Onshore Wind Energy Potential in Sri Lanka

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***Abstract* — Wind power production has grown substantially in the world over the past two decades, making wind the fastest-growing non-fossil energy source. The growing rate of installed capacity of wind power was reported to be less than 20% from 2000 to 2019 and anticipated to increase by another 50% by the end of 2023. Wind resources in Sri Lanka show varied wind energy potential in different regions. Adapting new wind technologies, such as large turbines and tall towers, can optimize wind generation in different regions while increasing the wind power potential for the country. In this study, the wind tower hub height is used as the primary factor to evaluate the impact of new technologies. It is shown that by increasing the tower height by 20-40 m over the standard 80 m hub height, wind power can be generated at a competitive cost in Sri Lanka.**

Keywords—wind energy, tall wind tower, annual energy production, capacity factor, Levelized Cost of Energy, Sri Lanka

I. INTRODUCTION

Wind energy generation has grown substantially in the world over the past two decades. The growing rate of installed capacity of wind power was reported to be less than 20% from 2000 to 2019 and is anticipated to increase by a further 50% by the end of 2023 [1]. According to a recent study, wind resources in the entire world exceed the current electricity demand. However, wind energy generation today accounts for only 6.7% of the global electricity supply [2]. With the evolvement of new technologies, large-capacity wind turbines supported by tall towers have accelerated wind power development in certain countries. By using tall towers, wind turbines are able to operate in steadier, higher wind speed conditions. This results in increases to both the capacity factor and Annual Energy Production (AEP), ultimately reducing the Levelized Cost of Energy (LCOE) with an increase in hub height. According to a recent report [3], the LCOE of land-based wind energy in the US has declined by over 70% in the past 12 years (Fig.1). The average turbine capacity and rotor size have seen significant increases over the same time period, while the hub height has seen a moderate increase due to transportation limitations. The land-based wind energy industry continues to trend toward larger turbines and bigger rotors, with a potential to reduce the LCOE by another 27% by 2035 [4]. Therefore, the use of tall towers will become more prevalent, and the industry will also shift toward using optimal tower hub heights as an effective way to increase AEP and reduce the LCOE.

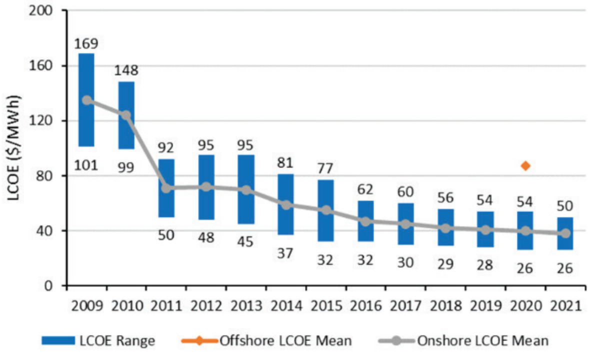

Fig. 1. LCOE of wind energy by time in the US

According to Ceylon Electricity Board (CEB) [5], approximately 11% of the total electricity generation was produced by Other Renewable Energy (ORE) by the end of the year 2018 (Table I). As shown in Fig. 2, ORE capacity, which includes mini-hydro, biomass, wind, and solar PV, was planned to be increased from 1245 MW in 2020 to 4330 MW by 2039, which includes 1323 MW, or 31% of wind energy in the ORE generation mix. It is expected that ORE's contribution will exceed the major hydro energy production beyond 2025 since no significant increase in the major hydropower capacity is expected. Despite this proposed plan, the suggested growth in wind power seems modest. Considering the economic challenges and frequent power cuts that Sri Lanka is currently facing, ramping up OREs to replace over 2 GW of thermal power generation from coal and fuel oil would be desirable. This is an achievable task through adequate planning and development of policies since the island nation has an abundance of

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resources to harvest wind and solar power. The studies have shown that Sri Lanka has a wind generation capacity of over 20 GW. As of May 2020, the installed wind capacity in the nation is 128 MW and the current plan suggests an addition of less than 1 GW by 2030 (Fig. 2).

