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Wind Energy Assessment for Five Locations in Saudi Arabia

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Abstract. This paper introduces a computer program to choose the most suitable wind turbine for each site according to technical and economical assessment. The criterion for choosing the most suitable wind turbine for each site is according to which wind turbine and site give a maximum capacity factor and minimum cost of energy($/kWh). This criterion is used because the decision of matching which depends only on maximum capacity factor is not enough because capacity factor is independent of rated power of wind turbine. Therefore, two wind turbines with the same performance parameters but different rated power get the same capacity factor for the same site but it does not get the same cost of energy($/kWh). The computer program has been applied on five locations in Saudi Arabia. The five locations are Yanbou, Dhahran, Douhlom, Riyadh and Qaisumah. The wind turbine parameters such as hub height, rated power, cut-in, rated, and furling wind speeds for ten commercial wind turbines are collected. The Weibull parameters have been estimated numerically and graphically for these five locations. The values of Weibull parameters obtained graphically are similar to the numerical one. Three methods have been used for estimating the cost of energy. The results from these three methods have been compared and the suitable one for Saudi Arabia economics has been selected.

Keywords: Weibull parameters; Cost of energy; Present value of cost; Yearly energy generated; Capacity factor.

1. Introduction

Wind turbine generator, WTG characteristics are different from one to another. Also, the characteristics of the wind speed are different from site to site. Pairing between the performance parameters of WTG and the wind speed characteristics of each site can increase the wind energy captured considerably and reduce the cost of the generated energy. The main performance parameters of the WTG are, cut in, rated and furling wind speeds respectively and rated power of the WTG. Also, the main characteristics of wind speed in a certain site are the shape parameter, k and the scale parameter, c that can be obtained from Weibull distribution statistical technique.

Different techniques are used for pairing between sites and wind turbines. Some of these techniques depend only on technical constraints or on economic constraints. But, the best technique for pairing between the performance parameters of WTG and the wind speed characteristics of each site should depend on both technical and economic assessments. In these studies [1-3], a simplified technique for pairing between sites and WTG depends only on capacity factor. This technique takes a decision depending only on technical constraints. These studies [1-3] omitted assessment in economic terms which is very important in the evaluation process, which should be included the technical and economic aspect to become reliable. On the other hand, a technical and economical assessment has been made of the generation of electricity using wind turbines at some of the most promising wind sites in Egypt and Saudi Arabia. The value of money method has been used to determine the present value of costs (*PVC*) of electricity produced per year. The electrical

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energy cost of kWh produced was estimated by dividing the present value of costs by the total energy production of the wind turbine over its life time [4-7].

In this study, the hourly mean wind speed data are being collected for five locations in Saudi Arabia for a complete year. The five selected locations are Yanbou, Dhahran, Douhlom, Riyadh and Qaisumah. Also, Matlab program is used to choose the most suitable WTG for each site according to technical and economic assessment. This proposed program can be used to handle many other sites and many wind turbines. The Weibull parameters (c, k) have been estimated numerically and graphically. Three methods have been used for estimating the cost of energy. The results from these three methods have been compared and the suitable one for Saudi Arabia economics has been selected.

2. Description of the Main Program

The flowchart of the main program is shown in Fig. 1, where technical and economical assessment have been done through choosing the best WTG for each site. The criterion for choosing the most suitable WTG for each site is according to which WTG and site give us maximum capacity factor, C_F , and minimum cost of energy($/kWh). The decision of matching which depends only on maximum C_F is not enough because C_F is independent of P_r. Therefore, two wind turbines with the same u_c, u_r and u_f but different nominal power, P_r, get the same C_F at the same site but not get the same cost of energy ($/kWh).

The data input to the main program are:

1- The hourly mean values of the wind speed data which collected at 10 m height for five locations Yanbou, Dhahran, Douhlom, Riyadh and Qaissumah.
2- The parameters (P_r , u_c , u_r, u_f, H) for ten WTG are collected and extracted from Excel data file.

The data output (results) from the main program are:

1- The estimation of weibull parameters numerically and graphically, capacity factor, the yearly energy output, average no. of WTG, and the cost of energy using three methods and comparing between them.
2- The best WTG for each site according to technical and economical assessment.

