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Techno-Economic Assessment of Wind Farm Repowering: A case Study of Zafarana Station, Gulf of Suez, Egypt.

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Abstract— The Zafarana wind farm was commissioned on phases since 2001 till 2010 with a total installed capacity of 545 MW. The development of the plant was not optimum, as some late phases was developed upstream of earlier one and the site utilization was not optimized as one plot. The wind farm is located at the Gulf of Suez, an area with abundant wind resource and strong infrastructure. Therefore, repowering scenario was favored over decommissioning or revamping as it enables to exploit and optimize the wind resource at the site and make use of the existing infrastructure of the old plant while using up-to-date wind technology. A techno-economic assessment showed that the repowering of Zafarana, with new turbines that better match the site conditions and optimized micro-siting, can increase the installed capacity from 545 MW to 750 MW. The repowering at the currently permissible tip height of 100 m is economically feasible, however this feasibility shall improve as height restriction is relaxed to 125 m. This will lead to improvement in the capacity factor and consequently annual energy production, such that the cost of generated energy will go down from 67.5 to 47.5 US$/ MWh calculated at IRR=14%. This cost takes into account the cost of early decommissioning of part of the plant, which has not expired yet. If the improvement in capacity credit due to the repowered project is considered, the feasibility of the repowering project shall improve such that the net cost per MWh will approach 40 US$/MWh (at IRR on equity of 14%).

Keywords— Wind Farm, Repowering, WAsP, Zafarana, Gulf of Suez

I. INTRODUCTION

Wind electricity generation costs significantly reduced due to the technology advancement, the rapid deployment of wind farms, and the optimal resource assessment and project design. This led to prices that are below the grid parity compared with conventional fossil-fuel based generation. Due to the rapid advances in wind farm technology, bigger and more efficient WTGs are available on market. This turned the existing machines to become obsolete calling for update or replacement even before their planned end-of-life [1].

End-of-Life scenario should be decided at the early steps of the wind farm project to avoid any un-necessary costs at the end of the project. There are three common end-of-life scenarios that are commonly selected, namely; dismantling, refurbishment, and repowering. Dismantling (or decommissioning) refers to the complete removal of the wind farm to return the site to its original status before the project. On the other hand, refurbishment (or revamping) is extending the service life of the WTGs by replacing major components like generators and controllers. Finlay, repowering refers to replacing part or all of the old WTGs with newer, bigger, and more efficient ones capable of harvesting more energy annually.

Wind Farm repowering has many advantages including the increased Annual Energy Production (AEP) due to the improved performance (higher efficiency and lower noise) and higher hub heights and consequently possible larger turbine diameters of the new turbines, better micro-siting and resource assessment techniques, improved electric grid integration, improved visual impact [2], and reduction of operation and maintenance costs [3]. In addition, the environmental impact of newer wind turbines is greatly reduced [4] due to the lower number of turbines used which reduces the avian mortality, the visual impact, and the land use. On the other hand, higher investment costs and the longer and more complex authorization process may affect the success of repowering initiative.

Repowering is still a relatively new concept and more effort is directed toward techno-economic and feasibility studies of new wind projects. Countries with old generation deployment are more likely to have repowering market. Denmark and California are examples of repowering pioneers, as they were in the head of the list of wind generation deployment projects. Other countries like Germany, Spain, Italy, UK, India [5] [6][7] have good repowering potential given their significant wind capacity installations of old and small WTGs.

Many studies reported the economic viability of repowering in addition to other environmental benefits. Colmenar-Santos et al. [8], and Filgueira et al. [9] reported that repowering is more profitable than the construction of a new farm provided that the new wind turbine generators suitable matches the wind characteristics at the site and the existing infrastructure can be reused. Same conclusion was obtained by Villena-Ruiz et al. [10] and Nivedh et al. [11] for two different real case studies in Spain and India; respectively. On the other hand, studies of [12] and [13] suggested that partial repowering is more profitable than total repowering even without any public subsidies.

In Egypt and the middle-east region, the wind installations are relatively few. So, the repowering potential is still picking-up. However, planning the end-of-life scenario is a good step for a successful project. Table I shows a list of wind projects in service in Egypt a long with the commissioning date. This installed capacity is expected to increase to 20 GW to satisfy the ambitious goals of the Integrated Sustainable Energy Strategy (ISES) of Egypt, which targets 42% renewable in the Egyptian energy mix by 2035 [14].

