Effect of site and size of wind turbine on its economic operation.

S. Bajaj, K. S. Sandhu

***Abstract*—** Effective, efficient and economical generation of power for the society is a big challenge today. Economic Power generation to fulfill the demands of the consumers is necessary for any country. Renewables like wind, solar, hydro etc. play an important role in facilitating the adequate amount of power generation for the masses. Among these renewable energy sources, generation of power from wind energy may be classified as an Effective, efficient and economical way. This paper includes the economics analysis of wind power generation of three different locations having different mean wind speeds. Seven wind turbines with different dimensions and ratings have been employed for such analysis. Further an attempt has been made to compare the economics of different wind turbines of different power ratings at different location on the basis of levelized cost of energy (LCOE). It is observed that economics of wind power plant depends upon site specification and characteristics of different wind turbines. Also with increase in power rating of the wind turbine, the levelized cost of energy for the given location decreases. It has been seen that for a particular location with increase in the rotor diameter the LCOE deceases. Analysis show that that for any wind turbine LCOE will decrease with the increase of the mean wind speed for a given installation site.

***Keywords*—**Renewables, wind energy, economics of wind energy, levelised cost of energy (LCOE)

I. INTRODUCTION

Conventional sources like coal petroleum are depleting with time, moreover use of these sources also leads to environmental effects like global warming. With increase in population and considering the environmental changes there is a huge need to shift to renewable energy sources. There are many renewable energy sources that can be exploited efficiently and effectively, these include solar energy, wind energy, tidal energy etc. As per the statistics available due to many reasons wind energy seems to be effective in contrast to others. The contribution of wind power to the energy supply has reached a substantial share even on the global level. Total installed capacity worldwide by the use of wind energy conversion system is around 434 GW. The number of countries using wind energy as a source of power generation has also increased to 105. It is also expected that global capacity of wind power may increase to 600 GW in the year 2018[1-3][17-18].for generating tremendous amount of energy from wind it is necessary to encourage the establishment of more and more wind power plants. Wind power plants so as to produce the electricity for the masses should be economically viable so that the energy produced may be utilized on a larger scale. Economically sound wind power plants may also help in meeting the energy requirements of the population Many studies and research work has been performed to explore wind energy economics so that wind energy can economically be incorporated in the clean and efficient production of electricity. It can easily be inferred that wind energy economics include constituting factors that can either be controlled or can be kept in mind while establishing a wind power generating system so as to produce an economically viable source of electricity[24]. In case of wind energy, the cost of production mainly depends upon capital cost and operational and maintenance cost. So as to work with wind energy economics it is necessary to analyze the capital cost and the operational and maintenance cost for the wind energy system. Capital cost of wind energy may include all the costs incurred from procurement of raw materials to installation of wind turbine[25-27]. All costs incurred till the successful operation of wind energy system may be incorporated in the capital cost of the wind turbine. This may include planning and project cost, turbine cost, civil works, transportation, grid connection cost etc. After the installation of wind turbine for smooth and efficient operation, follows the 'operational and maintenance cost' which may be very low in case of wind energy. Hence it is necessary to study and analyze wind power economics so as to reduce or modify the cost of wind energy generation at a larger scale. It can be easily seen that for improving the cost of energy derived from a wind power plant it is essential to keep in mind these costs as they play an important role in determining the economics of wind power plants[28-29]. A wind farm project needs to be analyzed for its economic feasibility and acceptability before being set up. An investor may invest in the project if and only if it is economically viable. In this paper an attempt has been made

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S.Bajaj is a PhD research scholar in the school of renewable energy and efficiency, National Institute of technology kurukshetra, haryana, India 136119.(email:sahilbajaj2910@gmail.com)

K. S. Sandhu is professor in department of electrical engineering National Institute of technology kurukshetra, haryana, India 136119. (e-mail:kjssandhu@rediffmail.com).

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for analyzing different wind turbines at different locations for economical wind power generation. Different manuals published by NREL [19] gives us a guideline so as to evaluate a wind power plant economically. Many techniques have been illustrated so as to analyze the economic viability of a wind power plant. The various economic analysis used may be : Cost benefit analysis, Benefit to cost ratio, Simple payback period, Initial rate of return, Levelized cost of energy (LCOE), Cash flow analysis, Discounted cash flow (DCF) analysis, Net Present value (NPV), etc. each and every analysis technique above has its advantages and drawbacks. Many researchers have studied economics of wind farm projects and found that several methods for the economic evaluation of the wind project can give different results. As seen from literature the predominant economic analysis techniques are COE, LCOE and NPV [4-7].

