Chapter 17
Site-Specific Design Optimization of Wind Turbines at Low Wind Speed Sites of North-East India

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Abstract The utilization of the wind energy at a location primarily depends on the wind speed and right kind of machine installed at the site. The selection of machine for a site needs to be in such a way, so that maximum amount of energy can be effectively harnessed from the available wind spectrum. Wind speeds in the North-Eastern region of India are relatively low, highly fluctuating in directions, and localized in nature. The low wind speed creates difficulty to provide high starting torque to larger capacity machines with relatively higher rated wind speed. Thus, the region could be favorable to smaller machines having low cut-in and low rated wind speed. The present work aims to analyze the feasibility of installation of low capacity wind machines by estimating the capacity factors and annual energy generation at selected sites of the region. The low capacity machines can be used as an off-grid energy system to provide electricity access in the remote locations of the region.

Keywords Site-specific design · Capacity factor · Annual energy generation

1 Introduction

Wind power is considered as one of the fastest growing renewable energy sources, which is cleaner and cheaper alternative to the carbon-based fossil fuels. Large-scale wind farms are being established in potentially good wind sites both in onshore and offshore. Wind resource assessment is essential before installation of any wind machines, because the power output of the wind turbine depends on the site characteristics and topography. The utilization of the wind energy at a location depends primarily upon the availability of the wind spectrum. The selection of machine for the site needs to in such a way that maximum amount of energy can be effectively harnessed from the available wind spectrum. Site-specific design perfectly matches with the available wind speed and the machine characteristics for optimum energy generation or reduce the cost of energy generation.

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Ohunakin et al. estimated capacity factor, annual energy generation, and cost of energy generation of two commercial wind turbines in six high-altitude locations of Nigeria [1]. Boccard reported the discrepancy in reported and actual capacity factors of wind turbines and the consequence of the miscalculation of capacity factors located in Europe [2]. Huang and Wan presented a generalized and systematic methodology for installation of wind turbine generators using capacity factor curves for maximum energy generation at a specific site [3]. Jangamshetti and Rau investigated statistical models for wind resource assessment and observed that the capacity factor calculated based on analytical method closely matches with the actual capacity factor obtained at field [4]. The study concluded that the analytical model can be used for accurate assessment toward wind turbine installation at a potential site. Fuglsang et al. reported the results of site characteristics inclusion in wind turbine design process in a European project [5]. The study observed that optimized site-specific design increase the annual energy yield and reduce the cost of energy generation. The study concluded that wind turbine should be design based on site particularly for low-wind location. Ayodele et al. estimated capacity factors of commercially available wind turbines, based on local wind characteristics in the Western Cape region of South Africa [6]. The study examined the influence of power curve of turbine on the capacity factor. It is concluded that Weibull distribution is the most suitable model to represent the wind distribution of a site. Jowder statistically analyzed and determined the most suitable locations in Kingdom of Bahrain [7]. Weibull parameters are estimated by using different methods. The study also investigated the site matching of wind turbine by estimating capacity factors of commercially available turbines. The optimum site selection has been done based on annual and monthly variation of capacity factors.

The wind resource assessment has been carried out at a few locations in the North-Eastern part of India [8]. The mean wind speed in the region is 1.8–4.9 m/s, which are relatively low in comparison with the coastal regions of India [8]. The wind in the region is also highly fluctuating in directions, turbulent in nature due to its topography, and usually localized in nature. The feasibility of installation of off-grid wind systems from available low-potential wind resource is an alternative option considering the non-availability of power in most of the remote localities of the region. This study aims at analyzing the feasibility of installation of low capacity wind machines in the region by estimating capacity factor and annual energy generation at the selected sites.