Table I List of wind projects in service in Egypt [15], [16]

Station	Power (MW)	Turbine Manufacturer	Start Date
G. of ElZayt	580	Gamesa G80/2000	2018
Ras Ghareb	262	Gamesa G97/2000	2018
West Bakr	252	SG2.6-114	2019
Zafarana 1	30	Nordex N43/600	2001
Zafarana 2	33	Nordex N43/600	2001
Zafarana 3	30	Vestas V47/660	2003
Zafarana 4	47	Vestas V47/660	2004
Zafarana 5	85	Gamesa G52/850	2006
Zafarana 6	80	Gamesa G52/850	2007
Zafarana 7	120	Gamesa G52/850	2008
Zafarana 8	120	Gamesa G52/850	2010

Wind Farm decommissioning in Egypt is expected to spark next decade as most of the turbines are built in the 2000s. Zafarana Station may be the most probable candidate to be considered. The layout of the station is shown in Fig.1 (with turbines represented by the dots) and the details are described in Table I above. The station is the oldest installation in Egypt and it was constructed over the period from 2001-2010 with a total combined capacity of 545 MW. Since parts of the station already passed 20 years in service, it's time to think about the end-of-life scenario that should be executed.

Repowering of Zafarana Wind Farm Can be a good Choice for many general and site-specific reasons. In general, repowering can benefit from the rapid advancement in design practices and technology, and make use of the existing infrastructure. On the other hand, Zafarana wind farm site is at the Red sea area with annual average velocity of 9.5 m/s. This wind resource makes the site very tempting to reuse, in addition to the long term accurate wind data built over years of service. Also, the site contains eight plants which are built on phases from 2000-2010 without a comprehensive master plan. This led to low capacity factor and high shading effect as well as no integrated optimal micro-siting for the whole site. Finally, the farm was built using the available technologies at that time (turbine capacities range from 600- 850 kW and hub height from 40 -60 m) which makes repowering with new Mega-Size technology a cost-effective option.

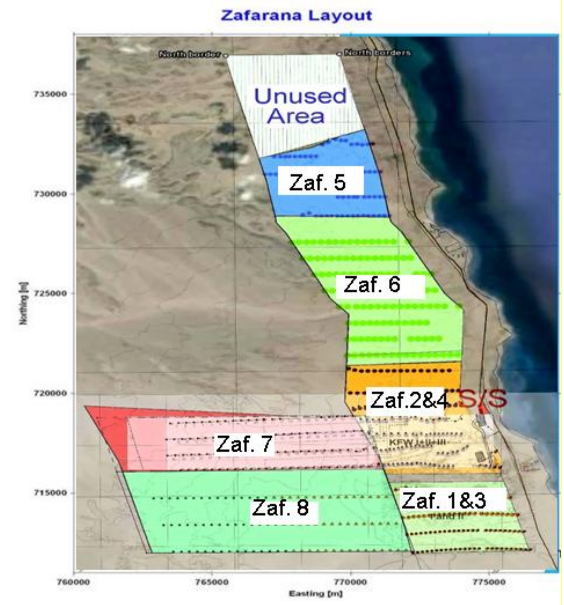

Fig. 1 Zafarana Wind Station Layout [15]

In the present work, a techno-economic study is performed to evaluate the profitability of repowering the Zafarana wind farm at the Gulf of Suez, Egypt. Since the annual average wind velocity is around 9.5 m/s, a great return is expected from repowering the site with new Mega-Size WTG technologies while using the existing infrastructure at the site. Two industry standard software tools are used for Wind Resource Assessment and energy yield calculations, namely; WAsP and RETScreen. Two scenarios are considered based on sticking to the designated tip-height limit of 100 m or slightly relaxing it to 125m. In both cases, WAsP will be used to precisely optimize the turbines' locations (micro-siting) to maximize the energy yield and, hence, reduce the cost of energy. RETScreen's financial model is used to judge the economic feasibility of the repowering project.

