COST OF ENERGY REDUCTION FOR OFFSHORE WIND ENERGY IN SOUTH-CENTRAL COAST, VIET NAM

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Abstract - This article aims at reducing the cost of energy by targeting the optimal power of the wind generator of offshore wind farms in a region in Vietnam. The research employs various scaling laws for mass and cost calculations. The calculations are implemented using wind data of a specific region on the South-Central Coast. The permanent magnet synchronous generator with high efficiency, light-weight, and compact design will be used for the wind generator. The levelized cost of energy as a function of the generator's nominal power is then built to figure out the optimal power of the wind generator. Results show that future offshore wind farms with monopile foundations having a mean wind speed of about 6.5 m/s should be installed with a turbine's nominal power of 7 MW.

Key words - Offshore wind; permanent magnet wind generator; levelized cost of energy

1. Introduction

Electricity produced from renewable energy is receiving more and more attention and accounts for a large proportion of total electricity generation in Vietnam as well as in many countries around the world. Wind energy is considered indispensable among many renewable energy resources to tackle environmental problems and ensure sustainable development across countries. In 2050, offshore wind is expected to represent nearly 17% of the total global installed wind power (about 6044 GW) [1]. In the energy-mixed structure, wind power has many advantages such as high-capacity factor and large installed capacity wind farms can be built [2]. Currently, together with the available modern technologies, the development of wind energy is strongly supported by many incentive policies. Offshore wind energy is preferable to the onshore counterpart due to the high and stable offshore wind speed. In addition, the installation of offshore wind farms is not strictly limited. However, the offshore energy cost is still high and not competitive with the onshore and traditional means of electricity production due to the high capital and operational costs. Therefore, the need to reduce offshore energy costs is essential. In this article, the wind energy cost is presented in the form of levelized cost of energy (LCOE) which is a good criterion to compare various electricity generation technologies.

One of the solutions to reduce the LCOE is to increase the nominal capacity of the turbine because it can reduce the total number of wind columns (with the same capacity as the wind farm), reducing construction and installation costs. In Vietnam, the current onshore wind farms have a rated capacity of about 2 MW, the current offshore wind power projects are deploying wind columns with a rated capacity of about 4 MW and tend to further increase [3]. Increasing the turbine's nominal power helps reduce the number of turbines as well as utilize power-independent components. Therefore, the energy cost is expected to reduce. However, very high turbine power will lead to much larger turbine components making manufacturing, transportation as well as installation difficult. In addition, some components' costs will significantly increase. This compromise raises the question of which turbine's power could minimize the LCOE. Depending on the wind conditions of the region to be considered, the optimal turbine's power will vary.

This article works on the wind data of the Phuoc The commune, Binh Thuan province, Vietnam. The direct-drive permanent magnet synchronous generator is assumed for the wind generator due to advantages such as high efficiency, compact design, and high-power density. In addition, direct-drive means no gearboxes are used to improve the system's reliability. In this article, the calculation is made for a single turbine, although in reality a wind farm usually consists of a number of wind turbines. This is to better investigate the impact of the turbine's nominal power. If the number of turbines is taken into account, then the impact of the wake effect as well as the wind farm's layout must be considered. In addition, the number of turbines will not be an integer as the turbine's nominal power increase gradually (if the wind farm's total power is fixed). The main contribution of the research is to suggest the optimal turbine power to increase the economical values of wind farms in the investigated area.

2. Methodology

2.1. Levelized cost of energy - LCOE

The LCOE is an economic indicator to evaluate the net present cost of electricity generation over the entire lifetime of the project. It is a useful criterion and is commonly used to compare different generating technologies.

The LCOE is calculated as the sum of all costs incurred during the life of the project divided by the total energy generated during that period (AEP_{net}) calculated as (1) [4, 5]:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{AEP_{net,t}}{(1+r)^t}} \quad (1)$$

where: $CAPEX_t$ is capital expenses in year t; $OPEX_t$ is operating expenses in year t, r is the discount rate, which is 10% in this article; $AEP_{net,t}$ is annual net energy production in year t; T is the system lifetime which is 20 years in this article.