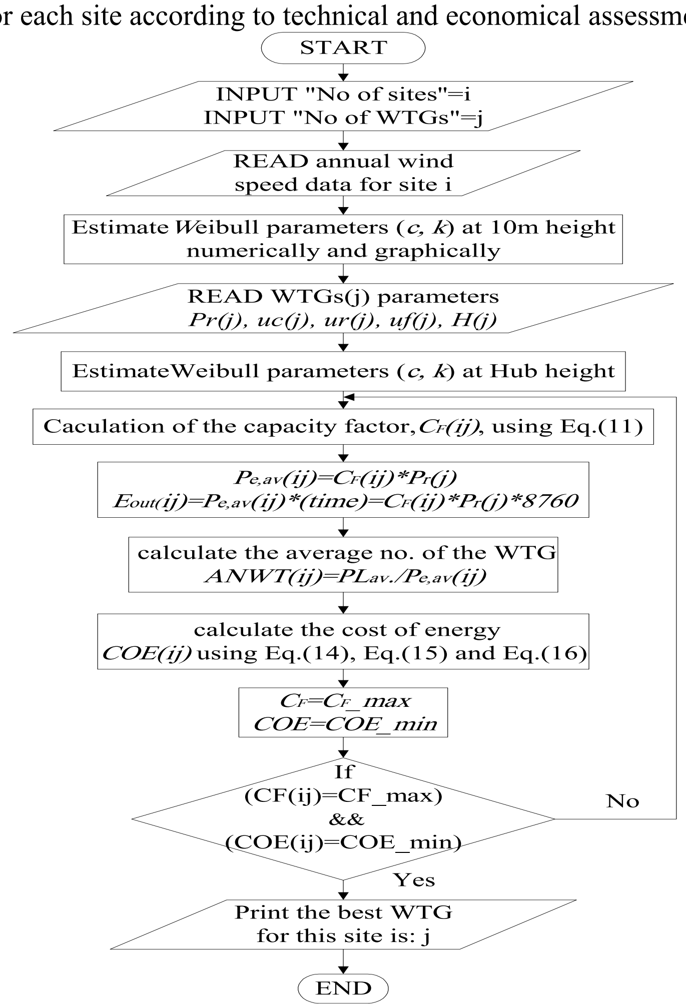

Fig.1. the flow chart of the main Matlab program.

3. Mathematical Analysis

3.1. Weibull Parameters Estimation

The wind speed, u is distributed as the Weibull distribution if its probability density function is [8]

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (k \succ 0, u \succ 0, c \succ 1) \tag{1}$$

And the cumulative distribution function can be estimated by integrating Eq. (1)

$$F(u) = \int_0^u f(u)\,du = 1 - \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{2}$$

$F(u)$ contains an exponential as in Eq. (2) and that, in general, exponentials are linearized by taking the logarithm. In this case, because the exponent is itself raised to a power, we must take logarithms twice [4-6, 8].

$$\ln[-\ln(1 - F(u))] = k \ln u - k \ln c \tag{3}$$

This equation takes the form of straight line as shown:

$$y = ax + b \tag{4}$$

The values of a and b can be determined as follow:

$$a = \frac{\sum_{i=1}^{w} x_i\, y_i - \frac{\sum_{i=1}^{w} x_i \sum_{i=1}^{w} y_i}{w}}{\sum_{i=1}^{w} x_i^2 - \frac{\left(\sum_{i=1}^{w} x_i\right)^2}{w}} = \frac{\sum_{i=1}^{w}(x_i - \bar{x})\sum_{i=1}^{w}(y_i - \bar{y})}{\sum_{i=1}^{w}(x_i - \bar{x})^2} \quad , \quad b = \bar{y}_i - a\bar{x}_i = \frac{1}{w}\sum_{i=1}^{w} y_i - \frac{a}{w}\sum_{i=1}^{w} x_i \tag{5}$$

In these equations $\bar{x}$ and $\bar{y}$ are the mean values of x_i and y_i, and w is the total number of pairs of values available. The final results for the Weibull parameters are:

$$k = a \quad , c = \exp\left(-\frac{b}{k}\right) \tag{6}$$

Or by plotting $\ln u$ against $\ln[-\ln(1-F(u))$ should yield a straight line. The slop of the line is k and the intercept with the y-axis is $-k \ln c$ .Then, the Weibull parameters values can be estimated at any desired height (z_h) in meter, based on the records at the standard anemometer height of 10m by the following equation [6]:

$$k_h = k_{10} * \left[1 - 0.0881 * \ln\left(\frac{z_h}{10}\right)\right]^{-1} \tag{7}$$

$$c_h = c_{10} * \left(\frac{z_h}{10}\right)^{n} \tag{8}$$

$$n = [0.37 - 0.0881 * \ln(c_{10})] \tag{9}$$

Where n is the power law exponent (coefficient).

