

# Economic Analysis of WECSs Using LCOE and PVC Approaches in Northern Ethiopia

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## ABSTRACT

In this study, the relative economic contrast of wind energy conversion systems (WECSs) are examined using levelized cost of electricity (LCOE) and present value cost (PVC) as measures of merit of system life cycle cost. From the analysis of data and discussion, capacity factor and useful life of the wind turbine have a positive impact on the cost of electricity produced by the WECS, while the other input parameters of LCOE and PVC increase the system life cycle cost, as their values increase. The trend of capacity factors decreased linearly, and the simultaneous increase in LCOE and PVC was noticed.

**Keywords:** Levelized cost of electricity, life cycle cost, present value of cost, wind energy conversion system, economic analysis, Ethiopia.

## INTRODUCTION

Exploitation of wind energy conversion systems (WECSs) in the generation of electricity has been traced out in late 19th century with the instigation of windmill generators constructed in USA [1]. Eventually, it has been evidently endorsed that the wind is one of the clean forms of energy experiencing rapid growth during the last two decades. The growth may be attributed to the promotion of renewable energy sources, energy supply security, fuel diversity concerns, ecological awareness,

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and economic reasons [2]. In the recent times, wind power capacity has increased rapidly all around the globe, but the utilization rate in Ethiopia has still limited to very few sites which are constructed for water pumping as a primary requirement [3]. This may be attributed to by the country's overdependence on oil and gas as sources of energy for export and other socio-economic activities.

The increased wind power capacities installed throughout the world over a period of 2000-2014 are presented in Figure 1. According to 2011 Global Wind Energy Council (GWEC) statistics, all wind turbines installed in Africa had a capacity of 993 MW. Among the countries in sub-Saharan Africa, Egypt was leading in the continent with an installed capacity of 550 MW followed by Morocco and Tunisia each with an installed capacity of 291 MW and 114 MW respectively. The wind power development is decisively underway in other developing countries in the continent like Ethiopia, Kenya, Tanzania and South Africa [4]. Nevertheless, Ethiopia is endowed with all sources of energy resource such as hydro, solar, wind, biomass, natural gas, geothermal, etc., and has not been able to develop, transform and utilize for the optimal economic development of the nation [5]. In terms of gross domestic product (GDP) per capita, Ethiopia is ranked 174th of 179 and in terms of human development index (HDI), it is rated 169th of 177 [6, 7]. Most of the Ethiopians are living in the urban areas with an average power consumption of less than 50 kWh per year, while rural area electricity coverage is negligibly

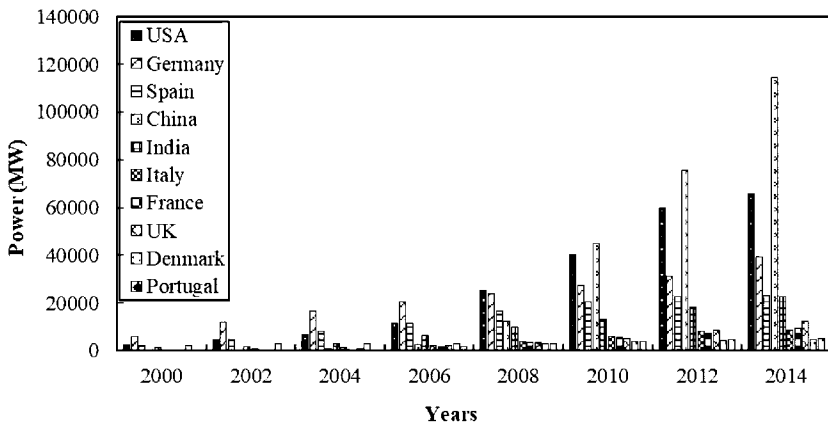


Figure 1. Top ten wind power capacities (MW) installed around the globe (between 2000 and 2014). Bars from left to right correspond to the countries listed above.

of about 2% among the total access of electricity within the country [8, 9].

Organizing the renewable energy sources is nowhere more acute than in the Third World nations due to essential urban and rural requirements as well as the economic development of the nation. However, these countries are importing fossil fuels and depleting biomass sources at home. As it is representative among the developing nations, Ethiopian rural community has often taken a back step when it comes to energy development schemes. Moreover, with increasing worries about deforestation, especially that of the fuel wood which is traditionally used by the rural community, now the attention is focused on providing them with alternative renewable energy sources. In this study, exploration of wind energy potential, the economic analysis of wind turbine applications in Ethiopia and relative analysis between Levelized cost of electricity (LCOE) and present value of cost (PVC) approaches have been investigated. The diverse locations spreading across the region are selected for this analysis namely Atsbi, Chercher, Mekele, and Senkata. The information presented in this paper will be constructive to the wind energy developers of government and private organizations that are interested in exploring the wind energy resources in the country.

## WIND CHARACTERISTICS OF THE SELECTED LOCATIONS

Wind speed data used were obtained from National Meteorological Agency (NMA), Mekele, over a period between 2002 and 2014. The data captured were at a standard height of 10 m using cup-generator anemometer in the selected locations. The recorded wind speeds were obtained on an hourly basis and thereafter transformed as mean wind speed for each month. The geographical locations of the selected areas are given in Table 1. Energy pattern factor method (EPPM), was utilized in evaluating the Weibull  $k$  and  $c$  parameters [10, 11].

