Towards a sustainable 2022 FIFA World Cup in Qatar: Evaluation of wind energy potential for three football stadiums

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Abstract
This study analyzes the feasibility of satisfying the demand of three Football Stadiums for the 2022 FIFA World Cup in Qatar, using the wind’s kinetic energy. For all three selected locations (Lusail, Al Rayyan, and Al Wakrah), the wind potentiality is calculated through an environmental parameters study, from which the wind power density is obtained. Furthermore, a commercial wind turbine with proper characteristics is selected, and the same case study for each location is presented, to quantify the capacity that wind energy offers for satisfying the maximum energy demand of each associated stadium. In addition, the environmental benefits and the time required by each wind farm to satisfy the energy demand are computed. The results reveal that the conditions enable the use of wind energy for this purpose, based on a 5.06 m/s, 4.63 m/s, and 5.18 m/s velocity mean for Lusail, Al Rayyan, and Al Wakrah, respectively; from which values of 187.49 W/m², 150.96 W/m², and 187.29 W/m² of wind power density are obtained. Also, the proposed wind farms could produce 69,952.56 MWh/year, 59,550.19 MWh/year, and 75,333.70 MWh/year, respectively. Moreover, the wind farms should produce energy for a period of 5.64 h, 4.41 h, and 5.23 h, to satisfy the maximum demand by a football match in its associated location. Additionally, to avoid the implementation of a storage system, the electricity obtained from the wind is connected to the power grid, decreasing the quota of fossil fuel power plants. In consequence, Qatar will eliminate the emissions of approximately 23.376 tons of CO₂ in total per trio of matches held in these stadiums. Finally, a post 2022 FIFA World Cup scenario is analyzed, obtaining a positive outcome from both environmental and economic perspectives, in which an average of 14,675 tons of CO₂ and 6.03 Million US$ can be saved annually.
Introduction

Environmental awareness is a fundamental topic in the whole world, generating countless studies devoted to improving the human environmental footprint. However, one source of greenhouse gases (GHG) is deeply connected with the population growth, this is the energy consumption. Since most of the electricity in the world is produced from hydrocarbon power plants, the increase in generation has as a consequence of a higher GHG production. Furthermore, there are global events that creates pick demands of energy in a specific region or country, generating a large amount of focalized GHG emissions that could have not been estimated while planning the power plants in that area; in consequence, provisional sources of power generation are installed, most of which are fossil-fuel based. For these reasons, focusing on renewable forms of energy to satisfy planned and pick demands, will contribute to lower this negative effect. One green form of technology that has been increasing its efficiency and lowering its cost is wind energy (IRENA International Renewable Energy Agency, 2018). This form of renewable energy has grown from 91,632 MW of installed capacity in the world in 2007 up to 513,547 MW in 2017 (IRENA, 2020); meaning that it is considered a well mature technology that could be used to satisfy energy requirements while lowering the GHG emissions in the process.

One example of accelerated energy demand growth is Qatar. This country has experienced an industrial and populational increase which created a higher demand that must be met; in this particular case, most of it is satisfied via fossil fuel plants (natural gas and petroleum) which are not environmentally friendly (Marafia and Ashour, 2003). Furthermore, in the year 2022, the FIFA World Cup will be hosted by this country, meaning that a large quantity of energy will be produced during this event, generating a potential escalation of GHG generation at the same time. Also, since Qatar presents one of the highest CO2 per capita worldwide, an environmentally friendly approach to meet this growing demand must be followed (Ferroukhi et al., 2013; Qader, 2009). For these reasons, the country has developed the Qatar National Vision 2030, which has environmental development as one of the four pillars; this approach focuses on lowering the pollution and facing any environmental issue that affects the world (General Secretariat for Development Planning, 2008).

Regarding the wind potential of Qatar to produce energy, several studies have been made. These have concluded that the country has the potential to use this technology in a small to medium scale, based on measurements made between 10 and 25 m above the ground that generated a potential energy capacity around 306 kWh/m²/year (Alnaser and Almohanadi, 1990; Moghbelli et al., 2011). However, these studies made the calculations based on velocity measured taken close to the ground, meaning that this potential could increase with more altitude, since wind speed rises with height, possibly enabling the use of slightly larger turbines. Furthermore, one particular study indicated that the application of this technology in Qatar is economically feasible since energy production from a wind farm could be 15% lower than a traditional power plant (Marafia and Ashour, 2003). Furthermore, one paper indicated that the use of wind energy could be economically beneficial to the Qatar’s oil and gas industry, concluding that by replacing diesel and gas power
plants for a $5 \times 3.4 \text{ MW}$ wind farm, up to 3.32 million US$ could be saved (Méndez and Bicer, 2019). The results obtained by the mentioned studies, concur with region-wide analyzes, which indicated that the GCC has both economic and technical viability to install wind farms even at a large-scale depending on the location (Al-Salem et al., 2018; Ferroukhi et al., 2013; Munawwar and Ghedira, 2014; Rehman et al., 2016).

