Feasibility of Utilizing Wind Electricity for King Abdulla Medical City (KAMC) at Kingdom of Bahrain

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Abstract:

This paper explores the potential of utilizing wind electricity (wind energy) to power part of King Abdulla Medical City (KAMC) at Arabian Gulf University (AGU), Bahrain. Installing a 1 MW- wind turbine is found to produce, annually, 2,221 MWh - which is enough to power about 37 houses and save an annual emission of CO_2 equivalent of 1,710 tons, i.e., saving 700 ton of oil. Two scenarios - Scenario A and B - (each consists of 3 sub - scenarios) are made for the assessment of installing a 1 MW - wind turbine. The net present value (NPV) is found positive in both scenarios, even if the coefficient of performance (CP) was assumed as 30% and the wind turbine production was assumed to degrade annually by 1% (30 % segregation degradation after 30 years). The NPV in the lowest optimistic scenario (Scenario: 2A) is found at US$ 4.0 million with US ¢7.4/kWh. In this scenario, if the production is calculated without consideration of the inflation rate, then the cost US¢ 1.5/kWh. For the most optimistic scenario (Scenario 1A), which assumes CP = 40%, the cost US¢0.95/kWh, when considering the inflation and without it US¢1.1 / kWh. In Scenario 1C, US¢ 0.95/kWh if reported.

Received: 22/04/2021
Revised: 19/08/2021
Accepted: 02/09/2021

Keywords: Wind Turbines, King Abdulla Medical City, Building Integrated Wind Turbine, Wind Energy Potential in Bahrain.

Introduction

Arabian Gulf University (AGU) has announced its latest developments, which are building a substantial medical city under the name of “King Abdulla Medical City, KAMC”. The funding was made available from the Saudi Arabian government; the Kingdom of Bahrain offered an area of 1,000,000 m^2 for this project in a wonderful location in the south of Bahrain (latitude 25.70° N and longitude 50.61°E).

As part of AGU’s green policy, the amount of the required electricity for the city (about 20 MW) should be from clean energy (solar and wind energy). The university has already planned to install PV solar panels (about 1 MW) at the rooftops of the buildings, including car parking. This will represent a share of nearly 5% of clean energy out of conventional electricity.

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The work on this project had started in June 2019 and is expected to finish in December 2021. KAMC will be in operation during the first quarter of 2022. KAMC will have 288 patient rooms, 17 clinics and 17 operation theatres. The infrastructure is expected to be completed within 24 months and will receive patients in early 2021.

There are many reasons to incorporate the use of wind energy to produce wind electricity (green energy) in KAMC. These reasons are as follows:

1. AGU's mission is to adopt the best practices in environmental standards in all its projects.
2. AGU prioritizes the Sustainable Development Goals (SDGs) and demonstrates to the world community its commitment to be green.
3. KAMC is located far south of Bahrain, a relatively rich location in solar and wind energy.
4. AGU will aid Bahrain in preserving natural resources.
5. KAMC will contribute to an overall positive impact on the environmental performance of the energy sector.
6. The project will secure power generation at night-time and during any unexpected climate change periods.
7. Wind turbine normal costs have shown to have dropped by more than 40 % while the electricity unit (kWh) tariff is nearly increasing for non-domestic from 21 fils (USD¢5.5) in 2016, to 23 fils (USD¢ 6.0) in 2018, 26 fils (USD ¢ 6.8) in 2019, and to 29 fils (USD ¢7.6) in 2020.
8. By 2025, average electricity costs generated by the sun and wind (GCC) could drop by as much as 59% or more.

The available roof area is 102,494 m^2 which can be used for both solar electricity using PV solar cells and wind energy.

The utilization of wind energy in University campuses had become a point of importance. Universities set as a model for sustainability and clean energy and environment. There are many university campuses, worldwide which, invest in wind energy to reduce their Carbon footprint, reduce its electricity costs, and provide learning opportunities for students. For example, the University of Delaware had built in 2010 its wind turbine system enough to produce electricity to its buildings at the Lewes campus and to 108 homes in the city. In 2004, Carleton College in USA, became the first college in the country to own an active utility-grade wind turbine, located about 2 km east of campus. In 2011, the college had added a second 1.68 MW wind turbines. Now, both turbines supply 55 to 70 % of the college's electricity demand reducing sustaintial CO2 emission equivalent (Environment America, 2021). The University of Maine, USA, developed the first grid-connected offshore wind turbine in the Americas (Bradford, 2019). The Southwestern University in Texas purchases Renewable Energy Credits (RECs) from wind farms equivalent to 100% of its electricity consumption. According to Bradford (Bradford, 2019), more than 40 colleges and universities in USA obtaine 100% of their electricity from renewable energy sources. In UK, 20 of leading universities are suppose to have purchased wind energy electricity from British wind farms based on power purchase agreements (PPA) in 2019 (Off Grid Energy Independence, 2019).

This paper explores the potential of using wind energy to power part of King Abdulla Medical City (KAMC), Arabian Gulf University (AGU) in the Kingdom of Bahrain. Technological, economic and architectural aspects will be tackled herein.

In fact, the utilization of wind energy in Bahrain has been studied thoroughly. There is plenty of data that support the utilization of wind energy for KAMC. Some papers were published in the early 1990s, including (Abdulla, 1992), (Alnaser, 1995), (Baharna and Mahdi, 1991), (Feregh, 1993), (Som and Rajab, 1993), and others as recent as 2019-2020 like that of (Haji, et al., 2019) and (Elgabiri, et al., 2020). Analysis conducted by the University of Bahrain on the 10-year wind data set from the meteorological weather station shows that Bahrain enjoys an annual mean wind speed of 6.9 m/s at 60 m height (extrapolated), resulting in an average annual power density of 440 W/m^2 (Al Buflasa, et al., 2007). The strongest wind regime was found in the central and southern parts of the main island of Bahrain. According to the one-year wind speed measurements from the tall mast at 50 m height, the most prevailing wind speed occurred at around 6 m/s. The highest wind speed reached almost 7 m/s, as shown in Fig. 1 (SEU, 2017).

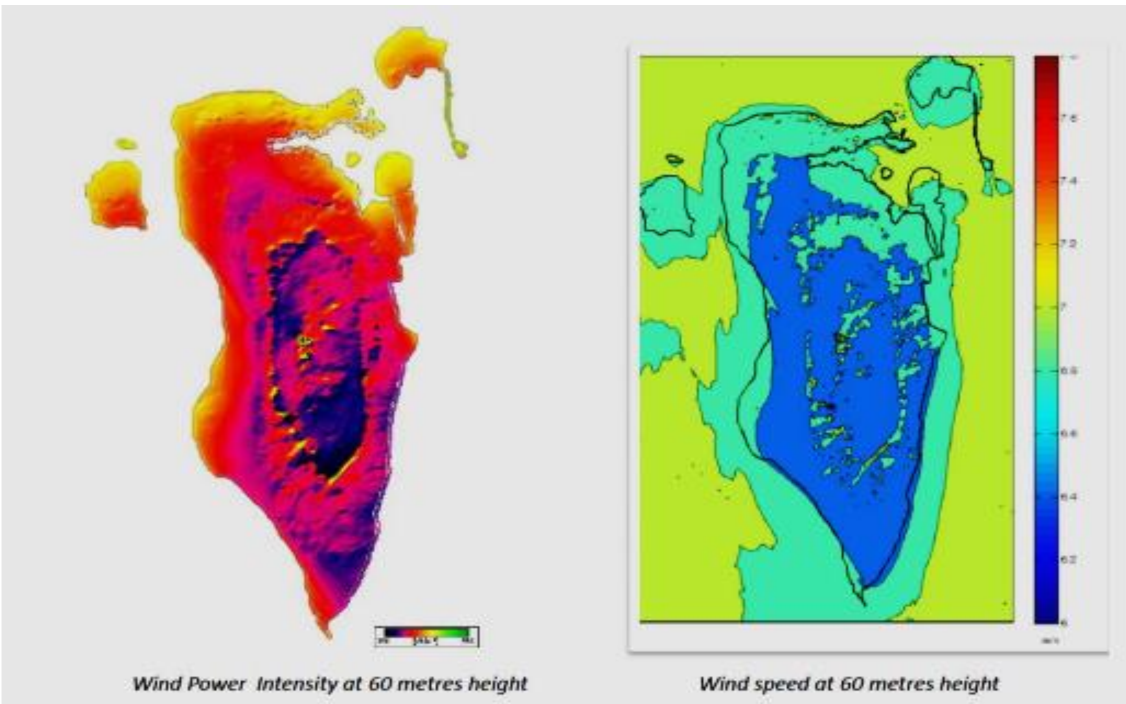


Fig 1: Atlas of wind over the land of Island of Bahrain
at the Kingdom of Bahrain; consisting 11 islands (SEU, 2017).

The Sustainable Energy Authority (SEA) – in collaboration with EMD International and with the support of the United Nations Development Programme (UNDP)- had developed and launched Bahrain Wind Energy Atlas (SEU, 2017). It consists of Wind Data Predictions and accurate prediction supported by actual collected data. Such an atlas encourages AGU to consider investment in wind energy in its great KAMC project. Fig. 2 shows the contour of wind energy in the Arabian Gulf as Bahrain is located nearly in the middle – west side. The average wind speed is about 6.2 to 6.5 m/s at the height of 100m (SEU, 2017).