Weibull parameters and wind characteristics for the selected locations are presented in Table 2. It can be observed that the minimum annual mean wind speeds among the selected locations are 2.71 m/s at Senkata, while the maximum is 4.39 m/s at Mekele. Therefore, Mekele has the highest annual mean wind speed and power density among the locations considered in this study. Even though the most probable wind speed ( $V_F$ ) is a statistical characteristic feature which may not be directly connected to the wind energy, it does not necessarily mean that Mekele

**Table 1: Geographical locations of selected locations**

Sl. No	Locations	Latitude °N	Longitude °E	Elevation (m)	Duration
1	Atsbi	13.87	39.73	2630	2002 – 2014
2	Chercher	12.53	39.77	1767	
3	Mekele	13.29	39.28	2084	
4	Senkata	14.32	39.34	2480	

**Table 2:**

**Weibull parameters and wind characteristics of the selected locations at 50 m height**

Sl. No	Locations	Annual mean wind speed (m/s)	Average power density (kW/h)	PNL Classification	k	c (m/s)	V <sub>F</sub> (m/s)	V <sub>E</sub> (m/s)
1	Atsbi	3.26	22.11	1	4.24	3.59	3.37	3.81
2	Chercher	3.40	25.80	1	3.79	3.77	3.46	3.88
3	Mekele	4.39	70.07	1	3.75	4.87	4.48	4.85
4	Senkata	2.71	13.67	1	3.59	3.01	2.73	3.26

has much higher wind energy potential than the other selected locations [12]. However, the efficiency of a wind turbine is closely related to these parameters, especially VE, which should be as close as possible to the design or rated wind speed of the system. Therefore, the proposed wind turbine if installed at Mekele would likely produce more power than other locations.

In addition, the average power densities (PD) are 22.11, 25.80, 70.07 and 13.67 W/m<sup>2</sup> at Atsbi, Chercher, Mekele and Senkata respectively. According to wind resource category based on the Battelle-Pacific Northwest Labs (PNL) wind power classification scheme, all the selected locations are falling under class 1 (PD < 100 W/m<sup>2</sup>) category which is considered as unsuitable for wind power development, although, the generated wind energy can be used for water pumping and small-scale electricity production. For a contemporary wind turbine, the cut-in wind speed required by it to start generating electricity is generally between 3 to 5 m/s. Depending on the size of the wind turbine, the peak of power output can be attained when the wind speed (rated wind speed) is in the range of 10 to 15 m/s. For water pumping system, the wind turbine can be operated at a lower wind speed; however, it can be effectively func-

tional when the wind speed is more than 3 m/s. Based on the required quantity of water, a site with a mean wind speed around 2.0 m/s can be considered for wind-powered pump applications [14]. Similarly, depending on the end use of the generated power, it can be revealed that, these locations may be suitable for utilization of wind energy.

METHODOLOGY USED IN THE STUDY—  
ELECTRICAL POWER OUTPUT FOR SELECTED WECS

WECS is composed of an electric generator mounted on a suitable tower, wind turbine controller, battery bank, an inverter, and balance system. Considering such a big system, annual energy production (EP) for a potential site can be evaluated using obtained wind speed data belonging to that site and the power curves related to selected WECS [1, 15]. The method of calculation requires combining the power curves of the considered turbine with the wind speed data arranged in the form of time-series. Figure 2 shows the power curves of the wind turbines considered for selected wind turbines at Mekele.

Prediction of wind energy output from the selected WECS can rely on cut-in, rated and cut-out speed. According to the power curves of the wind turbine, an algebraic equation of degree 'n' can be expressed as:

$$P_i(v) = \begin{cases} 0, & v < Q_i \\ (a_n v^n + a_{n-1} v^{n-1} + \dots + a_1 v + a_0), & Q_i \leq v < Q_r \\ P_R, & Q_r \leq v < Q_o \\ (a_n v^n + a_{n-1} v^{n-1} + \dots + a_1 v + a_0), & Q_i \leq v < Q_o \\ 0, & v \geq Q_o \end{cases} \quad (1)$$

where  $a_n$ ,  $a_{n-1}$  and  $a_o$  are the regression constants,  $Q_i$  is the cut-in speed,  $Q_r$  is the rated speed,  $Q_o$  is the cut-out speed,  $P_R$  is the rated power, and  $P_i(v)$  is the power generating in related wind speed. The total energy generated by wind turbine over a period of time can be computed by adding up the energy corresponding to all the possible wind speeds in the related conditions, at which the system is operational. Thus, energy output from the turbine can be calculated by Eq. (2).

