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Qatar 2022: Facing the FIFA World Cup climatic and legacy challenges

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Abstract

The 2022 World Cup creates great opportunities for the country of Qatar, but also poses significant challenges. In this study the main challenge of maintaining thermal comfort conditions within the football arenas is presented, with respect to the heat stress index (HSI) and the aero-thermal comfort thresholds established for opened stadiums. Potential cooling strategies for delivering tolerant comfort levels are introduced, followed by their functional strengths and limitations for the hot-humid climate of Qatar. An estimation of the cooling load for semi-outdoor stadiums in Qatar is also presented. The results, produced by dynamic thermal modelling, indicated that a load of 115 MW h per game should be at least consumed in order to provide both indoor and outdoor thermal comfort conditions. Finally, the use of solar energy technologies for the generation of electricity and cooling are evaluated, based on their viability beyond the 2022 World Cup event, towards the nation’s targets for sustainability and lasting legacy.

Highlights:

- Provision of aero-thermal comfort conditions within the sport facilities.
- Higher efficiency of solar sorption systems in hot-humid climates.
- An estimated cooling load of about 115 MW h per game is required.
- Balancing techniques to meet carbon neutrality commitment.
- Forthcoming local and national community benefits.

Keywords: Dynamic thermal modelling; Stadiums; Thermal comfort

1 Introduction

Sport is a dynamically growing sector that may successfully contribute to economic development and profile enhancement of the corresponding host county, through various channels [1]. Sport mega-event organisations may operate for the benefit of international development, strengthening of urban infrastructure construction and services, with regard to sustaining prosperity [2].

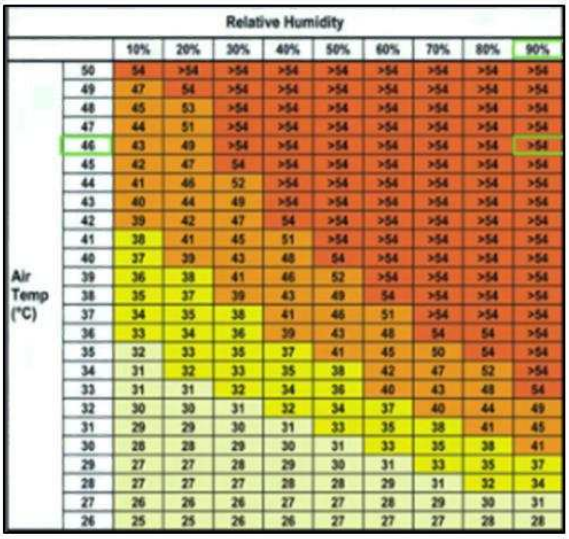
Qatar, the FIFA's World Cup 2022 host city, aims to achieve these targets, as part of the country's long-term aspirations, based on the four Pillars of the Qatar National Vision 2030 [3]. The nation plans the implementation of social, economic, human and environmental strategies that will ensure the provision of adequate reserves for future generations, via development [3]. The World Cup will be a significant milestone on this journey, since it will be the first Middle Eastern country hosting this important sporting event [4]. The winning bid, nevertheless, demands from the host county to accelerate the enactment, as well as the implementation of its plans, as far as the research and the constructional segment of the event are concerned.

Awareness of the successful and on time event's delivery has been expressed, due to the limited existing infrastructure and the large conceptual design ideas that have been revealed. Although Qatar has gained recognition for its ability to host large scale events, regarding previous events, such as the FIFA U-20 Football Cup 1995 [5], XV Asian Games 2006 and AFC Asian Cup 2011, concerns have been raised in the media, surrounding the effective implementation of the proposed events, due to its prominent climatic characteristics. The Qatar Football Association (QFA) has committed to deliver, within FIFA's technical requirements, conditions that will satisfy both the player and user thermal comfort criteria, by developing cooling technologies classified as environmental friendly, thus promoting sustainability [6].

The present study focuses on the various challenges that Qatar will confront, particularly related to the provision of comfort conditions in hosting areas, using pioneering environmentally friendly cooling technologies. The holistic approach of the spatial and temporal characteristics is presented, followed by analytical scientifically based interpretations concerning the attainment of aero-thermal comfort with technologies that are to be implemented within the context of the requirements that FIFA has set and the commitments that Qatar has made. A preliminary assessment of the cooling load requirements during the event is also presented, produced by dynamic thermal modelling software. The importance of the results will give an overview of the energy load that needs to be either produced from renewable sources or balanced from the national electrical grid as Qatar has committed to deliver a carbon neutral World Cup and a legacy based on sustainable development principles.

2 Climate

Qatar experiences living conditions under a temperature range of 25-46^{o}C during the summer season [7] that if combined with a relative humidity of up to 100%, can create a sensation of temperature more than 50^{o}C [8]. These temperatures greatly exceed the exposure threshold of National Oceanic and Atmospheric Administration's (NOAA) heat stress index, as depicted in Fig. 1. Temperature values of such intensity are extremely dangerous and may cause heat illnesses to people that have prolonged exposure to direct sunlight [9].



		Relative Humidity								
		10%	20%	30%	40%	50%	60%	70%	80%	90%
Air Temp (°C)	50	54	>54	>54	>54	>54	>54	>54	>54	>54
	49	47	54	>54	>54	>54	>54	>54	>54	>54
	48	45	53	>54	>54	>54	>54	>54	>54	>54
	47	44	51	>54	>54	>54	>54	>54	>54	>54
	46	43	49	>54	>54	>54	>54	>54	>54	>54
	45	42	47	54	>54	>54	>54	>54	>54	>54
	44	41	46	52	>54	>54	>54	>54	>54	>54
	43	40	44	49	>54	>54	>54	>54	>54	>54
	42	39	42	47	54	>54	>54	>54	>54	>54
	41	38	41	45	51	>54	>54	>54	>54	>54
	40	37	39	43	48	54	>54	>54	>54	>54
	39	36	38	41	46	52	>54	>54	>54	>54
	38	35	37	39	43	49	54	>54	>54	>54
	37	34	35	38	41	46	51	>54	>54	>54
	36	33	34	36	39	43	48	54	54	>54
	35	32	33	35	37	41	45	50	54	>54
	34	31	32	33	35	38	42	47	52	>54
	33	31	31	32	34	36	40	43	48	54
	32	30	30	31	32	34	37	40	44	49
	31	29	29	30	31	33	35	38	41	45
	30	28	28	29	30	31	33	35	38	41
	29	27	27	28	29	30	31	33	35	37
	28	27	27	27	28	28	29	31	32	34
	27	26	26	26	27	27	28	29	30	31
	26	25	25	26	26	27	27	27	28	28

Fig. 1 Heat index chart [9].

In an event with an extended duration, such as the World Cup, visitors will be exposed involuntary to the extreme and unprecedented (for some) temperatures [10]. However, if adequate mitigating measures, including shading and rehydration are provided, occupants can show a certain tolerance to the adverse environmental conditions prevailing in hot climates [11], [12].

The situation is considered to be more complicated when assessing the heat stress risk regarding the football players. Experimental studies have shown that the probability of placing player’s integrity into danger is extremely high, when exercising in hot climates, because their core temperature may be increased up to 41.5^{o}C [13]. Under harsh playing conditions, not only their thermoregulatory response is disrupted, but also their exercise performance is compromised [10], [14].