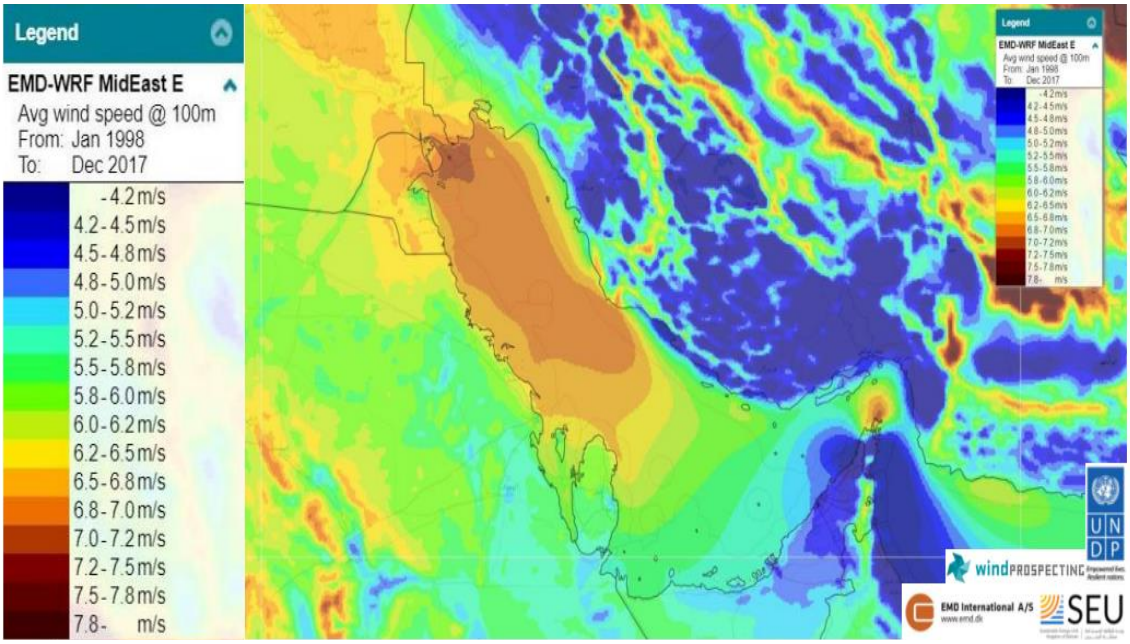


Fig 2: The average wind speed distribution at the Arabian Gulf at the height of 100m. data is from Jan 1998 to Dec 2017 (SEU, 2017).

Figs. 3-5 shows Bahrain Mesoscale (3 km) average wind speeds at the height of 50 m, 70 m and 100 m. The data were collected from 1994 to 2017. The location of KAMC is close to a military base area which may restrict the installation of wind turbines with a hub height of more than 50 m. Therefore, there are two options in utilizing wind energy; these are onshore and offshore. The onshore Wind Energy Potential has the following characteristics (Darwish, 2019):

1. Utilization is fairly good.
2. Locations in the central and southern parts (unpopulated) are favourable for wind energy production (500- 27,000 m2).
3. The mean wind speed is 6.9 m/s at 60 meters height and is higher at 100 m (as per the University of Bahrain measurements).
4. Twenty percent of the land area is suitable for the immediate construction of onshore wind farms, including AGU's new project (KAMC).
5. The northern, western, central region, and far southern (east side) parts of the the KAMC site have the highest wind power density (W/m2) – as shown in Fig 6.

Meanwhile, the offshore wind energy utility has the following characteristics (Darwish, 2019):

1. Has a prevalence of mean wind speeds faster than 7.3 m/s (steady).
2. Useful for wind turbines with a blade diameter greater than 100 m with a hub height of 100 m.
3. Has power density larger than 400 W/m2.
4. Can make utilization of more than 30% of the sea area.
5. Provides annual production expectation is 26 TWh, i.e. equivalent to 4 GW capacity (18 hours/ day of operation).

The wind power density (W/m^2) is usually calculated by the knowledge of the wind speed (v) that may sweep an area (A) of the rotors as follows (Al-Salem, et al., 2018) and (FT Exploring 2021):

$$P = \frac{1}{2}\, \eta\, \rho\, A\, v, \qquad (1)$$

where ρ is the mean air density (1.225 kg/m^3 at average atmospheric pressure at sea level and 15˚C) and η is the efficiency which consists of **aerodynamic efficiency** (η_a)**, i.e** The efficiency with which the blades convert available wind power to rotating shaft energy, **mechanical efficiency** (η_m), i.e. due to changes the blade's rotating speed to a speed that better suits the generator due to turbine shaft that drives the gear box and also due to friction in bearings and finaly the **electric efficiency** (η_e), i.e. converting the mechanical energy into electrical energy where the frequency of the current is unsteady and will not match the exact 60 Hz (or 50 Hz in some countries) of the electric power grid. Therefore, Eqn.(10) can be written as:

$$P = \frac{1}{2}\, (\eta_a \times \eta_m \times \eta_e)\, \rho\, A\, v^3 \qquad (2)$$

The combination of these three efficiencies is known as Power Coeffeicient (C_p) ,i.e. $C_p = \eta_b \times \eta_m \times \eta_e$ and ,therefore, Equation 2 can be written as:

$$P = \frac{1}{2}\, C_p\, \rho\, A\, v^3 \qquad (3)$$

In general, ηb = 0.397 (39.7%), ηm = 0.96 and ηe = 0.94 ,which means that $C_p = \eta_b \times \eta_m \times \eta_e$ = 0.397 x 0.96 x 0.94 = 0.358 (35.8%) (FT Exploring 2021)**.** Detailed research on the wind power density on locations in the Arabian Gulf region is presented in Table 1 (Al-Salem, et al., 2018).

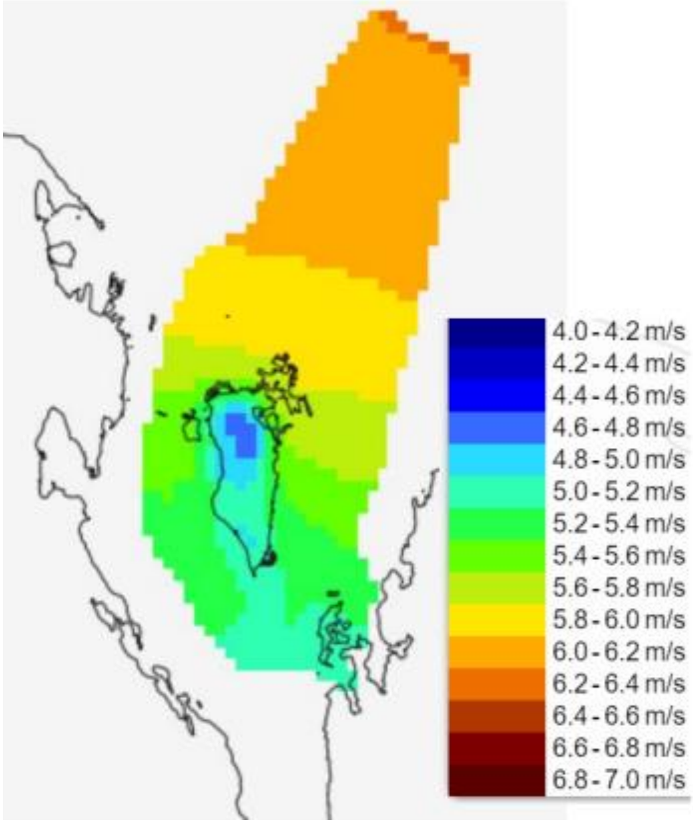


Fig. 3: Bahrain Mesoscale (3km) average wind speed at a height of 50 m. The data were collected from 1994 to 2017 (SEU, 2017).

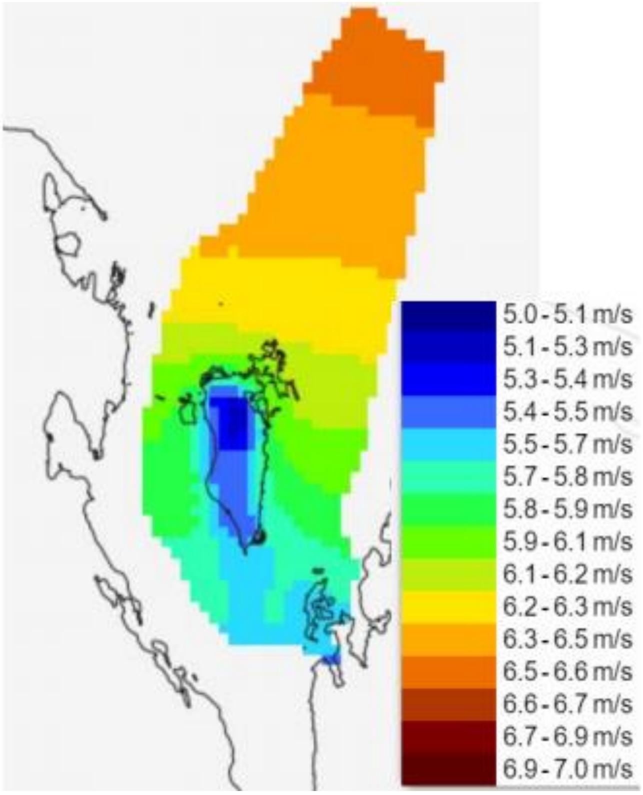


Fig. 4: Bahrain Mesoscale (3km) average wind speed at the height of 70 m. The data were collected from 1994 to 2017 (SEU, 2017).

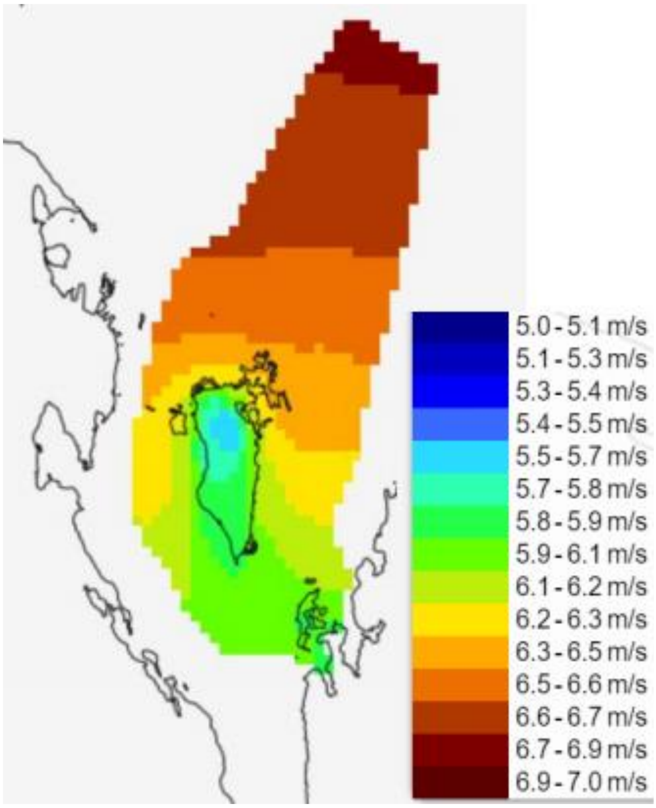


Fig. 5: Bahrain Mesoscale (3km) average wind speed at a height of 100 m. The data were collected from 1994 to . 2017 (SEU, 2017).

