Chapter

Low Specific Power Wind Turbines for Reduced Levelized Cost of Energy

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Abstract

Wind turbines with Low Specific Power (LSP) are envisaged as one of the modern-day manifestations to reduce the variability in wind generation, lower the cost of energy, increase the penetration to larger areas and better utilize the transmission system. In this regard, this chapter analyzes the characteristics of a LSP turbine synthesized close to a target Specific Power of 100 W/m^2 (LSP-105) based on ground-based measurements at varying site conditions representing various IEC wind classes. The overall analysis suggests that, under reasonable scenarios, low-specific power turbines could play a significant role in the future wind energy fleet, with their impact being particularly noticeable in low wind areas of the world. The analysis reveals that LSP turbines would provide a higher capacity utilization factor (CUF), even in low wind sites, and may reduce the Levelized Cost of Energy (LCOE) to an extent of 60%. On the other hand, the grid utilization pattern is found to be improving with LSP wind turbines in the medium and high wind sites. The results further suggest that reducing the cut-off wind speed could be one of the successful strategies to optimize the cost of LSP turbine in low wind sites.

Keywords: capacity utilization factor, grid utilization, LCOE, power curve, specific power, wind class, wind turbine

1. Introduction

Although renewable energy is now a considerable element of our energy mix [1], it is predicted that it will play an even greater role in the future transition toward clean energy and sustainable power supply. Wind and solar power, two of the most important sources of the clean energy transition, suffer from intermittency and variability, which, if not addressed, could slow the pace of the climate-neutral transition and raise total energy system costs [2]. Furthermore, with increasing penetration, the variability will increase the portion of underutilized grid infrastructure, necessitating the need for grid flexibility and ancillary support. From the standpoint of market value, this may also result in lower marginal costs, which will have an impact on the project's economics [3]. During high wind periods, the marginal value of wind is expected to reduce due to the higher amount of wind energy flowing into the grid [4], and during low wind hours, the generation tends to be low to meet the demand.

In general, considering different wind regimes, wind turbines are designed to withstand a class of wind speeds as specified by International Electro-technical Commission (IEC). IEC Class I is for the high windy sites, those with an annual average wind speed of 10 m/s. Class II is designed for locations with an average wind speed of 8.5 meters per second at hub height. Class III is for even lower windy sites, with an average wind speed of no more than 7.5 m/s. Class IV was also described in older IEC Standards, which is for very low-wind sites with an average wind speed of 6 m/s, but it has been superseded by Class S. This Special class "S" turbines are with design values chosen by the designer based on site-specific conditions. It is worth noting that while the majority of class I and class II wind sites are exhausted and presently large areas suitable for class III and IV are available for development. Due to their extremely low CUF and higher LCOE, wind turbines now available in the market are uneconomical to operate in class III and IV locations. With LCOE being the prominent factor in deciding the share of the renewable mix, solar PV generation has surpassed wind generation in many countries. When these considerations are taken into account, the solution that is foreseen is the design of wind turbines with low specific power (LSP) in order to increase the deployment of wind power with reduced variability, lower LCOE, and suitability for low wind sites.

Modern-day wind turbines, especially the dominant, three-bladed, upwind turbine configuration, have undergone significant design improvements toward increased energy generation and reduced cost of energy [5]. Wind turbines have also become physically larger in several dimensions, including rotor diameter, hub height, and nameplate/rated capacity. Wind turbine design has also become tailor-made to the market environment in which the technology is going to be deployed, based on wind regimes, grid access, etc., and low specific power (LSP) turbines are considered as one of such manifestations.

As swept area increases with the square of blade length, increasing the blade length of a turbine will increase the power extraction and, with fixed generator capacity (rated power), reduce the Specific Power (SP) rating of the turbine. On the other hand, theoretically, decreasing the generator capacity while maintaining a constant swept area will also result in the desired designed specific power.

Reduced Specific Power turbines provide a number of advantages that have resulted in their widespread use in several wind markets, including India, China, and the United States, among others. Due to the larger size of the rotor, more energy can be captured when the wind moves past the blades of the wind turbine. Hence, for a given turbine generator capacity, the generator runs closer to or at its rated capacity for an increased percentage of the time duration in such reduced specific power wind turbine.

Hence, reduced specific power wind turbines naturally result in higher energy generation for their installed capacity, resulting in a higher capacity utilization factor (CUF). With the highly sophisticated control systems of modern wind turbines, this higher capacity utilization factor can often be achieved with a relatively limited impact on the overall turbine cost. In such cases, LSP wind turbines provide a direct path toward a lower levelized cost of energy (LCOE) by providing a higher generation per investment.

Further, as reduced specific power turbines have lower-rated wind speeds, resulting in evenly distributed power production over a wide range of wind speeds, the variability of wind generation is well mitigated with such turbines. With significant penetration of RE generation into the grid, such variability management will be extremely beneficial to grid managers, and the overall energy mix can be well managed with reduced storage requirements.

Further, the energy generation profiles resulting from reduced specific power turbines have also been found to increase the wholesale market value of wind energy [6]. Turbines with reduced specific power and taller towers can be conceptually correlated with higher electricity prices in some markets by producing less during high wind hours and producing more during low wind hours [7, 8].