Heat stress conditions of such extent have been recorded in previous World Cup venues organised in semi-hot regions, where midday kick-off times were rearranged, due to possible imminent heat risks [15], [16]. Similarly, the combination of heat stress and strain exercise was proven to be a dominating factor in players performance disruption during the 2006 World Cup held in Germany, with the temperature attaining just 30 degrees Celsius [17], [18].

Vigorous exercise of more than 30 min, to which players will be exposed, is of concern to the QFA, in order to devise strategies that will prevent hyperthermia and dehydration; two effects that will be compounded by the thermal environment [10], [19]. The commonly suggested measure to prevent the heat-induced effects is acclimatization that should include at least 100 min of high interval exercise [19]. World Cup teams are given 4 weeks prior to the event, in order to be prepared, but even then, they will be disadvantaged compared to the already weather-familiarised local teams [10]. As far as the players comfort levels are concerned, there are no established and widely approved method that can assess their tolerance, since it is a multidimensional process dependant on the personal physical and physiological response rate to the prevailing weather conditions [19].

The preservation of visitors’ comfort levels, who will not have enough time to allow for acclimatization, is going to be achieved by the integration of environmental friendly cooling technologies in all event-related facilities. These include stadiums, training sites and fan zones, which must offer comfortable ambient environment for all occupants [6]. However, these purpose built technologies have to be fully developed and consequently, their efficiency to be validated for the areas of interest. Irrespective of the mode of implementation, the resulting characteristics of the developed designs and microclimate should adhere to specific requirements in order to be approved by the International Federation of Association Football (FIFA).

3 Technical requirements for stadiums

The construction promise of delivering 12 football stadiums, three of which will undergo large-scale renovations, has set a bottom-up budgeting of USD 3 billion [6]. On the other hand, the revealed futuristic stadium designs seem to boost the budget's bottom line even further [20] that in combination with the controversial future social-related incorporation, has led to speculation that the World Cup will be conducted within 8 stadiums in total [20], [21]. Nevertheless, the decisive number of the football arenas is independent of the predefined conditions within the sport facilities. The stadium configuration is the most critical, since it has to combine various independent aspects, in the same design approach, producing a functional result. The awareness of FIFA, as an event owner, to maintain a high level profile, is reflected in the technical recommendations and requirements within the sport facilities that will ensure the favourable conditions for all occupants.

According to FIFA's official technical guide [22], the microclimate should be expected to provide the optimum comfort levels that, in point of fact, fluctuate depending on occupant's activity [23], [24]. In other words, spectators do not have the same comfort limits compared to the intensively exercised players. For this reason, FIFA requires a temperature range of 20-25.5^{o}C in all hospitality areas of the stadium [22]. This temperature barrier applies for all the areas within a sport facility, including the interior enclosed spaces, the spectator tiers, as well as the playing field. The generic stadium aero-thermal comfort thresholds for spectators are based on the revised bioclimatic chart [25] and are illustrated in Fig. 2.

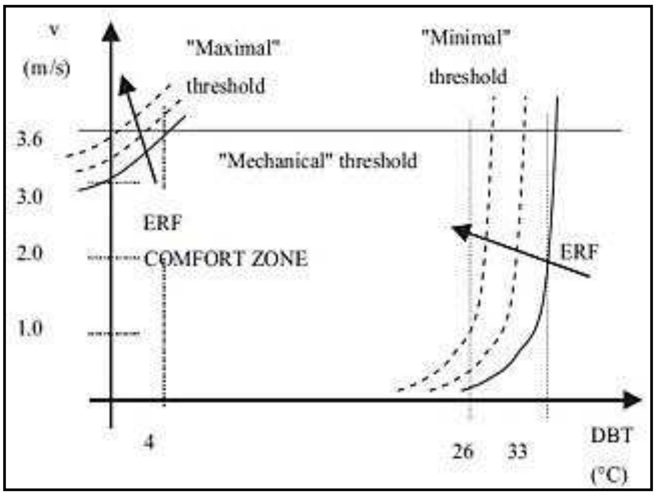


Fig. 2 Comfort zone with flexible outlines [25].

The chart is representative of the comfort thresholds set for spectators in open stadia and it incorporates four dominant climatic parameters; the air temperature, air speed, humidity and solar radiation (see Ref. [25], [26] for further details). When stadium configuration and outdoor environmental conditions do not allow the natural air distribution (within the temperature thresholds) to be implemented, moderate microclimate conditions should be produced, by passive or active cooling techniques [22].

3.1 Aero-thermal comfort master plans

The Qatari stadium design showcase discloses oculus roof configurations for the majority of the football arenas. Based on experimental wind tunnel tests, such a central opening is preferable in cooler climates, since it acts as a protector, attenuating the intense airflow beyond the playing field [27]. However, when combined with a peripheral continuous opening between the roof and the upper spectator terrace, leads to increase of local ventilation rates for the benefit of users in warm climates [26]. A football arena that takes advantage of the aforementioned oculus design features is the Stade de France. Its oculus configuration was assessed under summer weather conditions [28] and the resultant thermal regions of both comfort and discomfort are depicted in Fig. 3.

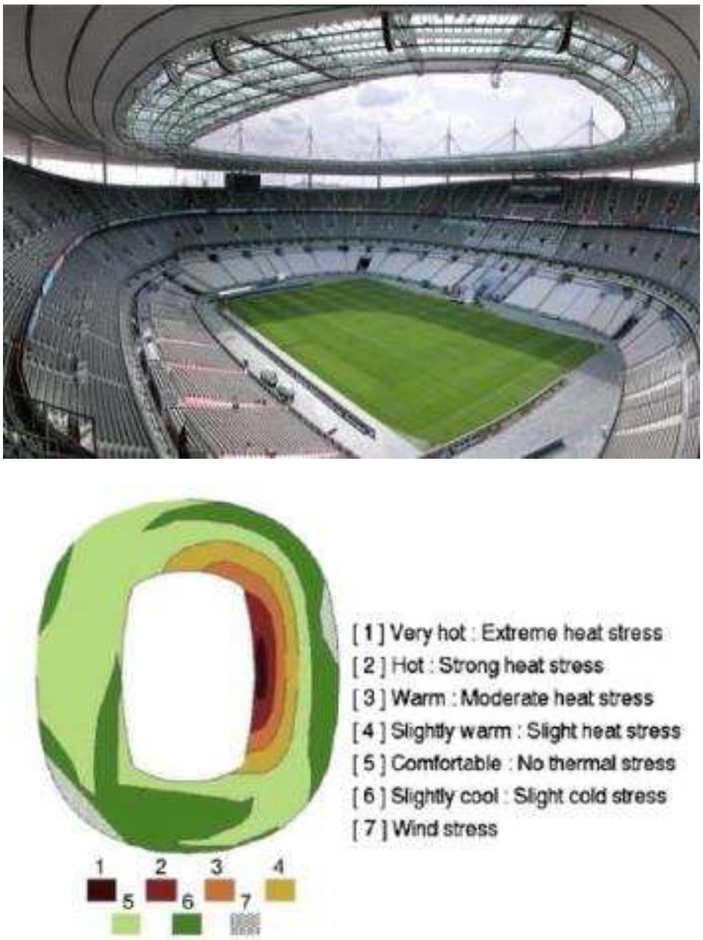


Fig. 3 Roof configuration of Stade de France (top) [29] and the thermal sensation map of the Stade de France (bottom) [28].

Despite the natural ventilation and the shading shelter actions that these design configurations may offer [30], some areas remain exposed to direct sunlight, due to the pitch's orientation requirements [22].