Further many researchers have worked on economics of wind power plants which is evident from the literature below. Julieta schallenberg [6] estimated the Techno-Economical factors for Wind Energy Production and found that Cost of Energy techniques may be adopted to analyse the economics of wind power plants. Yao et al[12] analysed 1 mw variable speed turbines parameters based on cost model. LCOE technique was used to analyse optimal parameter design for an economic wind power generation.

Different authors published articles showing the predominance of NPV and LCOE techniques for effective economic analysis of a wind power plant. In 2011 wagner souza et al[8] determined economic evaluations for wind power projects using different techniques like NPV, IRR,SPB etc. In 2013 mohammad rezaei et al[9] used LCOE technique for site specific optimization of wind turbines and found an optimal configuration for the same. In 2015 thomas muche et al[10] found an economically optimal configuration of onshore horizontal axis wind turbine using NPV technique. Finally in 2016 technical, economical and uncertainty modeling of a wind farm project was done using NPV technique by Svetlana et al[11]. From the above survey it is evident for a beneficial economic analysis of a wind power plant LCOE and NPV techniques can be used. Hence in this paper an attempt has been made made to compare and analyse different wind turbines of different power ratings at different location on the basis of levelized cost of energy (LCOE) technique.

II. Economic Analysis Methods for Wind Power Plants

Following methods can be used to find the economic viability of power plants.

A. Benefit to cost ratio

B. Simple payback period

C. Levelized cost of energy (LCOE)

D. Discounted Payback

E. Net Present value (NPV)

F. Internal rate of return (IRR)

The above six analysing techniques can be used for optimum and economic viability of a power plant. A schematic comparison of the above mentioned techniques is given in table I. The LCOE technique may have an upper hand for finding the economic viability of the power plant as it accommodates for all the costs incurred in the power plant in a given time period. This technique helps us to find the minimum cost at which wind energy produced should be sold so as to determine the economic viability of the wind power project. It also gives the levelized minimum cost at which the energy produced is to be sold so that the costs incurred during the power generation may also be recovered over a given time period easily. In this paper levelized cost of energy (LCOE) technique has been used to compare different configurations of wind turbines and location based for economical generation of power from wind energy. It can also be seen that minimum the LCOE more economically viable is the system. The above computation has been done with the help of MATLAB programming.

III. Cost of Energy for a Wind Power Plant

On the assumption that technology will mature and the size of wind farms may increase, the cost of energy can be computed using the following expression [12]:-

$$LCOE = \frac{C_{ICC} * R_{FCR} + C_{O\&M}}{C_{AEP}} \quad \text{(i)}$$

Where Levelized Cost Of Energy is the cost of energy, for computation of LCOE all costs incurred in establishing of wind power plant are considered hence this technique has an advantage over the other techniques for computation of economics of a wind power plant as it helps in determining the least cost of the electricity produced that may be attained by the customers so as to recover the investments. The levelised cost of energy technique has only one demerit as it does not include the project risks (very less for renewables) incurred as these are company technology and region specific. Hence LCOE can be used in computing economics of a wind power plant fruitfully. C_{icc} is initial capital cost which includes cost of turbine production, freight cost and balance of station. R_{fcr} is the fixed charge rate and can be computed with the help of life span of the project (i.e 20 years for this case) and a discount rate (8% in this case), $C_{o\&m}$ is the operation and maintenance cost and finally C_{AEP} is the annual energy production in kWh which is obtained by the power curve of the wind turbine taken and the availability of wind speed at different locations. With the help of the flowchart below a MATLAB program was designed for three different locations with seven different turbine configurations. Finally the LCOE was found as given in table II. The cost of energy computation technique can also be used for optimal design parameters based on cost of the energy. As the cost of the components is proportional to the mass of it. The sensitivity of the cost of energy changes with change in the values of the parameters governing the wind turbine like rotor diameter etc. They can be examined with the aid of a model of the way component cost varies in response. Figure below gives the flow chart (Fig. 1) for different cost of energy computation for a wind power plant [12]. LCOE of a wind power plant may be computed using various costs associated with it. The different costs associated with it are shown in the flow chart (fig. 1). A Matlab program for three different sites and wind turbines with different ratings is developed and the results are obtained for the same which may be fruitful in analyzing the economical operation of a wind power plant.

