Shortcut Sizing Approach of Outstanding Wind Turbine Size to Power a Certain Load for Locations within Annual Wind Speed Range of 3-12 m/s

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Power produced by wind rapidly turned to be one of the most economic energy varieties. Literature on sizing wind power systems are limited to specific wind speed and load profile for designated locations. Moreover, these case studies employed different brands and power capacity of wind turbines and batteries. Due to these huge discrepancies, it is very hard to generalize the outcomes of these studies for other locations. Generalizing the outcome to so many locations instead of a specific location is more practical for customers and researchers. In this study, there is no pre-selection of locations; instead, a range of annual wind speeds (3-12 m/s) were used as input data in the simulation tool to be representative of locations around the globe. The load profile is selected for small-scale applications (8 kW) with 10 operating hours. Six wind turbine types of different brand/power capacity are selected and evaluated under their respective minimum hub heights. HOMER simulation tool is used to obtain the values of the techno-economic feasibility parameters. The aim of this study is to use annual wind speed for determining the outstanding wind turbine size of optimum power duty to run a specific load around the globe. The outstanding turbine size is the one among the (6) turbines that wins the optimum techno-economic feasibility every time at each annual wind speed. The results showed that the outstanding turbine size that powers the load at each annual wind speed was PGE 20-25 (25kW). Also, the results showed that the other hub heights of the outstanding wind turbine lead to slight influence on the techno-economic parameters results at low annual wind speed (3-4) m/s and insignificant influence at higher annual wind speeds (5-12) m/s, that of confirms that the power duty of the outstanding turbine is reasonable at each annual wind speed. Validation test is performed the outstanding turbine using actual monthly wind speed data for (3) different tested locations as a case study, the results confirmed that the superior wind turbine size that can power (8 kW) load at the tested locations is still PGE 20-25 (25kW). Therefore, it can be concluded that annual wind speed is a sufficient data to predict outstanding wind turbine size of optimum power duty accurately to run 8kW load around the globe. Finally, this sizing approach can be adopted in future works to generalize the outstanding turbine size for other load profiles at so many locations around the globe.

Keywords: Wind speed; Certain load profile; Wind turbine; HOMER simulation
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1. Introduction

Winds can provide renewable, free, clean, and economical energy (fuel is not needed and there are no price fluctuations). Since renewable energy is a fertile and promising area, tremendous studies were conducted. Companies are also keen to highlight the cost-effectiveness of exploiting renewable energy at particular sites. Sometimes, HOMER has been used for simulation. This simulation tool was introduced by the National Renewable Energy Laboratory (NREL) and can be considered as global standard for preliminary techno-economic analysis of sustainable micro-grid systems such as remote power, island utilities and micro-grids [1].

In this section, an overview discussion will be performed based on table 1. Throughout the literature survey, the case studies that are done included sites from Africa, Asia, Australia, Europe and North America. Annual average wind speeds ranged from 2.13 to 7.38 m/s. However, all these speeds are under 10m/s. So many simulation research addressed stand-alone or grid-connected system. Some researchers tended to develop a hybrid wind power system considering ineffective winds at these spots. Thus, alternative power resources are necessary for sustaining the designed load.

So far, there is no research that generalizes the outstanding wind turbine size for a certain load to be applicable many locations around the globe. Also, studies investigating to which extent wind turbine size and hub heights are influential for wind power system are still limited and not discussed extensively using the parameters of the techno-economic feasibility. This study intends to explore the effect of variation in annual wind speed, sizes, and hub heights on the values of the techno-economic features of wind power system. Also in this study, the analysis will reveal the possibility of using annual wind speed data as a sufficient data to forecast the outstanding wind turbine size that can power certain loads at locations within the range (3-12 m/s) which seems practically more acceptable for researchers and clients to learn lessons. Given locations have not been preselected in current study, but a range of annual wind speed (3-12 m/s) is considered as data into HOMER for representing so many locations globally and to generate output.

2. Materials and Method

2.1 Research Design

The studied load is chosen commonly used for small-scale usages referred to previous studies detailed in table (1). It is assumed that 8 kW load is to work from 8:00 a.m. till 6:00 p.m. Hourly load profiles are assumed full loads (as illustrated in Fig. 2). Small-scale units usually need 8 kWh daily.

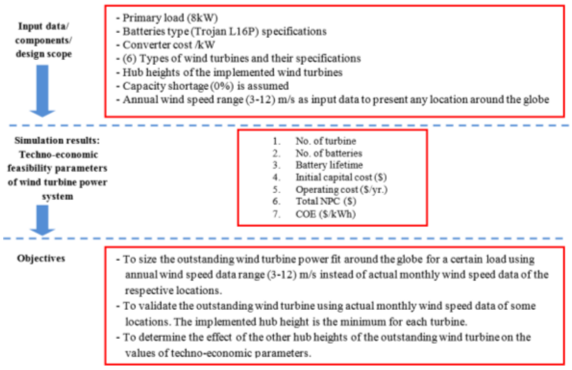

Fig. (1) Diagram of the methodology

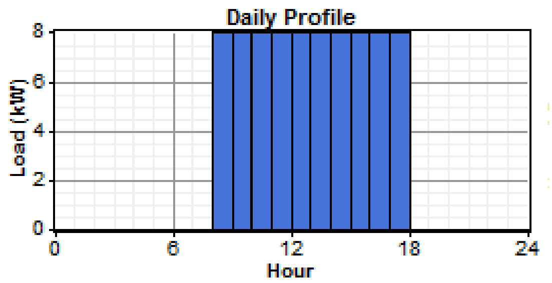

Fig. (2) 8kW load profile of a small scale wind power system operating 10 hour daily

In this work, the real monthly wind speed data that can describe respective location is not taken as input data in the base line of wind speeds. Instead of that, input data exclusively consists of annual wind speeds, which are directly keyed-in the sensitivity values window of HOMER within the range (3-12) m/s, as explained in Fig. (3). The annual wind speed values taken may generally applicable to any site all over the world. Wind speeds of 1 and 2 m/s are not considered in the current research, since the majority of minimum cut-in speeds of wind turbines are supposed to be around 3 m/s. Furthermore, the extreme annual wind speed value approached in the current research is 12 m/s which reflects extreme exceptional case under the index value of wind resource.

Since the analysis exclusively relies upon annual wind speeds, attained outcomes are treated as an initial index for techno-economic feasibility, while the real feasibility is expected to be greater than the attained outcomes. Broadly speaking, in this point of analysis, the outcomes of techno-economic parameters are sufficient for comparing data to predict the outstanding wind turbine system capable of feeding (8kW) load on a global scale.