Weibull parameters have been estimated numerically for the five sites as shown in table (1) and graphically for Yanbou as shown in Fig.2. The values of c, k obtained graphically are nearly similar to the numerical one.

Table (1): Estimation of the Weibull parameters (c, k) at 10m height.

Sites	**Numerically**		**Graphically**	
	c	***k***	***c***	***k***

Yanbou	5.777	1.970	5.885	2.249
Dhahran	5.858	3.238	5.839	4.038
Douhlom	5.307	1.551	5.939	1.963
Riyadh	4.017	2.462	4.015	2.453
Qaissumah	5.096	3.739	5.075	4.376

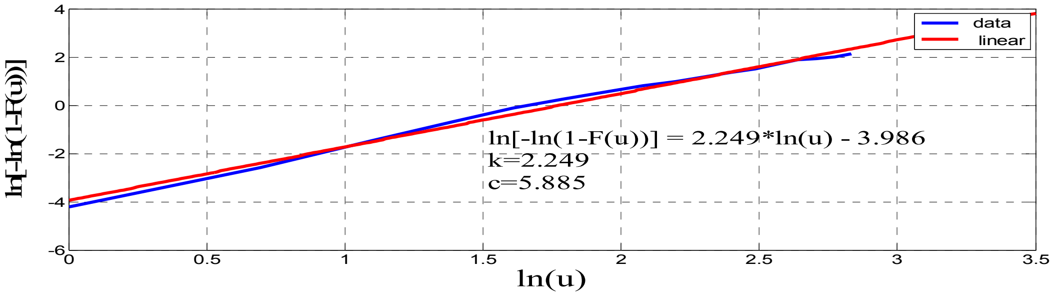

Fig. 2. Plotting ln(-ln(1-F(u))) against ln(u), for Yanbou as one from these five sites, through which *c, k* are estimated .

3.2. Energy Production and Capacity Factor

The yearly energy production of the turbine can be estimated using the following equation:

$$E_{out} = P_{e,ave}(\text{time}) = C_F * P_{er} * (8760) \tag{10}$$

Where C_F is the capacity which can be obtained from the following equation [8]:

$$C_F = \frac{\exp\left[-(u_c/c)^k\right] - \exp\left[-(u_r/c)^k\right]}{(u_r/c)^k - (u_c/c)^k} - \exp\left[-(u_f/c)^k\right] \tag{11}$$

The average number of WTG, *ANWT* required is given by the following equation:

$$ANWT = \frac{P_{Lav}}{P_{e,ave}} \tag{12}$$

4. Economic Analysis

There are several methods available for estimating the cost of energy [4-8, 10-15]. In this study, the cost of energy has been estimated using three methods as follow:

In method 1, the simple equation for getting the price of the whole system is [9];

Total Price = (*ANWT**P_r*Price of each KW of WTG+ *O&M* price) (13)

The price of each kWh=Total price**LF* /(E_{out}* Availability of WTG) (14)

Where P_r : the rated power of the WT, E_{out} : the actual yearly energy output, *LF* :the levelization factor.

In method 2, the value of money method has been used to determine the present value of costs (*PVC*) of electricity produced per year given by Lysen [10] and referred by Habali [11-12], Sarkar [13], Alnaser [14], Türkosy [15] , Rehman [7] and by Shata[4-6] . *PVC* method used under the following assumptions: The life time of the machine (t) was assumed to be 20 years. The interest rate (r) and inflation rate (i) were taken to be 8% and 6%, respectively. Operation maintenance and repair cost (C_{omr}) was considered to be 25% of the annual cost of the turbine (machine price/life time). Scrap value S was taken to be 10% of the turbine price and civil work. Investment (I) includes the turbine price plus its 20% for the civil work and other connections.

