor at each phase. According to the findings, Scope 3 (indirect supply chain) emissions are greater than Scope 1 (direct on-site) emissions, and the construction supply chain is found to be a significant contributor to the carbon footprint of the stadiums, accounting for 98% of the total GHG emissions. The results also show that electricity, district cooling, and waste generation are the three top contributors of GHG emissions with 35%, 25%, and 21% emissions, respectively. Moreover, it is vital to implement innovative approaches such as circular design for end-of-life material recycling and reuse of structural components, which can support a transition toward sustainable and carbon-neutral mega events. Thus, this study presents the role of circular economy in achieving carbon-neutral FIFA World Cup Qatar 2022. This research will contribute to enhancing the future benefits of the sustainable construction of infrastructure projects for mega events and help in harmonizing mega event strategies with national circular economy targets.
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1. Introduction

1.1. Overview

Greenhouse gas (GHG) emissions are one of the major issues that should be addressed to solve global climate change problems and establish sustainable development. Most of the current strategies for sustainable development are essentially linked to reducing the overall carbon footprint. The construction industry is one of the dominant sectors contributing to the carbon footprint of our society because it signifies the connections between energy, transportation, and building, which are considered the three main GHG emitters (Kibert, 2016). Globally, construction accounts for 40% of overall energy utilization, one-third of GHG emissions, 30% of unrefined material utilization, 25% of solid waste production, 25% of water utilization, and 12% of land utilization (UNEP, 2009). Therefore, more dedication need to be devoted to the construction industryto reduce the overall carbon footprint.

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https://doi.org/10.1016/j.cec.2023.100026
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To produce cost-effective and efficient sustainable strategies, measuring and reporting GHG emissions in the built environment is crucial, which can be achieved with the aid of life cycle assessment (LCA) (Fenner et al., 2018). A considerable amount of effort has been devoted to the assessment of construction performance based on LCA (Bovea & Powell, 2016; Carpenter et al., 2007; Colangelo et al., 2018; Goel et al., 2012).

Various stadiums, buildings, and other infrastructures are built to host mega sporting events (MSEs) such as the football World Cup (WC) Fédération Internationale de Football Association (FIFA). The most crucial challenge is exploiting the sustainability of such events and maintaining an optimistic legacy for future peers (Meza Talavera et al., 2019). Sustainability should be the foundation of the projects for all MSEs. The social responsibility of FIFA regarding sustainability is to demand sustainable planning and a road map from the host country to reduce carbon emissions linked to the built environment. It is vital to consider scope-based analysis for proper evaluation of the sources of emissions.

Generally, according to the GHG protocol, GHG emissions are studied by grouping them into three scopes. In this context, Scope 1 considers direct GHG emissions, Scope 2 refers to indirect emissions from the production of electricity, heating, steam, or cooling consumed by the reporting entity, and finally, Scope 3 deals with all other indirect GHG emissions, including waste disposal, outsourced activities, vehicles not owned or under the reporting entity's control, and the extraction and production of purchased materials and fuels. Previously, FIFA 2014 and FIFA 2018 reported their proportion of Scope 3 emission to be 97.90% and 98.59% of the total carbon emissions, respectively, which accounted for the highest Scope 3 emissions (Spanos et al., 2022). FIFA, along with the supreme committee for delivery and legacy (SCDL) of Qatar, promised to provide a carbon-neutral WC 2022. Qatar has aimed to deliver sustainable building structures, water consumption, waste management, and reduced carbon emission solutions to neighboring countries and leave a positive legacy of hosting an entirely carbon-free event. However, observing emission indicators involves innovative tools; thus, some researchers have supported and suggested blockchain technology and circularity (Shojaei et al., 2021; Upadhyay et al., 2021).

The notion of circular economy (CE) has recently gained much attention owing to its great potential to significantly reduce the carbon footprint through waste minimization and resource efficiency (Kucukvar et al., 2014, 2021). It proposes a novel approach for optimizing the use and value of materials throughout their lifecycle phases while contributing to waste minimization. In particular, an MSE, being resource intensive in nature and leaves a prolonged impact on the host and neighboring countries, requires the implementation of such novel strategies to reduce its negative impact on the environment and society.

1.2. Research significance and objectives

This study aims to compute the climate change impacts of the construction and operation phases of stadiums built for MSEs using a lifecycle-based approach, which is then used to implement CE to achieve the goal of carbon neutrality. Despite promising carbon neutrality in the events of the WC and Olympics through sustainable construction practices, it is uncertain whether such sustainable infrastructure projects can support the decarbonization initiatives of host nations without considering a scope-based analysis for the total carbon footprint. Therefore, this research uses all stadiums in Qatar as an example of sustainable infrastructures and conducts a scope-based assessment to identify potential leverage points to apply circular strategies in future events and make the carbon-net-zero transition come true. This research thus intends to achieve the following:

Quantify the scope-based climate change impacts of sustainable stadium designs for MSEs using all sustainable stadiums planned for the WC 2022 as a case study.

Identify significant contributors across each scope for planned decision making to mitigate climate change impacts.

Propose strategies for passing on a sustainable and circular legacy for MSEs.

Identify potential implementations of CE to achieve carbon-neutral MSEs.

2. Literature review

2.1. Mega events and sustainability

From the history of MSEs, we can doubtlessly admit that they have the power of uniting people regardless of their color, language, and borders. It is the dream of every country to have a chance to host an MSE such as the FIFA WC and Olympics at least once. Hosting an MSE brings direct and indirect social and economic benefits to the host country. Although MSEs have a fundamental contribution to the total financial growth of the host country, their negative environmental impacts cannot be ignored (Collins et al., 2009).

The concern over the environmental impacts on the host cities and neighboring areas due to the mega events is interestingly increasing worldwide. As a result, various approaches toward sustainability have been established to measure and control the overall negative impact of such events (Holmes et al., 2015). Among many other factors, GHG emissions are the main contributor to environmental threats. Reducing GHG emissions such as CO_2 emissions plays a significant role in global climate change mitigation. Each sporting event such as the FIFA WC generates GHG emissions from the planning phase to the end-of-life of the event. This includes GHG emissions related to multiple stages such as the construction of stadiums and buildings, material production and shipping, national and international transportation, water, electricity, waste management, and end-of-life management.

The concept of sustainability and environmentally friendly games was first introduced in the 1994 Lillehammer Winter Olympic Games (Chernushenko, 1996) with an attempt of hosting the games under the name “green games”. This was an inspiration for major MSEs such as Olympics and WCs to include the concept of sustainability in one way or another. After this, in 1996, the International Olympic Committee declared it mandatory for Olympics host bidders to practice environmental protection and sustainability (Gold & Gold, 2013). Subsequently, the 2000 Sydney Olympic Games incorporated environmental and sustainability dimensions in their bidding process. They succeeded in measuring the environmental impacts and achievements during the games (Searle, 2002). The 2004 Athens Olympic Games, even though proposed and committed to the implementation of environmental protection measures, failed to meet many of the sustainability and green games requirements (Tziralis et al., 2008).