$$E_P = \sum_{i=1}^n P_i(v) T \quad (2)$$

where  $n$  is the number of hours over the period of time considered as a

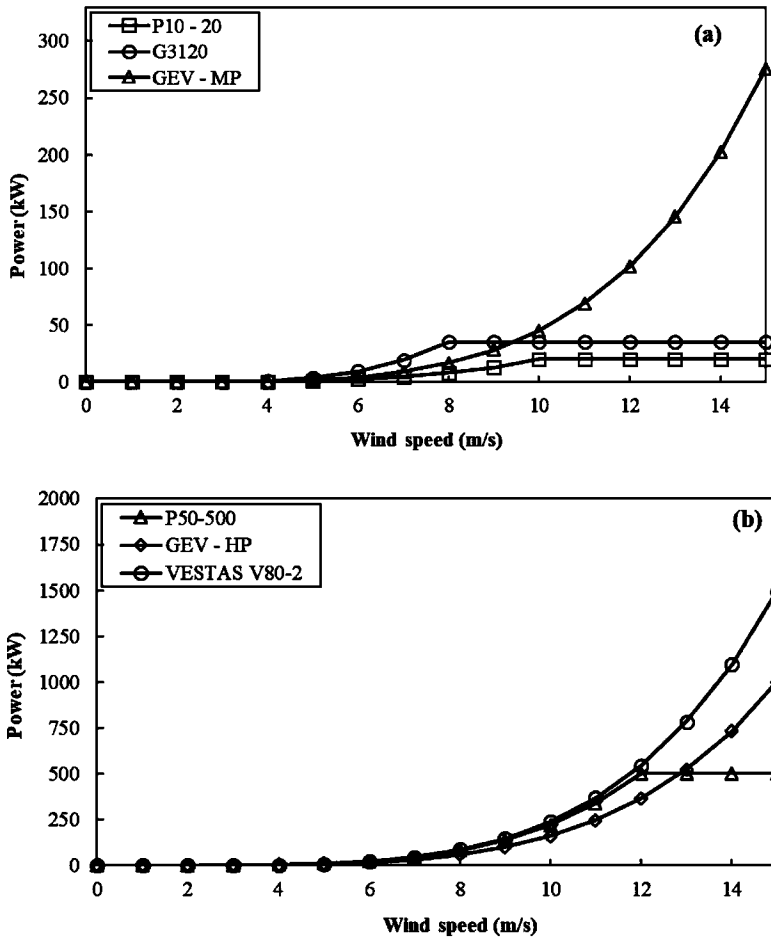


Figure 2. Power curves of wind turbines (a) rated power of 20, 30 and 275 kW (b) rated power of 500, 1000 and 2000 kW.

year, season or month,  $T$  is time duration. The capacity factor ( $C_f$ ) can be used to identify the site characteristics that are suitable for wind energy development and for the selection of wind turbine systems to be installed at a site with known wind speed characteristics [16]. It can be defined as the ratio between the actual energy produced by the system and the energy that could have been produced if the machine would have operated at its rated power throughout the time period. The annual value of the  $C_f$  can be calculated as:

$$C_f = \frac{E_p}{E_{rated}} \quad (3)$$

## ECONOMIC APPRAISAL OF WECS

Precise estimation of costs concerned in generating electricity over the life span of WECS is essential for economic viability of the location in order to produce energy at a low operating cost [17]. As it can be anticipated that, a new WECS always have low expenditures on operation and maintenance cost, however, the operation and maintenance cost increases as the useful life of power plant may decrease [2]. Other factors which can influence the cost of electricity produced by WECS includes the cost of construction and other infrastructures such as wind speed regime in the selected location, turbine lifetime, and discount rate [16-18]. Wind turbines can be widely divided into four different sizes ranging from the rated power such as micro (0-1.5 kW), small (1.5-20 kW), medium (20-200 kW) and large (200 >) [19]. The cost of any wind turbine system can be expressed in terms of money per kW. The cost of a wind turbine is mostly judged by the manufacturer, and is shown to be relying on the rated power (control systems and other accessories) and varies from manufacturer to manufacturer. Thus, choosing a specific turbine cost could be done by considering a band interval (minimum and maximum) as given in Table 3 [20].

Feasibility of WECS may depend on its ability to generate the energy at a low operation cost that influences the unit energy cost of electricity produced at a selected location. These factors may vary from country to country and region to region. The cost of electricity production using WECS includes the main parameters such as investment cost, operation,

**Table 3: Range of cost of wind turbines based on the rated power**

Wind turbine size (kW)	Min. specific cost (\$/kW)	Max. specific cost (\$/kW)	Average specific cost (\$/kW)
10 – 20	2200	3000	2600
20 – 200	1250	2300	1775
200 and above	700	1600	1150

and maintenance, electricity production/average wind speed, turbine lifetime and discount rate except for the cost of the fuel [21, 22]. Among the approaches (i.e. cost per unit kilowatt, cost per unit rotor area, cost per unit kilowatt hour) for quantifying the cost of wind turbines, cost of electricity per unit kilowatt hour, in this study LCOE with PVC approaches are adopted to examine the economic analysis of WECS in the selected locations [16].

### Extrapolation of wind speeds

The selected wind turbines are designed to operate at different hub heights when compared to the available measured data. Hence, the captured wind speed at 10 m height can be extrapolated to the required turbine hub height through power law expression given as [23]:

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^\alpha \quad (4)$$

where  $v$  is the wind speed at height,  $h$ ,  $v_o$  is the wind speed at original height,  $h$  and  $\alpha$  are the surface roughness coefficient, which can be evaluated as [24]:

$$\alpha = [0.37 - 0.088 \ln(v_o)] / \left[1 - 0.88 \ln\left(\frac{h_o}{10}\right)\right] \quad (5)$$

Moreover, the Weibull probability density function can be used to obtain the extrapolated values of wind speeds at different hub heights. However, the boundary layer development and the effect of ground are non-linear with respect to Weibull parameters. It can be expressed as [23, 25]:

$$c(h) = c_o \left(\frac{h}{h_o}\right)^z \quad (6)$$

$$k(h) = k_o \left[1 - 0.88 \ln\left(\frac{h_o}{10}\right)\right] / \left[1 - 0.88 \ln\left(\frac{h}{10}\right)\right] \quad (7)$$

where  $k_o$  and  $c_o$  are the shape and scale parameters at measured height,  $h_o$  and the hub height  $h$ , respectively. The exponent  $z$  is defined as [22]:

$$z = [0.37 - 0.088 \ln(c_o)] / \left[1 - 0.88 \ln\left(\frac{h}{10}\right)\right] \quad (8)$$

### LCOE Approach

LCOE is one of the most imperative indicators for evaluating the performance of WECS and can be applied to the techno-commercial ana-

lysts to calculate the unit cost throughout the economic lifespan of the project. The levelized cost can be described as the ratio between total annualized costs of WECS to the annual electricity produced by the system. The capital cost of WECS is given as:

$$C_{wecs} = C_{wt} + C_{bb} + C_{ci} + C_{in} + C_{misc} \tag{9}$$

where  $C_{wt}$  is the cost of the wind turbine,  $C_{bb}$  is the cost of the battery bank,  $C_{ci}$  is civil works and installation cost,  $C_{in}$  cost of the inverter and  $C_{misc}$  is miscellaneous cost such as connecting cables, control panel, and other components. The following expression can be used to estimate LCOE delivered by the WECS is given as:

$$LCOE = \frac{C_{wt}CRF_{wt} + C_{bb}CRF_{bb} + C_{ci}CRF_{ci} + C_{in}CRF_{in} + C_{misc}CRF_{misc} + C_{om}}{E_p} \tag{10}$$

where  $CRF_{wt}$ ,  $CRF_{bb}$ ,  $CRF_{ci}$ ,  $CRF_{in}$ ,  $CRF_{misc}$  presents the capital recovery factor (CRF) for a wind turbine, battery bank, civil work and installation, inverter and other miscellaneous components.  $C_{om}$  is annual operation and maintenance cost.  $EP$  is the annual energy production delivered by WECS. For a given discount rate ( $r$ ) and useful system lifetime ( $n$ ), the capital recovery factor and specific cost of WECS can be expressed as:

$$CRF = \frac{(1+r)^n r}{(1+r)^n - 1} \tag{11}$$

$$C_{wecs} = I_{wecs} P_R \tag{12}$$

where  $I_{wecs}$  is the specific cost of WECS. When it comes to the escalation of operation and maintenance,  $C_{om}$  in Eq. (10) considering the present worth of the annual cost throughout the lifetime of the WECS can be written as:

$$C_{(om)sec} = \frac{C_{om}}{r - e_{om}} [1 - (1 + e_{om})^n (1 + r)^{-n}] \tag{13}$$

where  $C_{om}$  is the operation and maintenance cost for the first year,  $e_{om}$  is an escalation of the operation and maintenance.

### PVC Approach

Estimation of cost per unit is made by estimating the specific cost per kilowatt hour, which can be expressed as PVC of the investment di-

vided by energy output during the wind turbines lifetime [26-28].

$$x_i = x_0 + \beta_0 e^{-\gamma r_i} (x_1 - x_0) + \alpha \epsilon_i \quad (14)$$

where  $I$  is the investment cost,  $C_{omr}$  is an operation, maintenance, and repair cost,  $i$  is inflation rate,  $r$  is the interest rate,  $T$  is a lifetime of the machine (in years) and  $S$  is scrap value. According to Ahmed Shata et al; Habali et al; Sarkar et al [26-28], the investment cost ( $I$ ) includes wind turbine price plus the cost of civil work and connection cables to the grid (20% of the basic cost). Operation, maintenance and repair cost ( $C_{omr}$ ) was considered to be 25% of the annual cost of the wind turbine (machine price/lifetime). The inflation rate ( $i$ ) and interest rates ( $r$ ) are taken as 10.4% and 5.08%, respectively, as per the Ethiopian context. The machine lifetime ( $T$ ) is assumed to have only 20 years. Scrap value ( $S$ ) is taken as 10% of the investment cost (machine and civil work).

## RESULTS AND DISCUSSION— PERFORMANCE OF SELECTED WECS

Six (small, medium and large) wind turbines with rated power ranging from 20 kW to 2 MW were selected for their performances and economic analysis at the selected areas in this study [29-34]. Technical specifications of the selected WECS are presented in Table 4.

The factors influencing energy produced by WECS can be taken into account during the related time period is the power response of WECS to the different wind velocities, regime, and distributions [35]. The annual average power outputs and energy outputs are presented in Table 5. It can be observed that the annual average energy output ranges between 6.749 MWh at Senkata using POLARIS P10-20 turbine model at a hub height of 36.6 m to 1548.264 MWh at Mekele using VESTAS-V80 at a hub height of 67 m. Nevertheless, POLARIS P 50-500 and GEV-HP wind turbines having higher hub heights than VESTAS V80-2 MW turbine model. Higher energy production is achieved using VESTAS V80-2 MW, because of its higher power rating than POLARIS P50-500 and GEV-HP turbine models at all the locations. Surprisingly it can be observed that irrespective of the locations, POLARIS P10-20 wind turbine model generates the least amount of energy with the most being given by VESTAS V80-2 MW wind turbine. Hence, VESTAS V80-2 MW model

Table 4: Technical specifications of the selected wind turbine systems

Parameters	Single DG placement	Single DG & Capacitors placement	Two DG placement	Two DG & Capacitors placement	Three DG placement	Three DG & Capacitors placement
Optimal locations of DG's	30	11	14, 30	30, 14	30, 12, 24	25, 14, 30
Optimal sizes of DG's(KW)	1000	1075	570,954	933,590	1000,848,938	1000 ,749,1000
Power factor	0.866	0.866	0.866,0.866	0.866,0.866	0.866,0.866,0.866	0.866,0.866,0.866
Total Real Power Injected(KW)	1000	1075	1524	1523	2786	2749
Optimal locations for capacitors	-----	23,32,30	-----	2,24,11,33	-----	33,2
Optimal sizes of capacitors(KVAR)	-----	150,150,900	-----	150,150,150,450	-----	300,300
Active power loss in KW	95.8117	65.7545	44.2993	32.8524	17.51	13.8543
% Loss reduction	54.58	68.83	79.00	84.42	91.69	93.43
Elapsed time	<b>21.270962</b>	<b>20.450268</b>	<b>17.391571</b>	<b>19.812635</b>	<b>18.444371</b>	<b>23.430</b>

at 67 m hub height may be considered as the preferable model for energy production at all the selected locations. Since it is well known that, the energy yield depends on the strength of wind speed at a given site and on particular WECS adopted in the study [2]. Among the selected locations in the investigation, Mekele exhibit higher energy production using all the WECSs.

Variation of  $C_f$  for selected WECS at selected locations is presented in Figure 3. In general, the  $C_f$  can be evaluated to reflect how effectively of a turbine could harness the energy available in wind spectra and can be expressed on an annual basis as a function of the turbine as well as the characteristics of wind regime [17]. For a reasonably efficient turbine at a selected location, the  $C_f$  may usually range between 0.15 and 0.4 [35-37]. In this study, least value of  $C_f$  is obtained 0.15% at Senkata using VESTAS-V80 turbine model at 67 m hub height. While the highest value is noted as 19.92% at Mekele using G3120 turbine model at 42.7 m hub height. From Figure 3, it can be observed that least values of  $C_f$  were obtained at Atsbi and Senkata, whereas the highest values were recorded at Mekele for all the selected turbine models. Hence, it can be suggested that considering selected WECS in the study Mekele has strong wind regime and hence most suitable for the wind energy production.