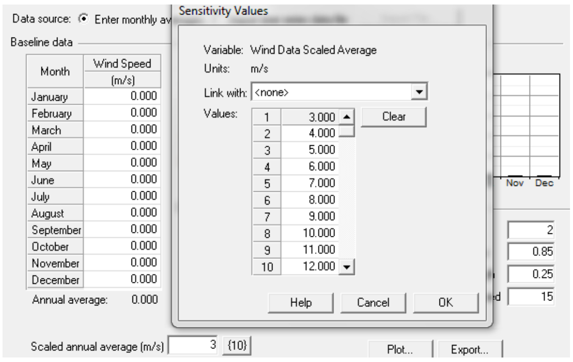

Fig. (3) Annual wind speeds entered into the software to represent any location around the globe

For the validation step of the proposed sizing approach, real monthly wind speed data will be directly keyed-in in the base line of wind speed. Table (2) illustrates The monthly wind speed data (m/s) for the three tested locations as a case study to predict the outstanding wind turbine size among the six wind turbines. If the results of this case predict the same wind turbine size to power the load, it can be concluded that proposed sizing approach is fit to predict the outstanding wind turbine around the globe for a certain load profile.

Table (2) The real monthly wind speed data (m/s) for the three tested locations

Month	Dammam, Saudi Arabia [23]	Ras Monief, Jordan [24]	Kokhanok, Alaska, USA [25]
Jan.	4.16	6.56	7.73
Feb.	4.72	6.76	10.01
March	4.72	7.17	8.53
April	4.72	6.17	7.22
May	5	5.85	7.09
June	5.27	6.49	7.84
July	4.72	6.95	7.03
August	3.88	6.22	6.68
Sep.	3.88	5.49	7.33
Oct.	3.61	4.83	6.86
Nov.	4.16	6.46	8.46
Dec.	4.16	6.14	9.32
Annual	**4.41**	**6.3**	**7.84**

2.2 Materials

Wind turbines have been designated from wind turbines listed in HOMER. The major criterion adopted to designate turbines is their anticipated suitability in terms of load demands. After series of evaluations, six categories of wind turbines with different sizes have been designated for stimulation purposes. These wind turbines are: BWC Excel-R, BWC Excel-S, Entegrity EW15, Fuhrlander FL 30/13, PGE 20-25 and SW Whisper 500. For every turbine, particular hub dimensions are advised by manufacturers. Thus, possible hub heights will be included in the simulation for the designated turbines. The assessed powers of the turbines ranges from 3 kW to 50 kW. Costs of all turbines were alliable in company's websites or in special journals. The costs of operation and maintenance are expected to comprise 85% and 2.5% of the capital cost, respectively. The specifications of each wind turbine are tabulated in table 3(a and b).

Trojan L16P battery has been chosen since it is more widely used and more economic. Capital cost for the battery is $320. Replacement battery may accrue additional $320, meanwhile the annual cost of operation and maintenance is set at $5. Batteries are expected to operate without any problem for the coming 4 years in the worst case [11]. Specifications of the L16P battery are illustrated in table (4).

Table (4) Battery Specifications

Battery model	Trojan L16P
Types of battery	Valve Regulated Lead Acid (VRLA)
Voltage (V)	6
Capacity rate	360 Ah
Dimensions (mm)	295 (L) x 178 (W) x 424 (H)
Weight (kg)	52
Quantity considered	1 - 100

Electronic power converters are incorporated to ensure energy flow between the AC and the DC bus. Power converters may be either inverters (when wind turbines supply DC current) or rectifiers (when wind turbines supply AC current). These convertors range from 0 to 20 kW. Capital and replacement cost is estimated by $1095 with zero cost for operation and maintenance.

2.3 Homer

Homer is adopted in the current study for simulating the life cycle cost of the system and for estimating capital costs, and costs of replacement, operation and maintenance, fuel, and interest rates. After simulation, all costs related to wind turbines are optimized so that optimal turbines are eventually determined. This software may be used for modelling small renewable or non-renewable systems and analyse the techno-economical features of the chosen power systems. Its main features are described below [26]:

i. Suggesting the lowest cost mixture of components that may run into electrical and thermal loads
ii. Simulating thousands of conceivable system designs
iii. Optimizing the life cycle cost and the sensitivity analysis for most inputs

Techno-economic features entail analyzing both technical and economic characteristics of any systems. Technical aspects focus on objective and possible configurations of turbines, grid connections, planning, and environmental issues. For the current study, the required technical analysis should contain the number of turbines and batteries, as well as indicating their lifetime. While, economic features include certain aspects like those related to cost, such as system's initial price, operation and maintenance expenses, total net present cost, and energy cost. [27].

3. Results and Discussion

In the first part of the discussion, the minimum hub height required by the wind power system will be adopted, the effects of wind speeds and wind turbine on each of the techno-economic feasibility parameters.

3.1 Determining the Outstanding Wind Turbine Size

The outstanding size of wind turbine will be determined based on the following evaluation parameters:

1. Most technically feasible at each annual wind speed with:
   - Number of turbines with optimal power duty (approach towards minimum)
   - Number of batteries with optimal power duty (approach towards minimum)
   - Battery lifetime (approach towards maximum)
2. Most economically feasible at each annual wind speed with:
   - Initial cost (approach towards minimum)
   - Total NPC (approach towards minimum)
   - O&M cost (approach towards minimum)
   - Levelized cost of energy COE (approach towards minimum)

3.1.1 Effect of Wind Speed and Wind Turbine Sizes on Number of Turbines

Figure (4) illustrates turbines number vs. annual wind speeds utilizing different wind turbines with diverse dimensions. This figure explains that greater annual wind speeds generate greater power outputs. Therefore, the number of required turbines to maintain the load becomes decreases gradually; increasing wind speeds may contribute in reducing turbines required by the system.

A turbine's size requiring the least number of turbines is so pivotal in the design of a wind power system. In this assessment, a turbine's size requiring the least number of turbines is the most convenient. According to Fig. (4), at speed of 3 m/s, just a couple of turbines (namely PGE 20-25 (25kW), and Fuhrlander FL30/13 (30 kW)) are technically able to maintain loads. Though, the system requires 4-6 turbines to perform the said tasks. This points out that low wind speeds requires greater numbers of turbines. PGE (25kW) with 4 turbines may be recommended for powering an (8 kW) load at a speed of 3 m/s. While, PGE (25kW) with single turbine may be recommended at a speed of 4 m/s. Turbine PGE (25kW), FL30/13 (30 kW), and EW15 (50kW) with single turbine are recommended at an annual wind speed of 5 m/s. While, PGE (25kW), FL30/13 (30 kW), and EW15 (50kW) with single turbine are recommended at an annual wind speed of 6-9 m/s. BWC-S (10 kW), PGE (25kW), FL30/13 (30 kW), and EW15 (50kW) with single turbine at an annual wind speed of 10 m/s. Lastly, all wind turbines mentioned above are recommended at an annual wind speed of 11-12 m/s, with single turbine except SW 500 (3kW). Consequently PGE (25kW), FL30/13 (30kW), and EW15 (50kW), were faster in attaining the lowest number of turbines at low annual speeds. So, turbine with the best performance for (8 kW) load in this analysis is the PGE (25kW), followed by FL30/13 (30 kW), and the EW15 (50kW) turbines.