With such a background, this chapter analyses the LSP turbine synthesized for a target SP of close to 100 W/m^2 (for the study, a wind turbine with 105 W/m^2 is considered). Based on ground-based measurements, these LSP wind turbines are compared with other prevalent wind turbines in the Indian market with a view toward evaluating the opportunities to continue the specific power reduction in the future.

This chapter analyses the improvement in %CUF with these turbines for the IEC site classifications (i.e., high wind, medium wind, low wind, and also one of the coastal site conditions) and induces thoughts on how grid utilization will be influenced by the low-specific power turbine compared to the present-day wind turbines. In order to reduce the cost of wind turbines, the chapter further analyses the opportunity of reducing the cost of wind turbines by reducing cut-off wind speeds (varying cut-off wind speeds to 20 m/s, 18 m/s, 15 m/s, and 13 m/s) in LSP turbines as it allows the turbine blades to be lighter [9].

This chapter is expected to be useful to various stakeholders in the sector by encouraging further research in this area, as LSP wind turbines are expected to play a vital role in the wind generation fleet going forward, particularly as wind penetration increases in lower wind speed regions.

2. Low specific power (LSP) wind turbine

This section explains the key properties of the LSP wind turbine, as well as the characteristics of other wind turbine types currently on the market, in greater detail. The influence of the CUF on different sites with the wind turbines under consideration is also investigated.

2.1 Wind turbine characteristics

The study covers available wind turbines with specific power (SP) ranging from 379 W/m^2 to 173 W/m^2, which represent multi-MW scale turbine types prevalently installed in the Indian Market. These wind turbine types considered in this study, when correlated with its period of deployment, clearly show that there is a definite, reduced specific power trend in India, the United States, China, and Brazil. However, this stands in contrast to most of the European market, where the average specific power is found to be high, although it is difficult to generalize.

Turbine name (units)	Rated power (kW)	Rotor diameter (m)	Specific power (W/m^2)
SP-379	2000	82	379
SP-345	2100	88	345
SP-295	2000	93	295
SP-271	2000	97	271
SP-245	3000	125	245
SP-210	3465	145	210
SP-200	2000	113	200
SP-180	2100	122	180
SP-173	3300	156	173

Table 1.
Wind turbine models considered in this study.

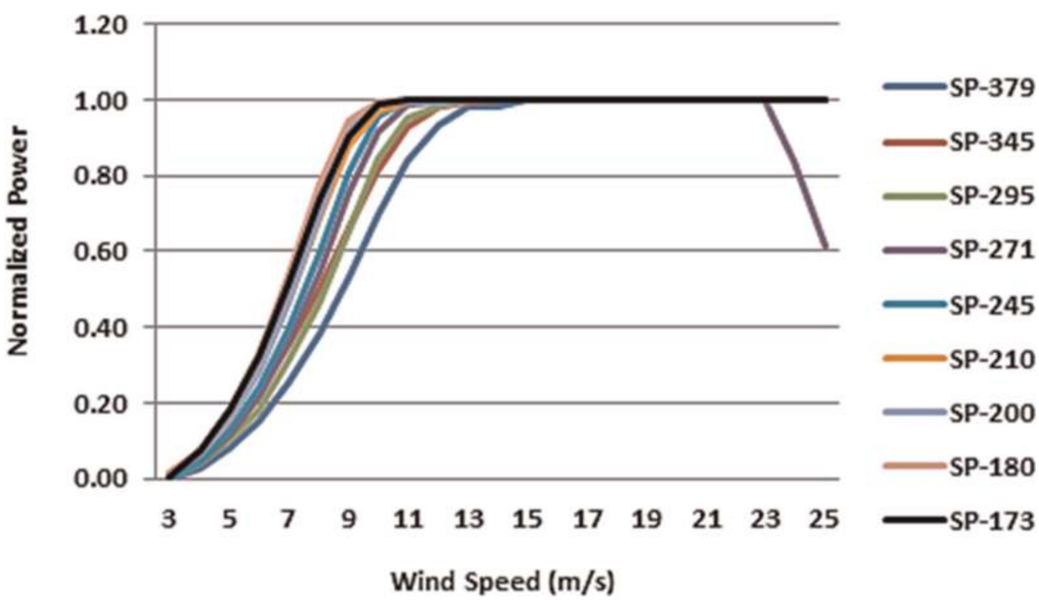

Figure 1.
Power curves considered for the study.

Table 1 shows the wind turbines considered in the comparison study against the LSP wind turbine model. The respective power curves (normalized) are shown in **Figure 1**. It is clearly evident from **Figure 1** that the power curve moves toward the left and is able to generate more energy at lower wind speeds, while the specific power is decreasing. To eliminate the influence of hub height variation in the comparison study, all wind turbines in the study are considered with the same hub height of 120 m.