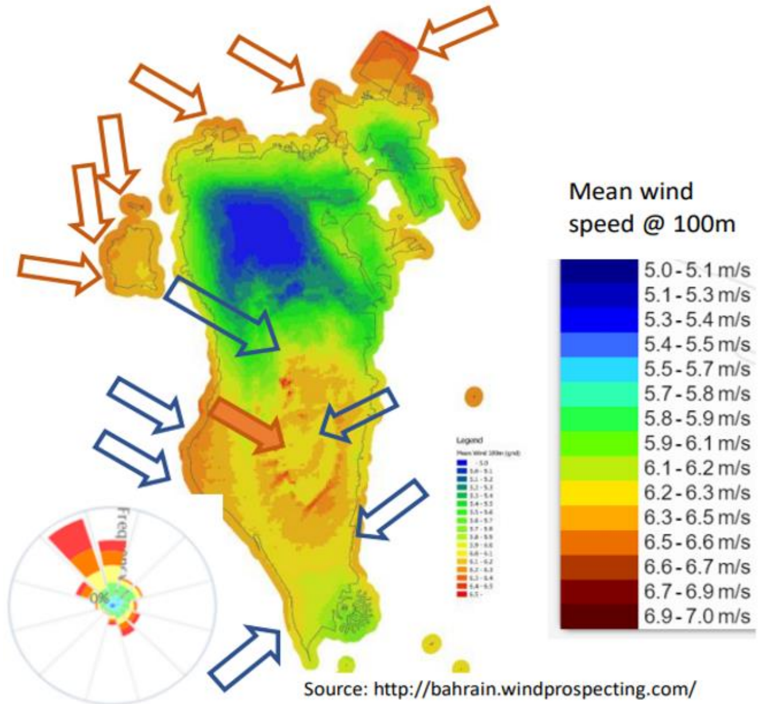


Fig 6: The Characteristics of Onshore Wind Energy Potential (Darwish, 2019).

Table 1: The monthly mean wind power densities (in W/m^2) for the period from 1979-2015 for selected locations in GCC countries at the height of 30 m above sea level (Al-Salem, et al., 2018).

	Kuwait E48° 18′0.0″ N29° 12′0.0″	Saudi Arabia E50° 30′0″ N26° 36′0.0″	Bahrain E50° 48′0.0″ N26° 18′0.0″	Qatar E51° 18′0.0″ N26° 12′0.0″	Unit Arab Emirate E54° 48′0.″ N25° 00′0.0″
January	141	349	385	329	138
February	175	381	428	389	168
March	175	326	356	348	176
April	156	233	247	240	151
May	157	255	282	296	160
Jun	259	405	428	387	115
July	233	272	276	264	110
August	167	184	188	169	77
September	125	154	163	143	71
October	101	166	179	161	64
November	124	279	310	276	107
December	139	329	357	297	113

Since wind speed increases with height, an empirical equation is used to estimate this variation as technology now offers large-scale wind turbines (more than 5 MW), requiring hub heights of more than 100 m. The common equation used for the variation of wind speed with height is the following (Perez, et al., 2004):

$$v_2/v_1 = [\, h_2/h_1]^{\alpha} \qquad (4)$$

where v_1 and v_2 are the mean wind speeds at heights h_1 and h_2, respectively. The exponent (α) depends on factors such as surface roughness and atmospheric stability, as shown in Table 2 (Al-Salem, et al., 2018). The exponent lies in the range 0.0 - 0.5, with the most frequently adopted roughness value being 0.5 with a roughness length of 0.0024. Eq. (2) can be written as follows:

$$v_2 = v_1 \left(\ln[h_2/r] / \ln[h_1/r] \right), \qquad (5)$$

where r is Roughness Length (m), v_2 wind speeds at a selected elevation from ground level h_2.

Table 2: Roughness classes and roughness length (Al-Salem, et al., 2018).

Roughness	Roughness Length m	Energy Index %	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 1250 meters
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 500 meters
2.5	0.2	31	Agricultural land with many house, shrubs and plants, or 8 meter tall sheltering hedgerows with a distance of approx. 250 meters
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings

Table 3 shows the mean monthly wind power density at an elevation of 30m for a selected location over the Arabian Gulf waters for the period of 1979-2015 (Al-Salem, et al., 2018). According to this table, the central region of the Arabian Gulf (Saudi Arabia, Bahrain and Qatar) has a good wind power regime for the economical installation of large-scale wind power production, lying in Class 2. However, the wind power potential is low during September and October.

Table 3: The Monthly mean wind power densities (W/m^2) and the annual wind Energy (kWh/m^2) for the period of 1979-2015 for selected locations in the Arabian Gulf at a hub height of 30 m above sea level (Al-Salem, et al., 2018).

G.C.C. Countries	Map Location	Mean Annual WPD w/m^2	Total Annual Energy (8760 hr) w/m^2
Kuwait	E48° 18′0.0″ N29° 12′0.0″	166	1454
Saudi Arabia	E50° 30′0″ N26° 36′0.0″	277	2426
Bahrain	E50° 28′0.0″ N26° 18′0.0″	300	2628

Qatar	E51° 18′0.0″ N26° 12′0.0″	275	2409
Unit Arab Emirate	E54° 48′0.″ N25° 00′0.0″	120	1051

The more available wind speed, the more economical the wind energy use becomes. (Alnaser and Alnaser, 2011) has also worked out the cost of power production in the GCC region from wind power plants. The cost of 1 kWh from wind electricity in the GCC may be from USD¢10 (38 fils), for a large turbine ≈ 2 MW at 80 m height with good wind speed, to USD¢ 15 (57 fils), for a large turbine ≈ 2 MW at 80 m height with modest wind speed, while the cost of kWh from grid-connected wind farm plant (20 MW) — with a cost of USD 38.6 million (BD14.5 million) —is US ¢ 6.7/kWh to USD¢ 8.8/kWh (26 fils to 33 fils), depending on the location of the wind farm. These prices may become less by 20% to 40% as the PV technology has fallen by 100% or more for the application in the GCC region.

Bahrain can use offshore wind to meet the target, i.e. generating 5% of capacity from renewable sources by 2025 and 10% by 2035, as detailed in the National Renewable Energy Action Plan (NREAP 2019 and SEU,2017). Ten favourable wind farm areas were identified in Bahrain's territorial waters, representing about 4% of the total maritime area, and capable of supplying 2.68 TWh/year of wind energy or almost 10% of the Kingdom's annual electricity consumption (Elgabiri, et al., 2020). The KAMC site is located in the southern part of Bahrain, where if offshore wind turbines are used, then the wind speed, at 150 m above sea level, would be about 6.8 m/s. This means a 1 MW wind - turbine will provide, annually, 4,380,000 kWh, if we assume that C_P of the wind turbine is 50% (very optimistic). This is enough to power 73 houses, each consuming a monthly average of 5,000 kWh of electricity. In their assessments (Elgabiri, et al., 2020), they used Vesta V150 for power calculations (Vestas Wind Systems, 2018). In low wind sites, it is better to choose a turbine with a large rotor diameter and a smaller generator which even at low speeds allows enough torque to be produced by the rotor to drive the generator (Schaarup and Krogh, 2001).

The Vesta V150 has a rated power of 4.2 MW with a rotor diameter of 150 m and a specific rotor power of 237.68 W/m2 with a nameplate capacity of each suitable wind farm area is calculated by multiplying the number of turbines by the rated power (4.2 MW). The annual energy production per turbine is obtained from the manufacturers' manual (Vestas Wind Systems, 2018), assuming 100% availability, 0% losses, standard air density and yearly average wind speed of 7.3 m/s. Two CPs were employed to estimate the annual energy production. First, the capacity factor was calculated from the manufacturer's annual energy yield for the Vesta V150 divided by the rated energy yield (4.2 MW x 365 x 24). Second, because the results seem somewhat optimistic, $C_P = 44.8$ % is chosen because it matches with the best European conditions, while a bias-corrected simulated C_P = 30% was obtained from RenewablesUK (RenewableUK, n.d.). This is nearly the same as that estimated by (Al-Jowder, 2009) who took into consideration Bahrain's specific air density in the equation.

Algabiri work (Elgabiri, et al., 2020) found that an offshore area of 407 km^2 of Bahrain maritime territory can provide sufficient space for the installation of 100's of turbines and 1.52 GW of wind capacity. The estimated number of turbines and annual energy yield -

under three CPs - are shown in Table 4, where it can be clearly seen that the C_P has a significant influence on eventual energy production.

Table 4: Energy production under 3 coefficients of performance, C_P, (capacity factors C_F) (Elgabiri, et al., 2020).

Average wind speed (m/s)	Number of turbines	Manufacturer's energy production per turbine (GWh/year)	Total energy production (TWh/year) capacity factor = 1	Total energy production (TWh/year) capacity factor = 0.448[2]	Total energy production (TWh/year) capacity factor = 0.3[b]
7.3	362	16.5	13.3	5.97	3.99

CF: capacity factors.
[2]CF = manufacturers' annual energy yield divided by the rated energy yield.
[b]CF from Renewables.ninja.

Bahrain Experience with 2 MW installed Wind Turbines

In 2018, EWA (EWA, 2018) had set up the experimental plant to produce electricity using solar and wind energy with a total capacity of 5 MW on a land of 12 hectares. The project includes installing 3 MW solar cells, the installation of two 2 MW wind turbines and a control operation and a control building. The total cost of these projects is BD 6.5 million (US$ 16.9 million). The plant is to be connected to the 11- kV power grid to take advantage of the electric power produced - Fig 7. The two wind turbines were installed with no constructional difficulties in terrestrial issues. These projects are part of Bahrain's 2030 economic vision of reducing carbon dioxide emissions to preserve the environment.

Fig. 7: The two installed wind turbines (@ nearly 1 MW) installed at Aldore site, Kingdom of Bahrain, as an experimental project to evaluate the use of wind electricity.

The current economics of wind power favours onshore wind. The capital requirements for an onshore wind power plant are about USD 1,700/kW (SEU, 2017). Wind turbines have an average lifetime of about 25-30 years. The main cost component in a wind project is the cost of a wind turbine, which accounts for about 70% of the total cost (SEU, 2017). In contrast, the operation and maintenance costs of onshore wind range between 20%-25% of the levelized cost of electricity (LCOE) (SEU, 2017) -which depends mainly on the availability and strength, i.e. in rich wind regions, the LCOE can be as low as 0.03 - 0.04 US¢/kWh (11 fils to 15 fils) (IRENA, 2016). Table 5 illustrates the weighted average LCOE in different parts of the world.