II. SITE DESCRIPTION

Figure 2 shows an elevation contour map of the area surrounding the mast, where the Zafazrana plant is installed. Mast location 2 852 551 m North, and 265 442 m East. Mast 7 is the reference meteorological Station for the Egyptian-Danish Zafarana wind farm project [15]. The distance to the coast line of the Gulf of Suez is about 2 km in the eastern direction. There are no sheltering obstacles close to the mast and the surface consists mostly of sand and gravels with a roughness length of less than 0.01 m

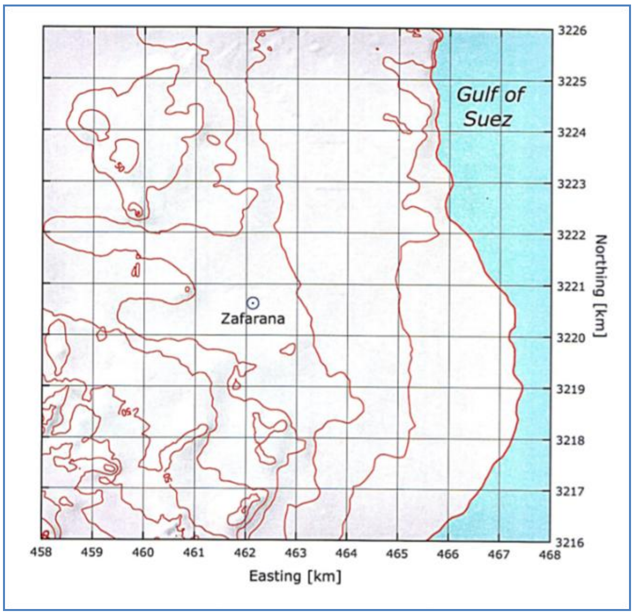

Fig. 2 Zafarana elevation contour map showing the mast location [15]

Site wind long term measurement data are available from the mast located inside the project zone since 1998. Wind data analysis and wind directional distribution for the long term measured wind regime around the mast, are shown in Fig. 3. Luckily, the site enjoys very clear prevailing wind direction from the north direction with 74.1 % of the wind measurements blowing at an angle of 0^o (North direction). This is very helpful in the design of the wind turbine control and active yaw mechanisms, which improves the turbine efficiency and the wind farm production [16]

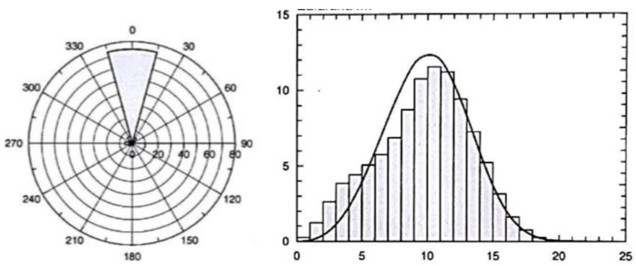

Fig. 3 Zafarana long term wind measurement and direction distribution [15]

III. WIND RESOURCE ASSESSMNET

Two licensed industry-standard software products were used in Wind Resource Assessment (WRA) for the purpose of comparison and accuracy; namely, WAsP-ver. 11 [17] and RETScreen [18]. WAsP has the advantage of being able to account for the effect of terrain topography and land cover on the performance of the wind farm. Also, it has the capability of calculating the wind farm performance including array losses using the park wake model. Finally, WAsP has a powerful micro-siting module that allows optimal layout of individual turbines to maximize the harvested energy. On the other hand, RETScreen has a fully integrated financial model. This feature is useful in evaluating the profitability of the repowering project. The combination of the two software products makes the wind calculation model more robust, and greatly reduces any uncertainties. Two 2MW wind turbine modules with diameters 80 and 90 m manufactured by Vestas [19], were tested for maximum AEP at hub heights of 60 m and 80 m, respectively. The output of the two software products is compared in Table II to assure robustness of the wind model. It is clear that both software tools produce the same results for the two tested turbine models.