2.2 Power curve of LSP wind turbine

The power curve of the LSP wind turbine is derived/synthesized in a unique way from one of the latest wind turbine models (SP-173) in the Indian market, not by increasing the blade length, but by reducing the generator capacity and keeping

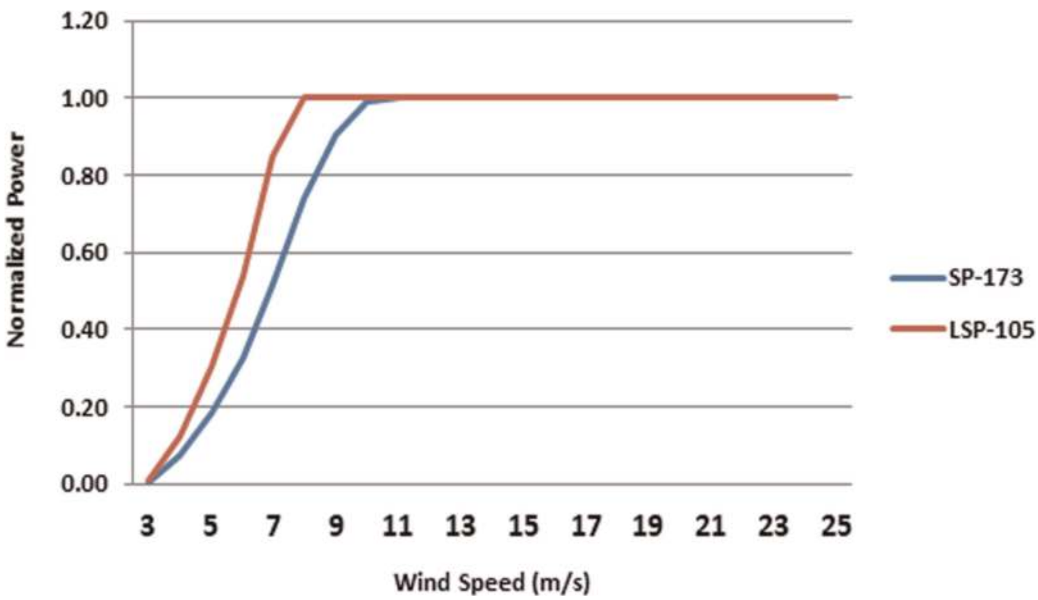

Figure 2.
Comparison of SP-173 and LSP-105. (derived from SP-173 by reducing the rated capacity to 2000 kW instead of 3300 kW).

the blade length constant. Considering the logistical and transportation-related constraints imposed by the longer blades [10], especially in complex terrain conditions, such a reverse approach seems to be justifiable. **Figure 2** shows the normalized power curves of SP-173 and LSP-105 (derived from SP-173 by reducing the rated capacity to 2000 kW from 3300 kW).

2.3 Wind sites

In order to understand the impact of Low Specific Power wind turbines on varying wind climate, four different wind sites have been chosen for the study. The sites have been chosen to represent high (High W), medium (Med W), low (Low W), and low-coastal wind (Low coast W) regimes, considering the future wind farm development possibilities. The sites are defined by 120 m hub height wind speed data derived from one continuous year of met. Mast-based standard measurement. **Table 2** depicts the site details, wherein **Figure 3** shows the wind speed distribution of the said four sites as below:

Site name (units)	Average wind speed @ 120 m (m/s)	Weibull "A" (m/s)	Weibull "k"
High W	10.4	11.69	2.29
Med W	8.5	9.60	2.62
Low W	6.9	7.80	2.66
Low coast W	6.3	7.02	2.82

Table 2.
Details of sites considered for the analysis.

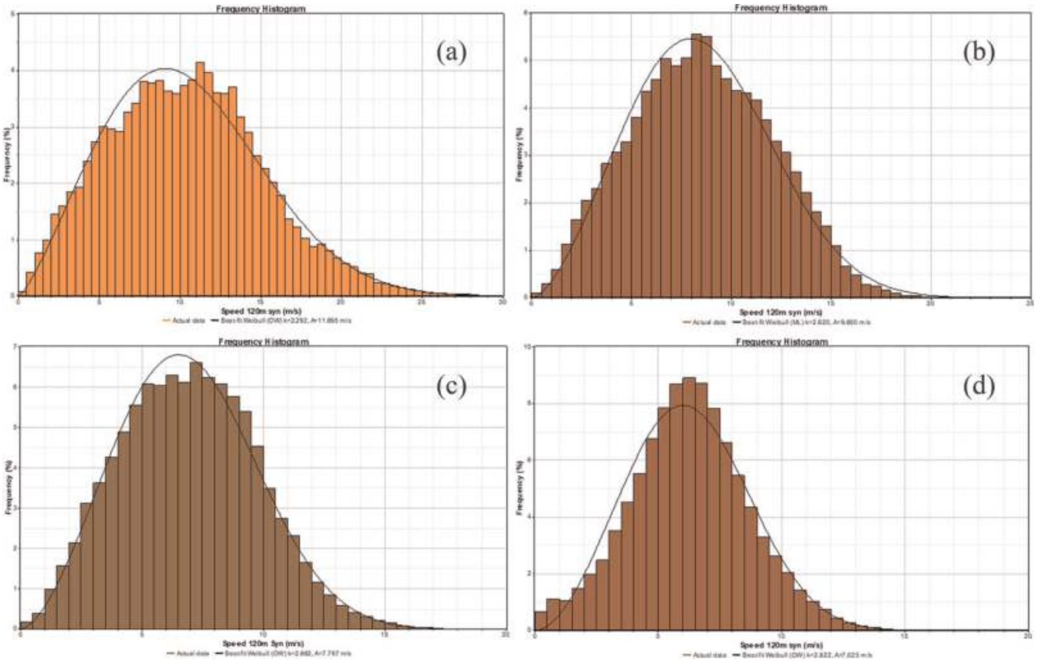

Figure 3.
Wind speed distribution of the sites considered in the study. (a) Represents the histogram of high W site, wherein (b), (c), and (d) represents the histograms for med W, low W and low coast W sites.