Table 5: The Levelized cost of electricity (LCOE) Onshore Wind by Region, 2014-2015 (Darwish, 2019).

Country	Weighted average LCOE (USD/kWh)	Weighted average LCOE (fils/kWh)[1]
China	0.053	20
Other Asia	0.12	45
North America	0.06	23
Europe	0.07	26
India	0.08	30
Central and South America	0.08 - 0.10	30 - 38
Oceania and Africa	0.08 - 0.10	30 - 38

Results and Discussion

The planned King Abdulla Medical City (KAMC) will be built on a land area of 1 million m^2. The availability of the roof area is very large. It can be used for rooftop PV solar panels as well as for building-integrated wind turbines (BIWT). The available roof areas are as follows:

Outpatient Building:	23,048 m^2
Clinic Building:	23,923 m^2
Inpatient Building (Wards Tower)	32,195 m^2
Service Building:	5,510 m^2
Parking Building:	17,808 m^2
Number of Parking spaces:	(562 parking spaces)

The planned electricity needed to power the whole of the Medical City is 20.08 MW, while the planned solar PV installation is 948 KW_p . Fig.8 shows a model of this great important project.

Fig.8 : Model of KAMC by Arabian Gulf University

KAMC is planned to be constructed on an area of 1 million m^2 at Durrat Al Bahrain – in the extreme southern end of Bahrain on an artificial island with rich solar and wind potential. The contribution of solar is about 4%. A 1 MW wind turbine may produce approximately 2,221,000 kWh annually, with a payback of 6 years while saving 1,710 ton annually. The location of KAMC is relatively close to the seashore (about 1 km from the east shore and 2 km from the west shore), i.e. exposed to night and day sea breeze. No major construction may obstruct the wind. The location's only downfall is that it is within proximity to Sheikh Isa Air Base to the northern side of the Medical City, which may restrict using wind turbines at hub heights of no more than 100 m.

Fig. 9: The Location of the Planned KAMC Project

It is well-known that the amount of wind energy that can be generated depends on the size of the wind turbine, C_P, average wind speed of the location and the annual average wind speed at the site. Table 6 presents the annual energy production in MWh for a range of turbines from 100 kW to 3.5 MW. For 1 MW wind turbine, the expected C_P of these machines may be as low as 16.5 % for an average speed of 5m/s and as high as 38.0 % for an average wind speed of 7.8 m/s (refer to Eqn 3). These figures derived worked published by FT Exploring Science and Technology (FT Exploring 2021).

According to Table 6 (Renewables First, 2021), if AGU installs a wind turbine of 1 MW capacity (horizontal axis) at KAMC, it will be able to produce, annually, around 2,221 MWh (2,221,000 kWh) of wind electricity, i.e., C_P= 25.5 %. This amount of energy will be enough to power 37 houses with average monthly electricity consumption of 5,000 kWh - which is the average household electricity consumption in Bahrain. This amount will represent 5% of the electricity planned needed power from the conventional energy source (natural gas). It will save an annual emission of CO_2 equivalent to 1,710 tons (1kWh from natural gas = 0.77 kg of CO_2). It will also save 700 ton of oil (1 kWh of oil burnt = 0.313 kg of oil (Alsabbagha, et al., 2021)).

Table 6: The annual energy production for a range of turbines from 100 kW to 3.5 MW retrived from Reneable First (Renewables First, 2021).

Power Output	Example	Annual Energy Capture (MWh) for the following Annual Average Wind speeds in m/s							
		5.0	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**
100 kW	NorventonED-100	176	220	264	306	346	382	413	441
800 kW	EnerconE53	1,208	1,521	1,841	2,160	2,469	2,764	*n/a	n/a
1 MW	EWT DW61	1,450	1,832	2,221	2,609	2,986	3,345	*n/a	n/a
3 MW	EnerconE82	2,941	3,788	4,698	5,647	6,611	7,570	8,507	9,407
3.5 MW	Enercon E126 EP3	5,972	7,388	8,816	10,214	11,554	12,815	13,986	15,058

i- The Cost of Each kWh Produced

Assuming that the cost of 1 MW wind turbine is USD 1.0 million (BD 0.378 million) and the lifetime of the wind turbine is 25 years – as per previous project been made in Bahrain but not completed -then the cost of each kWh can be estimated using Eqn. (6). If the cost of 1MW is BD 0.378 million, the lifetime of each wind turbine is 25 years, and the annually produced energy is 2,221,000 kWh -which will produce 55,525,000 kWh in 25 years - then the cost of each 1kWh will be **7** fils only- which is cheaper than the purchase cost from the utility (29 fils).

Cost of each kWh in file = {(cost of the wind turbine in BD)/(value energy produced during the lifetime of the wind turbine in kWh} x 1000 (6)

It must be indicated that this a very approximate calculation, as usually, economists use the net present value method (NPV) (Haji, et al., 2019). This requires knowing the cash flow (USD1 million = BD.378,000) at present (V_0) and the estimated cash flow value at the end (V_t) of the period (t) and the discount or inflation rate (d), i.e.,

$$NPV = V_0 + \sum \{ (V_t) / (1+d)^{t} \} \quad (7)$$

This annual amount of energy from 1 MW (which is 2,221 MWh) will be enough to power about 37 houses with 5,000 kWh/month electricity consumption.
The previous calculations were made based on a wind speed of 6 m/s with an operation range for wind speed from 4 m/s to 22 m/s, i.e cut in speed 3.9 m/s and cut out speed 22.1 m/s, with a rated speed of 16 m/s. However, if the hub of the wind turbine at the height of 150 m, then the wind speed at Durrat Al Bahrain will be about 6.8 m/s -where the energy produced will be higher as well as the cost of 1kWh will be lower. On the other hand, the restrictions due to KAMC's proximity to the airport base will only allow for height hubs to be of only 50 m, and hence the average wind speed will be about 5.7 m/s. This can be understood from Eqn. (5), and subsequently, the energy produced will be lower, and thus the cost of 1kWh will be higher. The work of (Elgabiri, et al., 2020), indicates that the wind speed for 150 m height in Bahrain's maritime area ranges from 6.3 to 7.5 m/s.

Meanwhile, the study conducted by (Al-Salem et al., 2018) shows that an annual wind power density of 2,628 kWh/m^2 can be attained. This means if the rotor size (r) for 1 MW is about 30 m at the height of about 120 m, then the obtained energy will be 7,428,729 kWh (= 2,628 x πx r^2). Assuming that the turbine's efficiency (or C_P) is about 40%, then the obtained energy will be 2,971,492 kWh which is close to that mentioned in (Algabiri et al., 2020).

Suppose AGU opts to install 5 MW to supply KAMC with green electricity, which represents a share of 25% of the electricity needed. In that case, the investment cost per kW is about USD 5 million (BD 1.89 million) – or cheaper. These 5 MW wind turbines will produce approximately 11,105,000 kWh annually.

ii. The Pay - Back Period

According to the site of (Windustry, 2021), the wind turbines under 100 kW cost roughly USD 3,000 to USD8,000 per kW of capacity (BD 1,134 to BD 3,024). A 10-kW machine (the size needed to power a large home) might have an installed cost of USD50,000 to USD80,000 (BD18,900 to BD 30,240). The cost of Commercial Wind Turbines - for a utility-scale - range from about USD1.3 million to USD 2.2 million per MW (BD. 0.491 million to BD. 0.832 million) of nameplate capacity installed. Most of the commercial-scale turbines installed today are 2 MW in size and cost roughly USD 3 to 4 million (BD. 1.134 million to BD. 1.512 million) in installation. The variation in the cost is due to the charges covering the wind resource assessment, site analysis expenses, construction expenses, permitting and interconnection studies, utility system upgrades, transformers, protection and metering equipment, insurance, operations, warranty, maintenance, repair and consultation fees. Other factors that will impact your project economics include taxes and incentives (Windustry, 2021).

If the cost of 1 MW wind turbine is USD 1.0 million (BD 0.378 million), the payback period can be approximated using the following equation:

$$\text{Payback period} = (\text{cost of wind turbine}) / (\text{value of electricity produced annually}) \quad (8)$$

Therefore, if the cost is BD 0.378 million and the cost of the annually produced wind electricity is BD 64,409 (taking the cost of 1 kWh = 29 fils), then the payback period will be 5.88 years (nearly 6 years). Eqn (8) is used in most (if not all) in feasibility studies as it approved to be simple, acceptable and close to complex calculations.

iii- Economic Analysis of Installing a 1 MW Wind Turbine at KAMC

The previous calculations are based on the experience of two wind turbines installed in Bahrain as a pilot study and previous work literature. Many assumptions were made herein, which may not be close to the actual situation in installing a 1MW - wind turbine (or more) at KAMC. Therefore, two main scenarios (each consist of 3 sub- scenarios) are provided to assess the economy of installing a 1 MW wind turbine.

Scenario 1: This will assume that the lifetime of the wind turbine is 30 years, the inflation rate is 3.5% annually, the investment cost is BD378,000 (USD = 1 million), the yearly expected production of wind electricity for a 1 MW wind turbine is 3,504,000 kWh, the coefficient of performance is 40%. The reason chosing the inflation at a rate of 3.5% because it is the most frequeqtly chosed figure in all banks and other financial sectors in Bahrain. This is supported by a study on Bahrain Inflation rate from 1986 to 2026 published in April 2021 which clearly shows an average of about 3.5% (O'Neill ,2021). Scenario 1 A is for a 1% annual reduction in the performance due to wear - and - tear, Scenario 1 B for a 0.5% annual reduction in the performance due to wear - and - tear. In scenario 1 C, the performance remains constant.

Scenario 2: This will assume that the lifetime of wind turbine is 30 years, the inflation rate is 3.5% annually, the investment cost is BD. 378,000 (USD = 1 million), the yearly expected production of wind electricity for a 1 MW wind turbine is 3,504,000 kWh, the coefficient of performance is 30%. Scenario 2 A is for a 1% annual reduction in the performance due to wear - and - tear. Scenario 2 B for a 0.5% annual reduction in the performance due to wear - and - tear, and in scenario 2 C the performance remains constant.