2 Methodology

Wind speed is the most important parameter to be considered in the design and operation of wind turbines since its probability density distribution greatly affects the performance of wind turbines. National Institute of Wind Energy (NIWE) has established 93 Wind Monitoring Stations in North-Eastern region of India, out of which nine stations are in operation as on 31.05.2020 [8]. Table 1 shows the number of wind monitoring stations established in the various states of the region. Wind

Table 1 Wind monitoring stations in NE states [8]

States	Installed	In operation
Arunachal Pradesh	17	7
Assam	18	–
Meghalaya	17	–
Mizoram	9	–
Manipur	15	1
Nagaland	6	–
Tripura	11	1

power density is mostly in the range of 0–100 W/m^2, and maximum wind speed occurs in the region during April–June months.

The prerequisite for the efficient planning and implementation of a wind energy project is primarily based on the wind regime characteristics. The characteristics of the wind regime of a location are defined by shape parameter (k) and scale factor (c) of Weibull distribution. Weibull parameters are helpful in estimating the probabilities of various wind speeds, such as mean wind speed and most probable wind speed, as well as their daily, monthly, or annual hours of availability for a particular site. Selection of right kind of machine or wind turbine needs to be chosen based on site characteristics in order to harness maximum wind power effectively. An important aspect in the selection of machines is the capacity factor, which is function of both the site characteristics (k and c) and machine characteristics (cut-in, rated, and cut-out wind speeds). In this study, capacity factors of five commercially available machines are estimated for the selected sites of North-East region of India. The annual energy generation is also estimated based on the capacity factor of the selected machine in these sites. The site parameters and mean wind speed data for a total number of 18 places of the North-East are obtained from C-WET [9]. Table 2 presents the mean wind speed and Weibull parameters for the selected sites of the region.

A wind turbine is designed to operate within a certain range of wind speed characterized by cut-in speed, rated speed, and cut-out speed. Five different capacity commercially available machines are selected for the analysis in this study. It is necessary to estimate the actual energy generation in a particular site from a wind machine. The energy generation is an important parameter because it affects the cost per unit electricity generation and determines the economic viability of a machine for a particular site. The energy generation depends on the site characteristics and machine characteristics. The ratio of actual energy produced at the site to the maximum energy can be generated based on its rated power of the machine which is known as capacity factor. The capacity factor (CF) is function of the site parameters (k, c) and the machine parameters (cut-in, rated, and cut-out wind speed). The capacity factor and annual energy generation can be estimated by using the following relations. Table 3 presents the commercially available wind machine characteristics data.

Table 2 Weibull parameters for various sites [9]

Location	State	Mean wind speed (m/s)	Weibull parameters	
			c (m/s)	*k*
Borgaon	Assam	2.4	2.7	2.3
P.Leikul	Assam	3.2	3.6	1.6
Tolpoi	Assam	2.5	2.8	2.0
Likabali	Arunachal Pradesh	2.9	3.2	2.2
Passighat	Arunachal Pradesh	2.3	2.5	1.8
Raga	Arunachal Pradesh	1.8	2.0	2.0
Phuldangsai	Tripura	3.8	4.3	2.1
Tlangsang	Tripura	3.9	4.4	2.1
Vanghmun	Tripura	3.5	3.9	2.0
Lunglei	Mizoram	3.9	4.4	2.1
Mamte	Mizoram	2.8	3.1	2.1
Reiek	Mizoram	3.8	4.3	1.7
Chawangkining	Manipur	4.5	5.0	1.8
Dolangkhnou	Manipur	4.4	4.9	2.0
Laimaton	Manipur	4.9	5.5	2.2

Table 3 Machine characteristics

Machine	Rotor diameter (m)	Rated capacity (kW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)
Machine A	29	225	3.5	14	25
Machine B	29	100	3	10	25
Machine C	29	60	3	9	25
Machine D	9	5	2.5	7.5	20
Machine E	6	1	1.9	6	15

$$CF = \frac{\exp\left(-\left(\frac{u_c}{c}\right)^k\right) - \exp\left(-\left(\frac{u_R}{c}\right)^k\right)}{\left(\frac{u_R}{c}\right)^k - \left(\frac{u_c}{c}\right)^k} - \exp\left(-\left(\frac{u_F}{c}\right)^k\right) \tag{1}$$

$$\text{Annual Energy Generation} = CF \times P_R(\text{kW}) \times 8760(\text{h}) \tag{2}$$