The 2006 FIFA WC in Germany and the 2008 Beijing Olympics became the center of attention by introducing “greening” initiatives to MSEs (Death, 2011; Long et al., 2018). The German WC claimed the achievement of carbon neutrality; however, they ignored emissions from international travels. During the FIFA 2006 WC, the transportation sector accounted for 79.63% of the total GHG emissions, with overnight stays, stadium construction, electricity, and heating accounting for approximately 12.70%, 4.52%, 2.72%, and 0.44%, respectively (Stahl et al., 2006). Although South Africa 2010 vowed to fulfill the “Green Goal 2010”, which showed some positive results toward the proposed policies, due to the lack of expertise and organized behavior, the game led to many controversies about wasting public money on stadiums and airports when the country needs housing, water, electricity, etc. (Kucukvar et al., 2021). From the environmental perspective, this WC ended as the most carbon-intensive WC ever (Death, 2011). According to reports, the 2014 WC in Brazil resulted in CO_2 emissions of 2.7 million tons. During the event, the transportation sector accounted for 83.70% of the total GHG emissions, with the venue, accommodation, merchandise production, and logistics amounting to approximately 9.60%, 5.70%, 0.60%, and 0.30%, respectively (Association FI de, 2014). Furthermore, the 2012 London Olympics (Gold & Gold, 2013, 2015) came close to meeting sustainability goals such as zero waste in landfills, with the majority of wastes reused, recycled, or composted, and a significant reduction in CO_2 emissions. For the 2016 Rio Olympic Games, Brazil submitted a proposal of creating sustainable and environmental-friendly strategies to transform the host city. However, reports showed that they failed to meet most of the requirements for sustainability (Trendafilova et al., 2017). The 2018 WC had undergone various studies to establish sustainability effectively and avoid flaws in previous mega events. Russia 2018 was viewed as an event that attempted to portray Russia as a reemerging force in need of renewing and urbanizing towns outside Moscow (Meza Talavera et al., 2019).

2.2. Sustainable construction and CE

The construction industry is energy-intensive and wasteful. Moreover, it is among the most prominent consumers of natural resources. Therefore, it plays a pivotal role in climate change (Murtagh et al., 2020; Pérez-Lombard et al., 2008). Globally, the construction industry is believed to consume more than 50% of the raw materials (Ruuska & Häkkinen, 2014). Besides, the use of heavy machinery and low-efficiency systems contribute greatly to GHG emissions. As a result, sustainability in construction has been steadily promoted by the global construction industry to reduce its negative impacts on the environment and society. Kibert (2016) defined sustainable construction as the foundation and responsible management of a healthy built environment following ecological principles and resource efficiency. This definition entails six principles, i.e., conserve, recycle or renew, reuse, protect nature, create nontoxic, and high quality. Hence, sustainable construction is geared toward the utilization of resources and energy-efficient and environmentally-responsible construction processes that ensure lifespan sustainability of the built environment.

The adoption of sustainable construction in the construction industry could reduce the environmental impact of a built environment throughout its lifespan and thus helps achieve the sustainable development of a nation. Over the years, innovative technologies and sustainable construction materials have evolved with an increased interest in energy conservation and environmental protection. GHG emissions in the construction industry can be reduced by using green and sustainable construction materials and implementing sustainable and green building designs, particularly in terms of energy efficiency (Kirchherr et al., 2017). Moreover, the inherently unsustainable nature of the construction sector in terms of high consumption of raw materials and waste generation requires the implementation of novel concepts such as CE, which promotes the reduced use of virgin materials and minimization of waste generation. Recently, Kucukvar et al. (2014) investigated the role of circular design in MSEs using an innovative reusable shipping container stadium as a case study under two scenarios: (a) a one-year operation and (b) 50 years of operation. Based on the analysis results, the authors concluded that using circular design can avoid up to 60% of human health impacts. In a similar study, Al-Hamrani et al. (2021) investigated the economic and environmental benefits of CE with a particular focus on the use of site-excavated boulders in cyclopean concrete in the construction of stadiums. Based on the results of the environmental LCA, the authors concluded that the use of cyclopean concrete can reduce GHG emissions by up to 32% without compromising the structural performance of the concrete.

2.3. CE and carbon footprint reduction

The notion of CE has evolved over the last few years and has gained significant interest from both scholars and practitioners. It is one of the recent approaches that can be used to mitigate environmental footprints and ensure a sustainable future. Kirchherr et al. (2017) defined CE as “an economic system that replaces the ‘end-of-use’ concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes”. According to this definition, CE is mainly driven by the following three imperatives, namely, reduce, reuse, and recycle (Kirchherr et al., 2017), with the objectives of minimizing the use of virgin resources and achieving sustainable development. By encouraging the implementation of recycling and reuse, CE eliminates the carbon footprint associated with the production of new materials. In addition, the use of recycled materials significantly reduces the carbon footprint in a cost-effective and eco-friendly manner. Moreover, CE significantly contributes to carbon footprint reduction through waste generation reduction. Thus, it is viewed as the driver for achieving environmental, social, and economic sustainability.

As a result, with the current trends oriented toward waste minimization and resource efficiency, the notion of CE has recently gained momentum not only among researchers in different disciplines, but also among policymakers. Moreover, there are global efforts to promote and implement CE. “Eco-cities”, “zero-waste cities”, and “circular cities” are global initiatives established to promote CE (Dong et al., 2021). China and European countries such as Germany are among those countries that have recognized the importance of CE and have developed legislation on its implementation (Merli et al., 2018).

Compared with other industries, the construction industry has a high potential to successfully adopt CE practices (Brambilla et al., 2019). In an ideal case, the implementation of CE in the construction industry will result in reduced waste generation via different strategies, including construction waste recycling, which in turn ensures sustainability during construction and reduces the carbon footprint. Apart from contributing to a sustainable environment, the implementation of CE has a high potential to ensure economic sustainability (López Ruiz et al., 2020) and create new business opportunities (Sehnem et al., 2021). However, research on the implementation of CE in construction and demolition waste management in the construction sector is limited (López Ruiz et al., 2020).

2.4. LCA

LCA is the main tool for assessing the potential environmental impacts of products or services at all stages of their life cycle. A product life cycle involves raw material extraction, product manufacturing, its use, and disposal or recycling (Singh et al., 2011). The International Organization for Standardization has implemented an iterative four-step model for LCA (Al-Hamrani et al., 2021; Singh et al., 2011). This includes the following:

Goal and scope definition: Defining the objective, scope, and boundaries of the work, as well as the functional unit and its linked core procedures.

Inventory analysis: Data collection and material and energy flow analysis in various phases of LCA.

Life cycle impact assessment: Analyzing various midpoint and endpoint environmental impacts using the collected data.

Interpretation: This step details the results of the environmental impacts.

Several studies on LCA have been reported. Al-Hamrani et al. (2021) conducted an LCA of one of the FIFA 2022 stadiums in Qatar, where cyclopean concrete was used to cast the under-raft foundation of the stadium by combining boulders and the concrete mix. The proposed method achieved a 32% reduction in GHG emissions compared with conventional concrete. Toboso-Chavero et al. (2019) proposed a concept called the Roof Mosaic approach for evaluating food—energy—water implementations on rooftops by experimenting on two different scales, i.e., buildings and neighborhoods of a highly populated city. According to their research, food production and rainwater harvesting on rooftops contribute to a minor reduction in CO_2 emissions while reducing the environmental impact on construction. In addition, when using energy systems such as solar thermal systems, along with rainwater harvesting, a significant reduction in carbon footprints can be achieved. However, this results in a higher environmental impact in the construction phase.

Zavadskas et al. (2017) proposed an optimal alternative to multi-attributed decision making (MADM) in construction called MADM-opt. On this basis, they analyzed the concept of passive housing and nearly zero energy building using Lithuanian Standards. Ortiz et al. (2017) proposed the use of recycled materials for construction by introducing a cement base material called steel-fiber-reinforced self-compacting concrete, using recycled aggregates. To perform LCA, Colangelo et al. (2018) compared four different recycled concrete mixtures, namely incinerator ashes, construction and demolition waste, blast furnace slag, and marble sludge. Their results showed that recycled concrete produced lesser environmental impacts than conventional concrete.