The assumption of production of 3,504,000 kWh of electricity from the 1 MW wind turbine, in both scenarios, is based on wind speed data measured at Durrat Al Bahrain (about 1 km south of the KAMC) at 8 m height (refer to Table 7 and Fig 10). Since the wind speed varies with height (Eqn.(5)) – which depends on the exponent α – then referring to Table 2, the suitable value for the location is $\alpha = 0.2$ as the most frequently adopted roughness value will be 0.5.

Tables 8-10 show the outcome of Scenario 1A, 1B and 1C, while Tables 11-13 show the outcome of 2A,2B and 2C. Table 14 summarizes the results of the economic analysis of the two scenarios.

Table 7: Actual measurement wind speed data and direction at the height of 8 m at Durrat Al Bahrain (Latitude 25° 57′ 27″ N and Longitude 50° 28′ 25″ E) for the period from 2016 – 2020 provided by the Meteorological Directorate, Kingdom of Bahrain.

Month	Mean Speed (m/s)	Prevailing Direction	Max. speed (m/s)
January	4.38	315°	18
February	4.40	315°	19
March	4.25	360°	24
April	4.40	45°	21
May	4.10	45°	23
June	4.85	315°	22
July	4.20	45°	16.5
August	3.95	45°	16.5
September	3.40	45°	15.5
October	3.50	45°	19.5
November	3.75	315°	18.5
December	4.05	315°	15
Average	**8.20**	**4°**	**14.35**

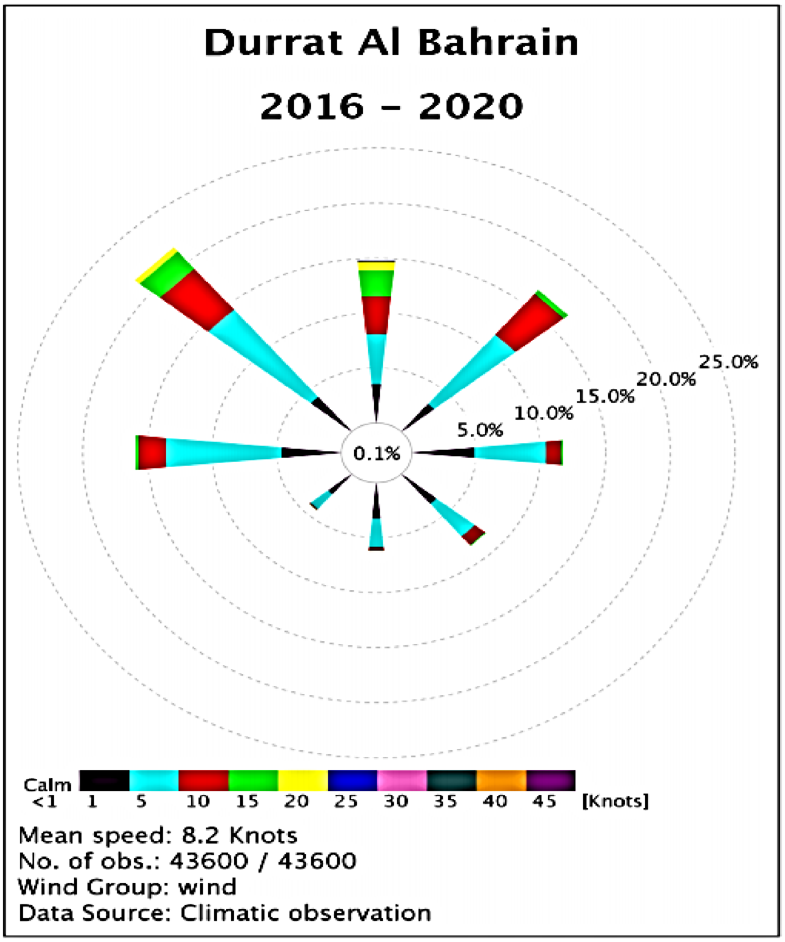


Fig 10: The wind frequency of the wind speed and direction measured at the height of 8m at Durrat Al Bahrain (Latitude 25° 57′ 27″ N and Longitude 50° 28′ 25″ E) for the period from 2016 – 2020. Data are provided by the Meteorological Directorate, Kingdom of Bahrain.

Table 8: Outcome of Scenario 1A for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 1A	
Investment =	-BD. 378,000 ; Lifetime of the turbine = 30 years.
Expected Unit production [kWh]	3,504,000 ; CP = 40% ; Performance reduces annually by 1%, due to wear - and - tear
Cost of government Unit price of kWh = BD 0.029 (29 fils); ; Inflation rate (d) =3.5%	

Years	Production (kWh)	Estimated Cash Flow (BD)	Present Value, PV (BD)
1	3,504,000	101,616	98,180
2	3,468,960	100,600	97,198
3	3,434,270	99,594	96,226
4	3,399,928	98,598	95,264
5	3,365,928	97,612	94,311
6	3,332,269	96,636	93,368
7	3,298,946	95,669	92,434
8	3,265,957	94,713	91,510
9	3,233,297	93,766	90,595
10	3,200,964	92,828	89,689
11	3,168,955	91,900	88,792
12	3,137,265	90,981	87,904
13	3,105,893	90,071	87,025
14	3,074,834	89,170	86,155
15	3,044,085	88,278	85,293
16	3,013,644	87,396	84,440
17	2,983,508	86,522	83,596
18	2,953,673	85,657	82,760
19	2,924,136	84,800	81,932
20	2,894,895	83,952	81,113
21	2,865,946	83,112	80,302
22	2,837,286	82,281	79,499
23	2,808,914	81,458	78,704
24	2,780,824	80,644	77,917
25	2,753,016	79,837	77,138
26	2,725,486	79,039	76,366
27	2,698,231	78,249	75,603
28	2,671,249	77,466	74,847
29	2,644,536	76,692	74,098
30	2,618,091	75,925	73,357
Sum	91,208,989	2,645,061	2,555,614
Net Present Value, NPV		BD 12,177,614	

4.1 Fils per kWh , considering the production (column 1) and investment (BD378,000)	28.0 Fils per kWh , considering the production (column 1) and sum of PV (BD. 2,555,614)

Conclusion: Installing a 1 MW wind turbine at the cost of BD.378,000 will save AGU, paying nearly BD 2.2 million for supplying solar electricity for 30 yrs. (**NPV = BD 2.2 million**).

Table 9: Outcome of Scenario 1B for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 1B	
Investment =	-BHD 378,000 ; Lifetime of the turbine = 30 years.
Expected Unit production [kWh]	3,504,000 ; CP = 40% ; Performance reduces annually by 0.5 % due to wear - and - tear .
Cost of government Unit price of kWh = BD 0.029 (29 fils); ; Inflation rate (d) = 3.5%	

Years	Production (kWh)	Estimated Cash Flow (BD)	Present Value, PV (BD)
1	3,504,000	101,616	98,180
2	3,486,480	101,108	97,689
3	3,469,048	100,602	97,200
4	3,451,702	100,099	96,714
5	3,434,444	99,599	96,231
6	3,417,272	99,101	95,750
7	3,400,185	98,605	95,271
8	3,383,184	98,112	94,795
9	3,366,268	97,622	94,321
10	3,349,437	97,134	93,849
11	3,332,690	96,648	93,380
12	3,316,026	96,165	92,913
13	3,299,446	95,684	92,448
14	3,282,949	95,206	91,986
15	3,266,534	94,729	91,526
16	3,250,202	94,256	91,068
17	3,233,951	93,785	90,613
18	3,217,781	93,316	90,160
19	3,201,692	92,849	89,709
20	3,185,684	92,385	89,261
21	3,169,755	91,923	88,814
22	3,153,906	91,463	88,370
23	3,138,137	91,006	87,928
24	3,122,446	90,551	87,489
25	3,106,834	90,098	87,051
26	3,091,300	89,648	86,616
27	3,075,843	89,199	86,183
28	3,060,464	88,753	85,752
29	3,045,162	88,310	85,323
30	3,029,936	87,868	84,897
SUM	97,842,758	2,837,440	2,741,488
Net Present Value, NPV		BD 2,363,488	

3.9 Fils per kWh, considering the production (column 1) and investment (BD. 378,000)	28.0 Fils per kWh,considering the production (column 1) and sum of PV (BD 2,741,488).

Conclusion: Installing 1 MW wind turbine at the cost of BD. 378,000 will save AGU, paying nearly BD 2.4 million for supplying solar electricity for 30 yrs. (**NPV = BD 2.4 million**).

Table 10: Outcome of Scenario 1C for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 1C	
Investment =	-BHD 378,000 ; Lifetime of the turbine = 30 years.
Expected Unit production [kWh]	3,504,000 ; CP = 40% ; Performance remains constant
Cost of government Unit price of kWh = BD 0.029 (29 fils); ; Inflation rate (d) = 3.5%;	

Years	Production (kWh)	Estimated Cash Flow (BD)	NPV (BD)
1	3,504,000	101,616	98,180
2	3,504,000	101,616	98,180
3	3,504,000	101,616	98,180
4	3,504,000	101,616	98,180
5	3,504,000	101,616	98,180
6	3,504,000	101,616	98,180
7	3,504,000	101,616	98,180
8	3,504,000	101,616	98,180
9	3,504,000	101,616	98,180
10	3,504,000	101,616	98,180
11	3,504,000	101,616	98,180
12	3,504,000	101,616	98,180
13	3,504,000	101,616	98,180
14	3,504,000	101,616	98,180
15	3,504,000	101,616	98,180
16	3,504,000	101,616	98,180
17	3,504,000	101,616	98,180
18	3,504,000	101,616	98,180
19	3,504,000	101,616	98,180
20	3,504,000	101,616	98,180
21	3,504,000	101,616	98,180
22	3,504,000	101,616	98,180
23	3,504,000	101,616	98,180
24	3,504,000	101,616	98,180
25	3,504,000	101,616	98,180
26	3,504,000	101,616	98,180
27	3,504,000	101,616	98,180
28	3,504,000	101,616	98,180
29	3,504,000	101,616	98,180
30	3,504,000	101,616	98,180
SUM	105,120,000	3,048,480	2,945,391
	NPV	BD . 2,567,391	

3.6 Fils per kWh , considering the production (column 1) and investment (BD.378,000).	28.0 Fils per kWh, considering the production (column 1) and sum of PV (BD 2,945,391).