2.4 Comparative analysis

The generation for the entire year is estimated for each of the considered wind sites and wind turbines using the latest tools and % CUF are plotted in **Figure 4**. The trend seems instructive and shows the industry's ability to achieve higher capacity

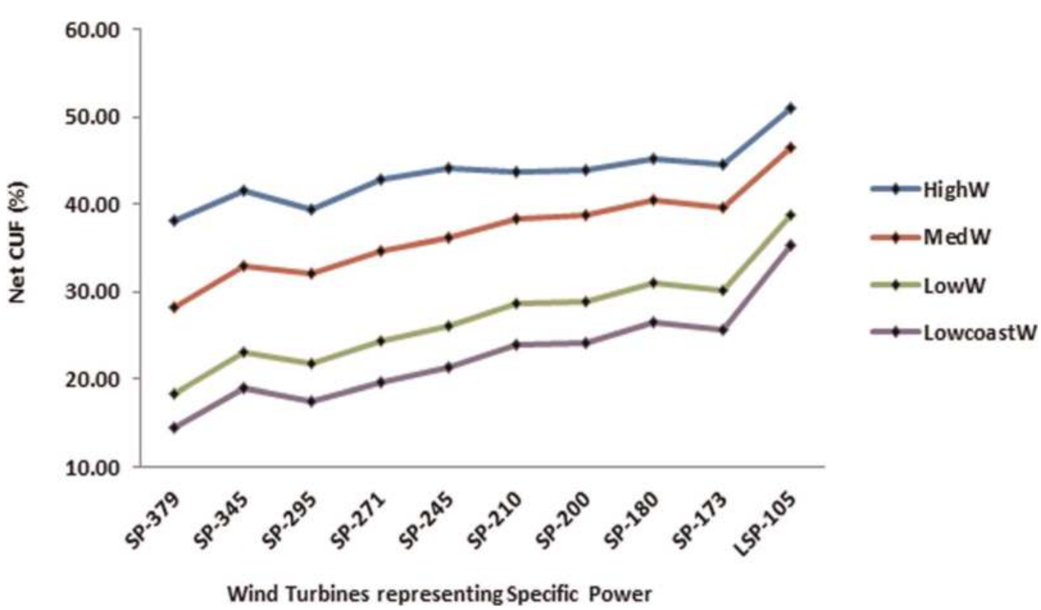

Figure 4.
Turbines representing specific power vs. net capacity utilization factor (%).

utilization factors by lowering the Specific Power of the turbines in the low and medium wind sites. Although the %CUF varies with respect to the wind potential, as obvious, there is a strong positive correlation found between the reductions in Specific Power with the increase in Capacity Utilization Factor (%) estimations. However, the increase in generation in the high wind sites is considerably lower (in the order of around 30%) compared to low wind sites (an increase of 110–145%). Moreover, the futuristic Low Specific Power wind turbine (LSP-105) simulated in the study is expected to produce appreciable generation in low wind sites resulting in lower LCOE. This is an encouraging phenomenon in particular for a situation when the wind penetration is increasing into the lower wind-speed regions.

Hence, it is evident that reducing Specific Power is undoubtedly enhancing the % CUF in all type of site conditions considered in this study, but highly significant in low wind sites. Of course, a higher capacity utilization factor is a mid-point, and it is not necessary that such wind turbine will have the economic superiority, as there is a cost to achieve it – a larger rotor assembly needs to be built and maintained for a given wind turbine capacity. As it is a trade-off between the increment in %CUF (indirectly, Energy yield) and cost for maintaining the larger rotor assembly, Levelized Cost of Energy (LCOE) may be the better metric to understand the realistic benefits (in terms of revenue) achieved from reducing Specific Power.

Interestingly, till date, the industry is able to maintain in such a way that the cost increment toward reducing Specific Power has not been enough to outweigh the LCOE benefit derived from the corresponding increase in generation. The empirical data from the United States shows that the historical trend toward reduced Specific Power turbines in the United States produces a trend with higher capacity factors and lowers LCOE [11].

In order to understand such trade-offs between cost and generation in the reducing specific power scenario, at varying wind regimes, LCOE was computed with respective cost and capacity factor differentials. The model inputs align with the traditional scaling theory - lower SP turbines will have a higher initial cost. For the financial estimation, standardized terms and numbers were assumed, which include, Debt: Equity of 70:30, Interest rate of 8%, Return on Equity (RoE) of 12% with the lifetime of the plant as 25 years. With regard to O&M expense, the same was assumed to be 1.5% of Capital Expense (CAPEX) with 3.84% escalation every year.

Figure 5 present the LCOE trend with the wind turbines with different SP for varying wind regimes. It is clearly evident from **Figure 5** that LCOE trend seems to be marginal variation for High and Medium wind sites but a definite LCOE reduction is seen in Low wind sites with the lower SP wind turbines. In case of the Low coast W site, the LCOE shows almost a 60% reduction with the LSP-105 wind turbine. It is noted that the trend shown is portrayed under the *traditional scenario* aligning with the scaling theory (lower SP turbines will have higher initial cost). In case, a *favorable lower SP scenario* is assumed, wherein cost/MW of both higher SP and lower SP turbines are same, then LCOE reduction in High and Medium wind sites may also be assured with reduced SP. We cannot ignore such *favorable lower SP scenarios* as Low SP turbines, being the present trend and gaining more market share, can have reduced cost through supply chain optimization and increased purchase volume [11].