3.1.2. Effect of Wind Speed and Wind Turbine Sizes on Number of Batteries

Batteries are useful for backing up in case the output of the system was insufficient to maintain the load. A system relying upon the lowest number of batteries is considered outperformed.

Figure (5) illustrates, during lower annual wind speeds, a system usually requires batteries. Though, when annual wind speeds rise, the system gradually becomes less dependent on batteries because higher rates of usable power are produced. This will make the system less dependent on batteries. This reiterates the fact that the bigger the capacity of the system, the less its dependence on batteries will be. Nevertheless, systems have to be compared for their costs to decide which one is the most optimum. Turbine with best performance in this round of analysis are EW15 (50kW) and PGE (25kW) respectively.

3.1.3 Effect of Wind Speed and Wind Turbines Size on Battery Lifetime

Figure (6) explains that batteries with longer lifetimes are optimal. Outstanding power systems are selected based upon their capability of preserving and extend battery lifetimes. Since it is not easy to determine battery's lifetime at diverse annual wind speeds, a clear trend may not be shown in Figure 6. Every turbine system has its own battery lifetime. Nevertheless, at speeds of 3- 4 m/s, the system cannot generate adequate usable power for the load. Therefore, batteries are broadly utilized. Therefore, its lifetime is shorter (~4 - 5 years) in comparison with greater annual speeds. When annual wind speed is ≥ 5 m/s, there is at least one system with a fit lifetime of up to 10 years for their battery bank system.

Figures (7) and (8) explain the interrelation between battery quantities and their lifetimes for two turbine sizes; BWC Excel-S (10kW) and PGE 20-25 (25kW). Figure (7) depicts instability in battery lifetime at various annual speeds. Meanwhile, Figure 8 highlights stability in battery lifetime at annual speeds of (5-12 m/s).

Using more batteries may be an indicator that the system is more reliant upon battery power. Since batteries are frequently used, their lifetime, to some extent, is low. On the contrary, using less battery may be an indicator that there is less reliance on batteries. Consequently, batteries exhibits longer lifetimes. For the whole annual speed range, turbine PGE 20-25 (25 kW) proved to have the longest battery lifetime (figures 7 and 8).

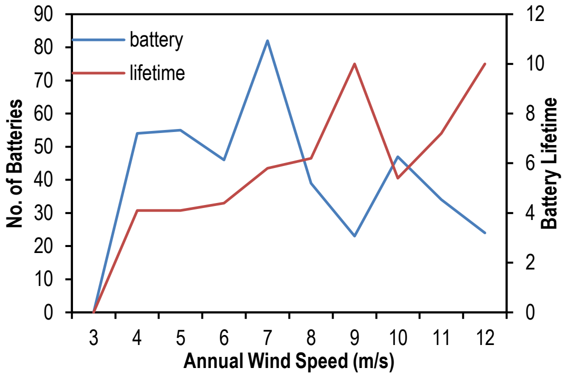

Fig. (7) No. of batteries and battery lifetime vs. annual speeds for BWC Excel-S (10kW)

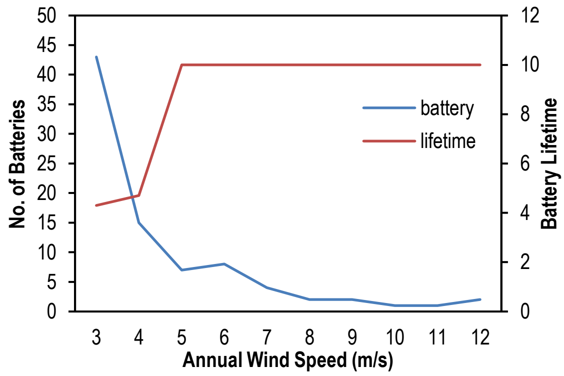

Fig. (8) No. of batteries and battery lifetime vs. annual speeds for PGE 20-25 (25kW)

3.1.4 Effect of Wind Speed and Wind Turbines Size on Initial Cost

This discussion will be dedicated to addressing system expenses, including the initial cost, cost of operation and maintenance, total NPC, and COE.

It is shown that there is an inverse relationship between initial cost and annual wind speeds, as a result of the amounts of turbines and battery bank size. Fuhrlander FL30/13 (30 kW) had the uppermost initial cost at an annual wind speed 3 m/s. From the 4 m/s onwards, EW15 (50 kW) had the uppermost initial cost.

Furthermore, PGE (25 kW) and SW 500 (3 kW) were optimal regarding initial cost, as they commonly entailed the minimal initial costs in Figure 9 at the annual wind speed range (3-7 m/s), the minimal initial cost has been recorded for PGE (25 kW). Meanwhile at annual speed range (8-12 m/s), the minimal initial cost has been recorded for SW Whisper 500 (3 kW).

3.1.5 Effect of Wind Speed and Wind Turbine Sizes on O&M Cost, Total NPC and COE

Here, the outstanding wind turbine is expected to have the minimum cost of operation and maintenance, net present cost, and minimum energy cost. The performance of these three parameters is comparable to that of the initial cost. From the 4 m/s onwards, Entegrity EW15 (50kW) entailed the greatest operation and maintenance cost, total NPC, and COE. The minimum cost of operation and maintenance, total NPC, and COE have been associated with PGE (25kW) from 3-8 m/s, then SW 500 (3kW) from 9-12 m/s.