Motivated by the studies indicated above and the fact that the 2022 FIFA World Cup will be held in Qatar, the present paper uses measurements taken on site to establish the wind potential that Al Rayyan, Lusail, and Al Wakrah have, to satisfy the energy demanded by the stadiums located in these communities during a football match. This approach is not limited to an energy potential point of view, the time required to generate the demanded energy is also estimated, also, both economic and environmental benefits are analyzed. To complement this approach, the effect of the LNG market price influence on such economic gain is addressed. Hence, the objectives of this paper are:

- Calculate the wind energy potential of Al Rayyan, Lusail, and Al Wakrah.
- Determine the average energy production of a wind farm in each location.
- Obtain the time needed by each wind farm to produce the required energy by its associated stadium during a football match.
- Assess the environmental footprint reduction originated by the implementation of wind energy.
- Determine the economic benefits of implementing wind energy for power production in Qatar.

**System description**

The present study examines the possibility to use the wind’s kinetic energy to satisfy the demand of three football stadiums; Lusail Iconic stadium in Lusail, Ahmed Bin Ali stadium in Al Rayyan, and Al Janoub stadium in Al Wakrah (See Figure 1). To do so, the energy potential for a single wind turbine located in these locations is analyzed. Furthermore, a $10 \times 3.4 \text{ MW}$ wind farm case study is also studied; however, for this case the wake effect is not considered; for this approach, the turbines are distributed one beside the other, avoiding the negative influence that an upstream turbine could create. In addition, due to the wind’s inconsistency, a battery storage system is normally used; however, this study takes a different approach. Instead of storing the energy produced and using it when a match is underway, this is directly supplied to the power grid substituting the original quota of fossil fuel power plants, relocating it towards the stadiums during match time. Overall, by using the winds potential, the GHG emissions of Qatar will be reduced, because this power source will generate more energy than the required by the stadiums; lowering the energy production from traditional power plants.

**Wind potential and environmental parameter analysis**

To calculate the potential energy generation by a wind farm in the studied locations, measurements such as wind speed and direction, ambient temperature, and atmospheric pressure were taken ten meters above ground level with a five-minute interval in each location by the Supreme Committee for Delivery & Legacy in Qatar. With these values, a more specific environmental study must be done.
Wind speed

The velocity of the wind was measured using an anemometer. However, these values cannot be used directly to estimate the potential energy that can be harnessed by a wind turbine with a hub located above the measured height, since wind speed is influenced and modified by two factors; height and terrain roughness. In the present study, the measurements for all three locations were extrapolated from 10 m to the selected turbine’s hub height which is 130 m using equation (1) (Hernández and Ortega, 2014)

\[ V = V_0 \left( \frac{H}{H_0} \right)^\alpha \]  

(1)

where

- \( V \) is the wind speed at the desire height \( H \).
- \( V_0 \) is the wind speed at the measured height \( H_0 \).
- \( \alpha \) is the Hellmann Index.

Due to the lack of natural or man-made obstacles, the friction coefficient for the three locations of this case is 1/7, which is the same as our previous study (Méndez and Bicer, 2019).

Applying equation (1), the measurements are extrapolated to the selected turbine hub height (130 m). Additionally, the wind speeds recurrence is calculated, obtaining the results shown in Table 1 and Figure 2. Based on these calculations, we can observe that the predominant wind speed is 3 m/s with having the highest recurrence in Al Wakrah, with 3459 hours as shown in Figure 2. Furthermore, in Al Rayyan wind speeds above 19 m/s has less than an hour of recurrence. Also based on Figure 2 in Lusail, velocities between 2 and 4 m/s have a relatively similar distribution within the studied period.
Carrying out a general comparison between the measurements in the studied location based on Figure 2 and Table 1. It can be observed that the most recurrent wind speeds are located within 2 and 6 m/s in Lusail and Al Wakrah while in Al Rayyan the distribution is smaller (between 2 and 5 m/s). For a more thorough examination, the values shown in Table 2 are determined. This table points out that the overall mean is higher in Al Wakrah (5.18 m/s), and the fastest wind speed was measured at Al Rayyan (28.31 m/s). Regarding the standard deviation, which represents the level of dispersion that the measurements have from the mean value; Table 2 reflects that these values are 3.17, 3, and 3.10 for Lusail, Al Rayyan, and Al Wakrah, respectively. Moreover, the standard error was calculated, obtaining values of 0.007, 0.006, and 0.006. These values reflect the maximum fluctuation of the velocity’s mean, which can be translated to a 0.14%, 0.14%, and 0.12% margin of error, respectively. Considering the calculations indicated above, the location with more regular conduct is Al Rayyan since it presents the lowest deviation.