In addition to the %CUF and LCOE, when looking into the market value of wind also, research results reveal that LSP turbines appear to be advantageous and generally provide greater wholesale market value than higher Specific Power turbines by

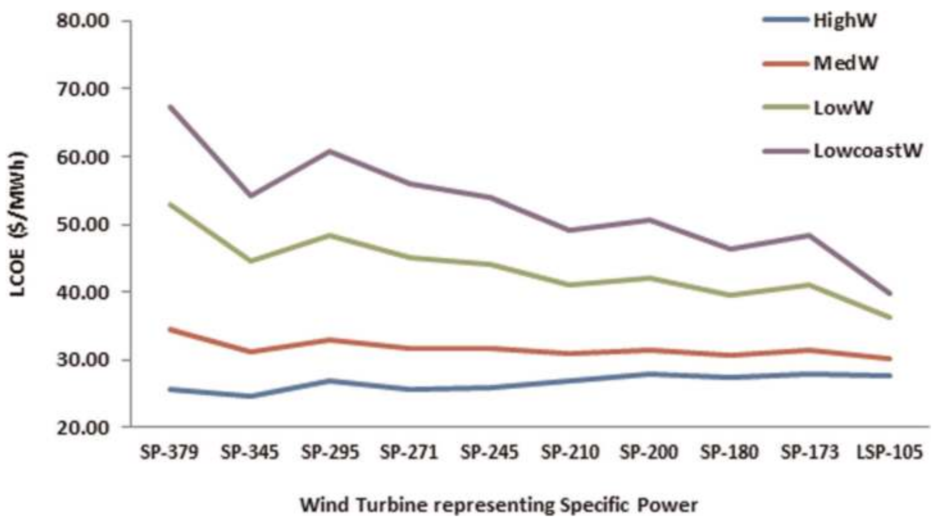

Figure 5.
LCOE trend with respect to specific power for different wind conditions.

shifting generation to lower wind hours. Recent European research [7, 12, 13] suggests that, in the future, the enhancement in market value provided by LSP turbines could become an increasingly significant selling point, presuming that wind penetration continues to increase.

3. Impact of low specific power wind turbine on grid infrastructure

One of the major problems of having high wind penetration in the grid is higher variability. On the one hand, this will call for under-utilized grid infrastructure (during low wind times). On the other hand, it will necessitate more grid flexibility and ancillary services/storage to compensate for the fluctuation. With more wind penetration into the grid expected in the future, it will be interesting to see how a LSP wind turbine will impact grid utilization versus conventional wind turbines. One such analysis is carried out and is represented in **Figure 6**. The hourly power production from all the wind turbines considered in the study is plotted against the number of hours (in percentage). For the purpose of comparison, all the turbines are normalized to 1000 kW. **Figure 6** clearly depicts that the grid utilization pattern generally increases with decreasing specific power. In particular, the futuristic LSP-105 is expected to utilize the allotted grid capacity (by generating at rated power) for a significantly longer time. At the high wind site, it is expected that the LSP-105 can generate at rated capacity for more than 50% of the time, even after accounting for the realistic loss factors. Despite the fact that the percentage time decreases with respect to medium and low wind sites, as shown in **Figure 6b** and **d**, we can see an improvement in grid utilization with lower specific power in all sites, with an outstanding performance from LSP-105.

With LSP turbines having higher capacity utilization factors, which lead to more consistent energy generation, the need for grid flexibility is expected to be less with a reduction in ancillary support. The European energy modeling study [9] justifies the same as the share of low Specific Power technology is seen to be higher in places where transmission constraints prevail. The study further emphasizes the