3 Results and Discussion

3.1 Capacity Factor

The capacity factors are estimated for five different commercially available machines for 15 different sites in various states of the region. Table 4 presents the capacity factors of all these machines in various sites. The machine A has the lowest capacity factor, and machine E has the highest capacity factor in all these sites. Capacity factor depends on the site characteristics and machine characteristics. It is observed that Chawangkining and Laimaton sites of Manipur show highest capacity factors for all the machines. The mean wind speed of these two sites is relatively higher in comparision with the other sites. It is worthy to mention that although a few more sites showed higher duration of wind availability in the desired range, i.e., in between cut-in and rated wind speed, the capacity factors are low. The maximum mean wind speed is 4.9 m/s at Laimaton, out of all these sites. However, the cut-in and rated wind speed for machine A is 3.5 and 14 m/s, respectively. Machine A has the highest cut-in and rated wind speed among the selected machine resulted lower capacity factors for all the sites. It means that machine A operates most of the time of the year near the cut-in wind speed in these sites. The maximum power coefficient (Cp) is also function of wind speed. The maximum power coefficient is lower at the lower wind speed regime. Hence, the power output or energy generation from machine A

Table 4 Capacity factors for different machines

Site	Capacity factor (%)				
	Machine A	Machine B	Machine C	Machine D	Machine E
Borgaon	0.39	1.47	1.91	4.49	10.95
P.Leikul	4.91	10.68	12.85	19.90	31.19
Tolpoi	0.89	2.73	3.45	7.05	15.03
Likabali	1.21	3.68	4.74	9.40	19.33
Passighat	0.78	2.32	2.89	5.90	12.67
Raga	0.10	0.46	0.59	1.68	5.01
Phuldangsai	4.63	11.50	14.51	23.68	38.28
Tlangsang	5.01	12.32	15.52	25.02	39.82
Vanghmun	3.70	9.23	11.59	19.42	32.63
Lunglei	5.01	12.32	15.52	25.02	39.82
Mamte	1.23	3.65	4.66	9.16	18.69
Reiek	7.33	15.49	18.58	27.36	40.17
Chawangkining	10.06	20.77	24.78	34.95	48.61
Dolangkhnou	7.84	17.73	21.78	32.40	47.23
Laimaton	9.28	21.50	26.61	38.84	54.74

which is operated near the cut-in wind speed with low power coefficient resulted lower energy generation than the energy generation at rated power.

The lower value of scale parameters also indicates lower mean wind speed of the site. It reveals that machine operates at rated power only for few hours in a year in such sites. It is also observed that as the rated wind speed reduces, capacity factor of the machines increases in all these sites. Moreover, machine E with rated capacity of 1 kW has lowest cut-in and rated wind speed among these machines exhibits higher capacity factor in all the sites. Hence, matching the machine characteristics with site characteristics is an essential assessment tool toward selection of right kind of machine for optimum power generation in a site. Low capacity machines, i.e., lower cut-in and rated wind speeds, are most suitable in low-windy sites. These kinds of machines can operate relatively longer hours in a year and generate maximum energy in a low-windy site.