Table II Wind farm output from the software products

	V80 HH 60m		**V90 HH 80m**	
	AEP (GWh/y)	CF (%)	AEP (GWh/y)	CF (%)
WAsP	2880.3	43.8	4396.3	66.9
RETScreen	2890.8	43.9	4401.9	67

Long term wind data measurement is processed by WAsP preprocessor, Observed Wind Climate Wizard, and it is used for the resource assessment and subsequently for AEP calculations. The grid resources map is calculated by WAsP taking into account the topography and the land cover of the site as provided by contour and roughness maps, respectively. Then, the power density (W/m^2) is calculated in the farm area. The wind turbine generators are inserted to calculate the energy yield. Figure 4 shows the detailed energy yield after inserting the WTGs and using the different micro-siting options. Siting of the turbines is optimized by applying basic consideration of 3.5-5 rotor diameters cross-wind spacing and 8-14 diameters down-wind spacing to minimize Wake effects. The program marks the turbines with higher wake losses. These turbines are moved across the resource grid to locations where they can harvest maximum energy. This manual repositioning of turbines to maximize the AEP is called micro-siting. The overall performance of the wind farm is finally calculated after considering all types of losses. In advanced versions of the software, computational fluid dynamics is used to accurately predict the effect of terrain and topographical features on the individual turbine performance.

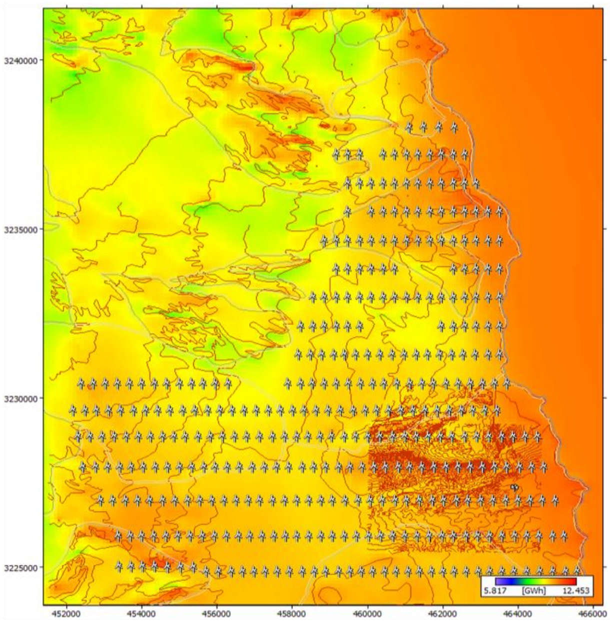

Fig 4 Grid resources map and micro-siting in WAsP

IV. FINANCIAL ANALYSIS

Financial analysis is performed using RETScreen software for the used two turbine types that have different specification. All the prices are based on a market research [14] and [20]. The cost estimate for the different plant components and the financial parameters used in calculating the electricity export rate and emission savings are shown in Table III.

Table III Financial parameters considered in the financial analysis

Item	Unit	V90 HH 80m	V80 HH 60m
CAPEX	(S/kW)	1,024	1,024
O&M (% CAPEX/y)	%	3.35	3.35
Inflation Rate	%	2	2
Discount Rate	%	9	9
Project Life	yr	20	20
Finance			
Debt Ratio	%	70	70
Debt interest Rate	%	7	7
Debt Term	yr	15	15
Debt Payment	$/yr	99,923,878	90,302,246
Income Tax Analysis			
Income Tax Rate	%	22.5	22.5
Depreciation	Straight-line		
Dep. Tax basis	%	100	100
Dep. Period	yr	20	20

V. REPOWERING SCENARIOS & RESULTS

Two repowering scenarios have been tested. First: increasing the turbine capacity while limiting the tip height to 100 m (set by Ministry of Defense). This is done by using a turbine model **V80-60 m**, from Vestas, that has a rotor diameter of 80 m with a hub height of 60m, such that suitable clearance between the blade and the ground is kept. Second: tolerate the tip height up to 125 m which is done by using a turbine model **V90-80 m**, from Vestas, that has a rotor diameter of 90 m with a hub height of 80 m. Increasing the blade diameter allow to increase the turbine recovery factor, which allows for higher capacity factor

There are three parameters that will affect the performance of the newly tested turbine models as follows:

1. The first turbine is 80m diameter and the second is 90 m diameter. This means that there is a 26.6% increases in rotor area. This allows the single turbine to harvest more power on the same location.
2. The tip height of the second turbine increases by 25 m above the first turbine. This is interpreted as an increase in the wind velocity due to less wind shear effect. As power is proportional to the cube of wind velocity, more energy is harvested by this increase in tip height.
3. The velocity ratio of the second turbine increases by 46% with respect to that of the first turbine. The velocity ratio is a measure of the degree of matching between the turbine performance and the site conditions. It is defined according to 'equation (1)' as follows:

$$\textit{Velocity Ratio} = \frac{V_{cut\ out} - V_m}{V_{cut\ out} - V_{cut\ in}} \qquad (1)$$