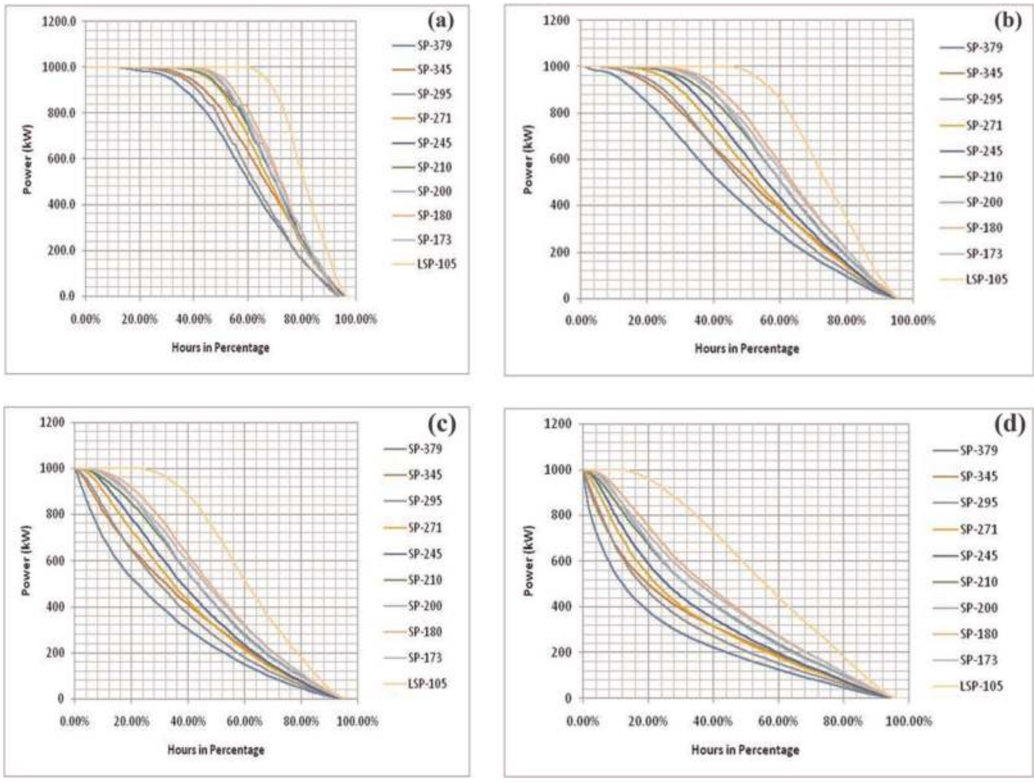

Figure 6.
Graphs to depict grid utilization pattern at high (a), medium (b), low (c) and low-coastal (d) sites.

introduction of low Specific Power technology into the Northern European energy system leads to a decrease in transmission investment, solar PV investment, and offshore wind investment.

4. LSP wind turbine with reduced cut-off wind speed

The square-cube law states when the diameter of a wind turbine's rotor increases, theoretical energy output increases by the square of the rotor diameter, but the volume and mass of material required to scale the rotor increases as the cube of the rotor diameter [14]. As on date, the wind industry has been able to maintain the scaling process economically by streamlining its processes, operations, material selection, etc. [15, 16]. Consequently, at some size, the cost of a LSP turbine may increase faster than the resulting energy output, making the further reduction of Specific Power uneconomical [17]. In such a scenario, reducing the cut-off wind speed of the wind turbine may be an area for consideration to reduce the cost. This low cut-off wind speed is particularly important since it does not need to be able to operate during high wind conditions leading to lighter turbine blades and reduced overall cost.

A recent European study used such unique LSP feature/Wind technology combining lower Specific Power (100 W/m^2) and low cut-off wind speed of 13 m/s [18] and the impact that both of these specifications has been found significant [9], wherein the comparative study reveals that the reduction of cut-off wind speed from 25 m/s to 13 m/s could have a blade mass that is up to 33% lighter than a conventional turbine of the same rotor diameter and that could lead to cost reduction. Furthermore, the mass of the blades is likely to have an impact on the cost of the rest of the turbine, meaning there could be savings in other parts such as nacelle, tower, and foundation as well.

Inspired by European studies [9, 18], a wide range of cut-off wind speeds were analyzed. The change in energy generation possibility at different wind sites is evaluated by reducing the cut-off wind speed of our Low Specific Power wind turbine (LSP-105) from 25 m/s to 20 m/s (LSP-105-20), 18 m/s (LSP-105-18), 15 m/s (LSP-105-15) and 13 m/s (LSP-105-13) as shown in **Table 3**. It can be seen from **Figure 7** that energy generation reduces on different scales, with respect to the wind sites, as cut-off wind speed reduces. It is seen that, in the low wind regions (Low W & Low coast W), the reduction in the generation is found to be very minimal and even the LSP-105-13 shows a similar generation profile compared to the LSP wind turbine with a 25 m/s cut off wind speed—a 2% reduction for the Low W site and a 0.6% reduction for the Low coast W site. This would have a major economic effect on the low wind sites, which have hitherto proved to be uneconomical.

It is noted that in the high and medium wind sites, it is not so economical to reduce the cut-off speed wherein there is a considerable reduction in generation (as

% Energy difference with respect to LSP-105 (25 m/s Cut-off wind speed)				
Sites	**LSP-105-20**	**LSP-105-18**	**LSP-105-15**	**LSP-105-13**
High W	3.58%	7.66%	19.65%	34.78%
Med W	0.01%	0.11%	2.56%	11.25%
Low W	0.00%	0.00%	0.22%	2.03%
Low coast W	0.00%	0.02%	0.12%	0.60%

Table 3.
Reduction in energy generation (%) while reducing the cut-off wind speed of the low SP wind turbine.