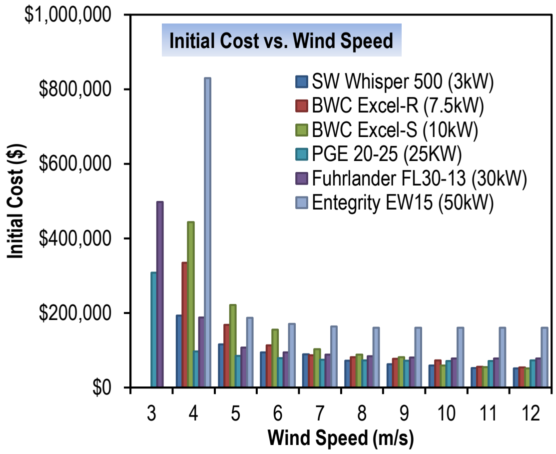

Fig. (9) Initial Costs vs. annual speeds for various dimensions of turbines

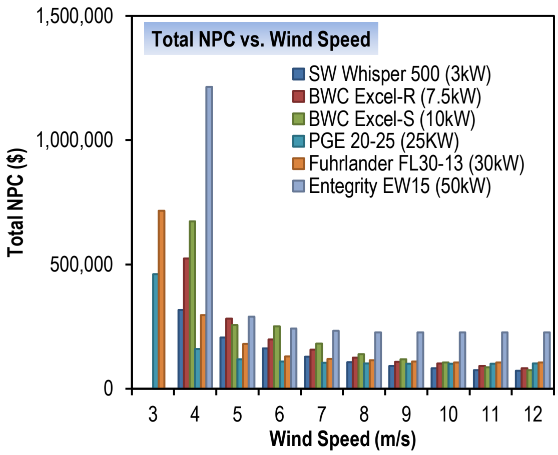

Fig. (11) Total NPC vs. annual wind speeds for various turbine sizes

3.1.6 The outstanding wind turbine size powering a specific load around the Globe

The outstanding turbine is addressed on the basis of techno-economic indicators. The outcomes set forth above may determine the outstanding turbines which may be possibly competent to feed the load (8kW) at all annual wind speeds (3-12 m/s) throughout all assessments. Results have indicated that there is a couple of discrete wind turbines. PGE 20-25 (25kW) proved excellent at wind speed range (3-8 m/s) regarding cost, size, and stability. SW 500 (3kW) proved excellent at an annual wind speed range (9-12 m/s) regarding system cost. While, under annual wind speed (9-12 m/s), PGE (25kW) is still the uppermost regarding system size and stability, and lag step from SW Whisper 500 (3kW) regarding system cost. It may be argued that under annual wind speed of (3-12 m/s) representing any site all over the world, the compromise indicated that the outstanding wind turbine is PGE (25kW) regarding system cost, size, and stability concomitantly.

Consequently, we can say that the outstanding wind turbine is the PGE 20-25 turbine; with rated power of (25kW) for feeding the (8kW) load. One of the key findings is that the power system required to sustain the 8 kW load is nearly three times greater than the load.

Specifications of the outstanding turbine PGE 20-25 (25kW) regarding system cost, size, and battery stability at all annual wind speeds are set forth in Figure 13. Clearly, number of turbines are at low annual wind speeds may be great in comparison with turbines operated at other annual speeds. Furthermore, many batteries were used, their lifetimes were still short, and indicating that reliance upon battery bank for powering loads may be common at low annual wind speed 3-4 m /s. Consequently, adopting greater hub heights at low annual wind speeds may be optimizing power capacity and eventually reducing the reliance upon batteries and enhancing battery life.

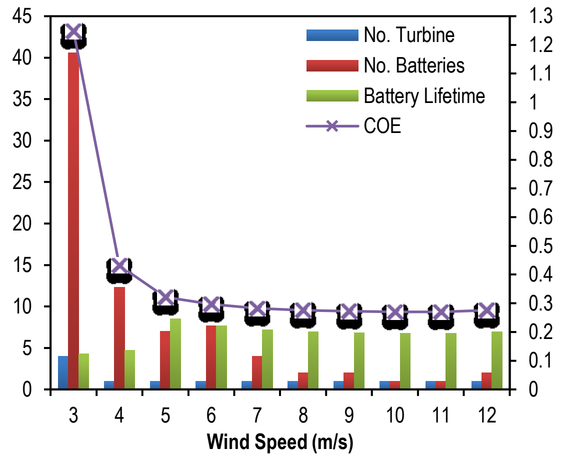

Fig. (13) No. of turbines, batteries & their lifetimes, and levelized COE of the outstanding turbine PGE 20-25 (25kW) vs. annual wind speeds

3.2 Effect of Different Hub Heights of the Outstanding Wind Turbine (PGE 20-25) on Optimizing the Techno-Economic Feasibility

We can conclude that the outstanding turbine size for 8 kW load of constant profile is the PGE 20-25 (25kW). The impact of hub heights provided by the manufacturer on power duty of the outstanding turbine system at various annual speeds shall undergo testing. In manufacturer's manual, the PGE turbine has 3 hub height categories; 25 m, 30 m, and 36 m. But in this part we will take only two hub heights, the lowest and highest (25 m and 36 m). If techno-economic results at higher hub heights may be not viable at given annual wind speeds, this means that wind turbine size and annual wind speed did impose more impacts compared to higher hub heights and it can be concluded that the proposed sizing approach versus the studied annual wind speed range.

3.2.1 Impact of Hub Height on Number of Turbines

Figure (14) illustrates that we may conclude that increasing hub heights may not usually affect the number of PGE turbines under the range of (4-12 m/s).

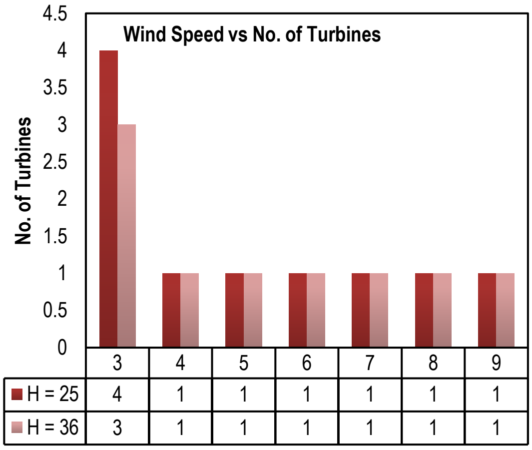

Fig. (14) No. of turbines vs. annual wind speed for PGE 20-25 turbine

3.2.2 Impact of Hub Height upon Battery Numbers

Figure (15) illustrates that for wind speeds of 5 m/s onwards, less than 15 batteries are required by the system. This may be normal as some designers might use a given number of batteries in the system simply because intermittent winds might possibly provide fluctuated energy supply. Thus, hub height did not remarkably contributed to reducing the number of batteries at annual lower wind speeds (8 batteries as a maximum). In other words, at low annual speeds, higher hub heights could not run the turbine to fit the power duty level.

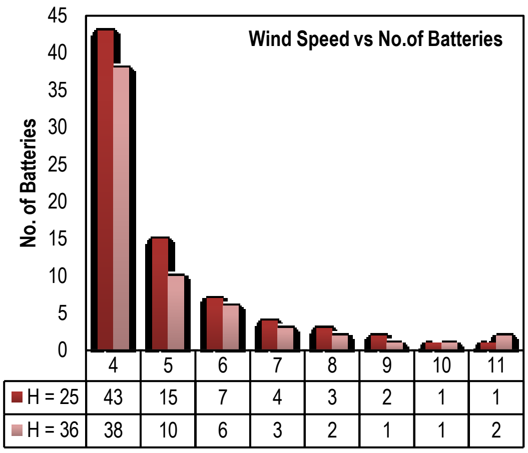

Fig. (15) No. of batteries vs. annual wind speed for PGE 20-25 turbine

3.2.3 Impact of Hub Heights on Battery Lifetimes

For lower annual wind speed of 3 m/s, all hubs for the PGE (25kW) turbine manifested short battery lifetimes (~4 years). For 4 m/s, battery life has enhanced to some extent (table 5). Though, later, annual wind speed of 5-12 m/s led to an optimum battery lifetime (up to 10 years), as shown in Fig. (16). This clearly indicates that at low annual wind speeds, higher hubs may not be very significant.

