Sector informed analysis of small wind turbine power production

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ABSTRACT

This report presents a single-parameter study of four small wind turbines measured during a U.S. Department of Energy–funded field campaign. To reduce barriers to performance validation under International Electrotechnical Commission (IEC) standards, turbine power output was analyzed for obstructed and unobstructed wind directions to assess the influence of nearby obstacles. Power performance data, collected by IEC test engineers, were filtered to remove fault and icing events and processed using a calculation tool developed by the National Renewable Energy Laboratory. Turbine power performance, efficiency, and expected annual energy production were compared across configurations. Results showed no significant differences between obstructed and unobstructed sectors beyond the calculated uncertainty margins. These findings suggest that reforming IEC site assessment requirements could reduce test time and cost while slightly increasing levels of uncertainty.

I. INTRODUCTION

In efforts to address increasing global energy demand, small distributed wind turbines (small wind turbines) have grown more centralized in environments without alternative sources, such as remote farms and isolated communities.[1] Because of small wind turbine efficiency and rapid deployment times, small wind turbines can drastically reduce energy costs for customers seeking self sufficiency.[2] The International Electrotechnical Commission (IEC) functions as the governing body for small wind turbines, primarily to regulate measurement and safety standards.[3] More specifically, the IEC 61400-12 standard series ensures that wind turbine power performance is evaluated in a precise and standardized fashion, such that turbine performance and characteristics can be compared internationally, and across a range of test conditions.

To evaluate small wind turbines using the standard, a site assessment is required to survey the turbine test location to account for terrain and obstacles that may influence test results.[4] Terrain features and obstacles include buildings, other turbines and hills that induce leeward turbulent eddies and wind wake vortices—reducing the wind's kinetic energy that a small wind turbine can extract (as shown in Figure 1).

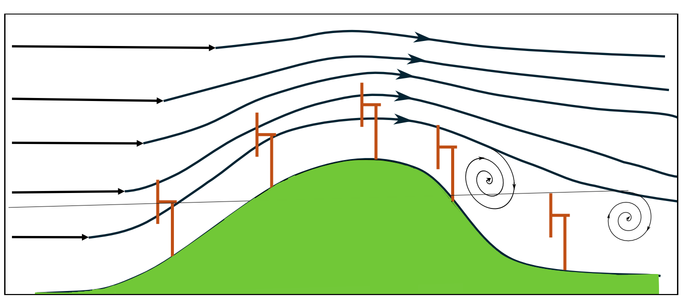


Figure 1: Friction between the air and the obstacle surface causes vortices to form, redirecting the velocity from the laminar direction

Wake effects on power production can be significant, with wind conditions and site layouts contributing up to 10% cost losses for wind farm operations.[5] The site assessment quantifies the effect obstacles have on power production, in addition to identifying wind directions that are relatively unobstructed to consider during testing. If wake effects are significant according to the standard, the test location must be calibrated—a lengthy process that takes smooth and turbulent measurements to perform flow corrections during testing.[6] However, for small turbines (defined by the IEC as turbines with a rotor-swept area less than $200\mathrm{m}^2$), the small blade size results in a consistent level of wind shear and loading across the small wind turbine swept area. Moreover, small wind turbines are most commonly deployed in low-height turbulent environments, where atmospheric mixing with the surface is most prevalent.[7] Thus, the conditions required for site assessments without calibrations is not necessarily representative of the conditions small wind turbines are deployed in.

To fulfill the DOE mission of reducing wind energy costs and market barriers, NREL has employees on the IEC committee charged with the creation and amendments to standards including the IEC 61400-12.[8] This year, there were proposed revisions to IEC 61400-12-1 Annex H (i.e. *Power performance testing of small wind turbines*), including a change to (or elimination of) the site assessment process. At the National Wind Technology Center (NWTC), NREL collected power performance data for a series of small wind turbines in a project from fiscal year 2008 to 2010. To inform the potential standard revision, power performance for each of the turbines was compared using unobstructed and obstructed wind data. The differences potentially quantified the role of wake turbulence on small wind turbines and examine the necessity of the site assessment process in different conditions.

II. METHODS AND MATERIALS

To conduct the obstacle analysis, the reports from the initial power performance tests were parsed to determine the scale of wake effect and wind directions that were unobstructed and used for testing. The excluded direction sectors were derived from:

$$D_e = \frac{2l_h L_w}{l_h + l_w} \tag{1}$$

Equation 1 then yields the criteria found in Table 1 and Figure 2, which classify turbulent effects as functions of both obstacle height and horizontal distance to the test turbine.