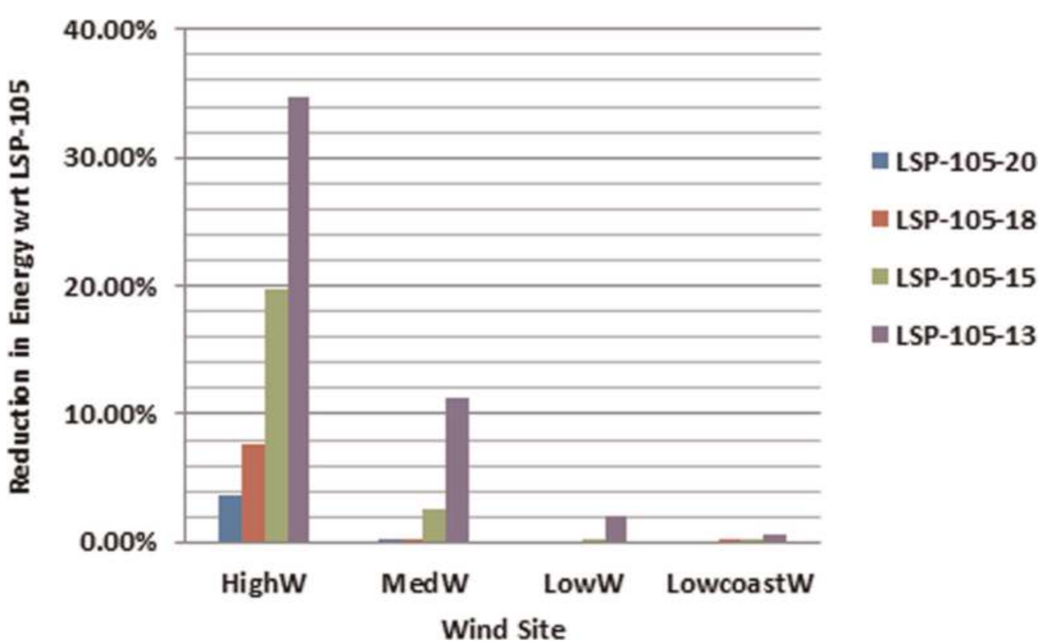

Figure 7.
Reduction in energy generation (%) while reducing the cut-off wind speed of the low SP wind turbine.

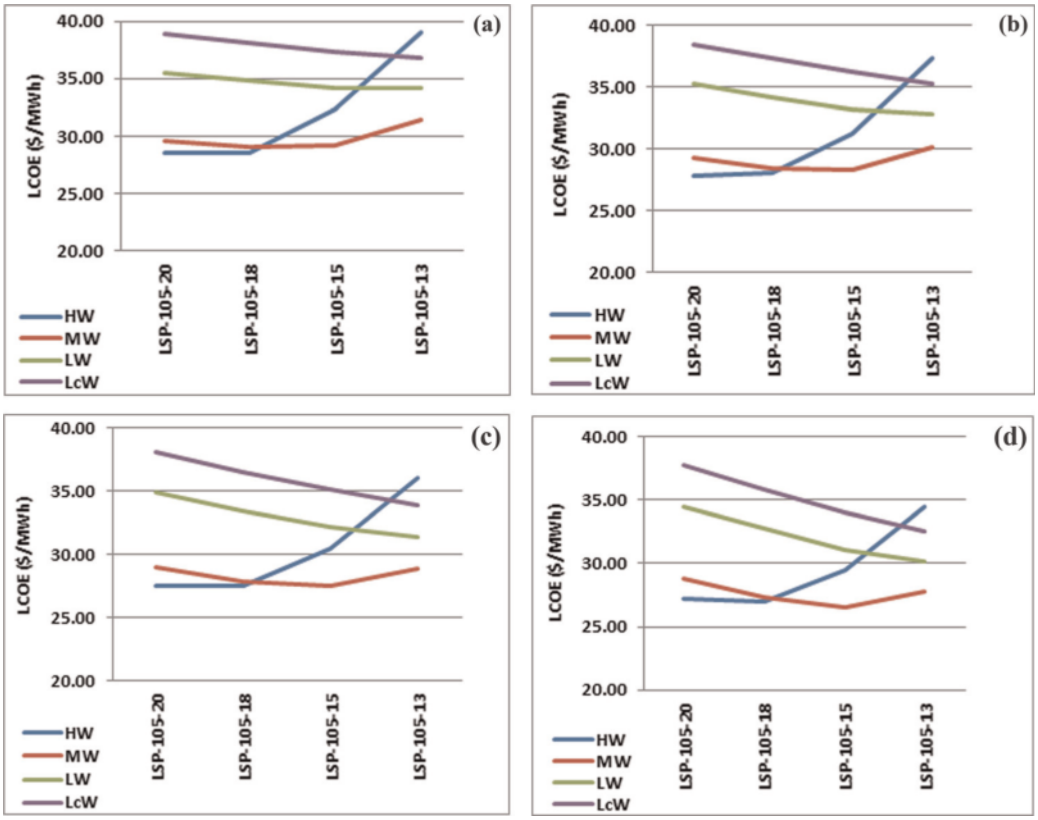

Figure 8.
LCOE sensitivity analysis for the reduction in cut-off wind speed of the low SP wind turbine – (a) shows 2% reduction in capital cost and (b), (c) and (d) shows 3%, 4% and 5% reduction respectively.

compared to a cut-off wind speed of 25 m/s, there is a reduction to the extent of 35% in terms of energy). The LCOE estimation also supports the said statement, as shown in **Figure 8**. The figure depicts a sensitivity analysis to understand the impact of reducing cut-off wind speed on LCOE, wherein the sensitivity analysis was carried out by reducing the capital cost of the LSP-105 by 2%, 3%, 4%, and 5% with respect to the reduction in cut-off wind speeds. Based on the graph, it is evident that even if the capital cost is categorically reduced to 5% for every cut-off wind speed reduction (viz., 20 m/s, 18 m/s, 15 m/s, and 13 m/s), the LCOE seems to be on an increasing trend in high and medium wind sites, mainly because of the anticipated energy loss at the higher wind speeds.

The results suggest that though reducing the cut-off wind speed will lead to significant energy loss in high wind sites and may impact the revenue and energy generation balance, in low wind sites it is economical to reduce cut-off wind speeds, as the expected reduction in blade mass and related savings will definitely outweigh the drop in energy generation. This is an encouraging takeaway in the present scenario and may lead to a conducive environment for more wind penetration into low wind sites.