3.2 Evaporative cooling strategies

Evaporative cooling techniques could be used in addition to the partial control of the air movement and solar radiation by structural configurations, since they are considered to be effective strategies for moderating climatic factors in desert climates [31]. Middle Eastern countries traditionally use passive cooling techniques, known as the ‘badgir’ wind tower, to deliver interior cool air, usually by creating an air route over a wetted mat or a pool of water [32]. Tangram Gulf Associates, presented a stadium configuration (Fig. 4) based on this technique that takes advantage of the Venturi effect to supply tolerant air temperatures under spectators’ tiers and to the stadium bowl [33]. However, there is little evidence on whether it is functional and if it can successfully deliver thermal comfort within the required thresholds.

Fig. 4 Evaporative cooling technique suggestion for 2022 World Cup stadiums [33].

3.2.1 Down-draft evaporative cooling tower

Down-draft evaporative cooling towers (Fig. 5) are recognised as an economic method, if not the only one, to reduce ambient temperatures up to 10^{o}C in semi-outdoor spaces [34]. Their integration in a stadium, nevertheless, should be considered at an early design phase, due to their space requirements for installation.

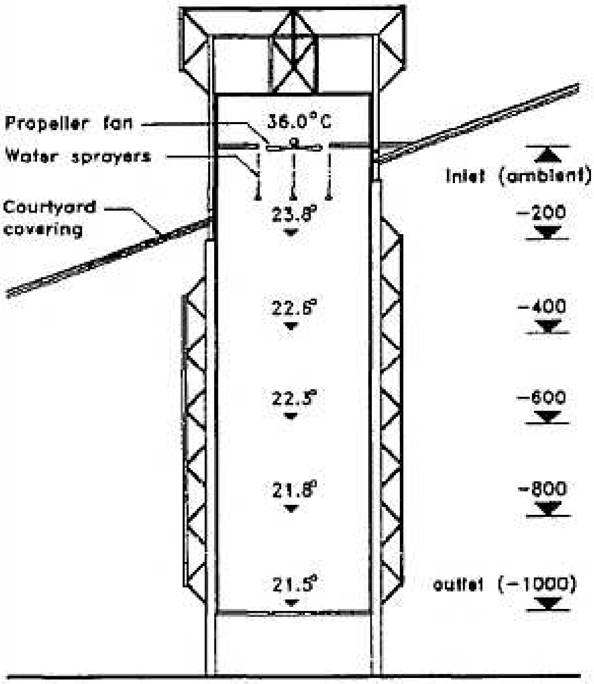


Fig. 5 Schematic section of evaporative cooling tower, showing installation in glazed courtyard and typical temperature profile during summer daytime operation [32].

3.2.2 Evaporative mist-cooling system

Evaporative cooling misting fans are already considered to be part of QFA’s intervention strategies for thermoregulatory stress prevention, in favour of football players [6]. Installation in playing fields and training sites is deemed necessary and applicable, since they are direct active cooling technologies that may reduce instantly the core temperature, protecting players’ performance and health [10]. Although this cooling strategy appears to be temporally and locally functional, its water intensity should not be overlooked [35], especially in a country like Qatar where more than 50% of water resources arise from energy-demanding desalination processes [36].

3.3 Solar cooling strategies

Solar-powered cooling technologies are the most likely and objectively applicable to be used in Qatari stadiums, since they can effectively produce low level air temperatures, in an energy-efficient way [37]. They are already developed technologies combining cooling techniques with an alternative power source. Examples of solar cooling systems applicable in stadium construction are presented in the following section.

3.3.1 Photovoltaic solar cooling

Solar cooling systems use photovoltaic panels to produce electricity, subsequently used to power a refrigerated system. Depending on the manufacturing material of the cell, the electricity conversion efficiency may vary from 10% to 15% [37]. The main disadvantage is that for every 1^{o}C increase over 25^{o}C, their performance is reduced for about 0.25-0.45% [38], due to the magnitude of the emitted heat. Summer temperatures in Qatar have an average value of 33.4^{o}C entailing a reduction in performance that cannot be overlooked.

3.3.2 Solar sorption cooling

Solar sorption cooling systems are heat-driven closed or opened-loop techniques that take advantage of the thermal energy collected from solar thermal panels. Depending on the type of the sorbent, closed sorption systems are classified as absorption and adsorption cooling cycles [39]. Two basic phases dominate their operation function; the condensation and evaporation of the refrigerant, as depicted in Fig. 6.

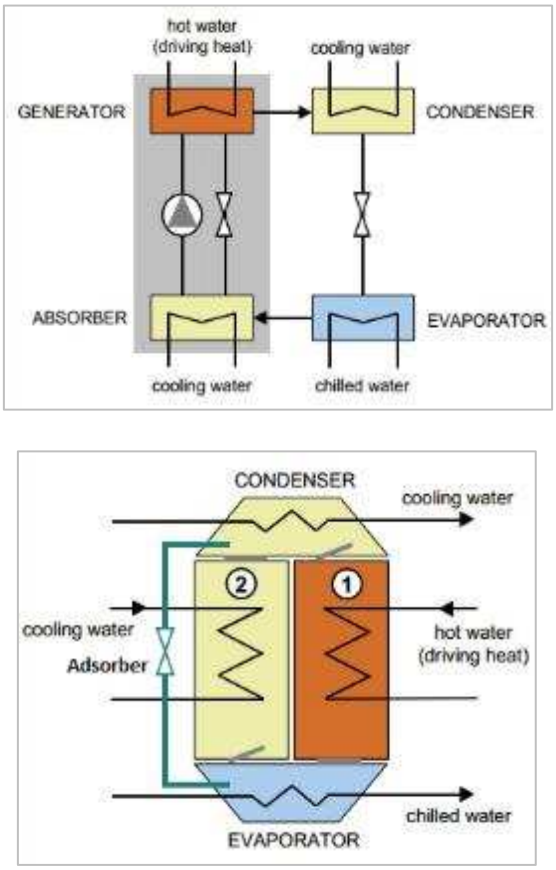


Fig. 6 Principle of an absorption (top) and adsorption chiller (bottom) [40].

The chilled water produced, after the evaporation phase, is used by air-handling units to supply the space with air of low temperature. With average thermal efficiencies of 0.7 (for single effect) or up to 1.4 (for double-effect machines) and 0.6, for absorption and adsorption systems respectively [40], their utilisation is recommended for hot and humid climates, as opposed to evaporative cooling systems whose performance may be attenuated above wet bulb temperature of 25^{o}C, due to the already moisturised air [41].

In the case of open-loop systems, there is not an active feedback load. In other words, the waste heat is rejected back to ambient. Their operation is based on air dehumidification using desiccants [42], as illustrated in Fig. 7. With an operative performance of 0.6, desiccant systems can successfully deliver cool air, with smaller driving temperatures than the closed-loop sorption systems [42].