A typical cost breakdown structure for offshore wind farms is illustrated in Figure 1 [6,7,8] including:

- Predevelopment and Consenting: P&C;
- Production and Acquisition: P&A;
- Installation and Commissioning: I&C;
- Operation and Maintenance: O&M;
- Decommissioning and Disposal:

The CAPEX is assumed one-time expense at the beginning of the project. In this article, this expense also includes the decommissioning cost, which occurs at the end of the project to clean the site.

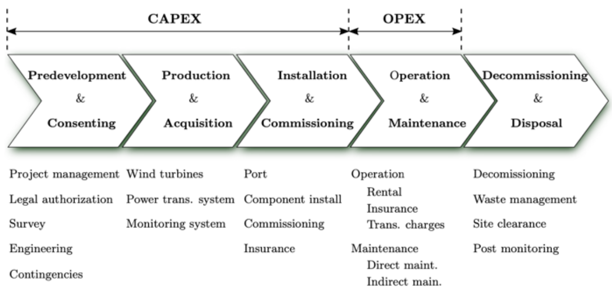

Figure 1. *Cost breakdown for offshore wind farms*

Shafiee et al. [8] presented a comprehensive data analysis for this cost breakdown`. The analysis utilized rich collected data from experiments, and references from experts, managers, and stakeholders of offshore wind farms. CAPEX and OPEX are two main important categories since they are related to the LCOE, which is a criterion to evaluate the performances of different generating technology concepts. CAPEX includes predevelopment and consenting cost (P&C), production and acquisition cost (P&A,) and installation and commissioning cost (I&C). The P&C cost consists of project management cost (about 3% of the CAPEX), legal authorization cost (about 0.13% of the CAPEX), survey cost, engineering cost (about 2840 USD/MW) and the contingency cost (about 10% of CAPEX). In general, the P&C is approximated as 511,100 USD/MW [8]. The P&A mainly consists of the cost of the turbine, whose components are detailed in Table 4. The power and transmission system is excluded in this article as only a single turbine is considered. The monitoring system includes the Supervisory Control and Data Acquisition (SCADA) and Condition Monitoring Systems (CMSs). As summarized from [8], this cost in USD as,

$$C_{P\&A} = C_{turbine} + 1,102,500 + 392,200P + 31140 \quad (2)$$

where $C_{turbine}$ is the cost of the turbine; P is the turbine's nominal power in MW.

The I&C cost involves all activities related to the construction of offshore wind farms, including the port cost related to the port activities, the component installations and commissioning cost for hiring vessels and crew members, and the insurance cost (proportional to the turbine's nominal power). In [8], the I&C cost is assumed to be 759,800 USD/MW.

The CAPEX, therefore, can be summarized in a short form as (3).

$$CAPEX = C_{turbine} + 1,459,000P \quad (3)$$

Most of the items are proportional (not necessarily linear) to the turbine's nominal power. Since a bigger capacity basically requires more materials, more costly installations, more power transmission charges, longer working hours for labor cost, more vessels, etc. Very few items are considered fixed such as annual fees for the use of port infrastructure (although, bigger capacity requires more port infrastructures).

In this article, the CAPEX is assumed one-time expense at the beginning of the project. This expense also includes the decommissioning cost which occurs at the end of the wind farm project. After the defined lifetime of a wind farm, all wind turbines and associated cables, sub-stations will be decommissioned. They could be removed or recycled depending on item types and project specifications, this cost is assumed 600 kUSD/MW [8]. The operating expense OPEX is assumed to be 130 kUSD/MW/year [9].