The present value of costs (*PVC*) is [4-6, 11-15]:

$$PVC = I + C_{omr}\left[\frac{1+i}{r-i}\right] \times \left[1 - \left(\frac{1+i}{1+r}\right)^t\right] - S\left(\frac{1+i}{1+r}\right)^t \tag{15}$$

The electrical energy cost of kWh produced in each region was estimated by dividing the present value of costs by the total energy production of the wind turbine over its life time (20 years).

In method 3, the cost of energy, *COE*, is calculated using the following equation [16-17]:

$$COE = \frac{FCR * ICC + LLC + O\&M + LRC}{AEP_{net}} \quad (16)$$

Where *COE*: Cost of energy, *FCR*: fixed charge rate, *ICC*: initial capital cost, AEP_{net}: net annual energy production, *LLC*: land lease cost, *O&M*:operating& maintenance cost, *LRC*: levelized replacement/overhaul cost.

5. Results and Discussions

In this study, five sites in Saudi Arabia have been selected. The five sites are Yanbou, Dhahran, Douhlom, Riyadh and Qaissumah. The hourly wind speeds of these sites are collected where the annual wind speed are used for each site. The wind site characteristics (*c, k*) are estimated graphically and numerically using Matlab program as shown in table (1) and Fig.2. Ten types of the commercially available WTGs are used from various manufacturers. The technical data of WTGs shown in Table (2) are obtained from [18]. The loads are assumed to be the same in each site and have 22.58333 MW as a maximum value. The annual average loads are used to find the average number of WTG required. Technical and economical assessments have been done through the sequence of this program. First, the wind site characteristics *(c, k)* at hub height and the average number of WT, have been estimated as shown in table (3). Second, the *COE* ($/kWh)using three methods and the C_F for each site and each WTG have been done as shown in table (4), table (5) and table (6). Finally, the WTG which has maximum C_F and minimum *COE* ($/kWh) is the best one for this site. According to this condition, the best WTG for all sites is Acciona (AW3000-116). For Yanbou, the maximum C_F and minimum *COE* are 0.532 and 0.0151($/kWh). For Dhahran, the maximum C_F and minimum *COE* are 0.51 and 0.0158($/kWh). For Douhlom, the maximum C_F and minimum *COE* are 0.487 and 0.0165($/kWh). For Riyadh, the maximum C_F and minimum *COE* are 0.264 and 0.0306($/kWh). For Qaissumah, the maximum C_F and minimum *COE* are 0.34 and 0.0237($/kWh). Fig.3 shows C_F and *COE* ($/kWh) of ten WTG and five sites in Saudi Arabia.

Table (2): The technical data of WTGs

No.	Manufacturer	Model	$P_r(kw)$	*D (m)*	u_c	u_r	u_f	*H(m)*
1	Gamesa	G128/4500	*4,500*	*128*	*3*	*13*	*25*	*120*
2	Nordex	N100/2500	2,500	100	3	12.5	20	100
3	Acciona	AW-70/1500	1,500	70	4	11.6	25	60
4	Acciona	AW-82/1500	1,500	82	3	10.5	20	80
5	Acciona	AW3000-100	3,000	100	4	12	25	98
6	Acciona	AW3000-116	3,000	116	3	10.6	20	98
7	Repower	3.2M114	3,200	114	3	12.5	22	93
8	Repower	3.4M104	3,400	104	3.5	12.5	25	78
9	Repower	MM100	1,800	100	3	10.5	22	78
10	GE Energy	1.5xle	1,500	82.5	3	12	20	80

Table (3) The Weibull parameters at hub height of each WTG and ANWT for each site

	Yanbou			Dhahran			Douhlom			Riyadh			Qaissumah		
Manuf.	*c*	*k*	*ANWT*	*c*	*k*	*ANWT*	*c*	*k*	*ANWT*	*c*	*k*	*ANWT*	*c*	*k*	*ANWT*
Gamesa	9.87	2.52	12	9.98	4.15	16	9.24	1.99	12	7.43	3.15	31	8.95	4.79	30
Nordex	9.49	2.47	22	9.59	4.06	28	8.87	1.95	23	7.1	3.09	55	8.59	4.69	53
Acciona	8.5	2.34	40	8.6	3.85	52	7.91	1.84	42	6.26	2.92	115	7.65	4.44	101
Acciona	9.04	2.41	30	9.15	3.96	32	8.44	1.9	32	6.72	3.01	63	8.16	4.58	50
Acciona	9.45	2.47	18	9.55	4.05	21	8.83	1.94	19	7.07	3.08	45	8.55	4.68	38
Acciona	9.45	2.47	14	9.55	4.05	15	8.83	1.94	15	7.07	3.08	29	8.55	4.68	22
Repower	9.34	2.45	17	9.45	4.03	23	8.72	1.93	18	6.98	3.06	45	8.45	4.65	44
Repower	8.99	2.41	18	9.1	3.95	24	8.39	1.89	18	6.68	3.01	49	8.12	4.57	49
Repower	8.99	2.41	25	9.1	3.95	27	8.39	1.89	27	6.68	3.01	54	8.12	4.57	43