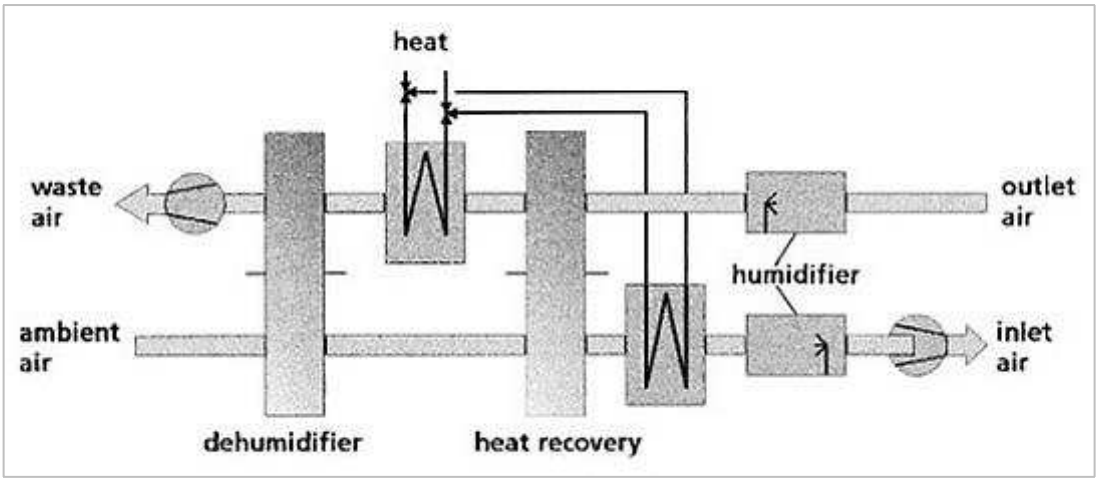


Fig. 7 Principle of a ventilation desiccant cooling system [42].

However, the combination of more than one of the previously mentioned solar sorption cooling technologies may contribute to an increase in the system's overall performance, providing lower air temperature values, in favour of energy and cost efficiency [44]. The potential of successfully operating a combined system of absorption and desiccant cooling cycle in hot-humid climates has been evaluated for enclosed spaces. With an overall coefficient of performance (COP) value equal to 1.55, this system can supply air temperatures of 23^{o}C, when the outdoor reaches 42^{o}C [44].

While there is adequate knowledge on the operation of these technologies, there is a lack of validation in open stadium design configurations in hot-humid climates. The adoption of an energy efficient and operative cooling system is of paramount importance, as it will act as a catalyst in environment improvement for the arena.

4 Stadium proposal

4.1 Description of design and technologies

Initial efforts at achieving thermal comfort conditions with zero carbon emissions were performed by Arup Associates in 2010, involving the design and construction of a small scale stadium of 500 seats (Fig. 8). The achievement of delivering a stadium facility with thermal comfort conditions of 23^{o}C, when the outdoor temperature had reached 45^{o}C, with zero-carbon emissions in total and entirely exposed to the weather conditions (open roof), was unprecedented [45].

Fig. 8 Proposed stadium top view (top) [46] and inside perspective view (bottom) [47].

In practice, arrays of solar thermal collectors are used to increase water temperature to 200°C. The heated water is stored in a tank, constituting the heat supplier for the cooling cycle that comprises of absorption chillers and cooling desiccants (see Ref. [45], [46] for further details). The combination of these two cooling systems was not randomly selected, since it has already proven its cost-efficiency and high performance in humid and warm climate operations [43]. The cooling load produced is then stored in eutectic tanks and when needed is supplied by air handling units into the stadium, developing thermal comfort conditions for users.

4.2 Aero-themal comfort provision mechanism

During the cooling process of the stadium, the low temperature air is delivered by localised under-seat air systems that circulate the clean cool air within the stadium bowl. The maintenance of the required temperature levels is achieved by the optimised material selection and geometric configuration that prevent the external hot air to penetrate, or be transferred via convection or conduction, and promote the spontaneous air recirculation, respectively.

The under-seat cooling strategy permits the direct thermal comfort delivery to spectators, improving instantly their surrounding environmental conditions. The strategy is also less energy intensive compared to an over-head cooling system, as it has been proven, by CFD simulations, for a large scale, semi-opened football arena in Middle East [12].

4.3 Design restrictions

The 500-seat stadium requires the cooling process to be undertaken 4 days before the starting day of the event [46]. The corresponding period of time for a large scale stadium would be significantly prolonged and the entire process more energy intensive. However, engineers show little concern over scale discrepancies, since the alternative option of using oil instead of water has already been considered, in order to bring the temperature in the storage tank to up to 200°C [48].

On the other hand, the uncertainty of stadium's response to windy weather needs to be further evaluated [48]. The counteraction of the buoyancy effect, when strong wind patterns prevail, tends to attenuate the cooling system performance. Restrictions on the spontaneous airflow are imposed by the creation of a primary vortex, naturally formed in centre of the bowl, in stadium configurations with enclosed perimeter, as has been proved by computational fluid dynamic (CFD) simulations (Fig. 9) [49].

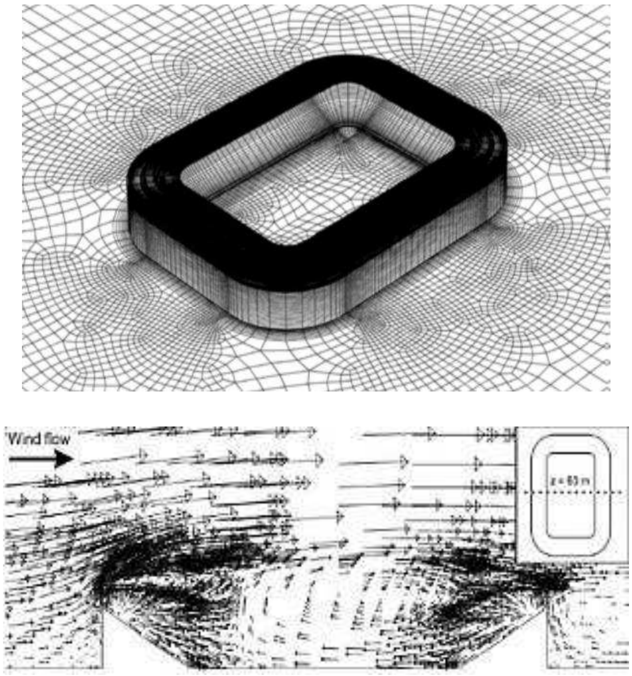


Fig. 9 Analysis grid of an enclosed stadium (top) and its vertical cross-section of the wind-flow pattern (bottom) [49].

Finally, a basic precondition for the implementation of such a cooling strategy is the consideration of a retractable roof in the stadiums design, in order to create the favourable conditions that during full occupancy will satisfy the majority of users. However, this does not conform to the submitted bidding designs that unveiled oculus roof configurations. For this reason, despite acknowledging the developed technology, the feasibility and effectiveness of the system, remain uncertain.

5 Estimation of energy consumption for cooling

5.1 Introduction

The absence of a real scale stadium in Qatar, integrated with cooling technologies, makes the experimental evaluation studies on the cooling load consumption requirements uncertain. However, accurate energy performance assessment studies on the early design phase are of major importance when aiming for sustainable or zero-carbon building structures [50]. For the purpose of this, building information modelling (BIM) coupled with building performance simulation (BPS) tools are commonly used for the prediction of buildings' thermal and energy behaviour under a plethora of user-defined criteria [51], [52]. The current study aims to investigate the cooling load requirements for a semi-open stadium configuration in the country of Qatar, adopting dynamic thermal simulation techniques, combined with BIM tools of high interoperability for the design of the model. The investigation study includes the simulation of physical, structural and operational parameters, providing an overview of stadium's energy performance, hoping to assist the decision-making process.