Conclusion: Installing 1 MW wind turbine at the cost of BD378000 will save AGU paying BD 2.6 million for supplying solar electricity for 30 yrs. NPV = BD 2.6 million (**NPV = BD 2.6 million**).

Table 11: Outcome of Scenario 2A for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 2 A	
Investment =	-BHD 378,000 ; Time Life of the turbine = 30 years.
Expected Unit production [kWh]	3,504,000 ; CP = 30% ; Performance reduces annually by 1.0 % due to wear - and - tear.
Cost of government Unit price of kWh = BD 0.029 (29 fils); ; Inflation rate (d) =3.5%	

Years	Production (kWh)	Estimated Cash Flow (BD)	Present Value , PV (BD)
1	2,628,000	76,212	73,635
2	2,601,720	75,450	72,898
3	2,575,703	74,695	72,169
4	2,549,946	73,948	71,448
5	2,524,446	73,209	70,733
6	2,499,202	72,477	70,026
7	2,474,210	71,752	69,326
8	2,449,468	71,035	68,632
9	2,424,973	70,324	67,946
10	2,400,723	69,621	67,267
11	2,376,716	68,925	66,594
12	2,352,949	68,236	65,928
13	2,329,419	67,553	65,269
14	2,306,125	66,878	64,616
15	2,283,064	66,209	63,970
16	2,260,233	65,547	63,330
17	2,237,631	64,891	62,697
18	2,215,255	64,242	62,070
19	2,193,102	63,600	61,449
20	2,171,171	62,964	60,835
21	2,149,459	62,334	60,226
22	2,127,965	61,711	59,624
23	2,106,685	61,094	59,028
24	2,085,618	60,483	58,438
25	2,064,762	59,878	57,853
26	2,044,115	59,279	57,275
27	2,023,673	58,687	56,702
28	2,003,437	58,100	56,135
29	1,983,402	57,519	55,574
30	1,963,568	56,943	55,018
SUM	68,406,742	1,983,796	1,916,711
Net Present Value, NPV		BD . 1,538,711	

5.5 Fils per kWh, considering the production (column 1) and investment (BD.378,000).	28.0 Fils per kWh, considering the production (column 1) and the sum of PV (BD 1,916,711).

Conclusion: Installing 1 MW wind turbine at the cost of BD.378,000 will save AGU, paying nearly BD 1.5 million for supplying solar electricity for 30 yrs. (**NPV = BD 1.5 million**)

Table 12: Outcome of Scenario 2B for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 2B			
Investment =	- BD 378,000 ; Lifetime of the turbine = 30 years.		
Expected Unit production [kWh]	3,504,000 ; CP = 30% ; Performance reduces annually by 0.5 % due to wear - and - tear.		
Cost of government Unit price of kWh = BD 0.029 (29 fils); ; Inflation rate (d) = 3.5%			
Years	Production (kWh)	Estimated Cash Flow (BD)	Present Value ,PV (BD)
1	2,628,000	76,212	73,635
2	2,614,860	75,831	73,267
3	2,601,786	75,452	72,900
4	2,588,777	75,075	72,536
5	2,575,833	74,699	72,173
6	2,562,954	74,326	71,812
7	2,550,139	73,954	71,453
8	2,537,388	73,584	71,096
9	2,524,701	73,216	70,740
10	2,512,078	72,850	70,387
11	2,499,517	72,486	70,035
12	2,487,020	72,124	69,685
13	2,474,585	71,763	69,336
14	2,462,212	71,404	68,990
15	2,449,901	71,047	68,645
16	2,437,651	70,692	68,301
17	2,425,463	70,338	67,960
18	2,413,336	69,987	67,620
19	2,401,269	69,637	67,282
20	2,389,263	69,289	66,946
21	2,377,316	68,942	66,611
22	2,365,430	68,597	66,278
23	2,353,603	68,254	65,946
24	2,341,835	67,913	65,617
25	2,330,125	67,574	65,289
26	2,318,475	67,236	64,962
27	2,306,882	66,900	64,637
28	2,295,348	66,565	64,314
29	2,283,871	66,232	63,993
30	2,272,452	65,901	63,673
Sum	73,382,069	2,128,080	2,056,116
Net Present Value, NPV		BD . 1,678,116	
5.2 Fils per kWh, considering the production (column 1) and investment (BD.378,000).		28.0 Fils per kWh, considering the production (column 1) and the sum of PV (BD 2,056,116).	

Conclusion: Installing 1 MW wind turbine at the cost of BD. 378000 will save AGU paying BD 1.7 million for supplying solar electricity for 30 yrs. (**NPV = BD 1.7 million**).

Table 13: Outcome of Scenario 2C for the economic assessment of 1 MW wind turbine to supply part of the wind electricity to KAMC by AGU, Kingdom of Bahrain.

Scenario 2C			
Investment =	-BHD 378,000 ; Lifetime of the turbine = 30 years.		
Expected Unit production [kWh]	3,504,000 ; CP = 30% ; Performance remains constant.		
Cost of government Unit price of kWh = BD 0.029 (29 fils); Inflation rate (d) =3.5%			
Years	Production (kWh)	Estimated Cash Flow (BD)	PV (BD)
1	2,628,000	76,212	73,635
2	2,628,000	76,212	73,635
3	2,628,000	76,212	73,635
4	2,628,000	76,212	73,635
5	2,628,000	76,212	73,635
6	2,628,000	76,212	73,635
7	2,628,000	76,212	73,635
8	2,628,000	76,212	73,635
9	2,628,000	76,212	73,635
10	2,628,000	76,212	73,635
11	2,628,000	76,212	73,635
12	2,628,000	76,212	73,635
13	2,628,000	76,212	73,635
14	2,628,000	76,212	73,635
15	2,628,000	76,212	73,635
16	2,628,000	76,212	73,635
17	2,628,000	76,212	73,635
18	2,628,000	76,212	73,635
19	2,628,000	76,212	73,635
20	2,628,000	76,212	73,635
21	2,628,000	76,212	73,635
22	2,628,000	76,212	73,635
23	2,628,000	76,212	73,635
24	2,628,000	76,212	73,635
25	2,628,000	76,212	73,635
26	2,628,000	76,212	73,635
27	2,628,000	76,212	73,635
28	2,628,000	76,212	73,635
29	2,628,000	76,212	73,635
30	2,628,000	76,212	73,635
SUM	78,840,000	2,286,360	2,209,043
Net Present Value, NPV		BD . 1,831,043	
4.8 Fils per kWh , considering the production (column 1) and investment (BD. 378,000)		28.0 Fils per kWh, considering the production (column 1) and the sum of PV (BD 2,209,043)	

Conclusion: Installing 1 MW wind turbine at the cost of BD 378,000 will save AGU paying BD 1.8 million for supplying solar electricity for 30 yrs. **(NPV = BD 1.8 million)**.

Table 14: Comparison of the Outcome of Scenarios 1 and 2 (along with sub-scenarios) for the economic assessment of 1 MW wind turbine to supply part of wind electricity to KAMC by AGU, Kingdom of Bahrain.

Category	Scenario 1		Category	Scenario 2	
A	CP = 40% ; Performance reduces annually by 1.0 % due to wear - and - tear.	Net Present Value, NPV BD 2,177,614 Cost of kWh = 4.1 fils (considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils (considering the production in column 1 and sum of PV (BD. 2,555,614).	A	CP = 30% ; Performance reduces annually by 1.0 % due to wear - and - tear.	Net Present Value, NPV BD 1,538,711 Cost of kWh = 5.5 fils (considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils, considering the production in column 1 and the sum of PV (BD. 1,916,711).
B	CP = 40% ; Performance reduces annually by 0.5% due to wear - and - tear.	Net Present Value, NPV BD . 2,363,488 Cost of kWh = 3.9 fils (considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils (considering the production in column 1 and sum of PV (BD. 2,741,488).	B	CP = 30% ; Performance reduces annually by 0.5% due to wear - and - tear.	Net Present Value, NPV BD 1,678,116 Cost of kWh = 5.2 fils , considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils ,considering the production in column 1 and sum of PV (BD. 2,056,116).
C	CP = 40% ; Performance remains constant	Net Present Value, NPV BD . 2,567,391 Cost of kWh = 3.6 fils (considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils (considering the production in column 1 and sum of PV (BD.2,945,391).	C	CP = 30% ; Performance remains constant	Net Present Value, NPV BD 1,831,043 Cost of kWh = 4.8 fils (considering the production in column 1 and initial investment (BD. 378,000). Cost of kWh = 28 fils (considering the production in column 1 and sum of PV (BD. 2,209,043).

Herein, the exciting finding is that the NPV is always positive even when the C_P was 30% and the wind turbine production was assumed to reduce annually by 1% (30 % after 30 years). The NPV in such a scenario (Scenario: 2A) is BD. 1.6 million (US$ 4.0 million) with 28 fils/kWh (USD¢7.4)-in using the sum of produced energy from the turbine after the period of 30 years -where it has lost 30% of its performance compared to its initial operation and the inflation rate increases 3.5% annually. This means that the summation of the Present Value (PV) of the annually produced electricity from the wind turbine will be BD 1.92 million (USD 3.84 million) @ 29 fils (US ¢7.6), which will be 68,406,742 kWh. However, in this scenario that we have considered, kWh production from the turbine without considering the inflation rate would make the cost per kWh to be only 5.5 fils (US¢ 1.5). For Scenario 1A, which assumes the coefficient of performance (C_P) to be 40%, the cost of kWh is 28 fils (US¢ 0.95) when considering the inflation, while without it, the cost would only be 4.1 fils (US¢ 1.1) per kWh. The lowest cost per kWh in these scenarios (3.6 fils = US¢0.95) is in scenario 1C where it is calculated by dividing the cost of investment (BD 0.378 million = USD 1 million) by the electricity produced by the wind turbine, assuming that it will always produce the same electricity units in its operation for 30 years. Table 14 is self-explanatory for the two scenarios.

iV- The Use of Vertical Axis Wind Turbine and Building Integrated Wind Turbine (BIWT) for KAMC

Vertical axis wind turbines are wind turbines with rotors that rotate around a vertical shaft with vertically oriented blades. The electricity produced is by utilizing wind power in the same way that horizontal axis wind turbines do. There are two types of vertical axis wind turbines. Both models (Luvsie, 2021) may be used for KAMC. The Savonius wind turbines have blades built around the vertical shaft in a helix form. A wide, solid wind-receiving area of the blades is one of the most significant features of a Savonius wind turbine (Luvsie, 2021). During operation, Savonius wind turbines can turn as fast as the wind speed. The classic Darrieus turbines have long, curved wings with each end attached to the top and bottom of the rotor shaft. Other model Darrieus turbines have three straight wings connected to the shaft parallelly. Once the rotation starts on the wings, the wind turbine can accelerate and rotate faster than the wind speed, making them a better option. An example of vertical axis wind turbines is a 6 kW to 15 kW installed at the height of 9 m (Fig 11), and its frontal area is 5 x 3 m with an approximate cost of US$ 1,000/kW (Darwish, 2019).