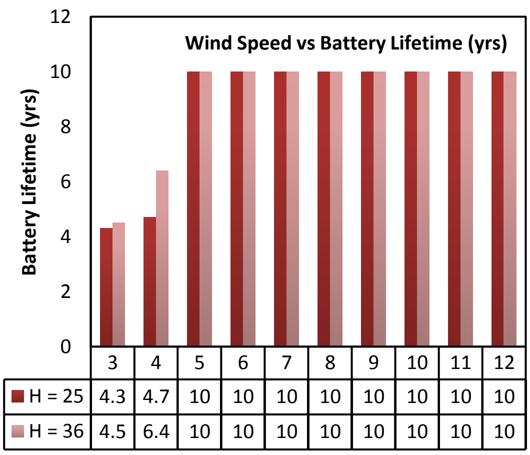

Fig. (16) Battery lifetime vs. annual wind speed for PGE 20-25 turbine

Table (5) Battery lifetimes for various hub heights at 4 m/s

Hub heights of PGE 20-25	Increase in Hub height	Battery lifetime / Increase in battery lifetime
25 m	-	4.7 / -
36 m	11 m	6.4 / 36.1%

Key findings:

i. Battery bank's lifetime at 3-4 m/s may be short as they operate for longer hours than higher categories of wind power.

ii. At annual wind speed 5-12 m/s, battery lifetimes may be optimal. Turbines produce adequate power within this range of wind speed for maintaining the load. In addition, they better recharge batteries.

iii. The impact of hub height may be illustrated exclusively at lower annual wind speeds (3 - 4 m/s). Even though when hub heights are extended, turbines are still very reliant upon battery power for sustaining the load at 3-4 m/s annual speed.

To sum up technically, the impact of hub height on the system is not significant, with the exception of at lower wind speeds (3-4 m/s).

3.2.4 Impact of Hub Height on Initial Cost of Turbine System

Initial cost cover system constituents only; it does not cover the cost of land and infrastructures for higher hubs. Table (6) illustrates the variation in initial costs at various annual speeds where is noted that at low annual wind speeds, the initial cost of the system is declined when hub height is increased since less equipment are required by the system. Yet, the variation in initial cost was non-significant from 4-12 m/s.

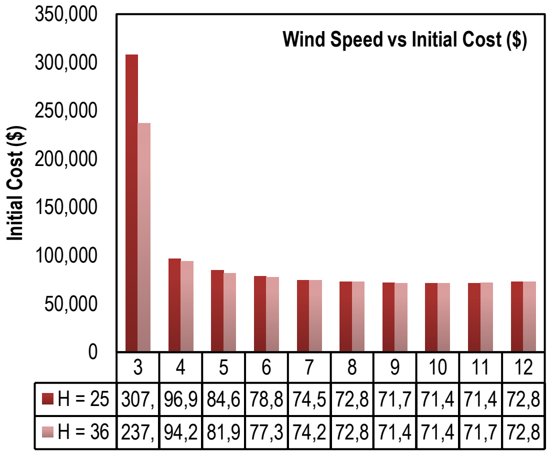

Fig. (17) Initial cost vs. annual wind speed for PGE 20-25 turbine

Table (6) How initial cost is declines when hub height is increased

Annual wind speeds (m/s)	Initial cost ($) / reduced initial cost	
	25	36
3	307,860 / -	237,220 / 22.9%
4	96,900 / -	94,205 / 2.7%
5	84,655 / -	81,960 / 3.1%
6	78,810 / -	77,395 / 1.8%
7	74,565 / -	74,245 / 0.4%
8	72,830 / -	72,830 / -
9	71,735 / -	71,415 / 0.4%
10	71,415 / -	71,415 / -

3.2.5 Impact of Hub Heights on Operation and Maintenance Cost, Total NPC and COE of System

Figures (18-20) depict the trends of operation and maintenance cost, Total NPC, and COE, respectively, against annual speeds. Figures (18-20) and tables (7-9) indicate that the impact of multiple hub height is significant, however the cost of the system is still high and uncompetitive at lower annual speed of 3 m/s. At annual wind speeds of 5 m/s onwards, the impact of two hub heights upon costs disappeared.

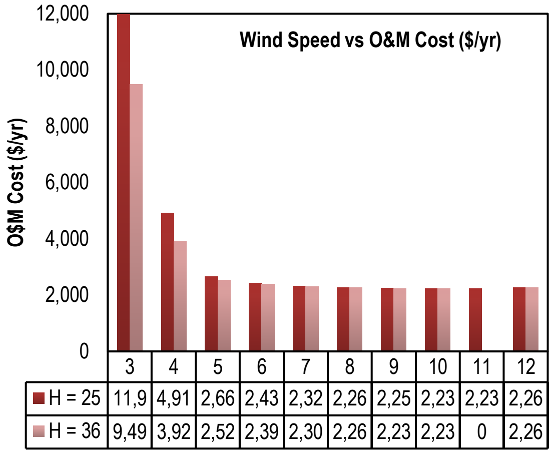

Fig. (18) O&M cost vs. annual wind speed for PGE 20-25 turbine

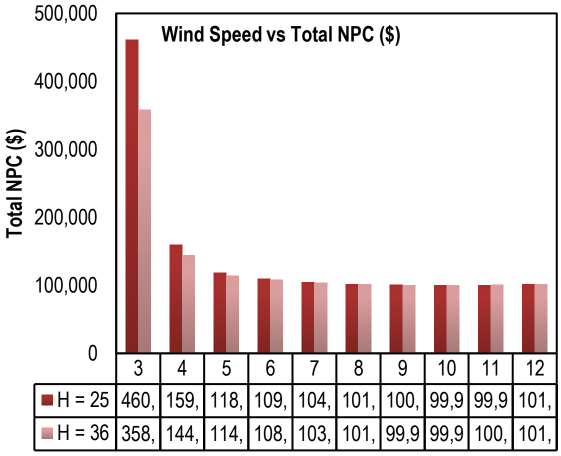

Fig. (19) Total NPC vs. annual wind speed for PGE 20-25 turbine

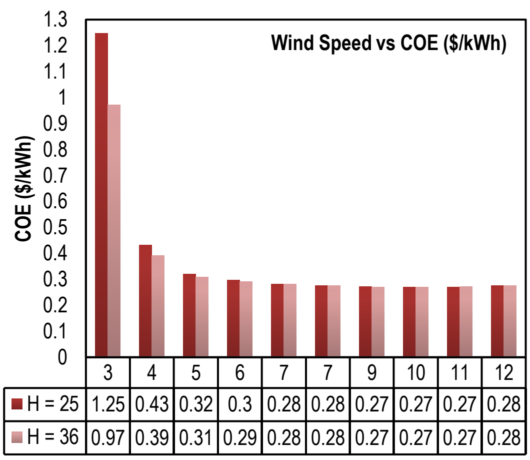

Fig. (20) COE vs. annual wind speed for PGE 20-25 turbine

Table (7) Reduction in operation and maintenance cost for various hub heights

Annual wind speeds (m/s)	Operation and maintenance ($/year) / reduced operation and maintenance cost	
	25	36
3	11,978 / -	9,492 / 20.7%
4	4,914 / -	3,920 / 20.2%
5	2,661 / -	2,529 / 4.9%
6	2,434 / -	2,399 / 1.4%
7	2,328 / -	2,304 / 1.0%
8	2,268 / -	2,268 / -
9	2,256 / -	2,232 / 1.0%
10	2,232 / -	2,232 / -