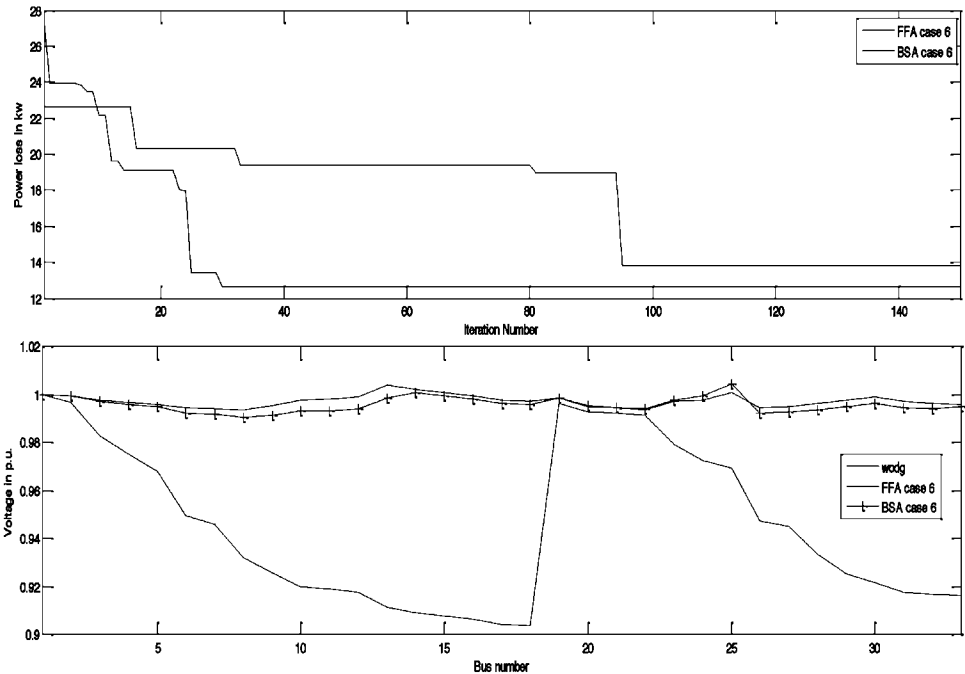
### **Economic analysis of selected WECS**

Tables 6-8 show the cost analysis of selected WECS in comparison to the LCOE and PVC approaches. The cost analysis was considered the minimum, maximum, and average costs in the respective locations are presented to compare respective variations in the cost. The obtained values using LCOE and PVC approaches are based on the band interval of costs presented in Table 3. It can be observed that obtained values using both approaches are comparable in all the locations using selected WECS and the value of costs increased in the order of Mekele, Chercher, Atsbi and Senkata.

Considering the average range of basic cost, the least cost per kWh were obtained as \$0.0017/kWh and \$0.0011/kWh using G3120 model at 42.7 m hub height for LCOE and PVC approaches respectively. At Mekele, the highest costs determined was \$0.0524/kWh and \$0.0354/kWh at Senkata using VESTAS-V80 model at 67 m hub height. In addition, the least predicted costs were obtained at Mekele due to the high wind speed velocity among the selected locations using all turbine models. Hence, viable electricity generation can be expected at Mekele. Accord-

**Table 5: Mean annual power output (kWh/y) and accumulated annual energy output (MWh/y) for the selected WECS**

Parameters	Proposed Methods		Existing Methods	
	FFA	BSA	GA/PSO [15] ICA/GA[15]	
Optimal locations of DG's	25 ,13 , 30	25 ,14, 30	14,25,30	13,24,30
Optimal sizes of DG's(KW)	866 ,836,1083	1000 ,749,1000	674,670,835	794.8,1069,1029
Power factor	0.905,0.88,0.9017	0.866,0.866,0.866	0.88,0.85,0.90	0.905,0.90,0.81
Optimal locations for capacitors	31 , 4	33,2	12,30,32	8,18,30
Optimal sizes of capacitors(KVAR)	300,300	300,300	150,450,150	150,150,300
Active power loss in KW	12.6509	13.8543	17.01	14.01
% Loss reduction	94.00	93.43	91.93	93.35
Elapsed time	<b>85.641540</b>	<b>23.430</b>	N/A	N/A



**Figure 3. Capacity factors for the respective WECS at the selected locations**

**Table 6: Cost analysis for selected WECS using LCOE and PVC approaches considering the maximum cost**

Parameters	Proposed Methods		Existing method
	BSA	FFA	Analytical Approach [17]
Optimal locations of DG's	11	12	18
Optimal sizes of DG's(KW)	1075	1000	800
Power factor	0.866	0.866	0.85
Optimal locations for capacitors	23,32,30	33,25,30	33
Optimal sizes of capacitors(KVAR)	150,150,900	150,300,750	800
Active power loss in KW	65.7545	64.5071	89.72
% Loss reduction	68.83	69.42	57.47
Elapsed time	<b>20.450268</b>	<b>46.594752</b>	N/A

ing to Ethiopian Electric Power Corporation (EEPCo) tariffs, the average specific cost per unit for all the selected turbines at Mekele is analogous to the cost per kWh production of EEPCo, except for VESTAS-V80 turbine model. In addition, there is a margin of profit by selling energy to EEPCo as the market price for each kWh production is 0.02 \$/kWh as on 16th of November, 2015 [38]. In comparison to the EEPCo power tariffs, the cost per kilowatt hour of electricity generated using LCOE and PVC approaches, Mekele is considered to be an economically viable option when compared to the unit cost of energy sold by EEPCo.