Considering the two turbines' alternatives mentioned above, and optimizing plant micro siting, the plant total capacity can become 750 MW instead of 545 MW. Detailed WAsP calculations are summarized in Table IV for the two turbine models along with the base case currently working at the site. In the two cases, the output power is increased to 750 MW by using fewer turbines with larger output. These fewer turbines have higher efficiency, lower visual and environmental impact. First turbine at 60 m hub height raises the NET AEP and capacity factor to 3008 GWh and 45.8 %, respectively, compared to 1400 GWh and 29% for the base case. Tolerating the tip height to 125 m, by using the second turbine V90 H80, increased the power ratio to 76% which means more coordination between the turbine and the site. This, in turn, increased the harvested energy and capacity factor to 4592 GWh and 69.9 %, respectively. Figure 5 shows the harvested annual energy in both cases discussed for repowering. The AEP of the site will be doubled by using the first turbine at tip height of 100 m. Relaxing the tip height to 125 m will triple the AEP for the reasons discussed above.

Table IV Estimated Gross and Net AEP for the two turbine models (WAsP Calculations)

Energy Yield and Systematic losses	Base Case (Current)	V80 60m	V90 80m
Rotor Diameter (m)	43 -52	80	90
Hub Height (m)	~ 50 m	60	80
Tip Height (m)	< 100	100	125
WT velocity ratio	-	52%	76%
WTG Rated Power (MW)	0.6-0.85 MW	2.0 MW	2.0 MW
Inst. Capacity(MW)	545	750	750
Gross AE Yield (GWh/a)	-	3855	5552
Total losses*	-	22%	17%
Net AE Yield (GWh/a)	**1400**	**3008**	**4592**
Capacity Factor	**~29 %**	**45.8%**	**69.9%**

* ***include array losses and all other technical losses***

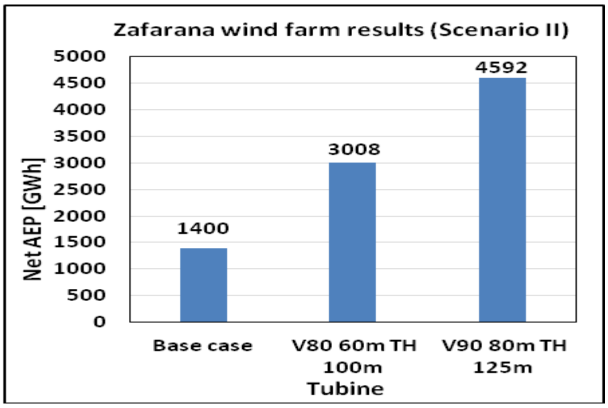

Fig. 5 Net Annual Energy Production from Repowering

The financial model output is summarized in Table VI calculated by RETScreen software. The first repowering scenario causes the CF and the AEP to increase by 58 % and 115% relative to the base case, respectively. The second repowering scenario causes a corresponding change of 141% and 228%, respectively. The gain in Case 1 is much larger due to the better matching between the site and the second turbine choice. Table VI also shows that repowering of Zafarana wind farm is feasible at tip height 100 m with electricity export rate 67 $/MWh at IRR=14%. If it allowable to increase the tip height of turbines to 125m and using higher velocity ratio wind turbine, the electricity export rate decreases to 48 $//MWh at IRR= 14% and the net power produced shall increase by 228% over the base case. It is important to mention that in the financial analysis the loss in energy generated due to the early retirement of some of the old plant specifically, which has not spent 20 years in service are discounted from the generated energy. In addition, Figure 6 shows the cumulative cash flow over the 20-year life time of the repowered project. It is clear that the discounted payback period is around 8 years. This is very reasonable and clearly proves the feasibility of the repowering project at IRR =14 %.