Table (8) Reduction in total NPC for various hub heights

Annual wind speeds (m/s)	Total NPC ($) / reduced total NPC	
	25	36
3	460,979 / -	358,555 / 22.2%
4	159,719 / -	144,313 / 9.6%
5	118,666 / -	114,295 / 3.6%
6	109,930 / -	108,060 / 1.7%
7	104,319 / -	103,694 / 0.5%
8	101,824 / -	101,824 / -
9	100,579 / -	99,954 / 0.6%
10	99,954/ -	99.954 / -

Table (9) Reduction in COE for various hub heights

Annual wind speeds (m/s)	COE ($/kWh) / Reduced COE	
	25	36
3	1.248 / -	0.971 / 22.1%
4	0.432 / -	0.391 / 9.5%
5	0.321 / -	0.309 / 3.7%
6	0.297 / -	0.292 / 1.6%
7	0.282 / -	0.281 / 0.3%
8	0.276 / -	0.276 / -
9	0.272 / -	0.27 / 0.7%
10	0.27 / -	0.27 / -

Financially, higher hubs were minimally significant vis-à-vis system cost at an annual speed range of 4-12 m/s. Though hub height slightly affects techno-economic features of systems, it is noted that systems with higher hubs are to some extent more desirable at lower annual wind speeds. Yet, if cost of the higher hubs is taken into consideration, the total project will be increased (cost of system and infrastructure for higher hubs).

After all, the impact of hub height on techno-economic features may be insignificant if compared to the impact of wind speeds and turbine types. In conclusion, for higher wind speeds, less equipment are required by the system, which consequently minimizes the all economic requirements.

3.3 Validating The Outstanding Turbine Using Actual Monthly Wind Speed Data Of Different Tested Locations As A Case Study

The tested locations are Dammam city in Suadi Arabia, Ras Monief in Jordan, and Kokhanok in Alaska, USA. The determined wind turbine size will be compared with the outstanding wind turbine size determined by the proposed sizing approach. If the wind turbine size is found same, this confirms that the proposed sizing approach is accurate for predicting the outstanding turbine size at any location around the globe.

Based on Fig. (21) and table (10), it is shown that a system with a lowest number of turbines, with the lowest number of batteries (with a standard lifetime) and lowest levelized energy cost may be PGE (25 kW). In conclusion, the outstanding turbine was the PGE (25 kW) for feeding 8 kW load at the three cities.

The results of the analyses established that the outstanding turbine size is still again PGE 20-25 (25kW). This clearly indicates that the shortcut sizing approach adopted in section 3.1 is accurate for determining the outstanding turbine that is confirmed using real monthly data at the tested locations. So, the proposed sizing approach is fit to predict the outstanding turbine at all locations all over the world.

4. Conclusion

This study tested the utilization of annual wind speed as a sufficient data (3-12 m/s) to predict the outstanding size of wind turbine to power a specific load 8 kW at so many locations around the globe. For this purpose, six wind turbine types with different power size are selected. The selection of the turbines was based on the appropriate power capacity range to run 8 kW load, on top of the initial cost of each wind turbine. The outstanding wind turbine size is determined based on the optimum results of techno-economic feasibility parameters using HOMER simulation tool at each annual wind speed. The six turbines performance versus the annual wind speed range is compared for each parameter. The results showed that the outstanding size of wind turbine is PGE 20-25 (25 kW). Validation results under three tested locations confirmed that the optimum wind turbine size is still PGE 20-25 (25 kW) that's the power system to sustain the 8 kW load is nearly three times greater than the load, one of the key findings. Moreover, the results showed that the outstanding wind turbine size and annual wind speed did impose more impacts on the values of techno-economic feasibility parameters compared to higher hub heights. Finally, it can be concluded that the annual wind speed data (3-12m/s) is a sufficient data to predict accurately the outstanding wind turbine size of optimum power duty to run 8 kW load around the globe assuming annual wind speed range (3-12) m/s as a representative of so many locations around the globe.

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Table (1) The R&D aspects covered by previous researcher's studies on components sizing and techno-economic features of wind power systems done by HOMER