The cost obtained using LCOE and PVC approaches are comparable irrespective of turbine models in all the locations. This is due to the sensitivity of LCOE to a small change in input variables. And is discounted and annualized by the PVC over the lifetime of the wind turbine. In order to investigate the transformation of several input parameters such as wind turbine cost, interest rate, operation and maintenance cost, the useful lifespan of the wind turbine, and another initial capital cost on the unit cost of electricity sensitivity analysis were carried out on GEV-MP wind turbine model at Mekele. The results of this analysis are presented in Figure 4. It is clearly observed from both figures (Figure 4(a) & (b)) that, a similar trend is observed for both the approaches (i.e., LCOE and PVC). The input parameters such as civil works, operation,

Table 7: Cost analysis of WECS using LCOE and PVC approaches considering the minimum cost

Parameters	Single DG placement	Single DG & Capacitors placement	Two DG placement	Two DG & Capacitors placement	Three DG placement	Three DG & Capacitors placement
Optimal locations of DG's	61	61	64,61	24, 61	15 ,61, 62	23,69,61
Optimal sizes of DG's(KW)	988	1000	306 ,1214	232 ,1289	514 ,936, 831	340 ,309, 1632
Power factor	0.866	0.866	0.866,0.866	0.866,0.866	0.866,0.866,0.866	0.866 ,0.866 ,0.866
Total Real Power Injected(KW)	988	1000	1520	1521	2281	2281
Optimal locations for capacitors	-----	62 ,22 , 61	-----	64 ,57 ,11	-----	60 ,32 ,49
Optimal size of capacitor(KVAR)	-----	450 ,300 ,150	-----	300 , 300 , 300	-----	300 ,150 ,450
Active power loss in KW	68.0584	42.7798	31.8014	18.6034	9.5628	5.1986
% Loss reduction	69.752%	80.987%	85.867%	91.73%	95.74	97.68
Elapsed time	75.045645	90.053564	88.819692	85.088916	86.747138	85.641540

Table 8: Cost analysis of WECS using LCOE and PVC approaches considering the average cost

Parameters	Single DG placement	Single DG & Capacitors placement	Two DG placement	Two DG & Capacitors placement	Three DG placement	Three DG & Capacitors placement
Optimal locations of DG's	61	61	61,23	62,9	61,20,62	19,22,61
Optimal sizes of DG's(KW)	1000	1000	1357,164	1350,170	767,514,100	294,219,1768
Power factor	0.866	0.866	0.866,0.866	0.866,0.866	0.866,0.866,0.866	0.866 ,0.866 ,0.866
Total Real Power injected(KW)	1000	1000	1521	1521	2281	2281
Optimal locations for capacitors	-----	62 ,22 , 61	-----	16,2,57	-----	7,2,3
Optimal size of capacitor(KVAR)	-----	450 ,300 ,150	-----	450, 150 , 300	-----	450,300,150
Active power loss in KW	66.9526	42.7798	30.2357	26.69	9.7196	7.6047
% Loss reduction	70.229	80.987	86.55	88.131%	95.678	96.61
Elapsed time	61.434655	90.053564	68.035410	69.090415	67.115659	62.518903

and maintenance cost, interest rate, wind turbine cost and battery bank show the linear variation whereas, capacity factor followed decreasing trend irrespective of the locations. In general, a site with wind resource providing high wind turbine  $C_f$  is desirable for economic considerations. In addition, by increasing the project time from 20 to 25 years, LCOE and PVC are observed to decrease by about 15%. For instance, there is an increase of about 20% in the unit cost of electricity if the percentage of civil work cost is increased from 40% to 50% of the total initial cost. The economic viability of wind energy system development can have a negative impact on these parameters.

## CONCLUSIONS

Appraisal of the wind turbine and economic analysis of the selected commercial WECS were examined across the Tigray region of Ethiopia. The findings are summarized as follows:

1. The annual average energy output ranges from 6.749 MWh in Senkata with P10-20 turbine model at 36.6 m hub height to 1548.264 MWh in Mekele using VESTAS-V80 at a 67 m hub height.
2. Capacity factor 0.15%, is obtained using VESTAS V80 turbine model at 67 m hub height, and 19.92%, is obtained in Mekele with G3120 turbine model at 42.7 m hub height.
3. The average range of basic costs between \$0.0017/kWh and \$0.0011/kWh were achieved for the G3120 model at 42.7 m hub height for the LCOE and PVC values at Mekele, and \$0.0524/kWh to \$0.0354/kWh at Senkata with VESTAS-V80 model at 67 m hub height.
4. Among the selected locations, due to the higher velocity of wind speed at Mekele, it has lowest costs for all WECS in the selected locations. Hence, Mekele can be recommended as a potentially viable option for wind energy development.
5. The sensitivity analysis established that the trend of capacity factor linearly decreases with the increase in the capacity factor. The useful life of the wind turbine can have a positive impact on the cost of electricity produced by the WECS, while other input parameters lead to increase in LCOE and PVC as their values increase.