Figure 1 presents the capacity factor of different machines for nine best sites. The capacity factor for machine A varies from 4.9% for P. Leikul to 10.1% for Chawangkining. The mean wind speed for P.Leikul and Chawangkining are 3.2 m/s and 4.5 m/s, respectively. However, machine A has rated wind speed of 14 m/s and rated power of 225 kW. It is important to mention that the mean wind speed of Laimaton is higher than Chawangkining. However, the capacity factor for Laimaton is lower than the Chawangkining. This happened due to the difference in Weibull scale parameter in these sites ($c = 5.5$ for Laimaton and $c = 5.0$ for Chawangkining). Higher scale parameter resulted availability of low wind speed in most of the time of the year. The capacity factor for machine E for Chawangkining and Laimaton is 48.6

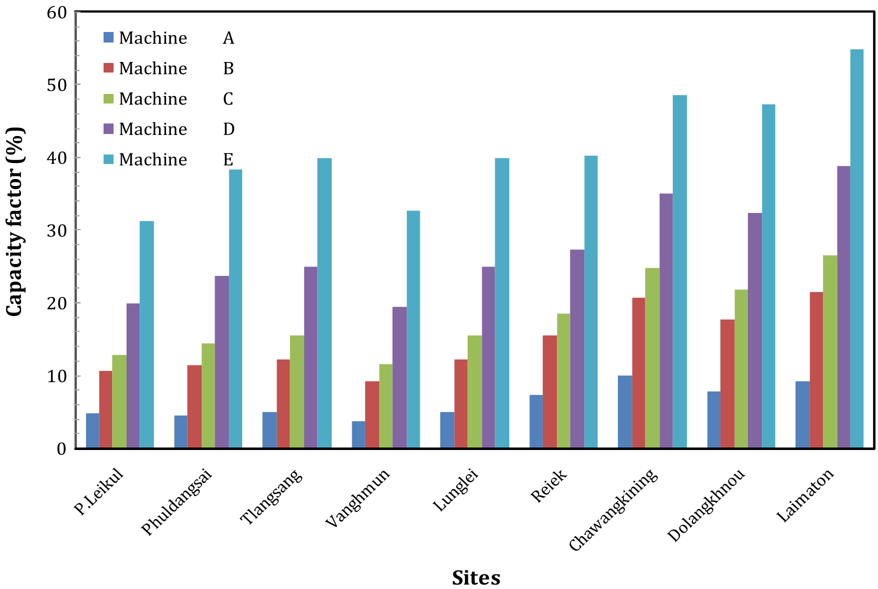

Fig. 1 Capacity factors for different machines in selected sites

and 54.7%, respectively. This is opposite to the machine A result. This is due to the cut-in and rated wind speed of machine *E* are 1.9 m/s and 6 m/s, respectively. Hence, the machine *E* is operated more number of hours in a year in Laimaton compared to Chawangkining. The capacity factor results show that low capacity machines such as machine *D* or machine *E* has higher capacity factor compare to relatively higher capacity machines like machine *A* or machine *B* or machine *C*.

3.2 Annual Energy Generation

Normalized annual energy generation is estimated for different machines in all the sites considered in this study. Normalized annual energy generation indicates the annual energy generation per unit power of the machine. This estimation is essential to compare different rated machines. Table 5 presents the normalized annual energy generation from different machines. It is observed that machine *A* is generating lowest normalized annual energy and machine *E* is generating highest normalized annual energy. Machine *A* is generating maximum energy in Chawangkining, due to maximum capacity factor of this machine at this site. Machine E has maximum generation in Laimaton due to the maximum capacity factor of this machine at this site. This analysis is significant, as annual energy generation is directly related with cost of energy generation. The cost of energy is lower for higher normalized annual

Table 5 Normalized annual energy generation of different machines

Site	Normalized annual energy generation (kWh/kW)				
	Machine A	Machine B	Machine C	Machine D	Machine E
Borgaon	34	129	167	393	959
P.Leikul	430	936	1126	1743	2732
Tolpoi	78	239	302	618	1317
Likabali	106	322	415	823	1693
Passighat	68	203	253	517	1110
Raga	9	40	52	147	439
Phuldangsai	406	1007	1271	2074	3353
Tlangsang	439	1079	1360	2192	3488
Vanghmun	324	809	1015	1701	2858
Lunglei	439	1079	1360	2192	3488
Mamte	108	320	408	802	1637
Reiek	642	1357	1628	2397	3519
Chawangkining	881	1819	2171	3062	4258
Dolangkhnou	687	1553	1908	2838	4137
Laimaton	813	1883	2331	3402	4795