To validate the data shown in Table 2, a statistical evaluation was performed. Using the same methods as in (Méndez and Bicer, 2019) both box and whiskers (see Figure 3) and Weibull distribution (Figure 3) were implemented.
Initially, box and whiskers plots are employed. This method facilitates to identify the middle 50% plotting a box which frames the lower and the upper quartile. A division line within the box is also plotted, this division specifies the median, which represents the 50th percentile, signifying that the number of measurements are equally distributed in the upper and lower part of the line. Also, the outer range of the data is represented by vertical lines (whiskers) that originates from the box. Finally, the maximum registered values are represented by x (Banacos, 2011).

As a complementary method, the Weibull distribution is employed. There are several approaches to this method, like those indicated by Singh et al. (2019) and by Sumair et al. (2020); however, all of these techniques are related and are used as a step to calculate the wind’s energy potential in certain location. In the present study, the selected method determines the wind regime’s characteristics, based on two parameters (shape and scale) (El Khchine et al., 2019). As done in (Méndez and Bicer, 2019) the calculations will be performed based on the median, also using quartiles via the implementation the following expressions (Justus et al., 1978).

\[
c = \frac{V_m}{\ln(2)^{\frac{1}{k}}}
\]

\[
k = \frac{1.573}{\ln\left(\frac{V_{0.75}}{V_{0.25}}\right)}
\]

where

- $V_m$ is the median speed.
- $V_{0.25}$ is the first quartile ($Q_1$).
- $V_{0.75}$ is the third quartile ($Q_3$).
- $c$ is the shape parameter.
- $k$ is the scale parameter.

Figure 2. Wind speed recurrence for the studied locations.
The boxplot of each location studied indicates that for Lusail (Figure 3(a)), the values located within the 1st and 3rd quartiles varies between 1.85 m/s and 9.47 m/s. For Al Rayyan, they fluctuate within 1.76 m/s and 8.65 m/s, and for Al Wakrah between 2.04 m/s and 11.33 m/s. These distributions indicate that Al Wakrah has the widest range (9.29) in which the 50% of the data is distributed. Moreover, for all three cases the median (also known as the second quartile) fluctuates within the values indicated above (see Table 2). It is also important to highlight that the boxplot shows that the fastest wind speed (28.31 m/s) was registered in Al Rayyan in December 2017.

The Weibull distribution analysis indicates that for Lusail the wind speeds with a higher occurrence probability are located between the 2–6 m/s spectrum (see Figure 4(a)). For Al Rayyan, this range is located within 2 and 5 m/s (see Figure 4(b)), and in Al Wakrah the speeds that more likely will occur (see Figure 4(c)) are the same as Lusail (2–6 m/s).

**Table 2.** Wind velocity summary.

| Location                      | Wind speed (m/s) |  |  |  |  |  |  |
|-------------------------------|------------------|--|--|--|--|--|--|
|                               | Mean  | Median | Standard deviation | Standard error | Mean error in % | Max. | Min. |
| Lusail (June 2016 – December 2018) | 5.06  | 4.41   | 3.17   | 0.007  | 0.14%    | 27.42 | 0.00 |
| Al Rayyan (December 2015 – December 2017) | 4.63  | 3.95   | 3.00   | 0.006  | 0.14%    | 28.31 | 0.00 |
| Al Wakrah (July 2015 – December 2017) | 5.18  | 4.51   | 3.10   | 0.006  | 0.12%    | 26.68 | 0.04 |

**Figure 3.** Wind speed Boxplot. (a) Lusail June 2016 – June 2018; (b) Al Rayyan December 2015 – December 2017; (c) Al Wakrah July 2015 – December 2017.
These results confirm that the mean of each analyzed location is placed within the ranges indicated above. Finally, by observing each statistical tool, as well as the wind recurrence of each place, it can be established that the values with the highest occurrence probability are located between the 1st and 3rd quartile.

Wind direction

Not only wind speed is important for a wind farm, but also the direction in which it moves is a key factor for the turbine’s distribution and orientation. This variable was measured by

Figure 4. Wind speed Weibull distribution. (a) Lusail June 2016 – June 2018; (b) Al Rayyan December 2015 – December 2017; (c) Al Wakrah July 2015 – December 2017.
implementing a vane, which orientates itself based on the direction in which the wind is blowing. Since the airflow path is known, the next step is to identify its course based on its origin. Hence by indicating a north wind, this means that the wind has a south to north movement. In order to define the direction of the wind, measurements implementing an instrument called vane must be used. Once the data is collected a graphical tool called wind rose may be elaborated. This plot is formed by bars that originates from the center and its length is determined by the recurrence of the wind in that direction (Ahrens, 1998; Méndez and González, 2009). Thence, by using the data recollected in the three locations, wind rose plots are obtained.