BIWT is the integration of wind turbines within the body of the building, either at the roof or within the structure. An example of BIWT within the building structure is Bahrain's World Trade Center building with three parallel wind turbines with capacity in each turbine being rated at 225 kW, totalling 675 kW of the wind power capacity. Each of these turbines measures 29 m in diameter. These wind turbines are expected to provide 11% to 15% of the main tower's total power consumption, or approximately 1.1 to 1.3 GWh a year, equivalent to providing the lighting for about 300 homes, thereby reducing carbon emissions average of 55 ton per year. The three turbines were turned on for the first time on 8 April 2008. They are expected to operate 50% of the time on an average day.

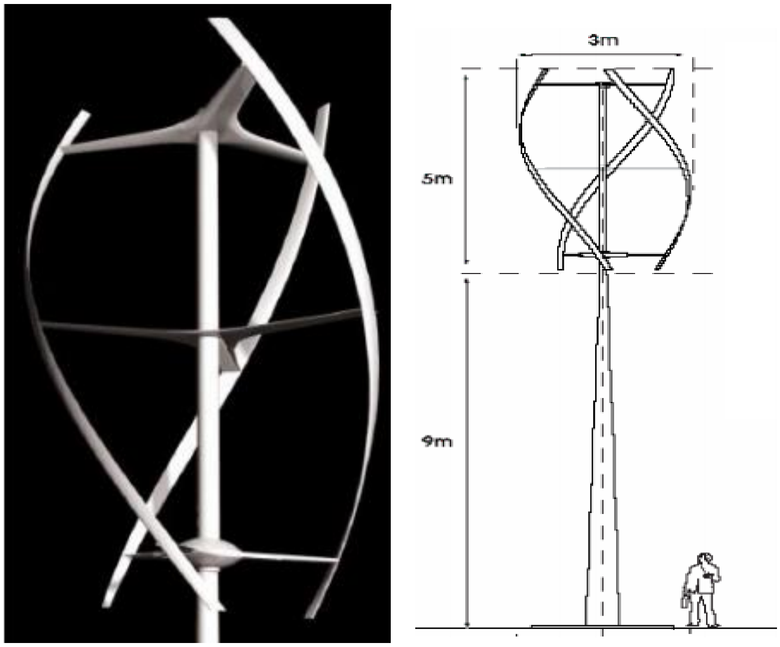


Fig.11: Vertical axis wind turbines are wind turbines with rotors that rotate around a vertical shaft with vertically oriented blades (Darwish, 2019).

The Strata SE1 residential tower in London (57 kW) is also close to the building, rooftop, or along the sides. It includes three wind turbines (19 kW each one) in its crown at 148 m off the ground. This installation can produce up to 50 MWh/year, enough to power 8% of total electricity consumption.

Optiwind technology (GreeTechmedia, 2011) is used for commercial customers, big box stores, schools, healthcare facilities, or government offices. The Optiwind's towers are about 17 m tall compared to 120 m for big wind. Such turbines do not need a crane to be erected rather than a hydraulic system to raise the tower. There is a series of 5-bladed fans mounted around a cylinder that acts to accelerate the wind and allows lower wind speed areas to enjoy the advantages of wind power. The cost of each kW is USD 2,500, i.e. USD ¢ 8 to 10 per kWh (GreeTechmedia, 2011). Optiwind's wind turbines are a good choice if:

I. There is good wind (class 2 or better wind at the site).
II. The customer spends more than BD 11,340 per year on electricity.
III. There is enough room depending on local zoning laws (there might be a need for up to 3.5 acres of land beyond the existing structure).

A good example of BIWT is the Oklahoma Medical Research Foundation (OMRF) (Tusla World, 2019), where 18 vertical wind turbines produce a capacity of 81 W (@ 4.5 kW) to provide a portion of the electricity used in the tower, making it the first medical research facility in North America to harness the wind to generate power (Fig. 12 and 13). The turbines were mounted and installed by Dallas-based SWG Energy Inc., USA, and Venger Wind Model 2 turbines constructed of aluminium and steel, making the turbines heavy-duty but light enough to harness the maximum amount of wind power. The energy created is fed directly into the tower's grid in a system that uses wind-generated power when available but seamlessly switches to OG+E power when necessary. Each about 8 m tall, the turbines stand in three parallel rows and are mounted in a specially designed hood that crowns the roof of OMRF's 40 m-tall research tower. The helical turbines, reminiscent of the shape of DNA (that OMRF study), are supposed to produce approximately 85,500 kWh of energy annually, i.e. enough to power seven average-sized homes for a year. This means that C_P is only 12%. According to them, this electricity generation is cutting CO_2 emission by about 800 ton annually and saving the equivalent of 166 ton of gasoline each year.

Fig.12 : The World's Largest Rooftop Wind Farm in Oklahoma Medical Research Foundation (OMRF) using Venger product , Oklahoma City USA (Tusla World, 2019).

Fig.13: Venger Wind constructs 18 V2 vertical axis (each is 4.5 kW-with start up speed as low as 1.5m/s) wind turbines on the medical center's roof as part of OMRF's sustainability strategy to create a zero-emissions research tower (Tusla World, 2019).

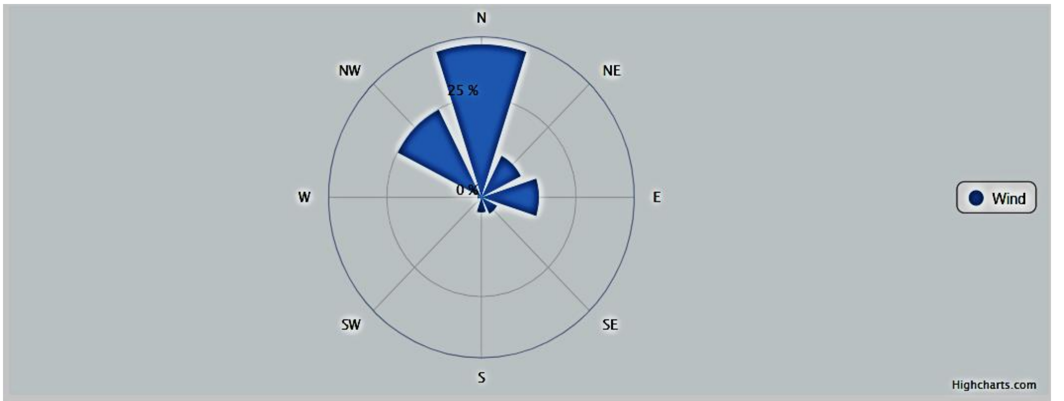
AGU may use a V2 4.5 kW vertical axis wind turbine - supplied by Venger wind company - on their rooftop buildings. This is the type of turbine that was installed atop the Oklahoma Medical Research Foundation building. It has the following specifications (VENGER WIND, 2021):

- Type : Helical Savonius VAWT
- Peak Power: 4.5kW
- Area Size: 6.20 m2.
- Height: 5.7 meters (18’8″)
- Weight: 665kg (1,466 lbs.)
- Start up Speed: 1.5m/s – 5.4 km/h

Each V2 4.5 kW wind turbine will produce annually 11,826 kWh for C_P 30, 15,768 kWh for CP 40% and 19,710 kWh for C_P 50%. Therefore, installing 50 such turbines will have a capacity of 225 kW (a share of 1.1% of wind energy from conventional energy) to produce 985,500 kWh annually, saving 758 ton of CO_2.

The future construction on the artificial island (Durrat Al Bahrain) – which is located south, about 1 km south of KAMC (Fig.14) will not affect the much prevailing wind on the wind turbines because data shows that a maximum of 4% of the frequency of wind direction is from the south (Fig.15). The expected construction includes five-star hotels and resorts, several marinas, offices, shopping malls and entertainment facilities.

Fig. 14: The location of KAMC compared to Durrat AlBahrain artificial island which will witness future expansion in construction.



Wind direction graph in Manama using average values according to our data.

N ▼ Northern	NE ▲ Northeastern	E ◀ Eeastern	SE ▼ Southeastern	S ▲ Southern	SW ◀ Southwestern	W ▶ Western	NW ▲ Northwestern
38.5%	**11.7%**	**15.2%**	**4.6%**	**3.8%**	**0.4%**	**1%**	**24.8%**

Fig. 15: Wind direction graph in Manama using average values according to our data (world Weather Information, 2021).

These observations are in line with early work made by (Al-Buflasa, et al., 2008), indicating that using Weibull parameters, the wind speed at the height of 10 m in Bahrain is only about 3.5 %.

It was reported previously (Al-Buflasa et al., 2008) that the scale factor, C, varies for different wind directions between 2.4m/s and 7.0 m/s, with a mean value of 5.2 m/s, while the shape factor, k, ranges from 1.9 to 2.9 with a mean value of 1.9.

V- Use Wind Turbines to Produce Electricity and Water

Another opportunity is to use French technology, combining wind energy to produce electricity and water (Macguire, 2012). Eole Water Company claimed in 2012 to have successfully modified the traditional wind turbine design to create the WMS1000, which can manufacture drinking water from humid air. In this machine, humid -warm air is drawn through the nose of the turbine via a device known as an “air blower”. The trapped air during this procedure is cooled via an electric cooling compressor situated behind the propellers, which is condensed and collected through a series of stainless-steel pipes to a storage tank in the base of the turbine, where then the water is filtered and purified (Fig. 16). The test result indicates the production of 62 L of water per hour, on average, with an average relative humidity of 45 % and an average temperature of 24°C for a wind speed of about 6 m/s. The water production will be more as wind speed, temperatures and humidity rate increase. The French Company (Eole Water) reported that the cost of the machine is BD. 253,846 (US$ 660,000) and BD. 303,846 (US$790,000) – depending on the location and the surrounding (The Week Magazine, 2020) .