TABLE I. ENERGY AND DEMAND CONTRIBUTION FROM OTHER RENEWABLE SOURCES (ORE)

Year	Energy Generation (GWh)		Capacity (MW)	
	Other Renewable	System Total	Other Renewable	Total System Installed Capacity
2004	206	8043	73	2499
2005	280	8769	88	2411
2006	346	9389	112	2434
2007	344	9814	119	2444
2008	433	9901	161	2645
2009	546	9882	181	2684
2010	724	10714	212	2818
2011	722	11528	227	3141
2012	730	11801	320	3312
2013	1178	11962	367	3355
2014	1215	12418	442	3932
2015	1466	13154	455	3850
2016	1160	14148	516	4018
2017	1464	14,671	563	4087
2018	1762	15,305	585	4048

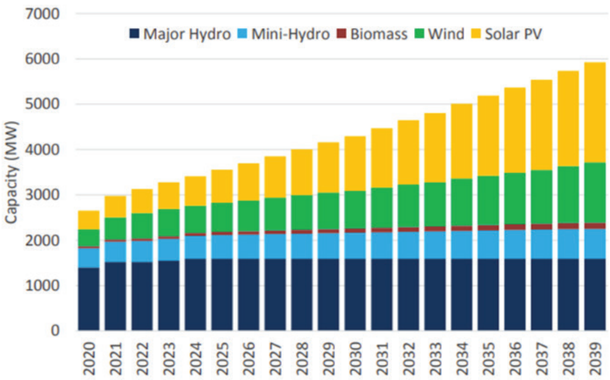

Fig. 2. Anticipated capacity of Other Renewable Sources over time in Sri Lanka

II. AEP AND LCOE ESTIMATES

A. Method

AEP of wind energy is commonly estimated from the probability of wind speeds at the site and the power curve of the chosen wind turbine for the project. To determine the frequency distribution of the observed wind speed, the Weibull distribution has been consistently used to represent the wind speed distributions as it conforms well to the mean wind speeds [6] and simplifies the AEP calculation without compromising its accuracy. The procedure for estimating the energy production from wind data includes three steps: (1) Weibull distribution and parameter estimation, (2) gross AEP prediction accounting for the variation of air density with height, and (3) net energy yields estimation. A brief description of each step is presented below.

1. The probability density function of the Weibull distribution for measured wind data is given by Eq. (1)

$$f(v_i;\eta,\beta) = \frac{\beta}{\eta}\left(\frac{v_i}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{v_i}{\eta}\right)^{\beta-1}\right], v_i > 0 \qquad (1)$$

where v_i in this study is the 1-minute mean wind speed at i^{th} minute in an hour, and η and β are, respectively, the shape and scale parameters of the distribution, which are determined by the maximum likelihood method.

2. To consider the impact of actual air density on the power curve, gross AEP is calculated using the varied air density at different heights, as indicated in Eq (2-3)

$$AEP_{gross} = \frac{\rho_i}{\rho_0}\sum_{d=1}^{day}\left[\sum_{h=1}^{24}\left(\frac{\sum_{i=1}^{n} P(v_i)p(v_i)}{n}\right) * 60\right] \qquad (2)$$

where ρ_0 is the air density at standard weather conditions and is assumed to be 1.225 kg/m^3, and ρ_i is the adjusted air density at i^{th} minute in an hour, accounting for the relative humidity at the desired heights. $P(v_i)$ is the power output for a given wind speed v_i at the standard weather conditions, $p(v_i)$ is the probability of wind speed v_i estimated from Weibull distribution using Eq. (1), and n is the number of wind speed data points available for each hour after filtering out any missing data.