In the case of stadiums, the Accor Stadium in Sydney, completed in 2000, was one of the first stadiums that considered maintaining sustainability with its unique green design concept. Laminated timber beams were used as a support to the roof of the green stadium. Furthermore, the stadium officials re-evaluated their strategies for greening the stadium by proposing new ideas in practice. For example, they introduced the concept of a closed-loop recycling program that attempts to achieve 100% recycling in food and beverage packaging (Vanderweil, 2008). The national Stadium of Taiwan is known as the first solar-powered stadium. This stadium contains 8844 solar panels, which can produce 100% electricity on game days. These solar panels also provide electricity to neighborhoods around the stadium (Aquino & Nawari, 2015).

2.5. Knowledge fragmentation

In this study, a systematic review is conducted to provide a comprehensive summary of the literature on the carbon footprint analysis. For this purpose, a five-step process is adopted, as depicted in Fig. 1.

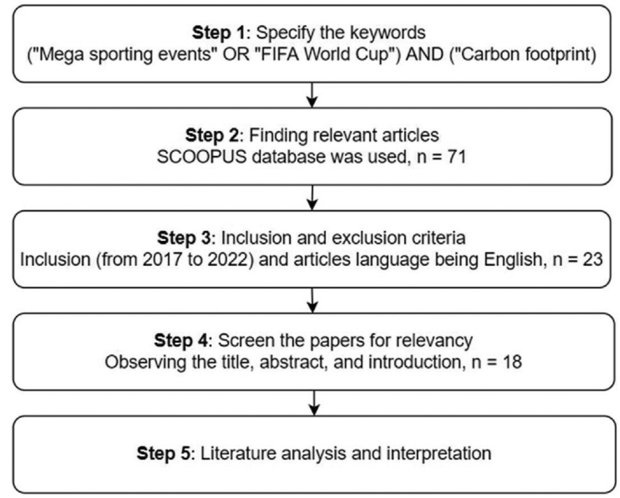


Fig. 1. Systematic review approach for this research.

As shown in Fig. 1, Step 1 involves the identification of keywords to develop a scope for selecting MSEs or FIFA WC articles, as well as those on carbon footprint. In Step 2, the SCOPUS database was chosen to assess peer-reviewed articles; the resulting collection had 71 articles. In the third step, inclusion and exclusion criteria are then applied to review the literature systematically, resulting in a total of 23 articles. The inclusion criteria are defined as follows: (i) Research of the most recent six years, from 2017 to 2022; (ii) peer-reviewed journal and research articles; (iii) English-language publications; (iv) subject areas were limited to environmental science, social science, and engineering. On the other hand, the criteria for exclusion are (i) unrelated to the subject of interest and (ii) books, conference papers, theses, magazines, and trade journals. In Step 4, the screening and eligibility check was applied to exclude papers unrelated to the scope, which consequently reduced the number of eligible papers to 18 (Fig. 1). In the 5th step, literature analysis and interpretation were performed. This type of method has also been used in previous studies (Al-Obadi et al., 2022; Khan et al., 2003).

Looking at the research trend in light of the screening results and the increasing number of papers related to the "MSE, FIFA WC, and carbon footprint" decision, it is observed that this trend is rising and gaining more attention from the research community in 2020 and 2021. However, the research community requires more attention to save the world from carbon emissions. Fig. 2(a) shows the fluctuating number of collected articles over the years. Only two related papers emerged in 2018 and 2019. These numbers jumped in the following years until 2021, yielding four papers in 2020, four papers in 2021, and finally two papers in 2022. There was an increasing research effort in 2020 and 2021 to investigate carbon emissions to respond to the high level of interest in this field. From the geographic distribution of the research sources shown in Fig. 2(b), the UK is capitalizing on the research efforts taken to investigate "MSE, FIFA WC, and carbon footprint" with 47% of the resulting research papers being conducted in the UK. The origin of the remaining papers were scattered in different countries.

We analyze the findings of the resulting papers to highlight to the research community that there is a critical need for research and development in this field.

3. Method

This study attempts to quantify the climate change impact of sustainable stadiums for the FIFA WC 2022. Carbon footprint analysis is applied to the eight stadiums constructed for this mega event. Table 1 presents some general information about each stadium (details provided at: https://www.stadiumguide.com/tournaments/fifa-world-cup-2022-stadiums-qatar/). This study applies a lifecycle-based approach that considers the construction and operation phases of all stadiums of FIFA WC 2022 according to the research flowchart shown in Fig. 3. More details are explained in the following sub-sections (see Table 2).

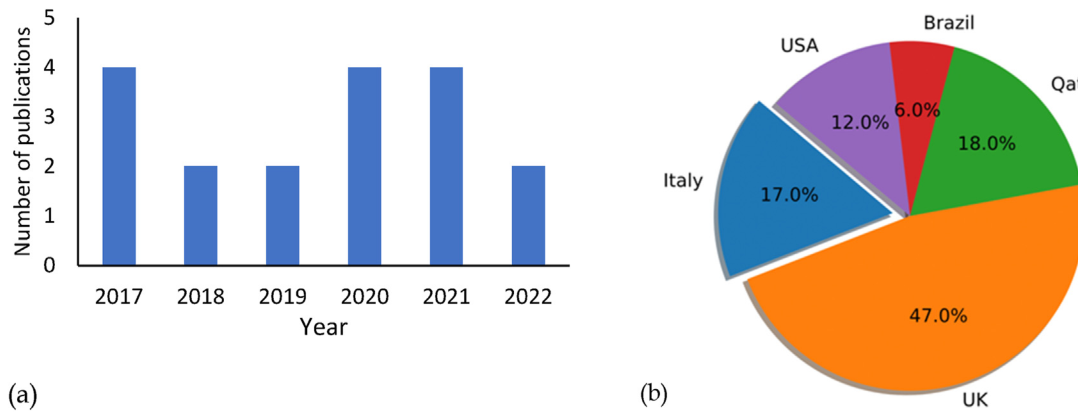


Fig. 2. Research trend on MSEs regarding FIFA WC and carbon footprint. (a) Annual distribution of articles over six years. (b) Geographical distribution of articles over six years.

Table 1
Stadium data.

Stadium	Location	Area (m^2)	Capacity (people)
Stadium 974	Doha	80,531	40,000
Lusail	Lusail	204,060	80,000
Khalifa International	Doha	81,832	40,000
Education City	Al Rayyan	148,112	40,000
Al Thumama	Doha	114,560	40,000
Ahmed bin Ali	Al Rayyan	114,600	40,000
Al Janoub	Al Wakrah	98,495	40,000
Al Bayt	Al Khor	237,089	60,000

3.1. System boundaries

The scope of this study includes two different phases, which are the construction phase and the operation phase, as depicted in Fig. 4. For each phase, Scopes 1, 2, and 3 were defined for each stadium based on the data provided by the WC 2022 organizing committee, as described in Section 1.

In this study, emissions of Scope 1 primarily come from activities occurring in the stadiums. Thus, emissions from on-site diesel, petrol, and fuel consumption during construction activities, maintenance, and refrigerant leakage during operation phase are considered in Scope 1. Emissions of Scope 2 during operation phase result from the use of electricity in the stadiums and district cooling. Scope 3 includes Scopes 1 and 2 supply chain emission activities and GHG emissions from waste, water use, wastewater, materials, and freight.

3.2. Lifecycle inventory

This study is a successful collaboration between experts from SCDL (the local organizing committee for FIFA 2022) and researchers from Qatar University. Lifecycle data for all stadiums were given to Qatar University by the supreme committee for conducting sustainability-related studies. Prior to handing over the inventory data to the authors, experts at the supreme committee had undergone a rigorous data collection procedure. However, the procedures adopted for data collection remain confidential. Ecoinvent V3.7.1 was used to calculate CO_2 emissions. The tCO_2 equivalent (tCO_2-eq) emission is calculated by multiplying the quantity of each contributor by the emission factor. The calculated emissions were then allocated to each scope. Table 1 lists the inventory data from all sources for each stadium.