5. Conclusion

The design of modern wind turbines has seen major changes over the course of history. For example, one of the most noticeable manifestations is the steady decline in the specific power of wind turbines over time. With an eye toward analyzing the prospects of further specific power reduction in the future, this chapter discusses the technological advantages provided by the low specific power (SP) turbine synthesized close to a target SP of 100 W/m^2, which was determined by ground-based measurements.

In accordance with the findings, low-specific power wind turbines can improve the capacity utilization factor, lower the cost of electricity, increase the value of wind, and better utilize the transmission system in all wind circumstances, albeit varying degrees. However, while the continuation of this trend toward lower specific power may not be sustainable, this analysis suggests that, under reasonable scenarios, low-specific power turbines could play a significant role in the future wind energy fleet, with their impact being particularly noticeable in low-wind areas of the world. Research into this area is predicted to be critical in the future, particularly in medium-to-low wind regimes, as these LSP wind turbines may be useful in identifying new potential sites and facilitating increased wind penetration into the grid.

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Appendix A: Basic definitions

A.1 Capacity utilization factor

Capacity Utilization Factor (CUF) is defined as the ratio of actual energy generation (kWh) to the maximum possible energy generation from a wind turbine/wind farm in a year.

$$\mathrm{CUF} = \frac{Actual\ Energy\ Generation}{Rated\ Capacity\ x\ 365\ x\ 24.} \tag{A.1.1}$$

CUF is a metric often used to evaluate the technical performance of a wind turbine/wind farm. It is a measure of "how well the plant is utilized".

A.2 Levelized Cost of Energy (LCOE)

Levelized Cost of Energy (LCOE) is the cost of generating electricity over its lifetime. It is an economic assessment and defines the minimum price at which energy must be sold for a project to break even.

A.3 Specific Power

Specific Power (SP) is defined as the ratio between the rated power of the turbine and its swept area [19], and is expressed in units of Watts per square meter (W/m^2) as shown below:

$$\text{Specific Power (SP)} = \frac{\text{Rated } Power}{\text{Swept Area}} \tag{A.3.1}$$

The specific power is required to be lower in order to extract more output from lower wind speeds. The following equation can explain the reason behind it by showing that power is proportional to the rotor area and wind speed [20].

$$P = \frac{1}{2}\rho A V^3 \tag{A.3.2}$$

Where, P–Power in the wind (W), ρ – Air Density (kg/m^3), A–Rotor swept area (m^2) and V–Wind Speed (m/s)

A.4 Wind class of a wind turbine

Wind class of a wind turbine helps to choose a suitable turbine for a particular site. The design of wind turbine and site conditions should complement each other for the successful operation of the wind turbine at the particular site, throughout its design life. As per the International Electro-technical Commission (IEC) standard IEC 61400-1, three wind classes (Class I, II & III) are categorized to represent high, medium, and low wind regimes. The classification is governed by the average annual wind speed (measured at the turbine's hub height), the speed of extreme gusts that could occur over 50 years, and how much turbulence is there at the wind site.

Generally, Class I turbines are designed to cope up with high average wind speeds in the range of 10 m/s. A Class II turbine is designed for windier sites up to 8.5 m/s average wind speed, whereas a Class III turbine is designed for a low wind site with the annual average wind speed up to 7.5 m/s. Each of the mentioned Wind Class further has subclasses to design turbines matching up with the wind turbulence at the site.

A.5 Power curve of wind turbine

Power curve of a wind turbine shows the relationship between the output power of the turbine and wind speed, provides a convenient way to model the performance of wind turbines. A typical power curve for a pitch regulated wind turbine is shown below (**Figure A1**):

A.6 Wind speed frequency distribution

Wind speed frequency distribution refers to the probability density function of wind speed and shows how well the wind speed values are distributed over the time period (maybe in a year).

The Weibull distribution is a two-parameter function (A & k) commonly used to fit the wind speed frequency distribution.

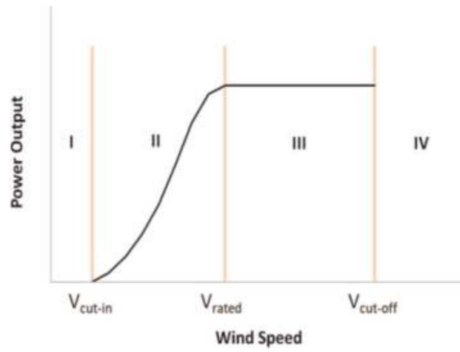

Figure A1.
Power curve of pitch-regulated blades.As shown in the figure, the power output in region-I is zero, as the wind speeds are less than the threshold minimum, known as the cut-in speed. In region-II, between the cut-in and the rated speed, the power production increases proportionally to the wind speed. In the region-III, a constant output (rated) is produced until the cut-off speed is attained through regulating the system. Beyond this speed (region IV) the turbine is shut down to protect its components from high winds; hence, it produces zero power in this region.

Weibull "A" (m/s) is known as the Weibull scale parameter; a measure for the characteristic wind speed of the distribution and it is proportional to the mean wind speed.

"k" is the Weibull shape parameter. It specifies the shape of a Weibull distribution and normally falls between 1 and 3. A small value for "k" signifies highly variable winds, while larger "k" describes relatively constant winds.

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