3. Net energy yields are estimated to account for the technical losses from the turbine and are given by Eq. (3-4)

$$AEP_{net} = AEP_{gross} \times technical\ losses \qquad (3)$$

$$Net\ capacity\ factor = \frac{AEP_{net}}{turbine\ capacity * 8760} * 100\% \qquad (4)$$

In Eq. 3, technical losses, including 15% of production losses and 2% of turbine availability losses, are taken as those recommended in an NREL study [4]. Turbine capacity is the rated power output of the considered wind turbine while the net capacity factor is a ratio of a turbine's AEP_{net} estimated from the wind data to the maximum amount it could produce without any interruption, which indicates whether the turbine is sited at a good wind location with an appropriate hub height. Given the assumed technical losses, the AEP and capacity factor

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reported in the remainder of the paper represent the net energy yields.

4. LCOE includes the upfront installed capital cost (ICC) in the initial construction phase and the fixed operation & maintenance (O&M) cost over the lifespan of wind turbines. The LCOE is commonly estimated as follows:

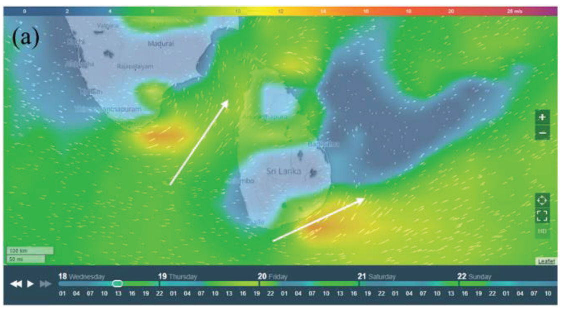
$$LCOE = \frac{ICC \times FCR + O\&M\ Cost}{AEP_{net}} \qquad (1)$$

where FCR is the fixed charged rate reflecting the cost of the debt and equity, and AEP_{net} is the net AEP estimates obtained from Eq. (3). It is noted that wind turbines are commonly designed to operate for 20 years, and thus the cost factors in the following LCOE estimation are based on this assumption.

III. Wind Energy Potential at Elevated Hub Heights in Sri Lanka

A. *Wind speed in Sri Lanka*

Wind resources in Sri Lanka show high correlations with two prominent wind flows that are influenced by seasonal monsoons. Previous wind measurements and weather simulation data [7] illustrate that in rainy seasons (i.e., May to September), Sri Lanka often experiences southwest to west monsoon, whereas northeast to east monsoon occurs during the dry season (i.e., November to March), as shown in Fig. 3. These two dominated monsoons lead to high wind speed on the north coast, as well as the northwestern and southeastern coasts. In addition, the central highland area shows increased wind speed with an increase in elevation. As shown in Fig. 4, the aforementioned coastal areas experience an average wind speed of nearly 7 m/s at 100 m, while a higher average speed of 8 m/s at 100 m is expected in the central highland areas.



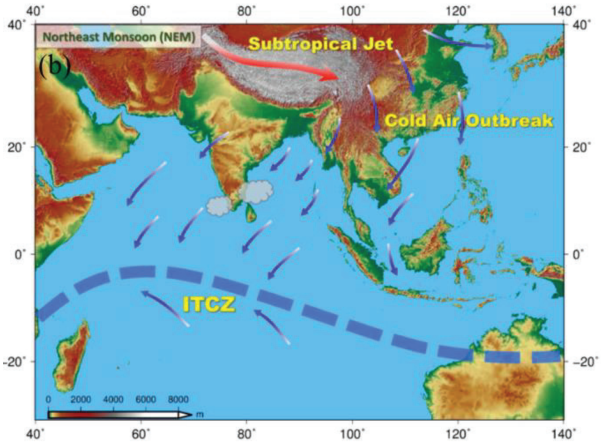


Fig. 3. Seasonal monsoons in the (a) rainy and (b) dry seasons in Sri Lanka [7]