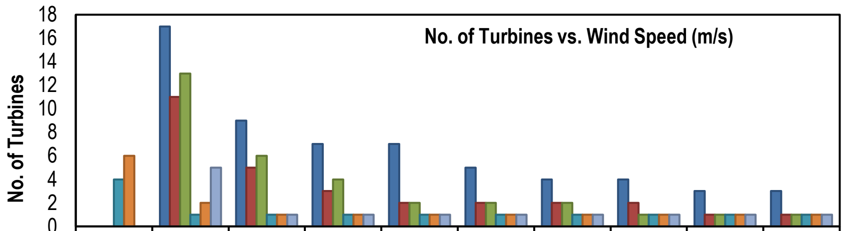
References	Location	Wind Speed	Wind power system type	Load profile (kWh/day)	Application
Ashourian et al. [1]	Tioman Island, Malaysia	Annual (3.18 m/s)	***Standalone***: Hybrid PV-Wind-Diesel-Battery-Fuel Cell	496	30 chalets
Sadeghi et al. [2]	Baladeh city, North of Iran	Monthly (3.0-4.0 m/s)	***Grid-connected***	NA	Residential buildings
Aagreh & Al-Ghzawi [3]	Ajloun city, Jordan	Annual 4.57 m/s @10 m height 6.76 m/s@ 60 m height	***Grid-connected***: Hybrid Wind-PV-Battery	97	Small hotel
Goodbody et al. [4]	Ireland	NA	***Grid-connected***: Hybrid Wind-PV-Diesel-Hydro-Biomass-Battery	12-25	Apartment, households and retail unit
Adaramola [5]	Ondo State, Nigeria	Annual (3.26 m/s)	***Standalone***: Hybrid Wind-PV-Diesel-Battery	25	Households
Osorio et al. [6]	Madrid (Cuatro Vientos), Burgos, Alto do Rodicio and Punta Candelaria, Spain	Annual Madrid (Cuatro Vientos) (3.92 m/s) Burgos (5.08 m/s) Alto do Rodicio (6.18 m/s) Punta Candelaria (7.38 m/s)	***Grid-connected***: Hybrid Wind-Diesel-Battery	Oct-March (63) Apr-Sept (62)	Dairy cattle farms
Fahmy et al. [7]	Hurghada, Egypt	Annual (6.93 m/s)	***Standalone***: Hybrid Wind-PV-Battery-Fuel Cell	60	Small Scale Brackish Reverse Osmosis Desalination Unit and a Tourism Motel
Moniruzzaman & Hasan [8]	Bandarban, Bangladesh	Annual (4.12 m/s)	***Grid-connected***: Hybrid Wind-PV-Diesel-Battery	35	Household/ small restaurant
Sadrul Islam et al. [9]	St. Martin Island, Bangladesh	Annual (4.71 m/s)	***Standalone***: Hybrid Wind-PV-Diesel-Battery	78	Households and shops
Badawe et al. [10]	Mulligan, Labrador, Canada.	Annual (6.26 m/s)	***Standalone***: Hybrid Wind-PV-Diesel-Battery	79	Microwave repeaters (telecommunication)
Abulqasem et al. [11]	Mrair-Gabis Village, Libya	Annual (3.7-4.4 m/s)	***Standalone***: Hybrid Wind-PV-Diesel-Battery	86	Small Scale Seawater Reverse Osmosis Desalination Unit
Chowdhury & Oo [12]	Australia	Annual (2.13–6.11 m/s)	***Grid-connected***: PV-Wind-Battery system	1000	Electricity generation
Ibrahim et al. [13]	Kuala Terengganu, Malaysia	Monthly (3.16 m/s)	***Standalone***: PV-Wind-Diesel-Battery-Fuel Cell system	20	Residential building
Thakur et al. [14]	Jabalpur Engineering College, Jabalpur, India	Monthly (4.0 m/s)	***Standalone***: PV-Wind-Diesel-battery system	2000	College
Fantidis et al. [15]	Plaka, Greece	Annual (6.44 m/s)	***Standalone***: Hybrid PV-wind, Wind-diesel	15.15-15.4	60 household electricity
Nandi & Ghosh [16]	Chittagong, Bangladesh	Monthly (3.0- 5.0 m/s)	***Standalone***: PV-Wind-Battery system	160	Households
Niazi et al. [17]	Nok kundi & Ormara, Pakistan	Monthly (4.1- 5.5) & (2.2- 5.1) m/s	***Grid-connected:*** Hybrid Wind-PV-Diesel	13.1	small houses
Shaahid [18]	Dhahran (East-Coast, KSA)	Monthly (3.3- 5.6 m/s)	***Grid-connected:*** Hybrid Wind-Diesel-Battery	351	100 of typical residential buildings
Amini [19]	Ghardaia and Djanet, Algeria	NA	PV systems, Wind generators and Batteries	NA	Rural Health Clinics
Amin et al. [20]	St. Martin Island, Bangladesh	Monthly (3.6- 6.5 m/s)	***Standalone:*** Hybrid Wind-PV-Diesel-Battery	1421	650 households.
Soe & Zheng [21]	Wetkaik village, Myanmar	Annual (3.7 m/s)	***Grid-connected:*** Hybrid Wind-Diesel-Battery	1167	850 households
Diab et al. [22]	(Alexandria, Qena and Aswan), Egypt	Monthly (4.8- 6.2 m/s) (4.3- 5.6 m/s) (4.3- 5.5 m/s)	***Standalone:*** hybrid PV/wind/diesel /battery	19,906	tourist village

Table (3a) Specifications of wind turbines

Wind Turbine	AC/DC	Rated Power (kW)	Rotor Diameter (m)	Hub Height (m)	No. of Blades
SW Whisper 500	DC	3	4.5	9.1, 12.8, 21.3	2
BWC Excel-R	DC	7.5	7	18, 24, 30, 37, 43, 49	3
BWC Excel-S	AC	10	7	18, 24, 30, 37, 43, 49	3
PGE 20/25	AC	25	20	24, 25, 30, 36	3
Fuhrlander FL 30/13	AC	30	13	19, 25, 29	3
Entegrity EW15	AC	50	15	25, 30	3

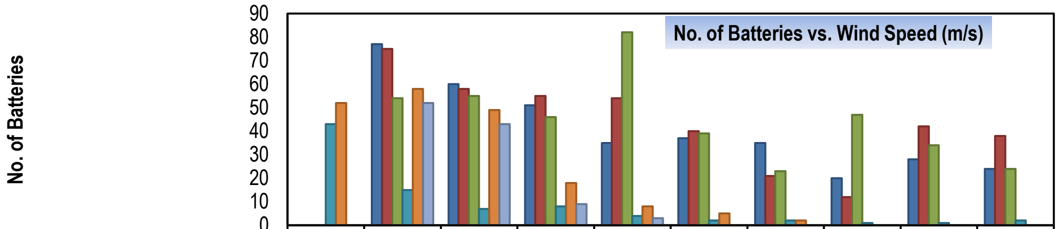
Table (3b) Continued specifications of wind turbines

Wind Turbine	Cut-In Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-Out Wind Speed (m/s)	Manufacturer	Cost ($)
SW Whisper 500	3.4	10.5	25	Southwest Windpower, USA	8,985
BWC Excel-R	3	13.8	25	Bergey Windpower Co., USA	26,870
BWC Excel-S	2.5	12	25	Bergey Windpower Co., USA	31,770
PGE 20/25	3.5	9	25	Energie PGE, Canada	70,000
Fuhrlander FL30/13	3	12	21	Fuhrlander, Germany	78,000
Entegrity EW15	4.6	11.3	22.4	Entegrity Wind Systems Inc., Canada	160,000



	3	4	5	6	7	8	9	10	11	12
SW Whisper 500 (3kW)	0	17	9	7	7	5	4	4	3	3
BWC Excel-R (7.5kW)	0	11	5	3	2	2	2	2	1	1
BWC Excel-S (10kW)	0	13	6	4	2	2	2	1	1	1
PGE 20-25 (25KW)	4	1	1	1	1	1	1	1	1	1
Fuhrlander FL 30-13 (30kW)	6	2	1	1	1	1	1	1	1	1
Entegrity EW15 (50kW)	0	5	1	1	1	1	1	1	1	1

Fig. (4) No. of turbines vs. annual wind speeds for different wind turbines with diverse dimensions



	3	4	5	6	7	8	9	10	11	12
SW Whisper 500 (3KW)	0	77	60	51	35	37	35	20	28	24
BWC Excel-R (7.5KW)	0	75	58	55	54	40	21	12	42	38
BWC Excel-S (10KW)	0	54	55	46	82	39	23	47	34	24
PGE 20-25 (25KW)	43	15	7	8	4	2	2	1	1	2
Fuhrlander FL30-13 (30KW)	52	58	49	18	8	5	2	0	0	0
Entegrity EW15 (50KW)	0	52	43	9	3	0	0	0	0	0

Fig. (5) No. of batteries vs. annual wind speeds for various dimensions of wind turbines