5.2 Description of the case study

5.2.1 Stadium description

The studied stadium structure was modelled in Autodesk Revit design interface and it represents a simplified version of a benchmark arena design that is widely used in literature studies [53], [54], [55], [56]; the Amsterdam Stadium, with a seating capacity of 50,000. The stadium's external dimensions of length x width x height are equal to 226 m x 190 m x 72 m respectively (Fig. 10a and b). It consists of two spectator terraces on the longitudinal direction of stadium's perimeter (Fig. 10c) and the oculus roof configuration with an area of 4400m^2 represents the only opening that was created for the current thermal analysis.

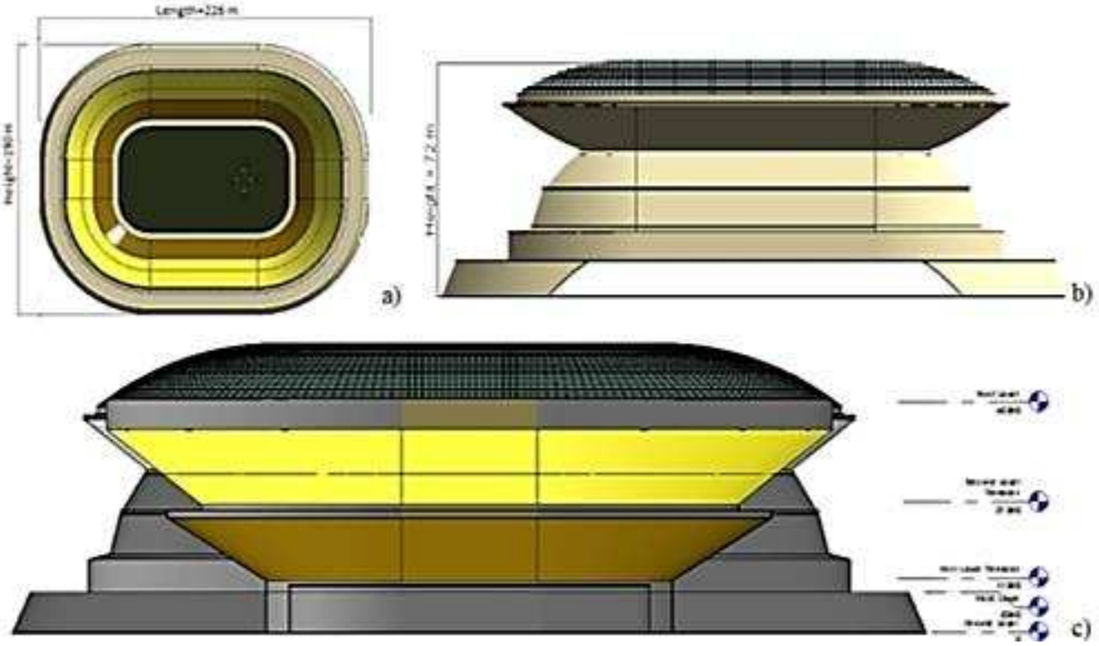


Fig. 10 (a) Top view of the stadium bowl, (b) external side view of the stadium and (c) cross-sectional view of the stadium.

5.2.2 Structural elements data

The stadium model was integrated with structural materials fully representative of real stadium structures. More specifically, the stadium façade consists of insulated metal sheets, the roof from translucent polycarbonate sheets to allow natural daylight penetration, the spectator terraces are concrete structures covered with PVC material to replicate the plastic seat surfaces and the floors are reinforced concrete slabs. A detailed description of the thermal materials of the construction elements are given in Table 1.

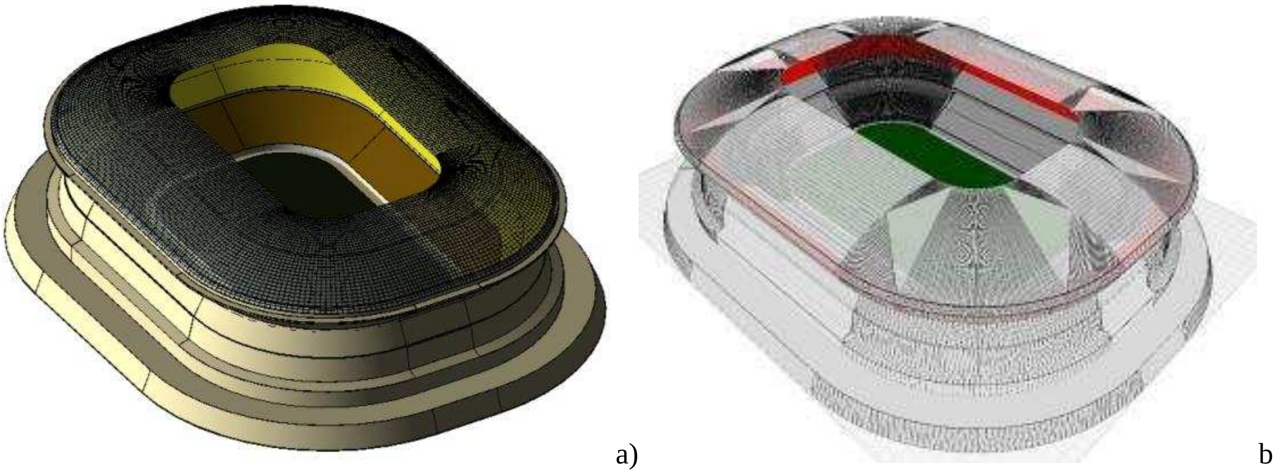
Table 1 Thermal properties of the selected structural elements that consweatist the stadium envelop.

Structural element	**Exterior walls**	**Spectator tiers**	**Roof**	**Slab**
Structural material	Insulated metal sheets	Concrete slab + plastic seat	Translucent polycarbonate sheets	Concrete slab
U-value (W/m^2 K)	0.55	3.0	2.1	0.88
Admittance (W/m^2 K)	1.0	5.2	2.0	6.0
Solar absorption (0-1)	0.5	0.77	0.6	0.467
Transmittance (0-1)	0	0	0.4	0
Total thickness (mm)	75	100	980	400

5.3 Thermal analysis parameterisation

5.3.1 Import design data

As mentioned earlier, the Autodesk Revit design software was used for the production of the stadium design. There were two main reasons that contributed to the selection of the specific software. Firstly, its fully detailed design interface enables the development of realistic models and secondly its high interoperability with the Ecotect dynamic thermal software permits the direct recognition of all structural and geometrical characteristics composing the thermal zones for the implementation of the analysis (Fig. 11).



a) b)

Fig. 11 (a) Stadium model designed in Revit software and (b) imported model to Ecotect software.

Another import precondition for the implementation of the performance simulation study was the creation of thermal zones, where the cooling systems will operate. Five thermal zones were created in total, relying on the study of Ocuncu et al. (2010) arguing that cooling mechanisms applied close to the area of interest are more effective and energy efficient than supplying with cool air the entire stadium bowl [12]. The zonal establishment was initially based on internal and external areas and subsequently on occupied levels. Table 2 presents the resultant thermal zones along with their volumes and maximum occupancy, followed by their illustration in Fig. 12 Cross-sectional view of the created thermal zones..