Distance*	**Sector****	**Max Obstacle Height from Terrain Surface*****
$< 2L$	360°	$< \frac{1}{3}(H - 0.5D)$
$\geq 2L$ and $< 4L$	Preliminary measurement sector	$< \frac{2}{3}(H - 0.5D)$
$\geq 8L$ and $< 16L$	Preliminary measurement sector	$< (H - 0.5D)$
$\geq 2L$ and $< 16L$	Outside preliminary measurement sector by $\geq 40°$	No Limit to Height

* From obstacle to wind turbine under test, or from obstacle to wind measurement equipment-where L is the horizontal distance between wind turbine under test and wind measurement equipment.
** "Preliminary measurement sector" is the valid sector which remains under evaluation of neighboring operating wind turbines, where all direction which are less than 40° outside shall also be considered.
*** H is the hub height and D is the rotor diameter of the wind turbine under test.

Table 1: Obstacle requirements for the site assessment

Thus, in order for close obstacles to be included in the test regardless of wind direction, they must be sufficiently small. For the small turbines considered in this report, that implies a height of less than four meters. Alternatively, farther obstacles in the included sector must be roughly less than 11 meters high. However, this analysis focused on data outside the preliminary sector, which may otherwise fail the assessment for height considerations. The obstacles of interest are the test data sheds, which are on the edge of the $< 2L$ height limit.

Additionally, when turbulence forms downwind of an obstacle, the mixing air spreads horizontally. The site assessment addresses this by ensuring that power performance is calculated only using wind directions in the defined "Preliminary sector," which is nestled in the "Undisturbed" region shown in Figure 2.

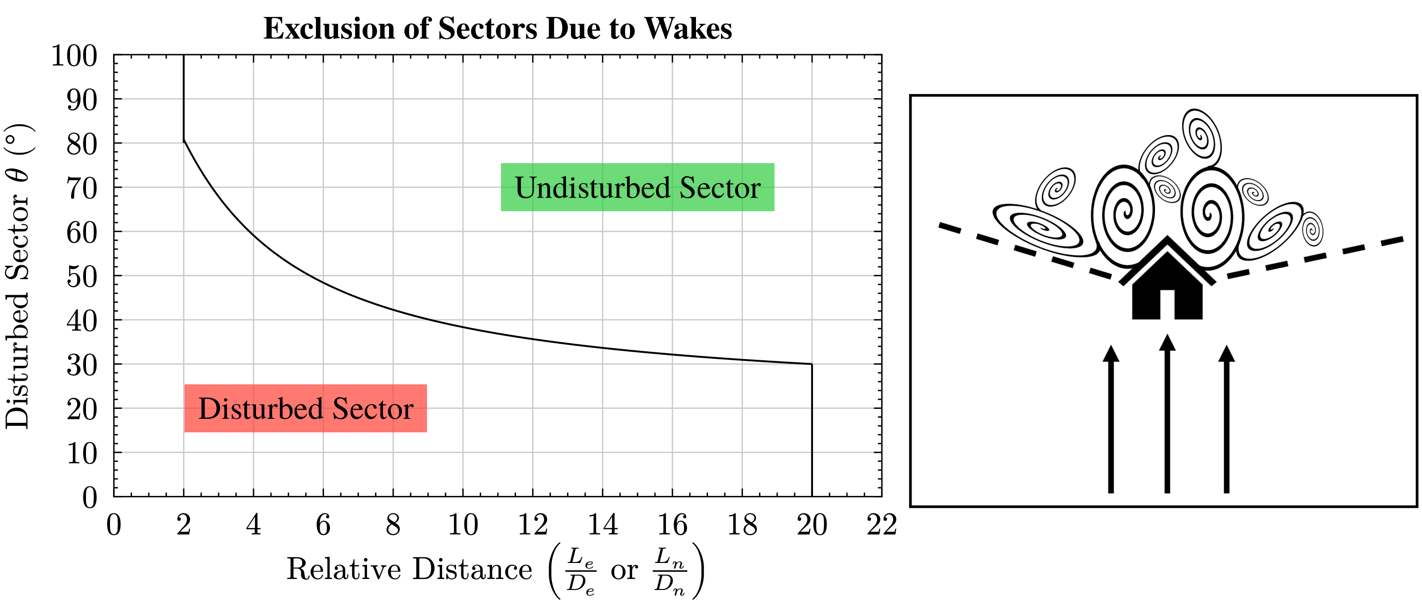


Figure 2: Wakes affect a cone-like area; the highest intensity is at 0° (straight) before dissipating