2.2. CAPEX component calculations using scaling laws

This section presents calculations of some main expense components of the wind turbine. It is noted that in a direct-drive wind turbine, gearboxes are removed. The main components of the turbine include rotor blades, rotor hub, nacelle (a turbine shaft, turbine bearing, power electronics modules, bed-plate, nacelle cover, generator), tower, transformer (placed in the bottom part of the tower), foundation (the bottom-fixed foundation with monopile is assumed in this article).

The mass and cost calculations of the above components are summarized in Table 1 [8, 10].

Table 1. *Mass and cost scaling laws of main components in the turbine*

Component	Mass [kg]
Blades	$3.55D^{2.06}$
Hub	$8,513P^{0.98}$
Main shaft	$159P^2 + 2,898P + 66.6$
Bearing	$125P^2 + 1,262P$
Power electronics	1000 kg/MW
Transformer	2000 kg/MW
Bed-plate	$115P^2 + 1,328P$
Nacelle cover	$1,150P + 385$
Tower	$2.84mth^{0.943}$
Monopile foundation	$1,137,000 + 0.1mth^{1.13}$
Generator's active	$m_{ref}(P/P_{ref})$
Generator's inactive	$2,183(R_{out}^3 + L_{tot}^3)$

where, D is blade diameter [m], which can be deduced from the turbine's nominal as (4), P is in MW, m_{th} is top-head mass [kg], which is the total mass putting on the tower, R_{out} is the outer radius of the generator [m] and

L_{tot} is the total axial length of the generator [m], m_{ref} is mass of reference generator [kg], P_{ref} is the power of the reference generator [MW]. The reference generator is a 10 MW permanent magnet synchronous one with an outer radius of 4.6 m, a total length of 2 m, and an active mass of 67.96 tons.

3. Annual energy production

This section focuses on the annual energy production (AEP) in the Phuoc The commune, whose position is shown in Figure 2.

Figure 2. *Phuoc The commune position*

The AEP strongly depends on the wind speed distribution as presented by (4) [10].

$$AEP_{net} = \eta.8760\int_{v_i}^{v_0} P(v)\,f(v)dv \qquad (4)$$

where η is system efficiency, which is roughly assumed to be 81% [11]; v_i and v_o are cut-in and cut-out wind speeds, respectively; *P(v)* is the instant power of the turbine, and *f(v)* is the density distribution function.

The turbine's power is calculated as (5) [12]. Figure 3 shows the turbine's power characteristic, at a wind speed higher than the nominal value v_n the power is kept unchanged until the cut-out wind speed is reached.

$$P = \frac{1}{8}C_p(\lambda,\beta)\rho_{\text{air}}\pi D^2 v_n{}^3 \qquad (5)$$

where C_p is the power coefficient depending on the tip speed ratio λ and blade pitch angle β, ρ_{air} is the mass density of the air which is 1.225 kg/m^3 at 15^{0}C.

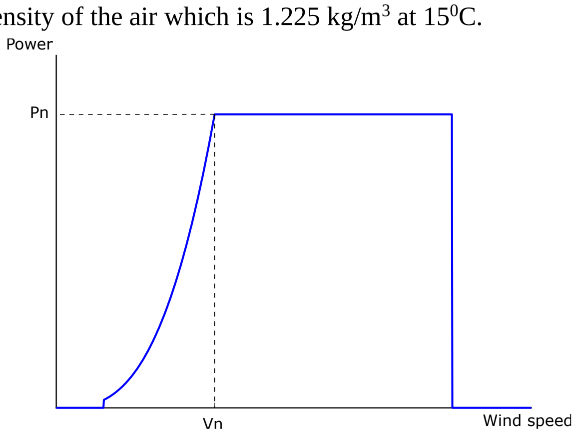

Figure 3. *A typical wind turbine's power characteristic*

In this article, the Weibull distribution function will be used for f(v) and given by (6).