4. Analysis and discussion

The results of the analysis of scope-based carbon footprints, the interpretation of the findings, the identification of carbon footprint

Table 2
Stadium data during construction phase and operation phase.

Construction phase	Ras Abu Aboud	Lusail	Khalifa International	Education City	Al Thumama	Al Rayyan	Al Janoub	Al Bayt
Diesel (m^3)	814	14,531	6088	3085	6371	16,478	10,365	13,191
Petrol (m^3)	0	125	0	0	6	0	0	0
Fuels (kWh)	8,633,584	155,242,787	64,546,677	32,709,146	67,606,623	174,707,691	109,893,245	139,856,532
Electricity (kWh)	306,564	0	0	8,729,134	0	0	0	1,596,310
Water use (m^3)	63,675	375,448	145,843	185,768	153,111	465,110	331,027	1,561,169
Materials (kg)	432,349,047	1,132,856,116	1,035,301,647	687,792,117	733,861,583	577,759,329	264,561,180	1,120,469,667
Freight (tkm)	687,412,363	694,829,663	371,982,272	434,588,458	130,258,396	197,295,888	147,261,791	323,272,213
Waste (t)	826,398	71,116	207,060	1724	20,754	40,133	107,462	167,560
Wastewater (m^3)	22,286	199,970	51,045	65,771	57,851	162,789	106,118	246,868
Operation phase	Ras Abu Aboud	Lusail	Khalifa International	Education City	Al Thumama	Al Rayyan	Al Janoub	Al Bayt
Electricity and cooling total (kWh)	4,384,835	8,592,342	5,824,214	11,414,851	9,530,885	8,214,580	7,827,914	19,748,754
District cooling (kWh)	2,621,894	3,796,457	2,190,704	4,645,978	4,152,062	3,501,750	3,597,425	7,124,272
Electricity (kWh)	1,762,941	4,795,885	3,633,510	6,768,873	5,378,823	4,712,830	4,230,489	12,624,482
Refrigerant type	R134A	R134A	R134A	R134A	R134A	R134A	R134A	R134A
Refrigerant leakage (kg)	0	0	0	0	0	0	700	0
Refrigerant leakage (kg/m^2)	–	–	–	–	–	–	0.0071	–
Water use (m^3)	18,981	76,297	8910	10,524	14,022	4956	48,162	6484
Waste generation (t)	1752	3504	1752	1752	1752	1752	1752	2628
Wastewater (m^3)	8636	34,715	4054	4789	6380	2255	21,900	2950
Maintenance of football field (tCO_2-eq/a)	13	13	13	13	13	13	13	13

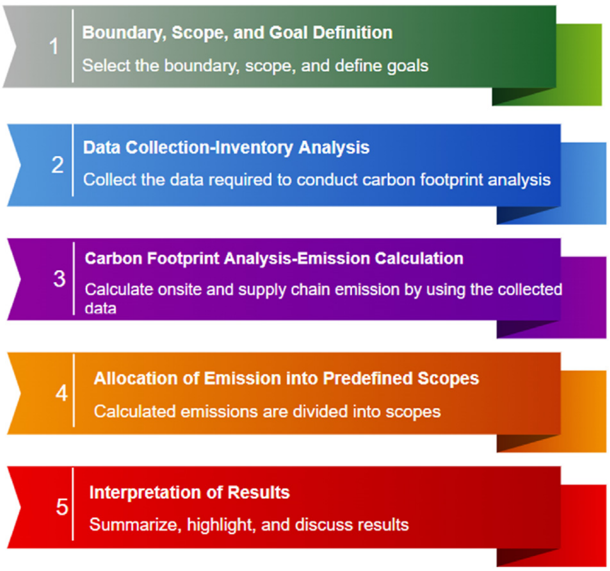


Fig. 3. Research methodology flowchart of this study.

hotspots, and solutions for reducing carbon footprints are discussed in this section. The percentage scope distributions of carbon footprints for the FIFA WC 2022 Stadiums in both phases (construction and operation) are depicted in Fig. 5. Scope 3 emissions (91% in construction phase) and Scope 2 emissions (61% in operation phase) contribute to the highest carbon footprint sharein the respective phase. Scope 1 emissions were approximately 9% and 15% in the construction and operation phases, respectively. Scope 2 emissions were 0% in construction phase (Fig. 5(a)), whereas Scope 3 emissions amounted to 24% in operation phase (Fig. 5(b)). Moreover, as shown in Fig. 5(c), which shows the percentage scope distributions of carbon footprints of the construction and operation phases, Scope 3 emissions accounted for the highest emission share of 90%, followed by Scope 1 with 9% and Scope 2 with 1%.

Notably, Scope 3 emissions include the supply chain emissions of Scope 1 activities. Fig. 6 shows the emissions of each scope per stadium. As shown in this figure, during construction phase, Scope 3 emissions from the Stadium 974 have the highest percentage, whereas those from Al Janoub stadium have the least percentage. During operation phase, the highest percentage of Scope 2 emissions is generated from the Al Bayt stadium. As shown in Fig. 6(c), Scope 1 emissions from both phases were the most in the Al Janoub and Ahmed bin Ali stadiums, whereas Scope 2 emissions were the most in the Al Bayt, Education City, and Al Janoub stadiums. Scope 3 emissions were the most in the 974, Lusail, and Education City stadiums. Scope 3 emissions in construction phase (91%) are greater than those in operation phase (24%). This is because emissions from the supply chain of a stadium during construction are mostly Scope 3 emissions, and during operation phase emissions are mostly due to waste, which is also in the Scope 3 category. Scope 2 emissions in