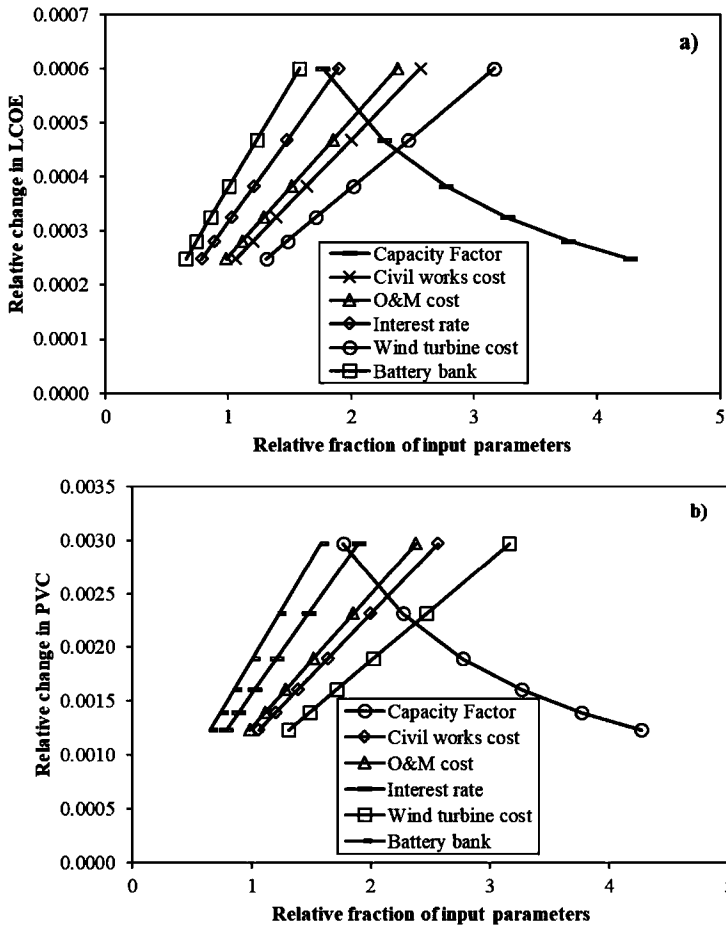


Figure 4. Sensitivity analysis of selected input parameters of a) LCOE b) PVC using GEV- MP model at Mekele

References

1. Burton T., Sharpe D., Jenkins N. and Bossanyi E. Wind Energy Handbook. Chichester: John Wiley & Sons, Ltd, 2001.
2. Gökçek M., and Genç M.S., Evaluation of electricity generation and energy cost of wind energy conversion systems (WECS) in central Turkey, Applied Energy, 2009, 86, pp.2731–2739.
3. Shiva Prashanth Kumar K., Satyanarayana G. and Nagaraju S., Wind energy potential and economic evaluation of WPS using WECSs in three selected locations of Northern Ethiopia, African Journal of Science, Technology, Innovation and Development, 2017. doi:10.1080/20421338.2017.1303990.
4. GWEC, “Global Wind Report Annual Market Update.” GWEC.net
5. Global Wind Energy Council (GWEC). <http://www.gwec.net>
6. Ethiopian Electric Power Corporation (EEPCo). Strategic management and programming. Facts in brief; 2011.

7. Breyer Ch., Gerlach A., Hlusiak M., Peters C., Adelman P., Winiacki J., Schützeichel H., Tsegaye S., and Gashe W. Electrifying the poor: highly economic off-grid PV systems in Ethiopia a basis for sustainable development, 2009. <<http://www.arcfinance.org/pdfs/news/EthiopiaPaper2009.pdf>>.
8. Hadagu A., Status and trends of Ethiopian rural electrification fund, 2006. <<http://www.bgr.de/geotherm/ArGeoC1/pdf/07%20A.%20Hadgu%20status%20of%20Ethiopian%20Electrification%20fund.pdf>>
9. Dalelo A., Rural electrification in Ethiopia opportunities and bottlenecks. Addis Ababa University; 2003. <[http://www.zef.de/fileadmin/webfiles/renewables/presentations/Dalelo\\_rural%20electrification%20ethiopia.pdf](http://www.zef.de/fileadmin/webfiles/renewables/presentations/Dalelo_rural%20electrification%20ethiopia.pdf)>.
10. Shiva Prashanth Kumar K., and Satyanarayana G., Statistical scrutiny of Weibull parameters for wind energy potential appraisal in the area of northern Ethiopia, *Renewables: Wind, Water and Solar*, 2015, 2(14), pp.1-15.
11. Satyanarayana G., and Shiva Prashanth Kumar K. Wind energy potential and cost estimation of wind energy conversion systems (WECSs) for electricity generation in the eight selected locations of Tigray Region (Ethiopia), *Renewables: Wind, Water and Solar*, 2016, 10(3), pp.1–13. doi: 10.1186/s40807-016-0030-8.
12. Bagiorgas H.S., Assimakopoulos M.N., Theoharopoulos D., Matthopoulos D. and Mihalakakou G.K. Electricity generation using wind energy conversion systems in the area of Western Greece, *Energy Conversion and Management*, 2007, 48, pp.1640–1655.
13. Iinca A., McCarthy E., Chaumel J.L., Retiveau J.L. Wind potential assessment of Quebec Province, *Renewable Energy*, 2003, 28, pp.1881–1897.
14. Meel J., and Smulders P. Wind Pumping: A Handbook (World Bank Technical Paper No. 101), World Bank, Washington, 1989.
15. Chang T.J., and Tu Y.L. Evaluation of monthly capacity factor of WECS using chronological and probabilistic wind speed data: a case study of Taiwan, *Renew Energy*, 2007, 32, pp. 1999–2010.
16. Sathyajith M. Wind energy fundamentals, Resource analysis and economics, Berlin Heidelberg: Springer-Verlag, 2006.
17. Gökçek M., Erdem H.H. and Bayülken A. A techno-economical evaluation for installation of suitable wind energy plants in Western Marmara Turkey, *Energy Exploration and Exploitation*, 2007, 25, pp.407–428.
18. Morthorst P.E., Cost and Price, Wind Energy—The Facts, The European Wind Energy Association, Brussels, 2004, vol. 2.
19. RET Screen—Software online user manual, Catalogue no.: M39-104/2004E-PDF. Minister of Natural Resources, Canada, 1997–2004. ISBN 0-662-36820-7.
20. Adaramola M.S., and Oyewola O.M., On wind speed pattern and energy potential in Nigeria, *Energy Policy*, 2011, 39, pp.2501–2506.
21. Morthorst P.E. Cost & price, wind energy—the facts, Brussels—Belgium: The European Wind Energy Association, 2004, vol. 2.
22. Shiva Prashanth Kumar K. Assessing wind energy potential for electricity generation using WECS in eight selected stations of Ethiopia. *International Journal of Ambient Energy*, 2017. doi: 10.1080/01430750.2017.1319415.
23. Akpınar E.K., and Akpınar S. An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics, *Energy Conversion and Management*, 2005, 46, pp.1848–67.
24. Ucar A., and Balo F. Evaluation of wind energy potential and electricity generation at six locations in Turkey, *Applied Energy*, 2009, 86, pp.1864–72.
25. Safari B., and Gasore J. A statistical investigation of wind characteristics and wind energy potential based on the Weibull and Rayleigh models in Rwanda, *Renewable Energy*, 2010, 35, pp.2874–80.
26. Ahmed Shata A.S., and Hanitsch R. Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt, *Renewable Energy*, 2006, 31, pp.1183–202.
27. Habali S.M., Mohammed A.H., Bassan A.J., and Adnan Z. Wind speed and wind energy potential of Jordan, *Solar Energy*, 1987, 38, pp.59–70.
28. Sarkar M., and Hussain M. The potential of wind electricity generation in Bangladesh, *Re-*