Table 2 Zonal division of the internal and external air conditioned areas of the stadium

Thermal zone		Description	Level	Volume (m^3)	Max. occupant number
1	**Internal**	Facility area	Ground	143,032	20,000
2		Facility area	First	57,127	10,000
3	**External**	Spectators’ tiers	Ground	75,031	25,000
4		Spectators’ tiers	First	104,881	25,000
5		Playing field	Ground	21,513	100

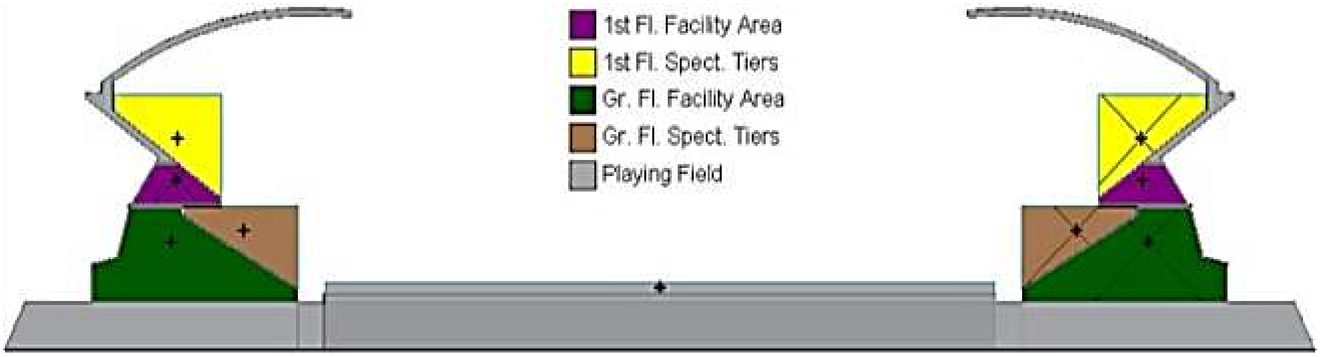
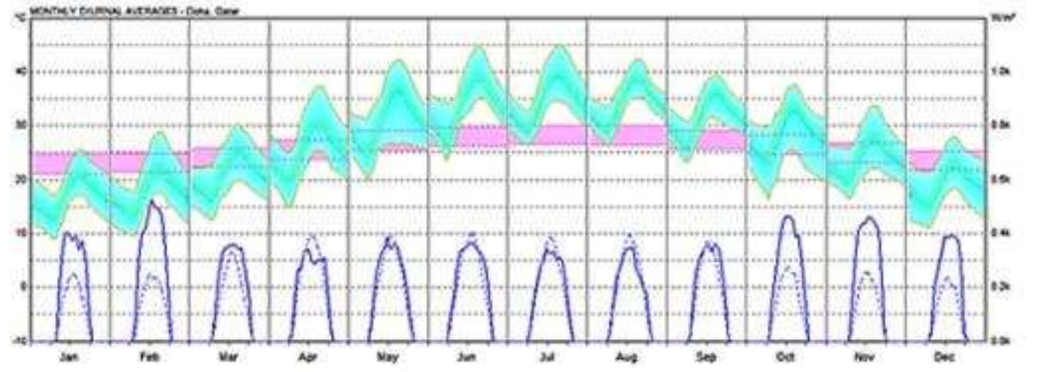
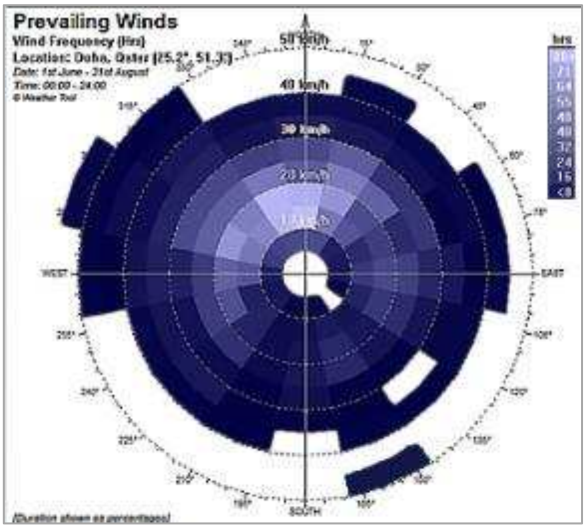


Fig. 12 Cross-sectional view of the created thermal zones.

5.3.2 Climate data

The accuracy of the analysis is strongly related to the simulation of the regional climate characteristics, in order to obtain representative results of the cooling loads requirements to maintain thermal neutrality. Thus, historic weather station data for Qatar, built-in the weather library of Ecotect software, were used. Table 3 presents an illustrative overview of the annual climatological data, with more detailed weather information on the summer months, since it is the common World Cup holding period.

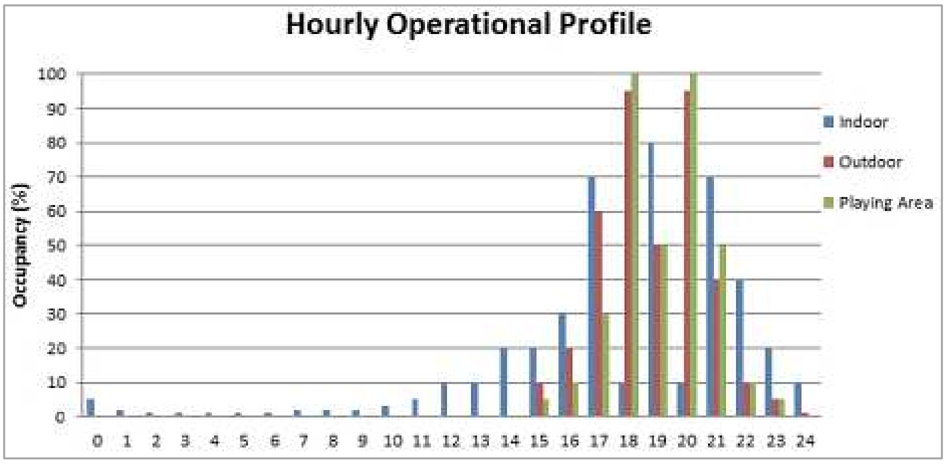
Table 3 Annual and monthly climate data for the country of Qatar, given by Ecotect weather library.

Climate characteristics	Description		
Annual data			
	Legend: ▬ Comfort Thermal Neutrality ▬ Temperature — Direct Solar		
Monthly data	**June**	**July**	**August**
Max. temperature (^oC)	41.8	43.9	41.1
Min. temperature (^oC)	23.5	26.3	26.3
Relative humidity (%)	38	45	52
Wind speed (m/s) & wind direction			

5.3.3 Thermal zone settings

The thermal performance assessment of the stadium areas requires the definition of additional characteristics for each thermal zone. These will correlate the human factor within the context of stadium's environment. The factors that affect the zonal environment and consequently the thermal comfort are associated with the internal gains, the wind sensitivity of the structure itself, the integrated cooling mechanisms and the operational schedule. The parameters were set under the following assumptions: (i) the stadium operates during summer period, (ii) FIFA's technical requirements regarding temperature, wind and lighting are fulfilled and (iii) the football games are conducted daily, during evening times, between 18:00 and 20:00. Table 4 summarises the numerical values assigned to the parameters governing the thermal analysis calculation.

Table 4 Zone management settings for the thermal analysis calculation.