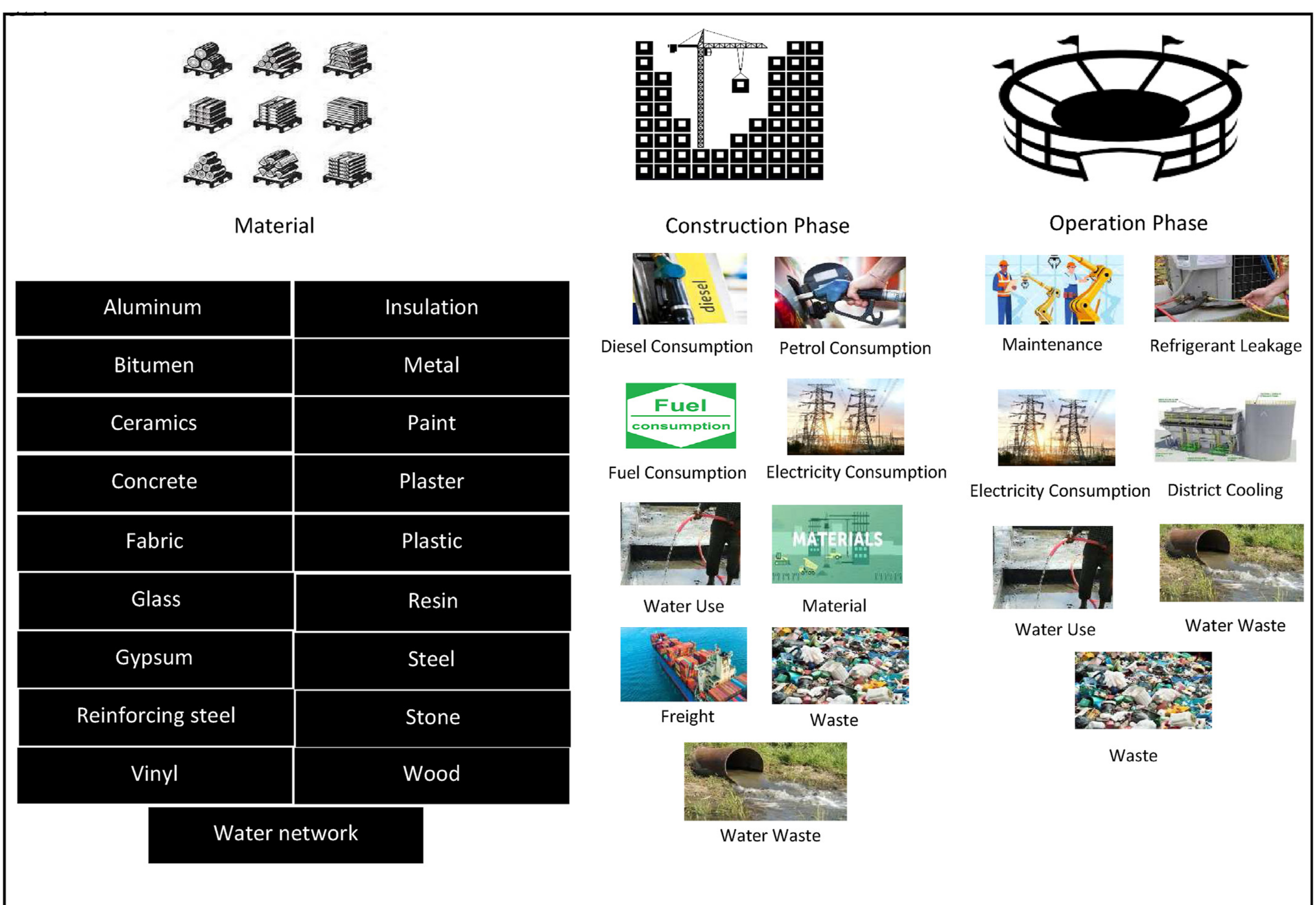


Fig. 4. System boundary used for the assessment of the stadiums.

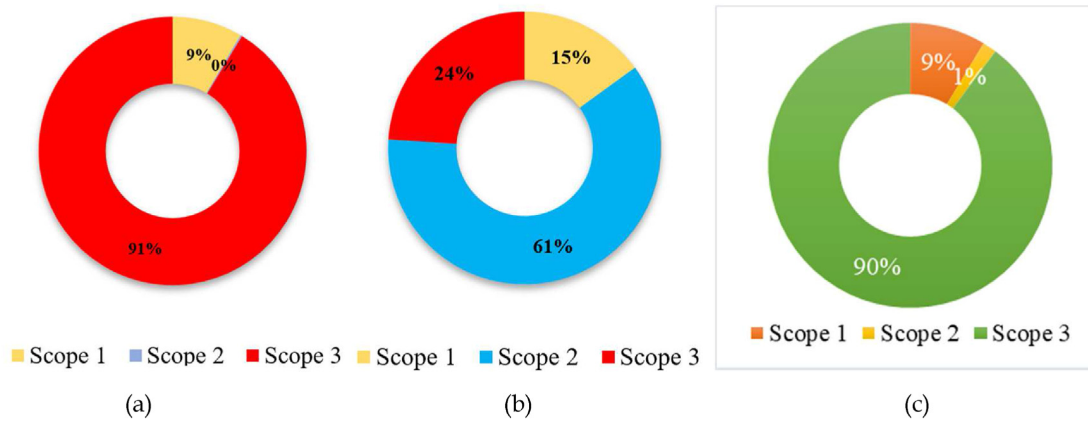


Fig. 5. Carbon footprint distribution of the three scopes during (a) construction phase, (b) operation phase, and (c) both construction and operation phases.

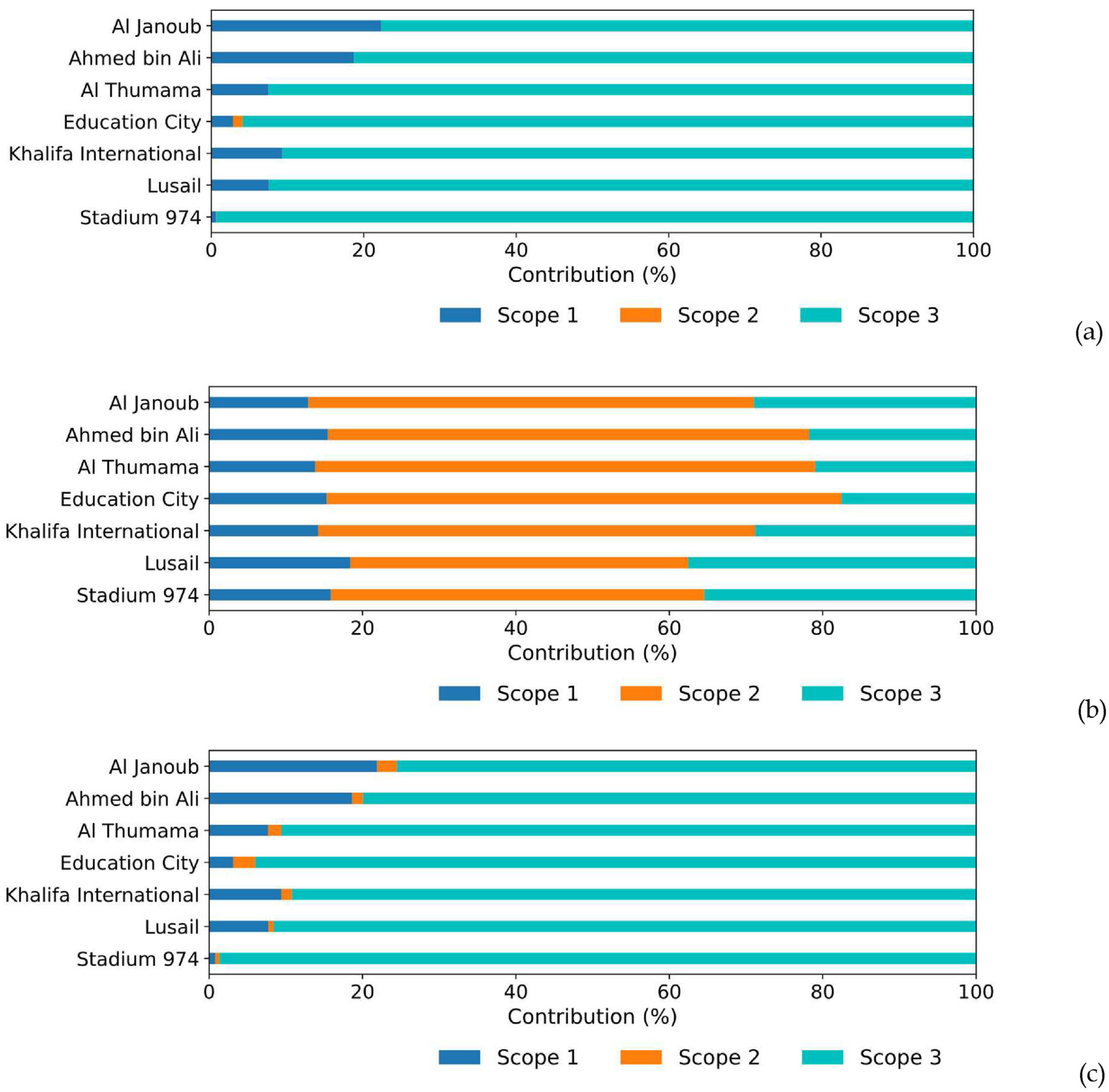


Fig. 6. Carbon emission distribution of the three scopes during (a) construction phase, (b) operation phase, and (c) both construction and operation phases.