The preliminary sectors for each small wind turbine were pulled from the power performance test report. During the test phase, the small wind turbines were analyzed for various tests, including durability, acoustics, and power performance. NREL engineers compiled data from a multitude of sensors mounted both on the test turbine and on a nearby meteorological tower. The collected data was compatible with a verified Excel tool that calculates power performance and annual energy production estimates from the data according to the standard. To conduct the obstacle study, the raw (unfiltered and compiled) data was trimmed to exclude confounding events such as data acquisition system (DAS) failures, blade icing, grid faults, and sensor failures. The events were deemed invalid by parsing the engineers' logbook and Excel workflow, which document notably long incidents. The remaining (valid) data was then iteratively input into the Excel tool in two stages. The initial stage only used data with wind from the preliminary sector directions. Then, the tool was run with wind data from every direction. The resulting normalized power performance plots and annual energy production estimates were then compared to determine obstacle influence. The process was then repeated for the other small wind turbines involved in NREL's small wind project to examine the result reliability, which is shown in Figure 5:

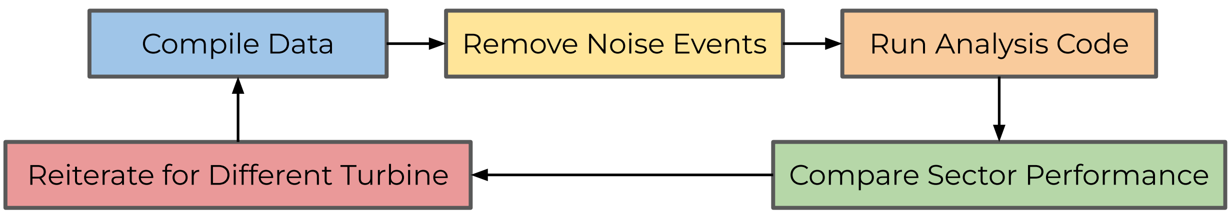


Figure 5: Flowchart demonstrating the analysis workflow

III. RESULTS AND DISCUSSION

Throughout the analysis, five small wind turbines were analyzed. The Viryd CS8 and Swift from fiscal year 2010, and the Entegrity EW50, Gaia, and the ARE 442 from fiscal year 2008. The turbines were run in different configurations and with different obstacle considerations. The small wind turbines range in size, efficiency, and power output.

A. Viryd CS8

The Viryd was a three-bladed, 8 kW rated turbine with fixed blade pitch (two blades at 1.4° and one at 1.1° from the hub plate). The Viryd had a tail fin, a passive yaw mechanism for facing the turbine upwind. The Viryd regulated its power output via passive stall, where increasing rotational velocities from high winds cause the fixed-pitch blades to stall from a high angle of attack—using drag to slow the turbine. After the site assessment process, winds from 211 to 38° true were considered in the original IEC power analysis.[9]

The NREL Flatirons campus test site is oriented such that the prevailing westerly winds compress downward from the continental divide through Eldorado Canyon, which accelerates wind speeds dramatically.[10] The canyon is situated roughly 292° from the test site. This results in most high winds (and turbulence) being invariant between the two stages as shown in Figure 6.

One deviation from the outlined methodology was the elimination of the sectors 79 to 150° true in the “all sector” stage. This was recommended by the engineer responsible for the Viryd IEC test in late 2011. The degree range was identified as a sector in which the Viryd could induce turbulence on the meteorological tower, which is 10 times closer to the turbine than larger obstacles of interest.