- newable Energy, 1991, 1, pp.855–7.
29. PolarisAmerica: <http://www.powerenergypr.com/documents/ModelP1020kWSpecSheet.pdf>.(2012).
  30. Endurance Wind Power: <http://www.endurancewindpower.com/g3120.html> (2012).
  31. Vergnet Wind Turbine: [http://www.thewindpower.net/turbine\\_en\\_88\\_vergnet\\_gev-mp-275-32.php](http://www.thewindpower.net/turbine_en_88_vergnet_gev-mp-275-32.php). (2012).
  32. Vergnet Wind Turbine: [http://www.thewindpower.net/turbine\\_en\\_289\\_vergnet\\_gev-hp.php](http://www.thewindpower.net/turbine_en_289_vergnet_gev-hp.php) (2012).
  33. Polaris America:[http://www.hasmak.com.tr/ruzgar\\_turbinleri/500kw\\_ruzgar\\_turbinleri.pdf](http://www.hasmak.com.tr/ruzgar_turbinleri/500kw_ruzgar_turbinleri.pdf) (2012). Accessed 19 March 2015.
  34. Vestas V80-2MW: <http://www.VESTAS.com/en/wind-power-plants/procurement/turbine-overview/v80-2.0-mw.aspx>. (2012).
  35. Ohunakin O.S., Adaramola M.S., Oyewola O.M. Wind energy evaluation for electricity generation using WECS in seven selected locations in Nigeria, *Applied Energy*, 2011, 88, pp. 3197–3206.
  36. Wind power and the UK wind resource: Environmental Change Institute. Oxford University, (2005). <http://www.eci.ox.ac.uk/publications/downloads/sinden05-dtiwindreport.pdf>. (2012).
  37. Renewable Energy Research Laboratory, University of Massachusetts at Amherst: Wind: capacitor factor, intermittency and what happens when the wind doesn't blow? [http://www.umass.edu/windenergy/publications/published/communityWindFactSheets/RERL\\_Fact\\_Sheet\\_2a\\_Capacity\\_Factor.pdf](http://www.umass.edu/windenergy/publications/published/communityWindFactSheets/RERL_Fact_Sheet_2a_Capacity_Factor.pdf). (2012).
  38. <http://www.eepco.gov.et/TarifIndex.php>

### **Competing interests**

The authors declare that they have no competing interests.

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### **Authors' contributions**

SPKK collected the wind data and carried out initial analysis. Wind turbine calculations were performed by DSNG. 'Background' section was drafted by DSNG and 'Results and discussion' section was jointly drafted by SPKK and DSNG. Both the authors compiled, abridged and eventually approved the manuscript to be submitted.

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## APPENDIX—Nomenclature

### Symbols

$c$	Weibull scale parameter, m/s
$C_f$	Capacity factor, (%)
$C_{wt}$	cost of the wind turbine
$C_{bb}$	cost of battery bank
$C_{ci}$	civil works and installation cost
$C_{in}$	cost of the inverter
$C_{misc}$	miscellaneous cost
$C_{om}$	Annual operation and maintenance cost
$C_{omr}$	operation, maintenance and repair cost
$E_p$	annual energy production
$e_{om}$	escalation of the operation and maintenance
$E_{rated}$	Rated energy, kWh/Year
$I_{wecs}$	Specific cost of WECS
$i$	Inflation rate
$I$	Investment cost
$v$	wind speed, m/s
$\bar{v}$	Mean wind speed, m/s
$k$	Weibull shape parameter, dimensionless
$P_D$	annual mean power density, $W/m^2$
$P_R$	Rated power, kW
$Q_c$	Cut – in wind speed, m/s
$Q_r$	Rated wind speed, m/s
$Q_f$	Cut – off wind speed, m/s
$r$	Interest rate
$S$	Scrap value
$T$	Lifetime of the machine (in years)
$V_E$	Wind speed carrying maximum energy, m/s
$V_F$	most probable wind speed, m/s

**Greek letters**

$\alpha$	Roughness coefficient
$\Gamma()$	Gamma function
$\rho$	Air density, kg/m <sup>3</sup>

**Abbreviations**

CRF	capital recovery factor
EEPCo	Ethiopian Electric Power Corporation
EPFM	Energy pattern factor method
GWEC	Global Wind Energy Council
LCOE	Levelized cost of electricity
NMA	National Meteorological Agency
PVC	Present Value of Cost
PNL	Battelle – Pacific Northwest Labs
WECS	Wind Energy Conversion System