Figure 5 indicates that the wind direction does not have only one dominant direction throughout the studied locations. In the case of Lusail (Figure 5(a)), the predominant direction is NW, which means that the majority of the measurements indicate a SE to NW wind flow. Al Rayyan (Figure 5(b)) has a different behavior, showing a predominance air movement towards NNW and NE. On the other hand, in Al Wakrah (Figure 5(c)) the wind has a wide of movement, indicating that the two highest recurrence directions are NW (air movement originated from the SE) and NE (wind with a SW to NE motion). Despite variability of the wind direction, turbines are capable of $180^\circ$ movements, using the majority of the wind’s kinetic energy available, by facing the dominant direction in every case.

**Other environmental parameters**

In order to proceed with the final step to calculate the winds potential to produce power, we must obtain the air density value which depends directly on the temperature and atmospheric pressure. The temperature was measured in Celsius ($^\circ$C) via a thermometer, but it was converted to Kelvin (K). Regarding the atmospheric pressure, this parameter was measured in hPa implementing a barometer, however, for calculation purposes it was converted to N/m$^2$. Once all the data was converted in to the adequate unit, the air density can be calculated by applying equation (4) (Hernández and Ortega, 2014)

$$\rho = \frac{P}{RT}$$
where
$q$ is the air density
$T$ is the temperature
$P$ is the atmospheric pressure
$R$ is the specific gas constant of the air ($287 \text{ J/kg K}$).

Table 3 indicates the summary of the environmental parameters with the adequate conversion and calculation for each location studied. In this case, it can be observed that the Air Density is the same, and that the value of the temperature and atmospheric pressure mean are similar throughout the measurement spots.

**Wind power density (WPD)**

After performing the proper environmental parameters analysis, it is possible to calculate the wind potential to produce power per unit area ($\text{W/m}^2$). By utilizing the data reflected in Table 3 and implementing equation (5), the WPD values are obtained (see Table 4) (Hernández and Ortega, 2014).

$$WPD = \frac{1}{2n} \sum_{i=1}^{n} \rho V_i^3$$  \hspace{1cm} (5)

where
$\rho$ is the air density ($\text{kg/m}^3$)
$V$ is the wind speed ($\text{m/s}$)
$n$ is the number measurements.


Energy production calculation

To estimate the quantity of energy that a wind turbine will generate, its power output at specific wind speed must be computed, and then multiplied by the recurrence of that velocity (in hours). A direct form of determining the power yield of a wind turbine is to compare its power curve with the wind speed being analyzed; nevertheless, when applying this method, the value of $\rho$ in which the power curve was created, must be compared with the density calculated in the location, in which the study is being performed. If these are different, then the values obtained are incorrect. Taking a more realistic approach, a calculation implementing the power coefficient ($C_p$) of the turbine can be done by implementing equation (6) (Sedaghat et al., 2016)

\[
P = \frac{1}{2} \rho AV^3 C_p
\]

where

- $\rho$ is the air density (kg/m$^3$)
- $V$ is the is the wind speed (m/s)
- $A$ is the rotor area of the turbine (m$^2$)
- $C_p$ is the power coefficient of the turbine

Results and discussion

The previous section indicated how the measurements were carried out and highlighted the environmental behavior in the three locations studied. In addition, the values reflected in Table 4 show the possibility of power production via wind turbines. Thus, the computation method explained in the previous subsection was implemented to carry out the calculations indicated in the present segment.

Scenarios comparison

In this section, two factors are compared. First, the layout, in which the energy production of a single turbine is matched with a 10 $\times$ 3.4 MW wind farm in each location; at this point, the time required to generate enough energy to satisfy the demand is considered. Second step analyses the best location, in which a single wind farm could be placed to meet the requirements of all three stadiums. In previous section, the wind recurrence was calculated and reflected in Table 1; however, not all the available wind is exploitable. Thus, the calculations done in the following subsections are based on the wind turbine cut-in speed.

Single turbine vs. wind farm. By implementing equation (6), with the data indicated in Table 1, and considering the same turbine selected on the previous study (Méndez and Bicer, 2019) (Senvion 3.4M140), which has 3.4 MW of nominal capacity, a 3 m/s cut-in velocity, a 130 m hub height, and a 140 m rotor diameter (Senvion 3.4M140 - 3.40 MW - Wind turbine, n.d.). The energy yielded by a single wind turbine is obtained in each location and presented in Table 5 and Figure 6.