Table 3
Percentage distribution of carbon footprint of stadiums (construction and operation phases).

Scopes	Activity- Construction phase	Distribution (%)-Construction phase	Activity- Operation phase	Distribution (%)-Operation phase
Scope 1	Diesel	8	Maintenance	0.2
	Petrol	0.01	Refrigerant leakage	15
Scope 2	Electricity	0.19	Electricity	35
	Water use	1	District cooling	25
			Water use	4
Scope 3	Materials	78	Waste generation	21
	Freight	11	Wastewater	0.1
	Waste	1	Electricity	0

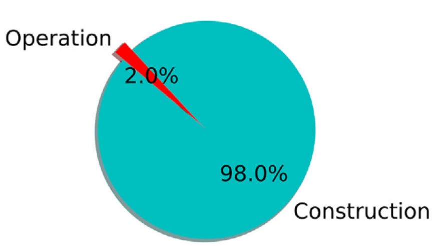
operation phase have a higher percentage than those in construction phase, indicating that electricity is a crucial energy source in operation phase, and these emissions account for almost 35% of GHGs emitted by the stadiums. However, Scope 1 emissions show that emissions within the boundaries of the stadiums, mostly because of maintenance and refrigerant leakage, are higher in operation phase than in construction phase.

The elements of the scopes and their contributions are summarized in Table 3. As presented in this table, during construction phase, material consumption has a major influence on the total carbon footprint of the stadiums (78%), followed by freight (11%). During operation phase, the highest contribution was from electricity use, district cooling, and waste generation, which amounted to 35%, 25%, and 21%, respectively. An additional vital contributor to carbon footprint consumption is refrigerant leakage (15%), which is the main element of Scope 1 emissions.

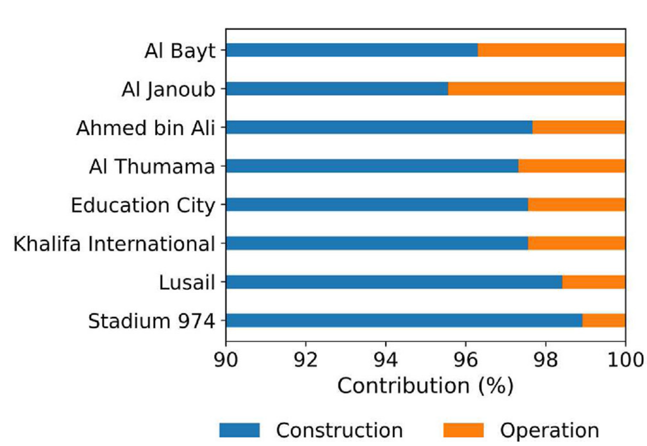
After analyzing the breakdown of scope-based carbon footprints, the comparison between construction phase and operation phase is also studied. Fig. 7 illustrates the proportion in emissions attributed to these two phases of the stadiums. As shown in this figure, the construction phase of the stadiums has the highest contribution with 98% of the total emissions (the emissions per stadium ranged between 97% and 99%). The construction phase is more dominant in the eight stadiums than the operation phase. The outcomes of this analysis demonstrated the need to prioritize the construction phase when developing carbon footprint reduction initiatives. The prioritization of components within the scopes is more reasonable and possible because the carbon footprint hotspots are evident among the scopes and the two phases of the stadiums.

After analyzing the scopes, it is crucial to emphasize the key carbon footprint contributors within each scope. Fig. 8 shows the carbon footprint distribution in percentage for the construction and operation phases. As shown in this figure, the three highest emission sources in the construction phase for the stadiums account for 97% of the total footprint, and the top four emission sources in the operation phase for the stadiums account for 96%. Material usage and electricity are powerful components of the total carbon footprint in construction and operation phases, respectively. Fig. 9 illustrates the details of the carbon footprint per stadium in both construction and operation phases.

The first component that needs attention is material usage, which is a significant contributor to the total carbon footprint of the stadiums in construction phase. As shown in Fig. 10, several materials in different proportions were used in the construction phase of the eight stadiums. Concrete has the largest amount in weight (4.06×10^9 kg) and has the largest carbon emission (3.87×10^5 tCO_2-eq), followed by metal, reinforced steel, and steel. Notably, although recycled concrete has large weight, the associated carbon emission is low. According to a previous study (Guggemos & Horvath, 2005), due to the longer installation procedure, transportation, equipment usage, and higher mass of concrete-frame structures, concrete has higher indirect energy use and emissions during construction phase. Considering the data per stadium, it can be concluded that some materials have a large weight, but their carbon emission is low. For instance, in the Al-Thumama stadium, there was 3.14×10^8 kg of concrete and a corresponding 3.79×10^4 tCO_2-eq, whereas plastic with a lower amount of 2.76×10^6 kg resulted in a higher carbon emission of 8.16×10^4 tCO_2-eq. This observation shows that materials with high emissions should be



(a)



(b)

Fig. 7. Percentage contribution of GHG emissions during construction and operation phases for (a) all stadiums and (b) each stadium.