Table V Financial Model Output (RETScreen)

	Base case	Case 1	Case 2
Turbine type	-	V80 HH60m	V90 HH80m
Capacity factor	~29 %	45.8%	69.9 %
AEP [GWh]	1400	3008	4592
WT capacity [MW]	545	750	750
Electricity export rate** [$/MWh]	-	67	48
% increase in CF	0	58 %	141 %
% increase in AEP	0	115 %	228 %

**** CALCULATED AT IRR=14%**

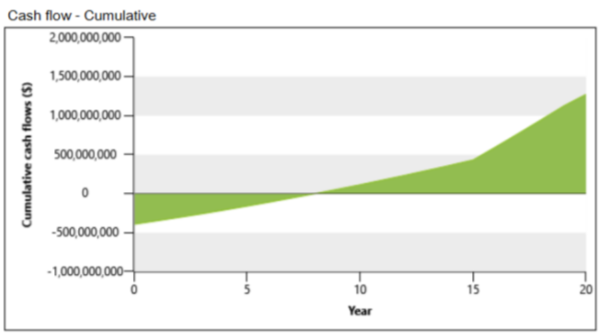

Fig. 6 Cumulative Cash Flow Diagram

More benefits from repowering is realized by calculating the capacity credits of the two repowering options. Based on the model developed by Sallam et al. [21], which is based on loss of load expectation (LoLE) based on a Peer analysis of the power system in Egypt, the expected Capacity Credit for Zafarana site has been found to be 60% of the capacity factor. Based on the average generation for the last five years, the current capacity factor of Zafarana is 29%. This makes its capacity credit equivalent to 17.4%. Accordingly, the capacity credit of the current installed capacity of 545 MW is 94.83 MW. In first repowering case, the repowering includes "V80 HH 60m". The new capacity factor of the plant will be 45.8%. Accordingly, the new capacity credit will be 27.5%. The equivalent thermal steam power plant capacity will be 206 MW for the 750 MW. Therefore, the additional avoided capacity due to repowering will be **111.2 MW.** In case the repowering includes the turbine "V90 HH 80m", the new capacity factor of the plant will be 69.9 %. Accordingly, the new capacity credit will be 41.94 %. The equivalent thermal capacity will be 314 MW for the 750 MW. Therefore, the additional avoided capacity due repowering will be **219 MW**. This improvement in the capacity credit due to repowering improves the feasibility of the project and reduces the energy price.

VI. CONCLUSIONS

- The repowering of Zafarana with new turbine with characteristics better matching with the site conditions (higher velocity ratio) and optimizing the micro-siting can increase the installed capacity from 545 MW to 750 MW.

- The repowering of Zafarana plant at tip height 100 m is economically feasible; however, this feasibility shall improve as height restriction is relaxed to 125 m instead of 100 m, in addition to use higher velocity ratio wind turbines. This will lead to improvement in the capacity factor and consequently annual energy production, such that the cost of generated energy (after discounting the potential lost of energy of the phased out plants) will go down from 67.5 to 47.5 US$/MWh calculated at IRR=14%. This is achieved based on the marginal increase in the generated energy above that of the early retired units.
- If the improvement in capacity credit for the repowered project is considered, the feasibility of the repowering project shall improve such that the net cost per MWh will approach 40 US$/MWh (at IRR on equity of 14%).

REFERENCES

[1] P. Del Río, A. Calvo Silvosa, and G. Iglesias Gómez, "Policies and design elements for the repowering of wind farms: A qualitative analysis of different options," *Energy Policy*, vol. 39, no. 4, pp. 1897–1908, 2011, doi: 10.1016/j.enpol.2010.12.035.

[2] C. Manchado, V. Gomez-Jauregui, P. E. Lizcano, A. Iglesias, A. Galvez, and C. Otero, "Wind farm repowering guided by visual impact criteria," *Renew. Energy*, vol. 135, pp. 197–207, 2019, doi: 10.1016/j.renene.2018.12.007.

[3] L. Serri, E. Lembo, D. Airoldi, C. Gelli, and M. Beccarello, "Wind energy plants repowering potential in Italy: technical-economic assessment," *Renew. Energy*, vol. 115, pp. 382–390, 2018, doi: 10.1016/j.renene.2017.08.031.

[4] E. Martínez, J. I. Latorre-Biel, E. Jiménez, F. Sanz, and J. Blanco, "Life cycle assessment of a wind farm repowering process," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 260–271, 2018, doi: https://doi.org/10.1016/j.rser.2018.05.044.