METHODOLOGIES	DESCRIPTION & EXPRESSION	REMARKS
Benefit to cost ratio analysis [5][12](BCR)	It is the ratio of present value of sum of benefits divided by present value of sum of costs $$BCR = \frac{\sum Ci_t}{\sum Co_t}$$	✓ For comparing mutually exclusive alternatives BCR cannot be used. ✓ The above technique doesn't include Monetary impact. ✓ BCR technique may be little imprecise for wind energy this may be due to consequent input and output of cash
Simple payback (SPB)[5][12]	This analysis may account for the time of projects cash flow to recover initial investment $$SPB = ICC / ARR$$	✓ SPB may be used to measure the extent of risk of the project, higher the return higher may be the risk. ✓ As it ignores value of economic resources over time hence solely using SPB wind project's economic viability cannot be decided
Discounted payback(DPB)[5][12]	It considers the value of capital over time by discounting net cash flows of each period, before adding them and comparing them with initial investment $$DPB = \frac{ICC}{AAR - (O\,\&\,M + LLC)}$$	✓ It takes longer period to recover than SPB ✓ It also accounts for operational and maintenance cost and land lease cost for the calculations but determining of payback may be arbitrary. ✓ As the DPB can be expected to take interest or rates that are not practiced by the financial market
Net present value(NPV)[5][14][15]	Net present value analysis is accepted as a measure of financial performance of the project. For energy projects this may be computed as:- $$NPV = AAR\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] - ICC$$	✓ NPV can change the engineering aspects of the project. ✓ NPV has disadvantage that may limit in the evaluation and management of projects ✓ As this needs to know the actual capital cost of the project, for energy projects , the process of defining the real value of capital cost is tedious. ✓ The type of response is money instead of being a percentage, if it was in percentage it would have been easier to compare projects in different currencies.
Internal rate of return(IRR)[5] [12]	IRR is a method to calculate the rate that cancels the net present value of cash flow. For investment to be attractive. IRR is greater or equal to rate expected by the investor. Higher the IRR better the investment. IRR represented as percentage and may be interpreted as return of a project. It is the discount rste that sets the NPV=0 $$NPV = AAR\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] - ICC = 0$$	✓ Depending upon the structure a project can have different IRRs as the equation obtained usually has more than 1 solution. ✓ IRR doesn't take in account different size of investment . for example for a small investment this may not be a fruitful IRR thereby giving less wealth
Levelised cost of energy(LCOE)[9][11][13]	The LCOE technique is the actual cost of producing 1Kwh of electricity it may be given as:- $$LCOE = \frac{FCR * ICC}{AEP} + \frac{O\,\&\,M}{AEP} + \frac{LLC}{AEP} = \frac{FCR * ICC + O\,\&\,M + LLC}{AEP}$$	✓ For computation of LCOE all costs incurred can be included for example operational and maintenance cost , land lease cost , etc. ✓ LCOE technique used for wind energy projects may be very fruitful for computing overall economics of a wind power plant as it gives the cost of energy generated that is the least cost of the electricity produced may be attained by the customers so as to recover the investments.

TABLE I. ECONOMIC ANALYSIS METHODS FOR A WIND POWER PLANT

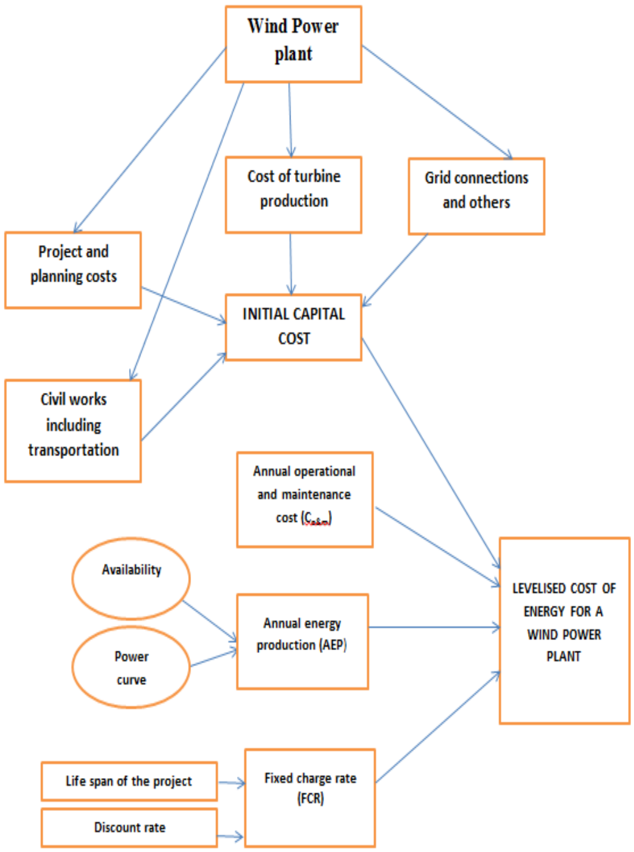

Fig. 1. Flowchart for the formulation of matlab program for LCOE

Keeping in mind the above flow chart (Fig.1) for computation of levelised cost of energy, MATLAB programming has been done taking in consideration different wind turbines at three different sites

IV. RESULTS

The following results may be obtained using modeling of cost equation with the help of MATLAB.