The results for one 3.4 MW wind turbine indicate that Al Rayyan has the lowest energy production in comparison with the other locations. Also, in Al Wakrah (February 2017), the
largest output is calculated with 1640.99 MWh, while the lowest was obtained in Al Rayyan (September 2017) with 144.70 MWh. Furthermore, regarding a yearly mean energy production, Al Wakrah has the highest value with 7533.37 MWh, followed by Lusail with 6995.26 MWh, and the lowest output is in Al Rayyan with 5955.02 MWh. These values concur with the WPD, and the recurrence calculations carried out in previous section, in

| Wind Speed (m/s) | Lusail June 2016 – December 2018 | Al Rayyan December 2015 – December 2017 | Al Wakrah July 2015 – December 2017 |
|-----------------|---------------------------------|----------------------------------------|------------------------------------|
| 3               | 192.08                          | 230.17                                 | 258.65                             |
| 4               | 555.74                          | 617.23                                 | 758.41                             |
| 5               | 989.77                          | 1012.68                                | 1356.40                            |
| 6               | 1423.48                         | 1427.35                                | 1890.85                            |
| 7               | 1785.84                         | 1611.93                                | 2107.07                            |
| 8               | 2017.13                         | 1558.26                                | 2379.07                            |
| 9               | 2168.41                         | 1585.82                                | 2700.14                            |
| 10              | 1717.26                         | 1358.57                                | 2317.57                            |
| 11              | 1094.62                         | 967.48                                 | 1833.92                            |
| 12              | 679.18                          | 655.28                                 | 1452.73                            |
| 13              | 440.44                          | 474.43                                 | 731.85                             |
| 14              | 306.36                          | 344.25                                 | 385.68                             |
| 15              | 215.73                          | 258.75                                 | 272.10                             |
| 16              | 154.55                          | 174.53                                 | 197.70                             |
| 17              | 110.24                          | 85.93                                  | 113.74                             |
| 18              | 77.80                           | 40.58                                  | 59.34                              |
| 19              | 2741                            | 3.06                                   | 6.09                               |
| 20              | 14.19                           | –                                      | 3.55                               |
| 21              | 3.28                            | –                                      | –                                  |
| >21             | 16.99                           | –                                      | 8.59                               |
| **Total**       | 13,990.51                       | 12,406.29                              | 18,833.43                          |

Figure 6. Energy generation by a 3.4 MW wind turbine in the studied locations.
which Al Rayyan presents the lowest WPD and the lowest wind speed mean. Also, the fact that Al Wakrah yields the most significant amount of energy is appropriate. Since this location offers the highest velocity mean and the most considerable number of hours with wind above 5 m/s, as indicated in Table 1 of wind speed section.

After analyzing the potential energy production of a single turbine, a case study for all the locations is proposed. This scenario consists of a wind farm composed by ten Senvion 3.44M140 wind turbines. For this case, the calculations of the energy production will be carried out without considering the speed reduction and turbulence increase that a turbine generates downstream. This phenomenon is known as wake effect, which is a spatial region that affects the energy production of any turbine that is located even partially in one or several wake sectors generated by other turbines in the wind farm (Burton et al., 2001). With this premise, the energy production of the case study in each location is plotted in Figure 7 and detailed in Table 6.

The results obtained for the case study in each location concurs with the behavior of the single turbine analysis. This means that comparing month by month production, Al Rayyan has the lowest energy output between the three locations, while Lusail and Al Wakrah have a similar performance except on February and March 2017 where in the southern city the production in significantly higher. Additionally, the yearly mean energy production has the same order, with Al Rayyan producing the lowest value with 59,550.19 MWh, behind the 69,952.56 MWh generated by Lusail, while Al Wakrah has the highest output of the three with 75,333.70 MWh.

With the calculations made in the previous sections, it was possible to obtain the time required by each location to satisfy the energy demand of the associated football stadium (see Table 7).

The demand for Lusail and Al Rayyan was facilitated by the Supreme Committee for Delivery & Legacy; however, for Al Wakrah the highest demand value available was assumed to execute the calculations. To obtain the maximum energy demand per match, a duration of 3 hours at full load was assumed, since a football game consists of two 45 minutes halves, in addition of pre and post-match events. Based on this information, the required time to satisfy the demand of each stadium was obtained by dividing its maximum energy and the average electricity production of the wind farm (see Table 8).

From the results indicated in Table 8, Al Rayyan will be the fastest location to produce the equivalent of the required energy of its associated stadium, followed by

![Figure 7. Energy generation by a 10 x 3.4 MW wind farm in the studied locations.](image)
Table 6. Energy production from a $10 \times 3.4 \text{ MW}$ wind farm in the studied locations.