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \qquad (6)$$

where k is the shape parameter, a higher shape factor represents a more constant wind speed. c is the scale parameter, which is proportional to the mean wind speed $\overline{V}$ determined by (7) [13].

$$c = \frac{\overline{v}}{\Gamma.(1+\frac{1}{k})} \qquad (7)$$

where Γ is the gamma function. The gamma function of a variable x is defined by (8).

$$\Gamma(\text{x}) = \int_0^\infty t^{x-1}e^{-t}dt \qquad (8)$$

Usually, the shape parameter k can be chosen as 2, which is a common assumption if no further information is available. In this study, k is determined from the wind speed measurement in the Phuoc The commune.

The wind characteristic is first examined as shown in Figure 4 for the wind speed recorded in 2015. Due to the geographical location of Phuoc The commune right next to the East Sea, the topography of the wind measurement area consists of mainly sand hills with small undulating terrain and no residential areas. Therefore, this research assumes that the wind measurement data is very close to the actual offshore wind data in the same area.

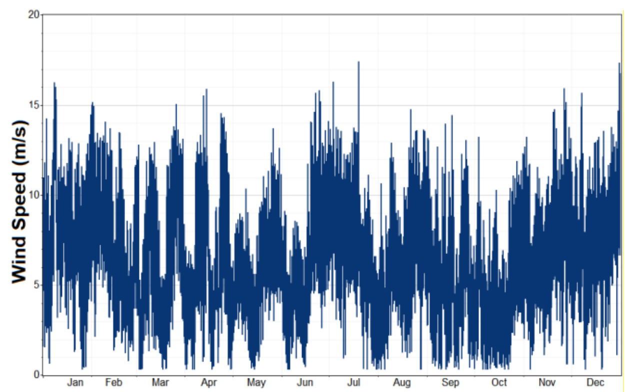

Figure 4. *Wind speed in the Phuoc The commune recorded in 2015*

The standard deviation is determined as (9).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k}(v_i - \overline{v})^2}{N-1}} \qquad (9)$$

From this, the standard deviation is calculated as 2.89.

The mean wind speed is summarized in Table 2.

The shape parameter k is expressed by (10) [14]

$$k = \left[\frac{\sum_{i=1}^{N} v_i^k \ln(v_i)}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N}\ln(v_i)}{N}\right]^{-1} \qquad (10)$$

Based on (7) and (10), parameters k and c can be derived as 2.33 and 7.156m/s, respectively. The Weilbull speed distribution for the Phuoc The commune is then displayed in Figure 5.

4. Result and discussion

In this study, the calculation of LCOE is considered to apply to the projects of installing new offshore wind farms. We will use wind measurement data from 2015. Although the data is not new, the average lifespan of a typical offshore wind farm is about 20-25 years. Therefore, the wind measurement data used in the study is still reliable and can be used as a basis for calculating and evaluating wind characteristics in Phuoc The commune area.

Table 2. *Wind data summary in Phuoc The in 2015*

Month	$\bar{V}$ (m/s)	**σ** (m/s)
1	7.551	2.905
2	7.245	2.891
3	6.417	3.315
4	5.822	3.190
5	5.561	2.239
6	6.038	2.772
7	7.130	2.734
8	6.241	2.574
9	5.263	2.480
10	4.652	2.427
11	6.798	2.595
12	7.448	2.730
Yearly average	6.344	2.890

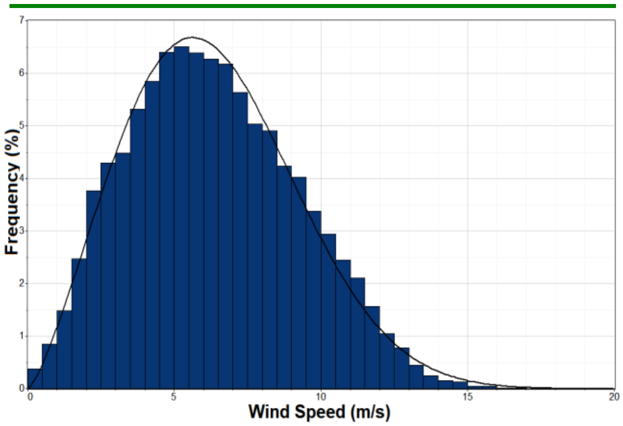

Figure 5. *The Weibull distribution function for the wind speed in Phuoc The commune, in 2015*