Turbine (rotor diameter)	Cut-in	Cut-out	Rated	Location 1 (kanyakumari)(LCOE)Rs/kWh (mean wind speed=5.41m/s)	Location 2 (Rameshwaram) (LCOE)Rs/kWh (mean wind speed=6.83 m/s)	Location 3 (BLANDFORDMTA)(LCOE)Rs/kWh(mean wind speed = 10.20m/s)
A27/225	3.5	25	12	13.646	9.4562	2.1754
Vestas-52(850kW)	3	25	14	11.4066	7.0364	1.8624
Allizeo-56(1000kW)	3	25	12	8.1123	5.2345	1.6645
Fl-70(1500kW)	3	25	11	7.0123	4.9965	1.4257
Vestas-82 (1650kW)	3.5	20	13	6.4727	4.1268	1.3597
Vestas-100(1800kW)	4	20	12	4.7800	3.0940	1.2580
Imp-83(2100kW) impsa	3	25	13	4.5645	2.9945	1.0034

Table. II. LCOE for different size and site configuration.

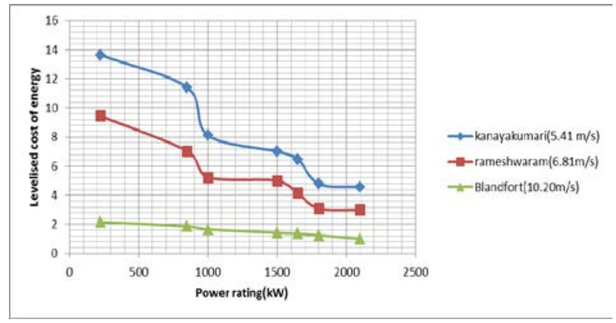

Fig. 2. LCOE Vs. power ratings for three different locations

From table II, fig. 2 is obtained, depicting data of three different locations it can be seen that the mean wind speed for location 1(Kanyakumari), location 2(Rameshwaram), and location 3(Blandfort) is 5.41 m/s, 6.83 m/s and 10.196m/s respectively. Hence for wind turbines A27/225, vestas 52, allizeo 56, levelised cost of energy (LCOE) obtained for location 1 and location 2 is high as compared to location 3 because mean wind speed for location 3 is more than location 1 and location 2 and also the mean wind speed for location 3 is nearer to the rated speed of given turbine. Similarly for vestas 82, fl-70 vestas 100 and impsa 83, the mean speeds of the given location are more nearer to the rated speed of the turbines hence giving low LCOE for location 3.

From the results obtained it can be seen that with increase in power rating of the wind turbine, the levelized cost of energy for the given location decreases also. Also it is observed that for a particular location with increase in the rotor diameter the LCOE deceases and any wind turbine LCOE will decrease with the increase of the mean wind speed for a given installation site.

The results have been taken into consideration for concluding in the following part.

V. CONCLUSION

Simulation results as discussed in the previous sections leads to the major observation as:.

A. All wind turbines are at same location:-

- With increase in power rating of the wind turbine, the levelized cost of energy for the given location decreases.
- As observed from the results above that for a particular location with increase in the rotor diameter the LCOE decreases.
- It can also be analysed that for any wind turbine LCOE will decrease with the increase of the mean wind speed for a given installation site.

B. Different wind turbines at different locations:-

From the above table it can be inferred that location 3 will be most appropriate location for setting up of wind power plant having wind turbines of higher power rating(225-2100Kw) as it has a higher mean wind speed as compared to location 1 and location 2. Location 1 and 2 will be suitable for establishment of wind turbine with comparatively low power rating for economical production of wind power as they have low mean wind speed as compared to location 3.

C. All wind turbines at different locations:-

From the table of results it can also be seen that vestas V-82 (1650kW),vestas 52(850kW), allizeo 56 , FL-70 and have higher LCOE for a given location as compared to V-100(1800kW) and IWP 83. This is mainly because the difference in cut-in and rated speed for V-100 and IWP 83 is less than V-82 and V-52. Therefore V-100 and IMP 83 will give rated power before the rated power for others is achieved and moreover V-100 and IMP-83 has higher rotor diameter than the other turbines taken in the table thereby having low LCOE for all the three locations.

As seen from the table vestas 82 and vestas 100 both can be adopted for installation at any location without any prominent change in LCOE. It is not in case of vestas 52(850).