| Wind speed (m/s) | Lusail June 2016 – December 2018 | Al Rayyan December 2015 – December 2017 | Al Wakrah July 2015 – December 2017 |
|------------------|----------------------------------|----------------------------------------|------------------------------------|
| 3                | 1920.78                          | 2301.66                                | 2586.51                            |
| 4                | 5557.44                          | 6172.32                                | 7584.13                            |
| 5                | 9897.74                          | 10,126.84                              | 13564.02                           |
| 6                | 14,234.81                        | 16,119.30                              | 21,070.66                          |
| 7                | 17,858.42                        | 15,582.56                              | 23,790.69                          |
| 8                | 20,171.32                        | 21,684.14                              | 27,001.43                          |
| 9                | 21,172.58                        | 17,172.58                              | 23,175.67                          |
| 10               | 10,946.19                        | 9674.82                                | 18,339.19                          |
| 11               | 6791.78                          | 6552.78                                | 14,527.28                          |
| 12               | 4404.45                          | 4744.30                                | 7318.45                            |
| 13               | 3063.61                          | 3442.53                                | 3856.80                            |
| 14               | 2157.29                          | 2587.46                                | 2720.97                            |
| 15               | 1545.47                          | 1745.25                                | 1977.04                            |
| 16               | 1102.36                          | 859.30                                 | 1137.36                            |
| 17               | 778.00                           | 405.83                                 | 593.38                             |
| 18               | 274.10                           | 30.56                                  | 60.85                              |
| 19               | 141.87                           | –                                     | 35.49                              |
| 20               | 32.85                            | –                                     | –                                  |
| 21               | >21                              | 169.94                                 | 8586                               |
| Total            | 139,905.13                       | 124,062.89                             | 188,334.25                         |

Table 7. Electricity and energy demand per stadium.

| Stadium                        | Maximum electricity demand (MW) | Maximum energy demand per match (MWh) |
|--------------------------------|---------------------------------|---------------------------------------|
| Lusail Iconic Stadium (Lusail) | 15                              | 45                                    |
| Ahmed Bin Ali (Al Rayyan)      | 10                              | 30                                    |
| Al Janoub (Al Wakrah)          | 15                              | 45                                    |

Table 8. Time required to produce the maximum energy demand per match, per stadium.

| Stadium                        | Maximum energy demand per match (MWh) | Average electricity production (MW) | Necessary time to satisfy the energy demand (h) |
|--------------------------------|---------------------------------------|-------------------------------------|-----------------------------------------------|
| Lusail Iconic Stadium (Lusail) | 45                                    | 7.99                                | 5.64                                          |
| Ahmed Bin Ali (Al Rayyan)      | 30                                    | 6.80                                | 4.41                                          |
| Al Janoub (Al Wakrah)          | 45                                    | 8.60                                | 5.23                                          |
Al Wakrah, and Lusail. However, it is important to indicate that Ahmed Bin Ali stadium has the lowest energy demand; meaning that if the three locations had to produce the same amount of energy, Al Wakrah would represent the fastest case and Al Rayyan the slowest.

On the other hand, the time required for a single turbine to produce enough energy to satisfy the demand for a single game in any stadium is ten times larger, which means that it would require between 2 and 3 days to generate the required 30 or 45 MWh. So, based on the average annual energy production and the time needed to satisfy the energy demand per game. The wind farm scenario is a better fit than a single wind turbine.

**Location selection for a wind farm.** Since a single wind farm can produce enough energy to satisfy the pick demand of all three football stadiums, the best location for its development is selected based on its energy production potential. From this perspective, Al Wakrah represents the best option, since it presents the highest annual energy production (on average). Furthermore, the Al Wakrah wind farm would require 13.95 h to generate the equivalent of the total energy demanded by the three stadiums.

**Environmental and cost assessment**

By generating the required energy for each match implementing a wind farm, the CO₂ production will lower, since this demand was originally going to be satisfied by hydrocarbon-based power plants. In this study, two predominant forms of fossil fuel burning plants in Qatar were taken into account; these are natural gas and diesel with an 80% and 20% share, respectively. Also, it is important to consider that igniting these types of fuel will generate 0.250 kg CO₂/kWh for diesel and 0.181 kg CO₂/kWh for natural gas (US Energy Information Administration, 2018).

Table 9 highlights the amount of CO₂ that could be saved just by implementing a wind energy to meet the demand per match. Since Al Rayyan presents the lowest requirement, it also shows the least CO₂ saving among the three cases with 8.766 tons of CO₂, while Lusail and Al Wakrah will prevent the production of 8.766 tons of CO₂ each. Hence, by using this renewable technology, a total of 23.376 tons of CO₂ will be saved per trio of matches in these locations.

From an economic point of view, the use of renewable energy indirectly represents an increase in Qatar’s gas export potential (which is its most substantial financial income).