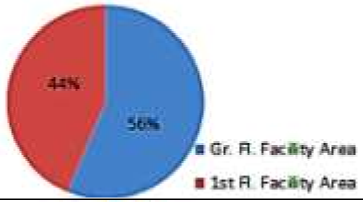
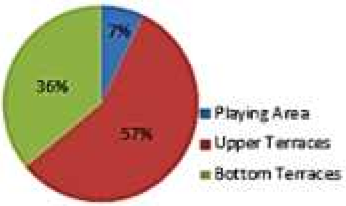
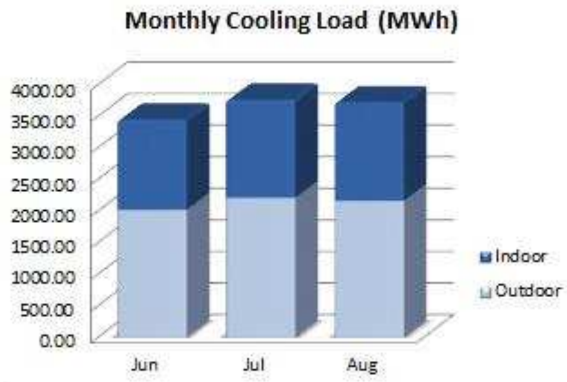
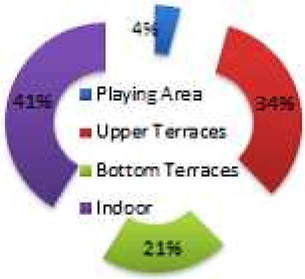
General settings	Indoor facility areas	Spectator terrace	Playing area
Clothing (clo)	0.40 (Shorts and t-shirts)		
Humidity	60%		
Air speed	0.50 m/s	0.7m/s	0.7m/s
Lighting level	600 lux [22]	Upper/lower=1500/2000 lux [22]	2100 lux [22]
Air flow rate	12 L/s/p		
Wind sensitivity	0.10 ACH	1.5 ACH	1.5 ACH
Thermal properties			
Active system (95% efficiency)	Full air conditioning	Mixed-mode (natural ventilation + cooling)	
Thermostat range	20.0– 26.0^{o}C [22]		
Hours of operation	10:00-24:00	16:00-22:00	17:00-21:00
User hourly operational profile			
			

5.4 Results and discussion

The thermal analysis generated results on the average monthly cooling load requirements per thermal zone. The results indicate that during July a cooling load of 3764 MW h or 125 MW h/day should be provided at the expense of users' thermal comfort. This value deviates over 8.4% from the cooling load requirements during June (3448 MW h or 115 MW h/day) and 1.0% during August (3726 or 124 MW h/day). Remarkable are also the values of the expended load for provision of pleasant ambient temperatures in external occupied areas. The cumulative cooling load is 31% more than the one required in indoor spaces. An analytic description of the monthly zonal cooling load requirements is presented in Table 5.

Despite the fact that the outdoor cooling mechanisms were scheduled to operate within a limited margin before and after the football game duration, the energy needs are exceptionally high. The direct interaction with the external prevailing environmental conditions, especially those related to the solar radiation and the ambient temperature are of great importance. This implies the necessity for a consciously selected conceptual design that will include an optimum stadium topology, integration with materials of high performance and cooling techniques that will be environmental friendly, delivering thermal comfort conditions and also compensating the energy intensive event.

Table 5. Monthly zonal cooling load results.

Stadium area	Thermal zone	Cooling load (MWh)			Graphic illustration
		June	**July**	**August**	
Indoor	Gr. Fl. facility area	801	877	882	
	1st Fl. facility area	623	673	676	
	Total	**1424**	**1550**	**1558**	
Outdoor	Playing area	148	158	154	
	Upper terraces	1154	1261	1232	
	Bottom terraces	724	796	782	
	Total	**2026**	**2215**	**2168**	
All thermal zones		**3448**	**3764**	**3726**	**Average daily cooling load**
					**June** **115** **In:47; Out:68 (MWh)** **July** **125** **In:51; Out:74 (MWh)** **August** **124** **In:51; Out:73 (MWh)** 

This case study is an initial attempt to estimate the energy cooling loads of a semi-open stadium in Qatar using a dynamic thermal simulation technique. However, results for the validation of the analysis are not reported in the literature. Therefore, it should be mentioned that future discrepancies between results of similar models could be observed due to the partly subjective selection of design and analysis parameters.

Although there is lack of energy simulation studies, legacy reports from previous World Cups in Germany and Cape Town have been published, providing information on stadiums' energy consumption during the events. Climatic and regional differences hamper the comparison. However, it is worth noticing that the previously conducted World Cup events were providing comfort conditions only to the enclosed areas of the stadium. Table 6 correlates the host countries based on their temperature fluctuations for the month of June and the average energy expenditures per match.

Table 6. Energy consumption comparison per World Cup game for three host countries.

Host country	Temperature in June (^{o}C) [57]	Average total energy consumption per game (MW h)	Energy for thermal comfort provision (MW h)
Germany	11.7-22.3	170 [58]	< 17 (Indoors heating only)
Cape Town	7.8-18.1	220 [59]	28.6 (Indoors heating and ventilation)

5.5 Research limitations

In study of the thermal performance of the semi-outdoor stadium, even if it is calibrated to the maximum possible, there are several limitations and assumptions that should not be overlooked. Uncertainties arising from the boundary conditions are considered to be the most usual one, due to difficulties of replicating the internal and external conditions occurring in the building structure [60]. Moreover, code limitations associated with the methodology used from the software are of great importance and should also be mentioned.

5.5.1 Internal uncertainties

Internal uncertainties are related to the thermal behaviour of the building regarding the zonal parameters. More specifically, the construction details, the operational schedule of the occupants and most important the cooling system function are based on rationally selected profiles that may vary from an actual stadium structure and a football event, respectively. Consequently, the internal heat gains, which are entirely dependent on these profiles, will deviate from the reality.

5.5.2 External uncertainties

External uncertainties rely on the fixed climate data assigned to the studied area. Although the weather conditions in Qatar are based on historic weather station data, they do not count climate change or the exact prevailing conditions for the current or future years.

5.5.3 Method uncertainties

The energy performance study was undertaken by the Ecotect dynamic thermal modelling software that uses the CIBSE Admittance Method. More specifically, the cyclic admittance method uses the resultant flux transfer values of the mean outdoor temperature over a repeated period of 24 h to determine the swing (mean to peak) and calculates the resultant indoor temperature based on the steady state heat balance equation, according to which all external and internal parameters are assumed to fluctuate sinusoidal ours (CIBSE, 2006). The Admittance Method assumes that the solar gain are not conducted out of the thermal zone (Rees, Spitler, Davies, & Haves, 2000) and along with the assumption of uniform distribution of the transmitted shortwave solar radiation over the room surfaces, the analysis results to overestimation of the convective gains and consequently the cooling load requirements (Beattie & Ward, 1999).

6 Bidding for carbon neutrality

6.1 FIFA’s green plan

The green policy that FIFA has adopted, delivering sustainable and zero-carbon World Cup venues, became a mandatory section in every host country’s master plan, since 2006 [62]. The first implementation of the environmental management, considering the reduction of the ecological footprint during football events, carried out in collaboration with the German Local Organising Committee, conducive to the 2006 World Cup [63]. The total electricity and heat demand of 12.6 GW h and 1.4 GW h respectively that were consumed during the venue, contributed to cumulative emissions of 2,890 tonnes of CO_2 equivalents [58]. Their compensation was achieved through balancing and offsetting strategies, most important of which were the installation of solar panels on the stadium configuration and the purchase of green electricity from hydropower [58].

The integration of environmental matters into the management plan was also considered in the 2010 World Cup, conducted in Cape Town. The total energy consumption of about 16.7 GWh accounted for the production of 16,637 tonnes of CO_2 equivalents [59]. The adverse effects on the environment were planned to be offset by practices aiming to the prevention of future greenhouse gases emissions including, for example, the funding of projects supporting the implementation of renewable-based energy production practices [59]. However, none of the previous World Cup events included a master plan for the provision of air-conditioned air into the stadium bowl, in order to improve the comfort levels. For this reason, the bid promise brings Qatar in an unprecedented, for the current status quo, situation because there have not been recorded technologies of known performance and energy consumption requirements preserving this scope.