From above it can be concluded that Levelised cost of energy technique may play an important role for determining economics of wind power plant. Study also considers the different technical factors such as power rating, rotor diameter, mean wind speed for computation of economics of a wind farm site. The analysis as presented may be adopted for developing new economically viable wind power plants with different wind turbine configurations. It may be helpful to decide the appropriate wind turbine for the given site for economic wind power generation. However research work may also be extended for future by including the effects of shape and scale function of weibull distribution for a specific site.

APPENDIX

COST CONSIDERATIONS FOR MATLAB PROGRAMMING

Cost model used for computation of capital cost

$$C = \frac{c_t[\sum_{i=1}^{n} W_i(p)] + \sum_{j=1}^{n} c_j W_j(p)}{[1-(\sum_{i=1}^{n} R_i b_i) - k_0]}$$

Where

C= Total cost of wind turbine(Rs.)

C_t=Transportation cost/ton (Rs).

C_j=Price of the jth material/ton (Rs).

R_i =Per unit cost of ith component.

b_i=Per unit manufacturing cost of ith component.

k_0=percentage value of cost which includes rate of interest on loan, consultancy, commission, maintenance etc.

$W_i(p)$=weight of ith component in tons as a function of turbine rating.

$W_j(p)$=weight of jth material used in construction in tons as a function of turbine rating.

In the above model for finite positive value of total cost, the term which appears in the denominator should have a range as below.

$$1 \le [1-(\sum_{i=1}^{n} R_i b_i) - k_0] \le 0 \text{ .}$$

Its maximum value may be one, which is true if

$$[-(\sum_{i=1}^{n} R_i b_i) - k_0] = 0$$

This is not possible. However its maximum possible value is desirable to reduce the cost of generation. This can be achieved by the maximum feasible reduction of b_i & k_0& it is true also.

For computation of FCR in matlab the following equation may be used

F=d/(((d+1)^t)-1)+d;

Where,

d=discount rate

t=life span of the project

For Operational and Maintenance cost

computation=0.007*AEP*60

Where AEP is annual energy production.

Cost of transportation(c_t)=3375;

Cost of iron(c_j_i)=3600;

Cost of steel(c_j_s)=4500;

Cost of copper(c_j_cu)=209400;

Cost of resin(c_j_r)=62230;

Cost of glass fiber(c_j_gf)=61130;

Weight of iron(w_j_i)=38.144-0.0179778*p+0.0000076437*p^2;

Weight of steel(w_j_s)=10.038+0.045269*p+0.0000020115*p^2;

Weight of copper(w_j_cu)=14.7224-(0.0069388*p)+0.0000029502*p^2;

Weight of resin(w_j_r)=2.4876+0.0183138*p+0.0000004023*p^2;

Weight of glass fiber(w_j_gf)=1.6224+0.0006532*p+0.0000002682*p^2;

B_j_i=c_j_i*w_j_i;

B_j_s=c_j_s*w_j_s;

B_j_cu=c_j_cu*w_j_cu;

B_j_r=c_j_r*w_j_r;

B_j_gf=c_j_gf*w_j_gf;

B=B_j_i+B_j_s+B_j_cu+B_j_r+B_j_gf;

r_i_1=0.35;

r_i_2=0.30;

r_i_3=0.29;

b_i_1=0.3;

b_i_2=0.1;

b_i_3=0.3;

k=0.09;

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Sahil Bajaj was born in Delhi, India on 29th October 1990. He did his B.Tech (Mechanical Engineering.) from Sikkim Manipal Institute Of Technology, Sikkim, India in 2012 M.Tech (Renewable Energy System) in 2014 from National Institute of Technology, Kurukshetra. He is currently a Phd, research scholar at school of renewable energy and efficiency NIT kurukshetra. His areas of Interest are wind energy, optimization theory, Research methodologies and Renewable Energy Systems.

Kanwarjit Singh Sandhu was born in Haryana, India on 21st December 1957. He received the B.Sc. Engg. (Electrical), M.Sc. (Power System) and Ph.D (Electrical Machines) degrees from Regional Engineering College, Kurukshetra University, Kurukshetra, India in 1981, 1985 and 2001, respectively. He joined the Electrical Engineering Department of Regional Engineering College, Kurukshetra, as Lecturer in January 1983. Currently, he is Professor in Electrical Engineering Department, National Institute of Technology, Kurukshetra (Formerly Regional Engineering College, Kurukshetra), India. He has more than 60 international journals and about 70 conference publications in the area of Machines & Energy. His areas of interest include electrical machines, wind energy conversion, power quality, artificial intelligence and power systems.