GE Energy	9.04	2.41	36	9.15	3.96	47	8.44	1.9	38	6.72	3.01	93	8.16	4.58	89

Table (4): The yearly energy output, capacity factor and cost of energy ($/kWh) for Yanbou and Dhahran

	Yanbou					Dhahran				
Manuf.	C_F	$E_{out}*10^{10}$	COE(1)	COE(2)	COE(3)	C_F	$E_{out}*10^{10}$	COE(1)	COE(2)	COE(3)
Gamesa	0.4179	1.6474	0.87	0.0193	0.035	0.316	1.2437	1.53	0.0255	0.046
Nordex	0.4178	0.915	1.567	0.0193	0.0346	0.321	0.7033	2.65	0.0251	0.045
Acciona	0.3772	0.4957	3.204	0.0213	0.0381	0.292	0.3832	5.36	0.0276	0.049
Acciona	0.5078	0.6672	1.768	0.0159	0.0284	0.472	0.6205	2.04	0.0171	0.031
Acciona	0.4289	1.1272	1.239	0.0188	0.0339	0.358	0.9397	1.78	0.0225	0.04
Acciona	0.5322	1.3986	0.805	0.0151	0.0275	0.510	1.341	0.88	0.0158	0.029
Repower	0.4088	1.1461	1.278	0.0197	0.0355	0.307	0.8594	2.27	0.0263	0.047
Repower	0.3763	1.1208	1.42	0.0214	0.0385	0.272	0.8087	2.73	0.0297	0.053
Repower	0.5048	0.796	1.491	0.016	0.0287	0.466	0.7351	1.75	0.0173	0.031
GE Energy	0.415	0.5453	2.647	0.0194	0.0347	0.320	0.4204	4.45	0.0252	0.045

Table (5): The yearly energy output, capacity factor and the cost of energy ($/kWh) for Douhlom and Riyadh

	Douhlom					Riyadh				
Manuf.	C_F	$E_{out}*10^{10}$	COE(1)	COE(2)	COE(3)	C_F	$E_{out}*10^{9}$	COE(1)	COE(2)	COE(3)
Gamesa	0.406	1.6019	0.9202	0.0198	0.036	0.163	6.4265	5.718	0.0494	0.088
Nordex	0.399	0.8733	1.7201	0.0202	0.036	0.164	3.5947	10.15	0.0491	0.087
Acciona	0.356	0.4683	3.5886	0.0226	0.04	0.131	1.7231	26.51	0.0614	0.109
Acciona	0.467	0.613	2.0949	0.0173	0.031	0.239	3.1336	8.016	0.0338	0.06
Acciona	0.402	1.0558	1.4122	0.02	0.036	0.169	4.4426	7.976	0.0476	0.085
Acciona	0.487	1.2788	0.9626	0.0165	0.03	0.264	6.9262	3.282	0.0306	0.055
Repower	0.395	1.1074	1.3693	0.0204	0.037	0.157	4.3966	8.687	0.0513	0.091
Repower	0.365	1.0861	1.5125	0.0221	0.04	0.134	4.0023	11.14	0.0599	0.107
Repower	0.467	0.7363	1.7422	0.0172	0.031	0.235	3.7011	6.896	0.0343	0.061
GE Energy	0.396	0.5197	2.9148	0.0204	0.036	0.162	2.1218	17.48	0.0499	0.089

Table (6): The yearly energy output, capacity factor and the cost of energy ($/kWh) for Qaissumah