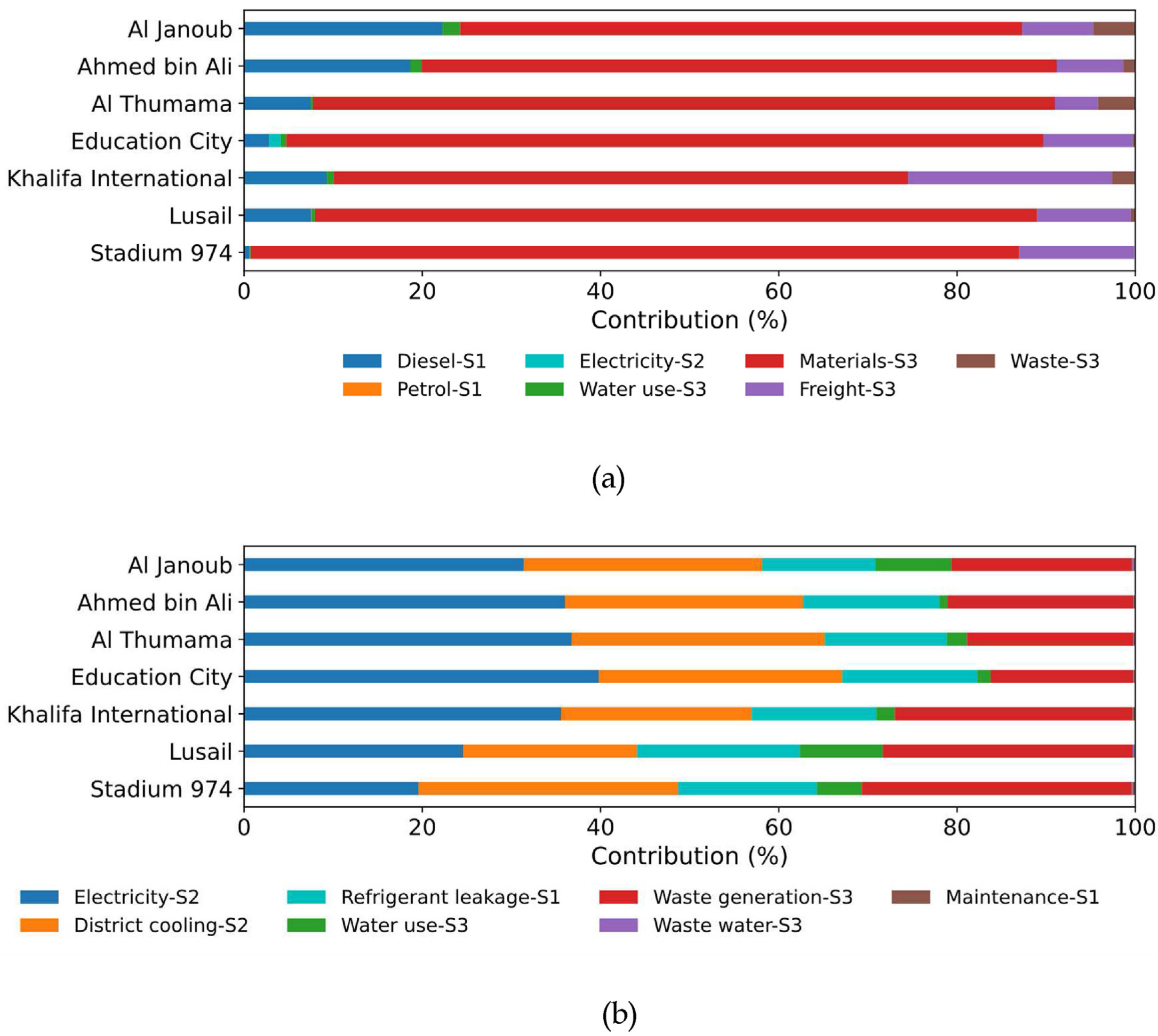


Fig. 8. Carbon footprint composition of each stadium. (a) Construction phase. (b) Operation phase.

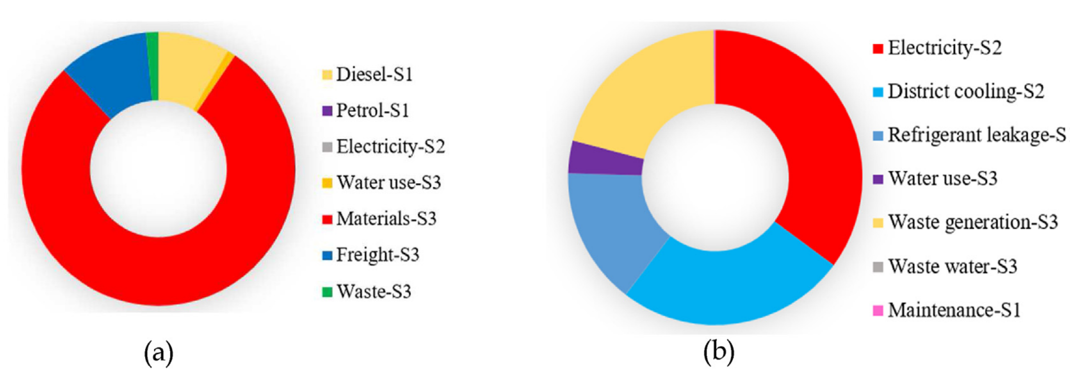
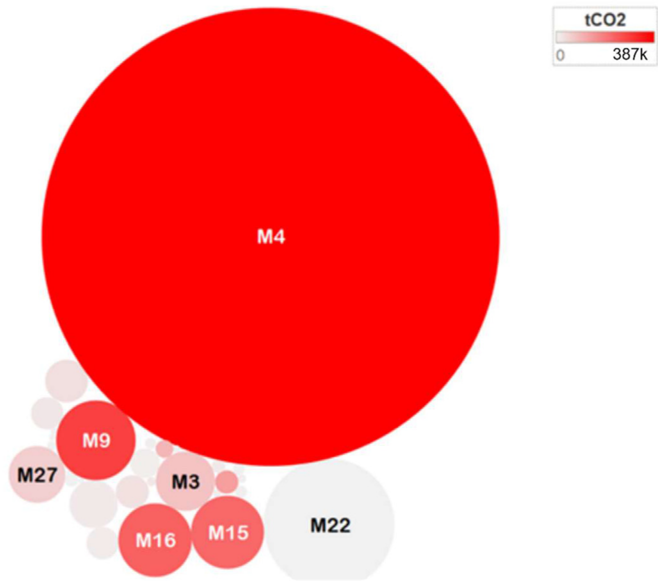


Fig. 9. Carbon footprint composition during (a) construction phase and (b) operation phase.

considered even if their weight is low. Fig. 11 shows the amounts of materials used compared with their tCO_2-eq for each stadium. Based on these findings, it is vital to consider the lifecycle impact of materials used in construction phase, starting from the design phase by using components and materials that can be enhanced and reused. Due to the fact that concrete accounts for enormous carbon emissions, Qatar considered using a lower amount of concrete (Kucukvar et al., 2021).

In operation phase, electricity use should be the focus as it has a high contribution to the total carbon footprint of the stadiums.



M1	Aluminium	M11 Paint	M21 Aluminium, recycled	M31 Plastic, recycled
M2	Bitumen	M12 Plaster	M22 Concrete, recycled	M32 Resin, recycled
M3	Ceramics	M13 Plastic	M23 Fabric, recycled	M33 Reinforcing steel, recycled
M4	Concrete	M14 Resin	M24 Glass, recycled	M34 Steel, recycled
M5	Fabric	M15 Steel	M25 Gypsum, recycled	M35 Stone, recycled
M6	Glass	M16 Reinforcing steel	M26 Insulation, recycled	M36 Vinyl, recycled
M7	Gypsum	M17 Stone	M27 Metal, recycled	M37 Wood, recycled
M8	Insulation	M18 Vinyl	M28 Other, recycled	
M9	Metal	M19 Wood	M29 Paint, recycled	
M10	Other	M20 Water network	M30 Plaster, recycled	

Fig. 10. Weight and carbon emission of materials used in all stadiums.

Fig. 12 shows the electricity carbon footprint contribution per stadium. The Al Bayt stadium has the biggest carbon footprint contribution. A crucial reason for the high amount of GHG emissions is the large amount of fossil fuels used for electricity generation. It may be useful to consider its end-of-use stage shares while making developing emission-reduction plans (Onat et al., 2014). In Qatar, the largest contribution of GHG emissions is from electricity generation. Electricity and heat generation contributes 53.65 million tons of GHG emissions (Ritchie & Rosr, 2020). This refers to the emission associated with the burning of fossil fuels for electricity generation and space heating. As space heating does not apply to Qatar, 53.65 million tons of GHG emissions are completely associated with electricity generation. Therefore, Qatar's GHG reduction strategies should focus on energy conservation. Energy conservation here refers to the conservation of electricity and water because Qatar and other Gulf Cooperation Council countries use co-generation plants to generate electricity and water (Dawoud, 2012).

It is important to understand the emissions for each stadium per area and person. As listed in Table 1, the total area of the stadiums is 1.08×10^6 m^2, and their combined seating capacity is 3.80×10^5 m^2. As the total carbon footprint in operation phase is 5.08×10^4 tCO_2-eq, the carbon footprint per seat is 1.79×10^4 tCO_2-eq. The total carbon footprint for each stadium per square meter and person were calculated, and the results are shown in Fig. 13. It can be seen that Al Bayt stadium had the highest carbon footprint per person, followed by the Education City stadium, and the Al Janoub stadium had the highest carbon footprint per square meter.