In this section, the LCOE (computed as (1)) will be computed at different turbine nominal powers with the wind speed characteristics determined from previous sections. Currently, the maximum nominal power of the wind generator is 14 MW (Haliade-X, [15]), the power range in this article will be chosen from 1 MW to 25 MW to cover the increasing trend of the nominal power. Despite the fact that the high nominal power is challenging with current technologies, we assume the scaling law applies to all powers. In addition, at each nominal power, a suitable nominal wind speed (the speed where the turbine gives the nominal power) will be chosen to further lower LCOE, consistent with the wind characteristics at the place being surveyed, at an average wind speed of $\bar{v} = 6.344$ m/s. The analysis result is summarized in Table 3 with some nominal powers. All LCOEs are shown in Figure 6.

As it can be seen, LCOE at first decreases as the nominal power increases, it is because of some initial expenditures, increasing the nominal power i.e., increases the annual energy production. The levelized cost is, therefore, decreased as a consequence. The cost reduction is more significant when the nominal power is in the range below 3 MW. At higher power, the LCOE increases due to some heavy components of the turbine. The lowest LCOE on this curve is about 107 USD/MWh at a nominal power of 7 MW. This result suggests using higher nominal power for future wind farms to be installed near Phuoc The region.

Table 3. *LCOE at different turbine's nominal powers*

Nominal power [MW]	AEP [GWh]	CAPEX [million USD]	LCOE [USD/MWh]
1	5.82	6.60	147.9
3	16.78	13.74	113.4
5	27.40	21.12	108.5
7	37.54	28.47	107.6
9	48.27	36.69	107.9
11	57.71	43.92	108.5
13	68.20	52.43	109.4
15	76.92	59.41	110.4
17	87.17	68.07	111.4
19	97.43	76.93	112.3
21	107.68	85.97	113.3
23	117.94	95.20	114.3
25	125.20	101.47	115.3

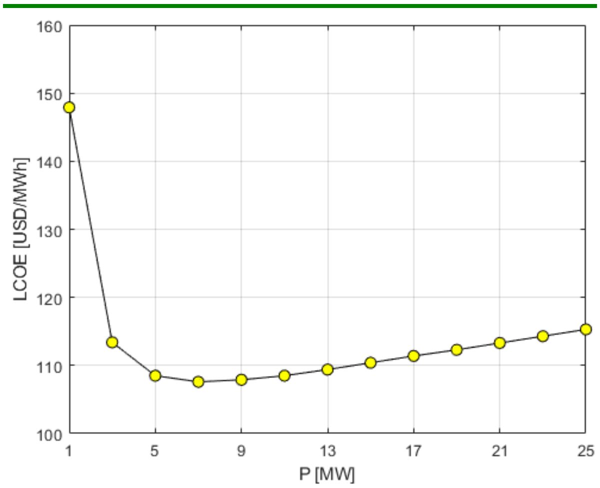

Figure 6. *LCOE at different turbine's nominal powers*

5. Conclusion

This article has analyzed the conditions in Phuoc The, a commune located in Tuy Phong, Binh Thuan (South-Central Coast) to suggest the range of future wind turbines to be installed nearshore or offshore in that region.

The main objective of the study is to make recommendations on the suitable capacity for wind conditions in Phuoc The commune to reduce the cost of LCOE power generation. The result of 7 MW is relevant concerning the current trend of increasing the turbine's power to bring more benefit to investors. Much higher power might be suitable for regions with higher mean wind speed as well as other conditions such as available space for installation. The result of 7 MW nominal power will also be applicable to other regions having similar wind conditions.

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