**Table 9.** CO₂ emissions from diesel and natural gas to satisfy the energy demand of each stadium.

| Stadium                  | Energy Source | Share | Electricity Production (MWh) | Estimated CO₂ emissions per match (Ton CO₂) |
|--------------------------|---------------|-------|------------------------------|---------------------------------------------|
| Lusail Iconic Stadium    | Diesel fuel   | 20%   | 9                            | 2.25                                        |
| (Lusail)                 | Natural gas   | 80%   | 36                           | 6.516                                       |
| Total                    | 100%          | 45    | 8.766                        |                                             |
| Ahmed Bin Ali (Al Rayyan)| Diesel fuel   | 20%   | 6                            | 1.5                                         |
|                          | Natural gas   | 80%   | 24                           | 4.344                                       |
| Total                    | 100%          | 30    | 5.844                        |                                             |
| Al Janoub (Al Wakrah)    | Diesel fuel   | 20%   | 9                            | 2.25                                        |
|                          | Natural gas   | 80%   | 36                           | 6.516                                       |
| Total                    | 100%          | 45    | 8.766                        |                                             |
The gas used to satisfy the electrical demand will be lower than before since this will be substituted by a wind farm, which does not require the use of gas. By using combined-cycle gas power plants, the 96 MWh energy demand per trio of matches represents 240 MWh of natural gas chemical energy (assuming 40% of efficiency). Furthermore, since the average heating value of natural gas is about 13.1 kWh/kg (Méndez and Bicer, 2019), this chemical energy production represents 18.32 tons of natural gas that could be exported for economic benefits. Moreover, considering that the average selling price of LNG is 415.2 US$/ton (Méndez and Bicer, 2019), approximately 7607 US$ can be saved per trio of matches. Regarding diesel savings, due to the reduction of diesel generators, assuming a 35% efficiency, the 24 MWh demand per trio of games represents 68.58 MWh of diesel chemical energy. Moreover, assuming a diesel price of 0.29 US$/L (Fuel Price, 2020), approximately 1993 US$ can be saved per trio of events held in the selected stadiums.

Beyond the 2022 FIFA World Cup

Once the global event concludes, the wind farm will maintain its operation, supplying energy not only to sporadic football matches, which will have a lower electricity demand than the one estimated during the cup but also contributing to the power grid, satisfying a section of it via renewable energy. With this perspective and based on this section, Table 10 highlights the yearly average production of energy that will be obtained from a 10 × 3.4 MW wind farm located in Al Wakrah. Furthermore, Table 10 also indicates the environmental and economic savings that this renewable source will generate, assuming that formerly 80% of the power production was originated by a natural gas power plant, while the remaining 20% from diesel generators.

Based on Table 10, Al Wakrah’s wind farm will have a positive impact. Not only from the energetic perspective, but also it will allow the State of Qatar to lower its yearly environmental footprint by 14,675 tons of CO₂ by eliminating the burning of natural gas and diesel. Furthermore, since a large part of the country’s income is originated by the exportation of LNG, a total of 4.78 Million US$ per year could be converted from consumption to profit, redirecting the once burned gas to the international market.

For a more in-depth study of the benefits of wind energy deployment in Qatar, three scenarios were analyzed (see Figure 8). These cases were based on the international LNG market value, in which:

- Scenario 1 considers the previously mentioned average LNG price of 415.2 US$/ton.

| Item                  | Yearly average production or savings |
|-----------------------|---------------------------------------|
| Energy production     | 75,333.70 MWh                         |
| CO₂ emissions         |                                       |
| Diesel fuel           | 3766.69 Ton CO₂                       |
| Natural gas           | 10,908.32 Ton CO₂                     |
| Total                 | 14,675 Ton CO₂                        |
| Economic savings      |                                       |
| Diesel fuel           | 1.25 Million US$                      |
| LNG                   | 4.78 Million US$                      |
| Total                 | 6.03 Million US$                      |

Table 10. Energetic, environmental, and economic outcome of a 10 × 3.4 MWh wind farm.
Scenario 2 is based on an increase of the market value of LNG to 622.8 US$/ton as registered in August 2018 (Bloomberg, 2020).

Scenario 3 reflects a low price of LNG at 207.6 US$/ton similar to January 2020 (Bloomberg, 2020).

In the three scenarios, the amount of burned gas remains the same. Figure 8 indicates that the annual environmental footprint will be reduced, for all three cases, since 14,675 tons of CO2 will not be generated due to the reduction of the use of gas-based power plants. From an economic perspective, such behavior is not obtained; Figure 8 indicates that the total financial gain depends on the international LNG market price. Scenario 1 showcases the average market value, meaning that on average 4.78 Million US$ will be obtained; however, at peak values, like the one indicated in the second case, this number can increase up to 7.16 Million US$, which represent a 49.79% growth from the average gain. Moreover, low prices can be encountered, like in scenario 3, in which Qatar can choose to export the LNG with a 2.39 Million US$ gain or wait for an increase in the market price and obtain a more significant income. So, in any scenario, the implementation of wind energy will generate both economic and environmental gain to Qatar since this LNG shifted from a once consumed product to a selling one.