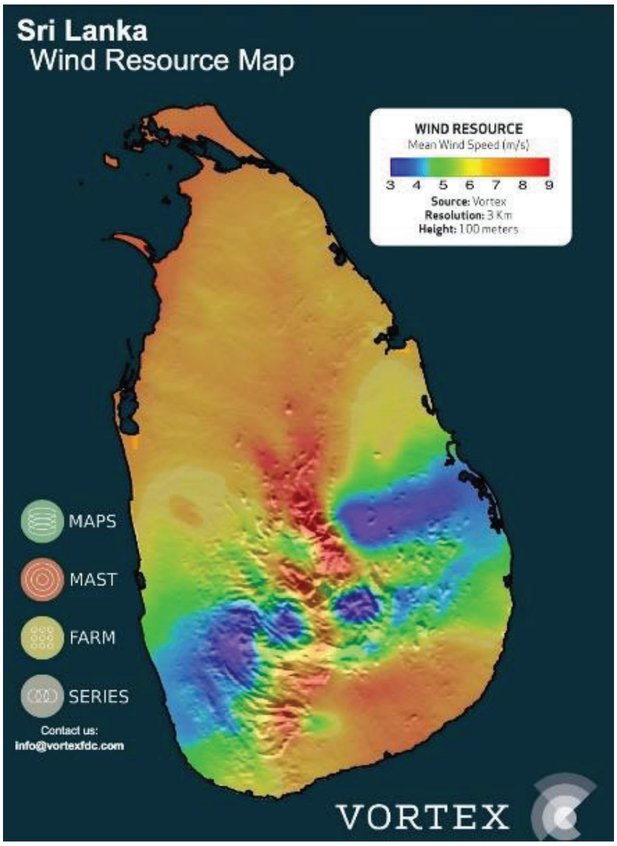


Fig. 4. Wind resources at 100 m in Sri Lanka [8]

B. *Land-based wind energy potential*

As discussed in the previous section, northern Sri Lanka exhibits excellent wind resources with an average wind speed of over 7 m/s at a 100 m elevation. A more refined study completed by NREL [9] evaluated five different regions in the country, naming Southeast Coast, Kalpitiya Peninsula, Mannar Island, Jaffna, and the National

Livestock Board cattle farm near Ambewela, to determine the potential for cost-effective land-based wind power development. Based on the available wind resource observations, proximity to transmission connection, terrain, community acceptance, land cost, site soil and environmental conditions, the Kalpitiya Peninsula on the west coast and Mannar Island and Jaffna on the north were identified as the promising sites for new wind power generation. As shown in Fig. 5, wind power production with a net capacity factor of 35% at these sites was estimated to be possible even at a lower hub height of 50 m [10]. To evaluate the wind energy potential in Sri Lanka, Fig. 5 compares the average net capacity factor results for the Southeast region, Northwest Island region, and Central Highland obtained from the NREL study [10] with those estimated for a chosen site in Iowa, US. A 2.32 MW turbine was used to represent the utility-scale wind turbine and predict the net capacity factors shown in this figure. Iowa estimates were used to compare the net capacity factors for the similar wind speeds presented in Sri Lanka. It is shown that wind turbines in Central Highland can harvest energy at a higher efficiency than the other two regions in Sri Lanka. While these capacity factors are lower than those shown for the Iowa sites, achieving a net capacity factor of 35% will lead to competitive LCOE. The Northwest region in Sri Lanka is considered to be a wind-pronounced region since it can provide a net capacity factor of 40% at a hub height of 100 m and above.

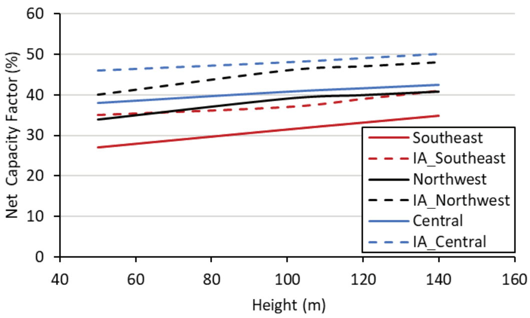
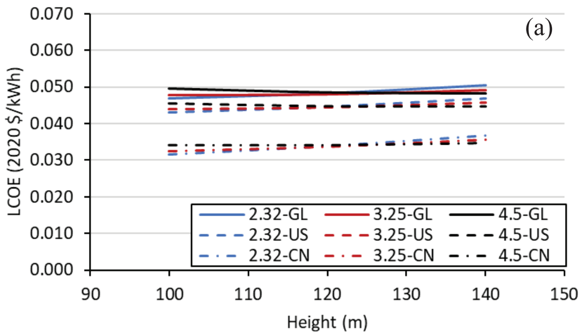