6.2 Strategies to meet carbon neutrality

In line with the ‘Green Qatar 2022’ plan, Qatar has pledged to deliver a carbon neutral World Cup [6]. For the implementation of this target, the maintenance of comfort satisfaction within the sport facilities should primarily rely on energy efficient strategies that will eliminate the dependence from hydrocarbon resources. The construction plan includes the installation of solar collector panels either integrated on stadiums, or located within an approximate distance from the football facilities, generating sufficient amounts of electricity, to partly supply the energy-demanding event [64].

Carbon neutrality is planned to be achieved using balancing strategies, including the production of surplus energy during one period of year that will be exported to the national electricity grid, in order to compensate the amount of the delivered energy during the event [64]. The theoretical base is clearly explained by Sartori et al.[65] and depicted in Fig. 13. The import/export balancing technique improves the efficiency of the system [65], due to the absence of high peaks in the electricity grid, since the stadium during the operational phase will self-consume the generated electricity power.

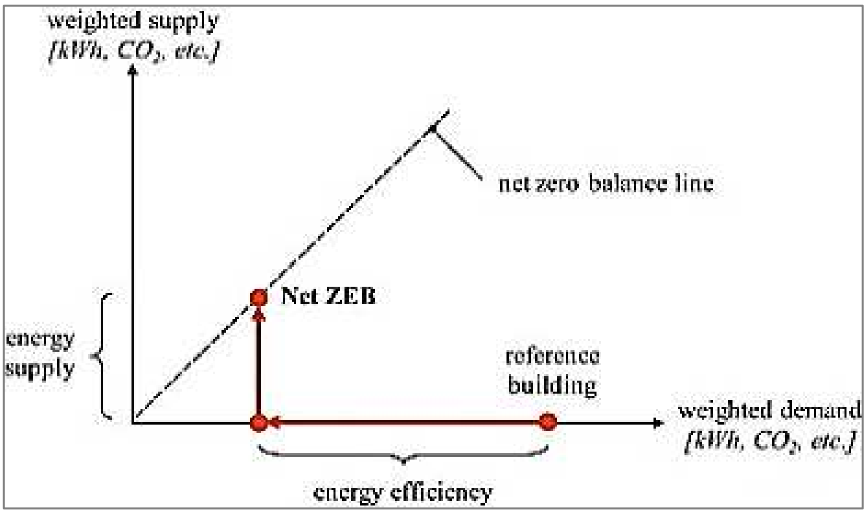


Fig. 13 Graph representing the net ZEB balance concept [65].

In the case of a stadium integrated with air conditioning units, an additional balancing strategy that could be adopted during its operation is for waste heat recovery. An effective and energy efficient practice would be to make use of the recovered heat on the water distillation process [66]. This strategy would be on one hand beneficial for the desalination dependent country of Qatar, and on the other hand a sustainable and economical technique for green water production [66].

6.3 Weather arising restrictions

Restrictions on the use of solar photovoltaic panels in terms of energy production values are due to the high regional temperatures that reduce the performance of the solar system. For this reason, engineers have considered solar thermal panels as an additional way of producing energy from heat [64]. However, both renewable energy producing systems need to be assessed and their behaviour to be tested under the harsh weather conditions, including not only the temperatures, but also the dust and the dew [48], in order to find the optimum technologies that will fulfil the carbon neutrality promise.

7 Lasting commitment

The World Cup 2022 is incorporated into a long-term development plan, aiming to the accomplishment of Qatar’s National Vision 2030 [6]. Focusing on the Four Pillars of Development, this mega-sport event will deliver not only to the next generations, but also to other Middle East countries a valuable heritage.

7.1 Contribution to local community

7.1.1 Social development

The stadium constructions, in association with the surrounding infrastructure, including the transport network and the urban renewal, presuppose their beneficial exploitation from the local community beyond the sporting venue. The multipurpose designed stadiums will be able to host future sport competitions, apart from football, as well as public gathering events [67].

The close vicinity of the sport facilities and the network connection among them will enable the accessibility to the sport arenas [6], encouraging more people to get involved in recreational activities. Furthermore, the organisation of public happenings will be facilitated, through the whole year, by the integrated cooling technologies that will deliver comfort conditions regardless of temperature variations.

7.1.2 Environmental and economic development

The development of cooling-supply technologies, mainly based on passive solar systems, will be a major investment for the country, since it is compatible with the long-term plan for sustainability [3]. The diversification away from the hydrocarbon sources, on which the Qatari economy and energy supply system are relied, will be partly replaced by the installation of solar panels that will import energy to the sport facilities when needed, and export the excess amount of energy to the electricity grid. In this way, the achievement of their commitment for carbon neutrality will be also implemented, since the generated energy will power intensive processes, heretofore dependent on oil and natural gas consumptions.

Considering that Qatar depends entirely on water desalination processes supporting a capacity of 1.2 Mm^3/d, at the expense of 101.52 GW h/d [68], solar thermal collectors could beneficially operate in favour of water desalting [68]. Taking advantage from the regional high temperature, their operation could enable the direct power supply of both heat and electricity-driven desalination units. Furthermore, the incorporation of solar energy on water recovery processes, through desalination, is in line with the nation's intention of decarbonising this energy expensive sector, moving towards a more sustainable and renewable-based system and economy [70].

7.2 Contribution to broad communities

The broader contribution of the World Cup 2022 will also support the economic and social development of surrounding Middle Eastern countries. The stadium designs, based on recycling and easily to assemble structural components, will allow the donation of part of the sport infrastructure to developing communities that aim to foster their sporting culture [6]. As part of this sustainable strategy, the country of Qatar will also benefit, since their small population is inadequate to support such a vast infrastructure capacity.

Furthermore, the commitment of developing cooling technologies, able to provide tolerant thermal conditions, will encourage their subsequent adoption from other countries, also dominated by harshly hot climates. In other words, the embracement of the Qatari environmental practices will accentuate further the global aspect of their environmental legacy.

8 Conclusions

This paper presented the various challenges that Qatar has to face, while approaching the 2022 World Cup. With respect to the requirements that FIFA has established, in order to ensure the provision of aero-thermal comfort conditions within the stadiums, both passive and active cooling techniques should be adopted. Conducive to preserve both visitors' and players' physical integrity, the thermal thresholds of 20.0-25.5^{o}C can be delivered either by evaporative or solar sorption cooling systems. Based on the climatic characteristics, the use of a combined system consisting of solar sorption techniques is deemed to be more effective for the cooling load production, especially when it is driven by solar thermal collectors to generate the required amounts of heat. The feasibility of these techniques, however, has not yet been tested on large scale arenas or under real weather conditions.

A dynamic thermal simulation was performed based on a simplified stadium design integrated with HVAC components. The results showed that a minimum cooling load of 47 MW h per game should be provided to produce an indoor thermal comfort environment, with an additional load of at least 115 MW h per game for the comfort neutrality of the semi-outdoor occupied areas.

The final decisions, though, should rely upon the sustainable concept of carbon neutrality that it is planned to be accomplished by balancing techniques and to the future viability of the event, two commitments adhered to the Qatari National development Vision for 2030, for the delivery of a World Cup widely remembered and a valuable legacy extended beyond Qatar's boarders.

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