	Qaissumah				
Manuf.	C_F	$E_{out}*10^{9}$	COE(1)	COE(2)	COE(3)
Gamesa	0.166	6.5481	5.507	0.049	0.086
Nordex	0.17	3.7274	9.442	0.047	0.084
Acciona	0.15	1.9675	20.33	0.054	0.095
Acciona	0.3	3.9452	5.057	0.027	0.048
Acciona	0.198	5.2073	5.806	0.041	0.072
Acciona	0.34	8.9273	1.975	0.024	0.043
Repower	0.16	4.4826	8.357	0.05	0.09
Repower	0.137	4.0674	10.78	0.059	0.105
Repower	0.294	4.6393	4.389	0.027	0.049
GE Energy	0.169	2.2262	15.88	0.048	0.084

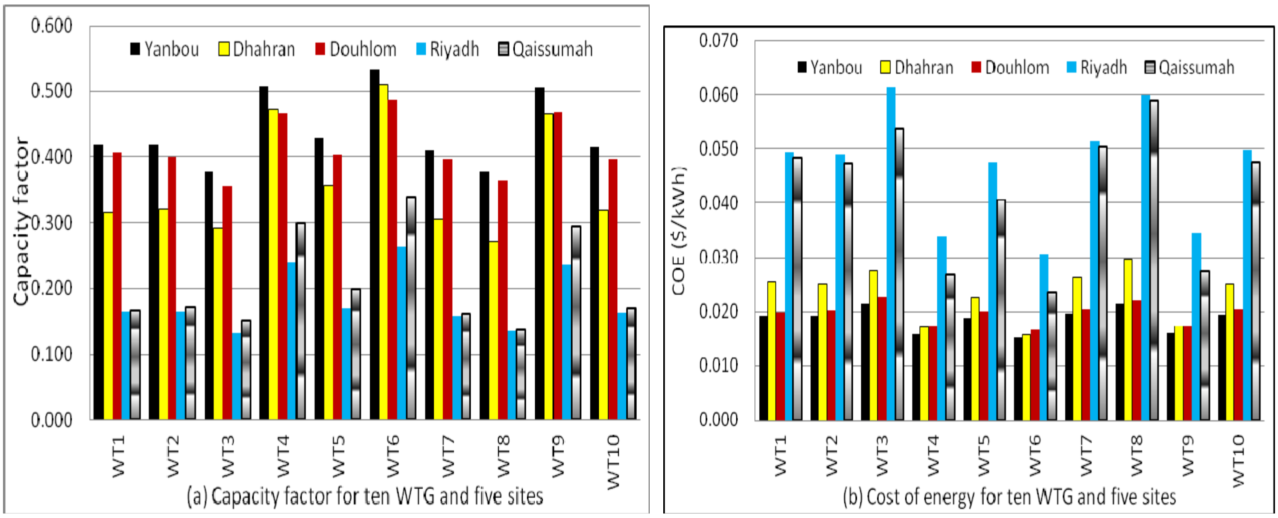

Fig. 3 The capacity factor and cost of energy for ten WTG and five sites in Saudi Arabia.

6. Conclusion

In this study, the Weibull parameters have been estimated numerically and graphically for five sites in Saudi Arabia. The values of *c, k* obtained graphically are similar to the numerical one. Technical and economical assessments have been done using Matlab program to choose the most suitable WTG for each site. It was found that the most suitable WTG for the five sites is Acciona (AW3000-116) which has maximum C_F and minimum *COE*. For Yanbou, the maximum C_F and minimum *COE* are 0.532 and 0.0151($/kWh). For Dhahran, the maximum C_F and minimum *COE* are 0.51 and 0.0158($/kWh). For Douhlom, the maximum C_F and minimum *COE* are 0.487 and 0.0165($/kWh). For Riyadh, the maximum C_F and minimum *COE* are 0.264 and 0.0306($/kWh). For Qaissumah, the maximum C_F and minimum *COE* are 0.34 and 0.0237($/kWh). Three methods are used for estimating the *COE*. Both of the second (using *PVC*) and third (*COE*) ones are preferred and more accurate because these two methods take into account all parameters affect the cost of energy such as investment cost, capital costs (interest rate and repayment of loan), land replacement/lease costs and the operation /maintenance costs. But the best method for Saudi Arabia economics is the second (using *PVC*) because the third method (*COE*) takes into account the land replacement/lease costs which can be negligable in Saudi arabia and because of the vast land available in Saudi Arabia.

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