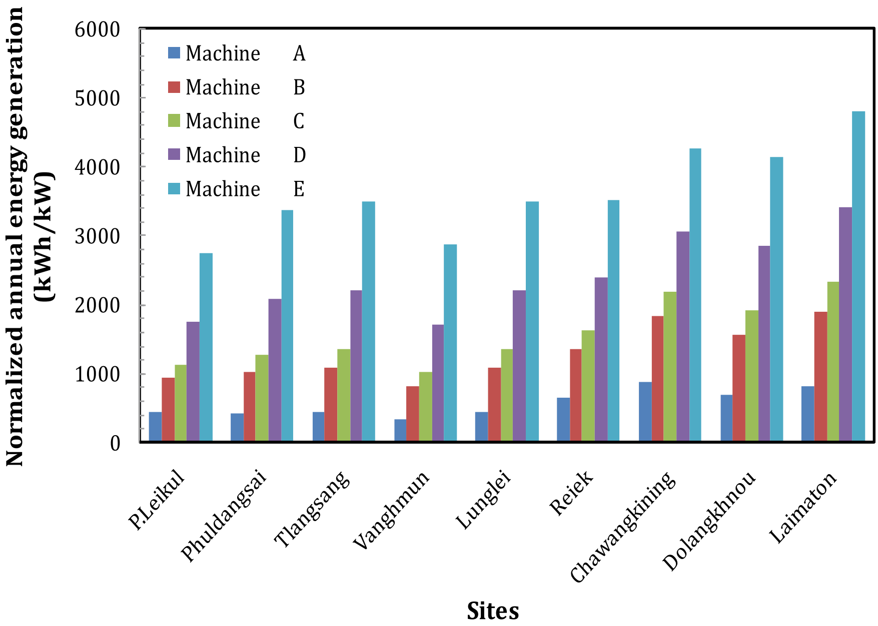

Fig. 2 Normalized energy generation from different machines in selected sites

energy generation. The cost of energy generation for machine E is the lowest among all the machines.

Figure 2 presents the normalized annual energy generation of different machines for nine selected sites. It is observed that the lowest normalized annual energy generation is in P.Leikul for machine *A* and highest normalized annual energy generation is in Laimaton for machine *E*. The normalized annual energy generation for the site Laimaton is 4795 kWh and 3402 kWh for machine *D* and machine *E*, respectively. The rated capacity of machine *D* and machine *E* is 5 kW and 1 kW, respectively. It can be concluded that Chawangkining, Dolangkhnou, and Laimaton are the best sites among all the sites selected for the analysis. The machine *D* and *E* are the most suitable machines for these low-windy sites. Off-grid wind energy systems of 1–5 kW capacity are most promising for Chawangkining, Dolangkhnou, and Laimaton sites. This off-grid system shall be able to provide power in these remote locations with lowest cost of energy.

4 Conclusions

The present study analyzed the feasibility of installation of wind machines in the North-Eastern region of India by estimating the capacity factors and normalized annual energy generation of few commercially available machines at selected sites of the region. It is observed that few sites have potential for installation of wind turbine. However, as the mean wind speed is relatively low in these sites, smaller capacity (1–5 kW) machines are most suitable for the region. It is found that Chawangkining, Dolangkhnou, and Laimaton of Manipur are the most suitable location for installation of the low capacity wind machines. The low capacity machines can be used as an off-grid energy system to provide electricity access in these remote locations of the region with lowest cost of energy. However, performance evaluation of demonstration off-grid wind energy systems at Chawangkining, Dolangkhnou, and Laimaton of Manipur needs to be carried out. Finally, it can be concluded that smaller capacity wind turbine as decentralized off-grid system has potential for installation in the selected places of the region.

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