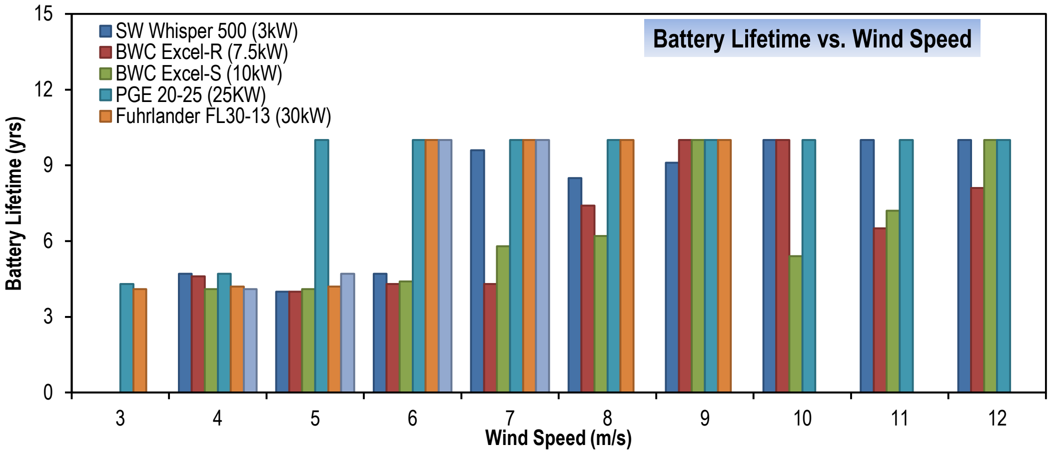
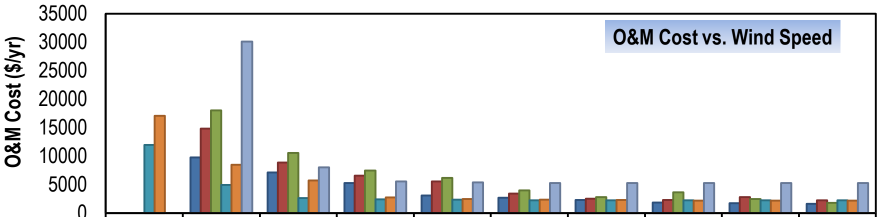
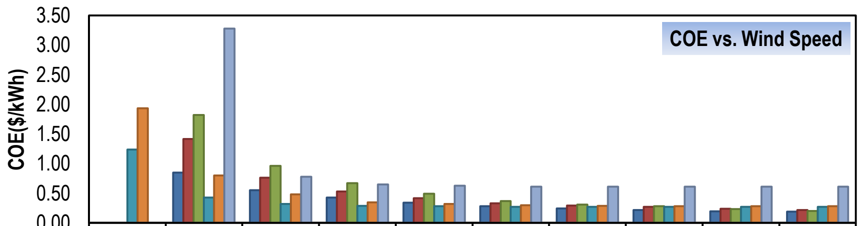


Fig. (6) Battery lifetime vs. annual speeds for diverse sizes of wind turbines



	3	4	5	6	7	8	9	10	11	12
SW Whisper 500 (3kW)	0	9,759	7,117	5,281	3,102	2,706	2,278	1,827	1,724	1,629
BWC Excel-R (7.5kW)	$0	$14,839	$8,886	$6,595	$5,574	$3,395	$2,506	$2,279	$2,790	$2,253
BWC Excel-S (10kW)	$0	$18,043	$10,547	$7,486	$6,191	$3,988	$2,830	$3,641	$2,449	$1,784
PGE 20-25 (25KW)	11,978	4,914	2,661	2,434	2,328	2,268	2,256	2,232	2,232	2,268
Fuhrlander FL30-13 (30kW)	17,060	8,478	5,710	2,750	2,476	2,370	2,274	2,203	2,203	2,203
Entegrity EW15 (50kW)	0	30,116	8,025	5,566	5,376	5,269	5,269	5,269	5,269	5,269

Fig. (10) Operation and maintenance cost vs. annual speeds for various turbine sizes



	3	4	5	6	7	8	9	10	11	12
SW Whisper 500 (3kW)	0.00	0.85	0.55	0.43	0.34	0.28	0.24	0.22	0.20	0.19
BWC Excel-R (7.5kW)	0.00	1.42	0.76	0.53	0.42	0.33	0.29	0.27	0.24	0.22
BWC Excel-S (10kW)	0.00	1.82	0.96	0.67	0.49	0.37	0.31	0.28	0.23	0.20
PGE 20-25 (25KW)	1.24	0.43	0.32	0.29	0.28	0.27	0.27	0.27	0.27	0.27
Fuhrlander FL30-13 (30kW)	1.94	0.80	0.48	0.35	0.32	0.30	0.29	0.28	0.28	0.28
Entegrity EW15 (50kW)	0	3.28	0.78	0.65	0.63	0.61	0.61	0.61	0.61	0.61

Fig. (12) COE vs. annual wind speeds for various turbine sizes

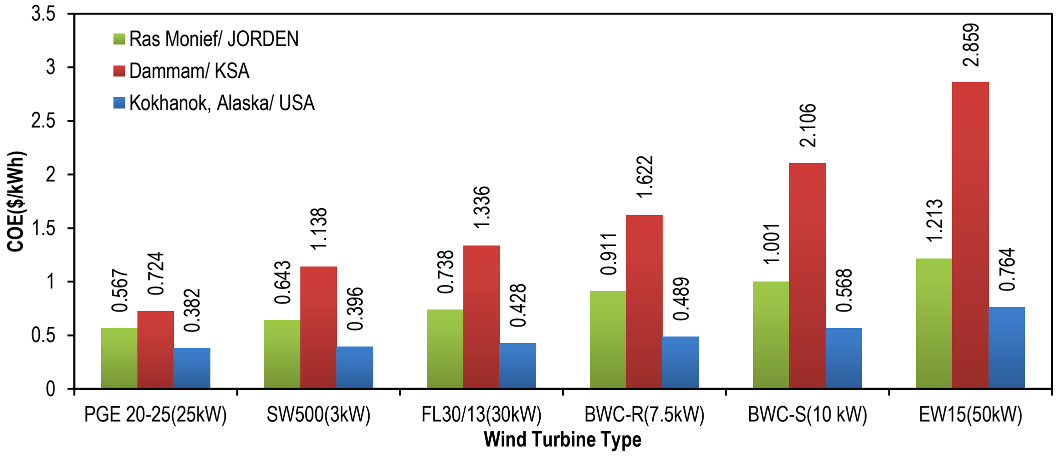


Fig. (21) COE versus wind turbine sizes for Al-Dammam, Ras Monief and Kokhanok (Alaska) together

Table (10) Outstanding turbine size based on techno-economic feasibility parameters for three tested locations

Case studies with real monthly wind speed data	Wind turbine sizes with minimum No. of turbines	Wind turbine sizes with minimum No. of batteries	Wind turbine sizes with maximum Battery lifetime	Wind turbine size with minimum COE	Predicted turbine size at the tested locations using monthly data	Outstanding turbine size predicted by annual wind speed data
Dammam, Saudi Arabia	25kW	@30kW: 82 @25kW: 86	All sizes	25kW	25kW	**25kW**
Ras Monief, Jordan	25kW, 30kW 50kW	25kW	All sizes	25kW	25kW	
Kokhanok, Alaska, USA	25kW, 30kW 35kW, 50kW	25kW	All sizes	25kW	25kW	