Conclusions

This study compares the potential of wind energy in three locations in Qatar. In addition, the average energy production by a single 3.4 MW wind turbine and a 10 × 3.4 MW wind farm for the three locations was calculated. Furthermore, the possibility to meet the demand by each football stadium via wind energy was also calculated, determining the time to generate such energy for each case, and the best option among the three locations. Finally, the impact on the CO2 footprint associated from electricity consumption from each stadium was also analyzed, calculating the tons of CO2 saved by using wind farms. Several important findings of this study are:

- The wind speed mean are 5.06 m/s, 4.63 m/s, and 5.18 m/s for Lusail, Al Rayyan, and Al Wakrah, respectively. Furthermore, the recurrent wind is located within 3 m/s and 22 m/s
77%, 74%, and 81% of the time for Lusail, Al Rayyan, and Al Wakrah, respectively; indicating that for the worst location (Al Rayyan) among others, the wind farm will produce energy at least 74% of the time.

- The wind direction is variable; however, it is predominant towards north; specifically, NW for Lusail, between NNW and NE for Al Rayyan, and between NW and NE in Al Wakrah. Meaning that to efficiently use the wind energy, the turbines should be facing south, modifying its angle of direction depending the location.

- The WPD obtained for the studied period was 187.49 W/m² for Lusail, 150.96 W/m² for Al Rayyan, and 187.29 W/m² for Al Wakrah confirming the possibility to implement wind energy in a small to medium scale in at least one of the three locations.

- A single wind turbine could produce in average 6995.26 MWh/year in Lusail, 5955.02 MWh/year in Al Rayyan, and 7533.37 MWh/year in Al Wakrah.

- A 10 × 3.4 MW wind farm is capable of generating in average 69,952.56 MWh/year in Lusail, 59,550.19 MWh/year in Al Rayyan, and 75,333.70 MWh/year in Al Wakrah. In this study, the wake effect was neglected, meaning that each turbine of the wind farm will produce the maximum output possible depending on the wind speed.

- A 10 × 3.4 MW wind farm will need on average, 5.64 h for Lusail, 4.41 h for Al Rayyan, and 5.23 h for Al Wakrah; to generate the maximum energy demand by the stadium located in the same community.

- Out of the studied locations, Al Wakrah represents the best option, since it presents the highest annual energy production. If the proposed wind farm is installed only at this location, it will require 13.95 h to generate the necessary energy to satisfy the demand of the matches by all three stadiums.

- By implementing wind energy to satisfy the energy requirement for these stadiums, a total of 23.376 tons of CO₂ will be saved per match. This is distributed in 8.766 tons of CO₂ per match for Lusail, the same value is saved for Al Wakrah, and 5.844 tons of CO₂ per match for Al Rayyan.

- During the 2022 FIFA World Cup, each trio of matches will save 9600 US$ due to the substitution of natural gas and diesel-based power generation.

- After the 2022 FIFA World Cup, Al Wakrah’s wind farm will continue its operations, saving an average of 14,675 tons of CO₂ per year in the power production process.

- Al Wakrah’s wind farms will generate an average saving of 6.03 Million US$ with the reduction of natural gas and diesel usage. Furthermore, out of this saving, 4.78 Million US$ could be converted into profit via LNG exportation.

- By implementing wind energy, any form of profit can be obtained from LNG exportation despite the market price. From the three scenarios studied, Qatar can benefit from an additional 2.39 million US$ considering the lowest LNG selling price, since the once consumed product is now a source of economic income.

**Highlights**

- Statistical analysis of environmental parameters, wind speed and direction in three locations.

- Wind power density quantification in each location.

- Calculation of time required to satisfy the energy demand of the world cup stadiums studied.

- Energy, environment, and economic benefits calculations during and after the world cup.
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**Appendix**

**Notation**

- **A** Turbine’s rotor area (m²)
- **C** Shape Parameter
- **Cp** Power Coefficient
- **CO₂** Carbon dioxide
- **H** Height (m)
- **H₀** Original height (m)
- **k** Scale Parameter
- **n** Number of measurements
- **P** Power (W)
- **P** Atmospheric Pressure (hPa, N/m²)
- **R** Specific gas constant (287 J/kg K)
- **T** Temperature (K, °C)
- **V** Wind Speed (m/s)
$V_0$ Wind Speed at height $H_0$ (m/s)
$V_{0.25}$ First Quartile or $Q_1$
$V_{0.75}$ Third Quartile or $Q_3$
$V_m$ Median Speed (m/s)

Greek letters

$\alpha$ Friction coefficient
$\rho$ Air Density (kg/m³)

Acronyms

GCC Gulf Cooperation Council
GHG Green House Gases
LNG Liquefied Natural Gas
NE North East
NNW North North-West
NW North West
SE South East
SW South West
WPD Wind Power Density