[5] L. Ziegler, E. Gonzalez, T. Rubert, U. Smolka, and J. J. Melero, "Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK," *Renew. Sustain. Energy Rev.*, vol. 82, no. October 2017, pp. 1261–1271, 2018, doi: 10.1016/j.rser.2017.09.100.

[6] F. J. Santos-Alamillos, N. S. Thomaidis, J. Usaola-García, J. A. Ruiz-Arias, and D. Pozo-Vázquez, "Exploring the mean-variance portfolio optimization approach for planning wind repowering actions in Spain," *Renew. Energy*, vol. 106, pp. 335–342, 2017.

[7] M. Goyal, "Repowering—Next big thing in India," *Renew. Sustain. Energy Rev.*, vol. 14, no. 5, pp. 1400–1409, 2010.

[8] A. Colmenar-Santos, S. Campíñez-Romero, C. Pérez-Molina, and F. Mur-Pérez, "Repowering: An actual possibility for wind energy in Spain in a new scenario without feed-in-tariffs," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 319–337, 2015, doi: https://doi.org/10.1016/j.rser.2014.08.041.

[9] A. Filgueira, M. A. Seijo, E. Munoz, L. Castro, and L. Piegari, "Technical and economic study of two repowered wind farms in Bustelo and San Xoán, 24.7 MW and 15.84 MW respectively," *2009 Int. Conf. Clean Electr. Power, ICCEP 2009*, pp. 545–549, 2009.

[10] R. Villena-Ruiz, F. J. Ramirez, A. Honrubia-Escribano, and E. Gómez-Lázaro, "A techno-economic analysis of a real wind farm repowering experience: The Malpica case," *Energy Convers. Manag.*, vol. 172, pp. 182–199, 2018, doi: https://doi.org/10.1016/j.enconman.2018.07.024.

[11] B. Nivedh, R. Devi, and E. Sreevalsan, "Repowering of wind farms - A case study," *Wind Eng.*, vol. 37, no. 2, pp. 137–150, 2013, doi: 10.1260/0309-524X.37.2.137.

[12] A. H. Syed, A. Javed, R. M. Asim Feroz, and R. Calhoun, "Partial repowering analysis of a wind farm by turbine hub height variation to mitigate neighboring wind farm wake interference using mesoscale simulations," *Appl. Energy*, vol. 268, p. 115050, 2020.

[13] T. Prabu and S. K. Kottayil, "Repowering a windfarm - A techno-economic approach," *Wind Eng.*, vol. 39, no. 4, pp. 385–397, 2015, doi: 10.1260/0309-524X.39.4.385.

[14] International Renewable Energy Agency (IRENA), *Renewable Energy Outlook: Egypt*. 2018.

[15] Mortensen N.G., Hansen J.C., Badger J., Jørgensen B.H., Hasager C.B., Georgy Youssef L., Said U., Abd El-Salam Moussa A., Akmal Mahmoud M., El Sayed Yousef A., Mahmoud Awad A., Abd-El Raheem Ahmed M., Sayed A.M., Hussein Korany M., *Wind Atlas for Egypt, Measurements and Modelling 1991-2005*. Cairo, Egypt & Roskilde, Denmark: New and Renewable Energy Authority, Egyptian Meteorological Authority and Risø National Laboratory.

[16] B. Dou, M. Guala, L. Lei, and P. Zeng, "Wake model for horizontal-axis wind and hydrokinetic turbines in yawed conditions," *Appl. Energy*, vol. 242, no. November 2018, pp. 1383–1395, 2019, doi: 10.1016/j.apenergy.2019.03.164.

[17] "WAsP. Wind Atlas Analysis and Application Program. DTU Wind Energy." Available: https://www.wasp.dk/download/wasp12-suite-installer.

[18] "RETScreen." https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465

[19] "Vestas, 2 MW Platform Product Brochure." https://www.vestas.com/en/products/2-mw-platform#! (accessed Oct. 20, 2020).

[20] International Renewable Energy Agency (IRENA)," *Electr. Storage and Renewables Costs and Markets to 2030, https//www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets*, October, 2017, [Online]. Available: www.irena.org.

[21] A. Sallam, "Developing a Mathematical Model for Evaluating the Capacity Credit of Wind Generation in Egypt," M.Sc. Thesis, Ain Shams University, Egypt, 2016.