5. Strategies for sustainable mega events and circular model

The results of this study have shown the importance of using an innovative approach to reduce the carbon footprint of mega events, such as the WC. In this context, a paradigm shift from a linear type of economy to a circular model or technique for end-of-life material recycling can support the transition toward sustainable carbon-neutral mega events (Geissdoerfer et al., 2017). To reduce emissions in the construction phase, it is important to carefully select low-impact construction materials. In this regard, the following should be accomplished: The development of optimum strategies for selecting materials and techniques; the optimization and development of sustainable or low-carbon and energy-efficient novel construction materials (e.g., low-carbon cement, lumber, straw, and compressed earth, all of which have smaller carbon footprints, are viable options); the monitoring of energy utilization during the building process; performance management beginning with the design phase. To reduce Scope 2 emissions, it is strongly suggested that the usage of on-site renewable energy be increased and stadium energy performance be optimized. Qatar's GHG reduction efforts should focus on energy conservation, including power and water conservation (Al-Thawadi & Al-Ghamdi, 2019). In addition, using renewable materials in food packaging will help reduce the impact during the operation phase of the stadiums (Abdella et al., 2020). Furthermore, as an end-of-life management method, wastewater from the stadiums during mega events can be purified and used in district cooling facilities and perhaps for

M1	Aluminium	M11 Paint	M21 Aluminium, recycled	M31 Plastic, recycled
M2	Bitumen	M12 Plaster	M22 Concrete, recycled	M32 Resin, recycled
M3	Ceramics	M13 Plastic	M23 Fabric, recycled	M33 Reinforcing steel, recycled
M4	Concrete	M14 Resin	M24 Glass, recycled	M34 Steel, recycled
M5	Fabric	M15 Steel	M25 Gypsum, recycled	M35 Stone, recycled
M6	Glass	M16 Reinforcing steel	M26 Insulation, recycled	M36 Vinyl, recycled
M7	Gypsum	M17 Stone	M27 Metal, recycled	M37 Wood, recycled
M8	Insulation	M18 Vinyl	M28 Other, recycled	
M9	Metal	M19 Wood	M29 Paint, recycled	
M10	Other	M20 Water network	M30 Plaster, recycled	

Fig. 11. Weight and carbon emission of materials used in each stadium.

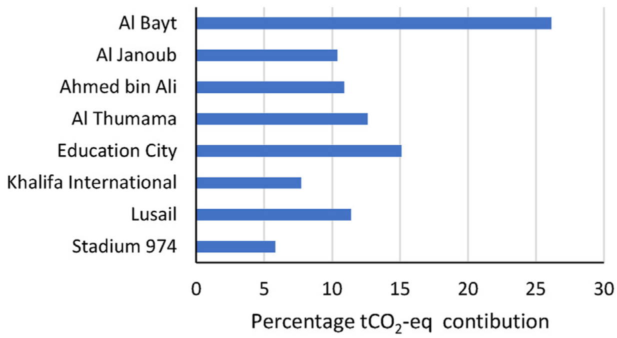


Fig. 12. Electricity carbon footprint contribution per stadium.

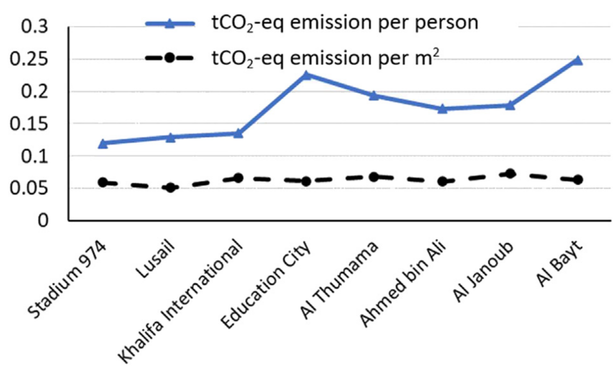


Fig. 13. Total emissions per square meter and person for the operation phase.

irrigation purposes inside the country. This guarantees that current resources are used effectively to assist FIFA's zero-waste objectives. It is important to develop a waste management strategy in stadiums. A host country should implement a program for collecting recyclable materials, food waste, and reusable things in the stadiums.

The implementation of CE is an effective strategy for achieving sustainability in mega events. Compared with traditional stadium construction methods, the use of a circular strategy in demountable stadium construction has yielded benefits by lowering the environmental load. One good example of the implementation of CE in the construction phase is the use of recycled concrete aggregates, which are created by reprocessing materials already used for construction such as sand and crushed stones. The use of such recycled materials significantly reduces the carbon footprint in a cost-effective and eco-friendly manner. Recycled aggregates can be used for bulk fills during road construction without compromising the quality. Moreover, this strategy substantially reduces the amount of landfill that may arise during construction phase. One more strategy that could be applied in the construction of stadiums is to use special paint for thermal insulation (such as nano paint), which reduces a significant amount of wastage during the implementation of a legacy plan. The post-tournament asset distribution program such as sharing shipping containers and stadium grounds and donating stadium seats to other countries contributes to the CE. The supreme committee guaranteed that assets purchased for the tournament were used afterwards. Such research can help us understand the contribution of CE practices in lowering Scope 3 emissions during a mega event.

Another CE practice that can help achieve carbon neutrality for a host country is implementing carpooling, which is the sharing of cars or other vehicles. This will help reduce the reliance on fossil fuels, resulting in a significant reduction in carbon emissions. In addition, it is recommended to create a bicycle path connecting cities so that people can use bicycles to travel to and from event venues. By providing bicycle-sharing facilities, more people can use these facilities, reducing pollution and carbon emissions in the long run. These facilities must be provided in more accessible areas in the host country to help travelers reach their destinations. Moreover, another important strategy for the carbon neutrality of the built environment, including stadiums, is the implementation of effective rehabilitation and retrofitting strategies. Advanced composites such as fiber-reinforced polymers (Naser et al., 2019; Teng et al., 2012), fabric-reinforced cementitious matrix (Awani et al., 2017), and steel-reinforced grout (Kennedy-Kuiper et al., 2022; Wakjira & Ebead, 2019) are among the effective repair and retrofitting materials reported in public literature.

It is worth mentioning here that increased awareness among the public is an important factor that should be considered in the sustainability plan. There should be awareness and training for people who are working in several sectors related to the country so that this will help in building local expertise in thinking and dealing with sustainable development in various sectors. The importance of the outcomes emphasized in this study stems from the commitment of Qatar to integrated construction and pioneering stadium designs that enable a carbon-neutral mega event, which is an important part of FIFA's sustainability strategy.

6. Conclusion and future recommendations

This is the first study to calculate the carbon footprint of FIFA WC stadiums using the accounting standards of WRI, with a focus on the stadiums in Qatar constructed for FIFA WC 2022. This study assessed CO_2 emissions during both the construction phase and the operation phase, and outlines the potential implementation of CE in achieving carbon-neutral mega events. The CO_2 emission was calculated using Ecoinvent V3.7.1 by multiplying the quantity of each contributor by the emission factor. The results of the carbon footprint study provide a valuable vision that can direct executives on what to focus on in order to lower the carbon footprint of stadiums.

Such a study can help establish efficient green building rating techniques (such as Global Sustainability Assessment System) that consider the carbon emission of stadiums (direct and indirect supply chain). The analytical results show that the construction phase (98% GHG emissions) is more dominating than the operation phase. According to the findings in this study, Scope 3 emissions had the greatest carbon impact throughout the construction period, whereas overall, Scope 2 emissions had the greatest carbon impact during the operation phase. These results also demonstrate that the top carbon footprint contributors of the stadiums are electricity usage (35%), district cooling (25%), and waste generation (21%). This study has demonstrated the need for the implementation of effective approaches and strategies to mitigate the impact of mega events on the environment. Future studies are recommended to assess the economic, environmental, and social aspects of stadiums and investigate the complete lifecycle (from construction to end-users). Therefore, we recommend applying a hybrid lifecycle sustainability assessment model to estimate the environmental, economic, and social impacts of CE strategies in the construction, operation, and end-of-life phases.

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.

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