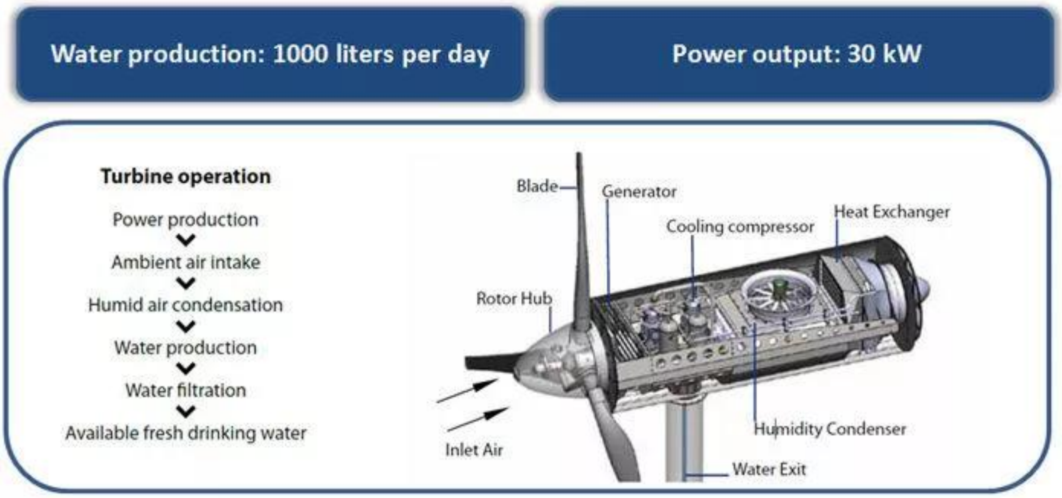


Fig. 16: The principal of the operation of Eole Water-Wind turbine model WMS1000 can produce electricity and water from humid air, producing daily 500 to 500 L of water (Macguire, 2012).

It is an opportunity for the KAMC project to incorporate Eole Water wind turbines as they produce electricity and water, particularly that they are ideal for humid, near seacoast areas and require wind speed of about 6 m/s and relative humidity of 45% (least). All these features are met near the Durrat Al Bahrain area. For such a wind turbine, the start-up wind speed is 2.5 m/s and the rated wind speed is 9.0 m/s with survival wind speed of 59.5 m/s. These figures suit well the wind condition in Bahrain.

This Eole water technology was installed in Abu Dhabi, UAE (Treacy, 2018), and it was reported that a working WMS1000 prototype model (30 kW, 24 m - tall in a desert near Abu Dhabi produced 62 L of water per hour (1,488 L per day = 1.488 m^3). The 30-kW wind turbine houses and powers the whole system. Air is taken in through vents in the nose cone of the turbine and then heated by a generator to steam. The steam goes through a cooling compressor that creates moisture, which is then condensed and collected. The water produced is sent through pipes down to stainless steel storage tanks, where it is filtered and purified.

The unit is expected to produce annually 105,120 kWh (for C_P= 40%) and 78,840 kWh (for C_P = 30%). However, extrapolating the data in Table 6, this size of a wind turbine will produce, annually, 79,200 kWh for an average wind speed of 6 m/s or 91,800 kWh for an average wind speed of 6.5 m/s, i.e., nearly in favour of C_P=35%. We have to recall that a typical house in Bahrain consumes annually about 60,000 kWh,i.e. the size of 20 kW- a wind turbine.

Assuming that the wind turbine will last for 30 years, then the cost of 1 kWh will be 97 fils (US¢ 25) – using Eqn.(6). This figure appears high, but when considering the amount of water that will be produced annually (543 m^3) - bearing in mind that every 1 m^3 of water costs 750 fils (US¢20), i.e. BD 408 (US$1,080) annually and BD. 12,217 (US$32,320) for 30 years' production- then the figure will be accepted. This will require us to consider only the cost of the turbine to produce electricity (BD. 241,629 = US$640,000), and hence the cost of 1 kWh will be 88 fils (US¢ 23).

Undoubtedly, the current prices for the role - water wind turbine have become much less now - like solar PV panels, batteries, and invertors. It must be noted that in our calculation of the cost of electricity, we assume the cost of 1 m^3 is remaining constant (BD 0.750 = US¢ 20) in the coming 30 years – which may not be the case. On the contrary, we may need to add to the cost of electricity an increase of 2% annually considering the maintenance, repair, inflation rate and insurance.

Acknowledgement

Many thanks and gratitude to Dr Khaled Ben Abdul Rahman Al -Ohaly, the President of Arabian Gulf University, for his guidance and valuable instructions. Many thanks to Shaikh Nawaf bin Ebrahim Al Khalifa, Chief Executive, Electricity and Water Authority, Kingdom of Bahrain and Ebrahim Abdulla Al-Kaabi, Deputy Chief Executive for Planning & Projects, EWA, for providing helpful information on the Wind Energy Projects for Bahrain. Thanks extend to Dr Khaled Tabarra, the project manager of KAMC and Dr Sabah Al-Junaind, AGU, for providing necessary information on the KAMC. The valuable feedback from my colleagues at AGU (Prof Soud Almahmid, Dr Maha Al- Alsabbagh, and Dr Mohammed Abido) is highly appreciated. Special thanks also go to Mr Nadr Ahmed, Directorate of Meteorology, for providing helpful information. Special thanks to Mr Khaled W Alnaser and Mrs Huda A R Albanae for conducting calculations on NPV. High appreciation to Mrs Luma AlSalah for editing the English language of the paper.

Conclusion

There is great potential and many advantages in using wind energy for KAMC under the administration of Arabian Gulf University. The average wind speed is about 6 m/s at the height of 50 m. Installing a 1 MW wind turbine will produce annually 2,221 MWh -which is enough to power about 37 houses with 5,000 kWh/month electricity consumption. This amount of energy production will save an annual emission of CO_2 equivalent of 1,710 ton, i.e. saving 700 ton of oil. Assuming the cost of 1 MW is BD 0.378 million, and the cost of annually produced wind electricity is BD 64,409 (taking the cost of 1 kWh = 29 fils), then the payback period will be 5.88 years (nearly 6 years) while the cost of each 1kWh will be 7 fils only!

Smaller BIWT– vertical axis – can be used (like Venger V2 @4.5 kW) to produce 19,710 kWh for CP 50% annually. Therefore, installing 50 such turbines will have a capacity of 225 kW (a share of 1.1% of wind energy from conventional energy) to annually produce 985,500 kWh, thereby saving 758 ton of CO_2.

There is an opportunity in the KAMC project to incorporate Eole water wind turbines (Model WMS1000) which produce electricity and water. They are ideal for humid – near seacoast area and require wind speed of about 6 m/s and relative humidity of 45% (least). These features are available in the location of KAMC, and hence a 30 - kW wind turbine of such model is expected to annually produce 91,800 kWh for an average wind speed of 6.5 m/s (CP=35%). Assuming that such wind turbine will last for 30 years and the unit will produce annually 543 m^3 for 30 years – with the cost of each m^3 of water at 750 fils, i.e. BD 408 annually and BD. 12,217 for 30 years production- then the cost of 1 kWh will be 88 fils (US¢ 23).

The future construction in Durrat Al Bahrain (1 km south of KAMC), which will include hotels, resorts, several marinas, offices, shopping malls and entertainment facilities, will not affect much the energy produced by the wind turbines. This is because the artificial island lies south of KAMC, where the frequency of wind blowing from the south contributes to about 5% (maximum) of the annual prevailing wind.

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جدوى استغلال كهرباء الرياح لمدينة الملك عبدالله الطبية (KAMC) بمملكة البحرين

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المُستَخلَص

تاريخ استلام البحث: 2021/04/22
تاريخ تعديل البحث: 2021/08/19
تاريخ قبول البحث: 2021/09/02

تسكشف هذه الورقة امكانية الإستفادة من كهرباء الرياح (طاقة الرياح) لكهربة جزء من مدينة الملك عبدالله الطبية في جامعة الخليج العربي، مملكة البحرين. وتشير الحسابات إلى أنه عند تركيب توربين رياح بقدرة 1 ميجاوات بالمدينة فإنه يمكن الحصول على طاقة كهربائية قدرها 2,221 ميجاوات – ساعة سنويا، وهي كافية لتزويد 37 منزلا بالكهرباء مما يقلل من انبعاثات مكافئ غاز ثاني اكسيد الكربون بمقدار 1,710 طن، أي توفير حرق 700 طنا من النفط.

وفي هذه الدراسة، تم وضع سيناريوهان (سيناريو A وسيناريو B) - (كل منهما يضم 3 سيناريوهات فرعية) - لتقييم نتائج تركيب توربين رياح بقدرة 1 ميجاوات. وتم االتوصل إلى أن صافي القيمة الحالية NPV يكون موجبا في كلا السينوريوهان، حتى وإن تم افتراض أن معامل الأداء (CP) للتوربين يساوي 30%، وإن التوربين سيكون عرضة للتدهور في الأداء بمعدل 1% سنويا (30% تدهور اجمالي خلال 30 سنة). كما توصلت الدراسة إلى أن NPV في السيناريو الأقل تفاؤلا (سيناريو 2A) يساوي 4 مليون دولار بسعر الوحدة من كهرباء الرياح قدرها 7.4 سنت أمريكي لكل كيلووات - ساعة. وفي هذا السيناريو، وعند افتراض أن الأنتاج لا يخضع لمعدل تضخم، فإن كلفة الوحدة الكهربائية تساوي 1.5 سنت أمريكي لكل كيلووات – ساعة. أما بالنسبة للسيناريو الأكثر تفاؤلا (سيناريو 1A)، الذي يفترض معامل أداء CP = 40%، فإن سعر الوحدة الكهربائية يساوي 0.95 سنت أمريكي فقط لكل كيلووات – ساعة عند افتراض وجود تضخم، أما في حال عدم وجود تضخم فإن سعر الوحدة سيساوي 1.1 سنت أمريكي لكل كيلووات – ساعة. وفي السيناريو 1C، فإن سعر الوحدة الكهربائية سيساوي 0.95 سنت أمريكي لكل كيلووات – ساعة.

مفاتيح الكلمات: توربين رياح، مدينة الملك عبدالله الطبية، توربين رياح مترابط مع المبنى، أمكانيات طاقة الرياح في البحرين.