Fig. 5. Net capacity factor comparison between sites in Sri Lanka and Iowa, US

As the electricity load is expected to grow 6-7% annually, the wind power potential identified in the west and north regions will help meet the generation growth [10]. Southeast regions, although showing comparable wind resources, have multiple reserved lands that need to be excluded from wind energy development. This can lead to more detailed environmental investigations.

C. *LCOE estimation*

Based on the prior production potentials predicted at the selected regions, LCOE was estimated for three turbine sizes, i.e., 2.32 MW, 3.25 MW, and 4.5 MW, representing today and future turbine technologies. Preliminary cost components in the LCOE equation (5) were obtained from available sources reflecting the cost differences of using wind turbines from manufacturers in the US, China (CN), as well as average global pricing (GL). Northwest, Central Highland, and Southeast regions were evaluated for expected LCOE as a function of hub height and turbine technology, as demonstrated in Fig. 6. It is shown that the US turbine manufacturers and global average pricing would deliver comparable LCOE estimates, while US turbines show slightly lower costs. By increasing the hub height to the range of 100-120 m and combining with turbines from China, LCOEs can be reduced to a minimum of \$ 30/MWh. Wind projects in the Southeast region of the country would lead to higher LCOEs compared to those in the other regions due to environmental permitting-related challenges. Since wind resource data in the Central Highland highly rely on the terrain, it is expected that the Northwest region will show the most promising economic benefits of deploying tall wind towers with optimal hub heights.



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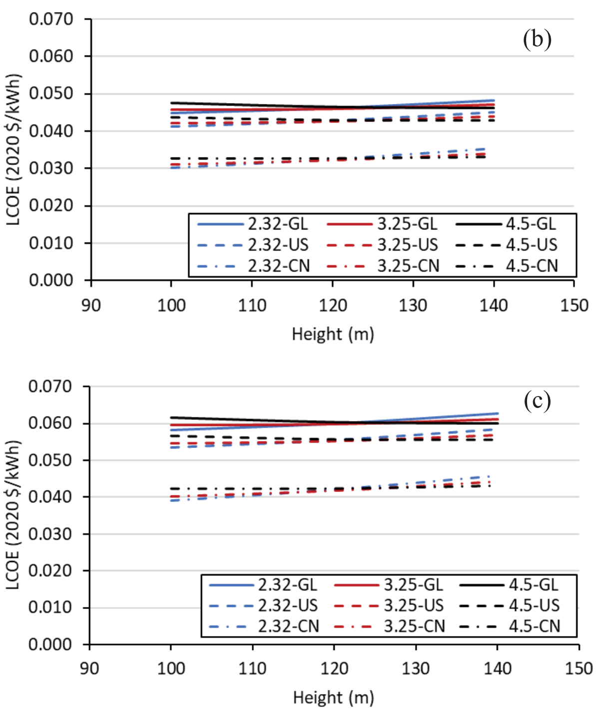

Fig. 6. LCOE estimates for different hub heights in the (a) Northwest, (b) Central Highland, and (c) Southeast of Sri Lanka

IV. Conclusions

Wind resources in Sri Lanka illustrate a substantial potential for land-based wind energy production. Based on the historical wind resource analysis and site feasibility studies, multiple regions in the country can produce wind power at the utility scale. From an investigation summarized in the paper, the following conclusions can be drawn.

- By increasing the hub height above 100 m, high capacity factors and low LCOEs can be achieved for potential wind farms in multiple regions in Sri Lanka.
- Elevating the hub height to 100-120 m can help increase the net capacity factor to 40%, reducing the LCOE to as low as $ 30/MWh.
- The Northwest region shows the most promising economic benefits of deploying tall wind towers because of favorable wind resources and minimal environmental concerns.

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