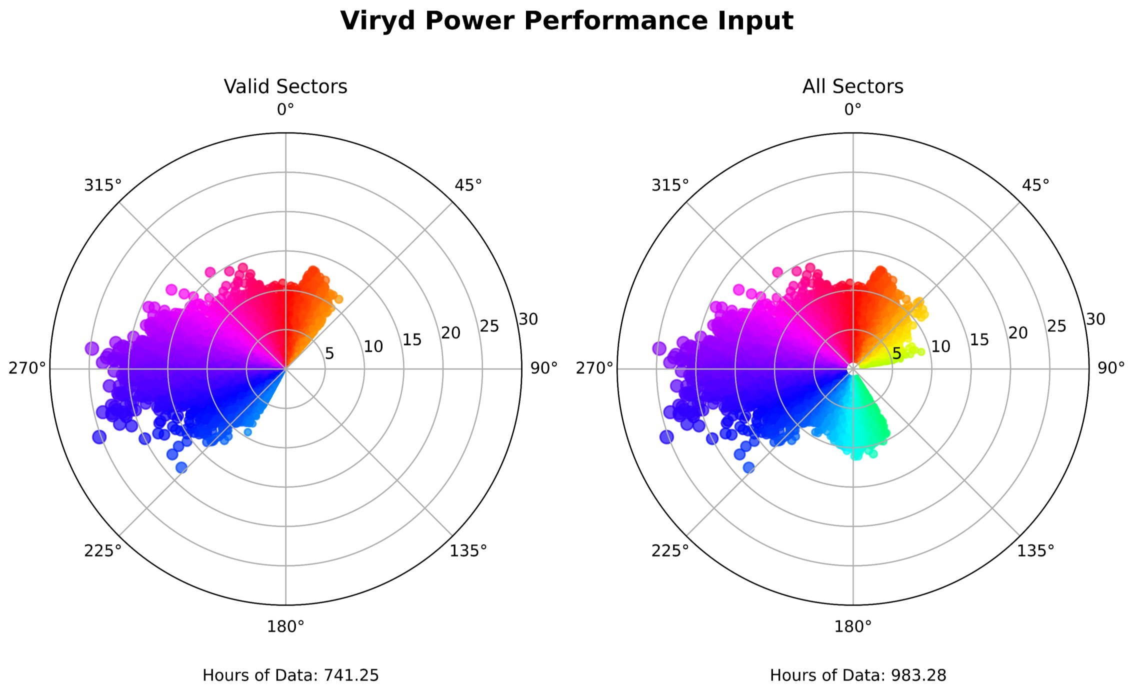


Figure 6: Wind data resource input where the azimuth is on the polar axis (° true) and the wind speed (m/s) is on the radial axis

The all sector wind data does not have additional significant wind events (no wind data above the 15 m/s). This is in spite of running 242.03 more hours of data into the analysis tool.

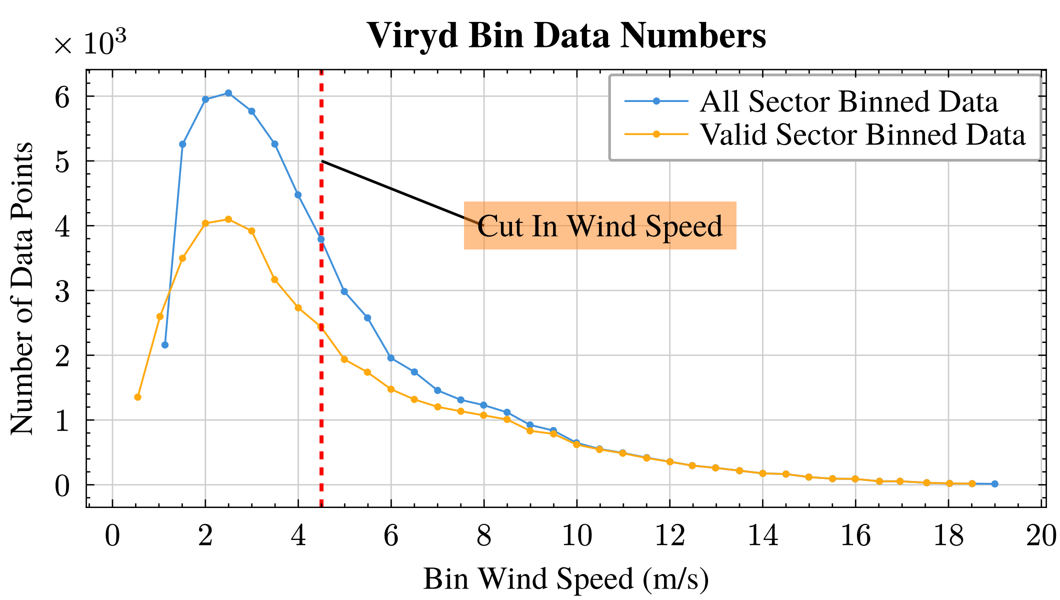


Figure 7: The number of data points within each wind speed bin

Thus, most of the additional data acquired with “all sectors” was in the 4.5-8 m/s wind speed range. Most obstacles outlined in the site assessment were hundreds of meters away, so including this additional data led to minimal changes in performance. This is further exemplified in Figure 8, Table 2, and Table 3:

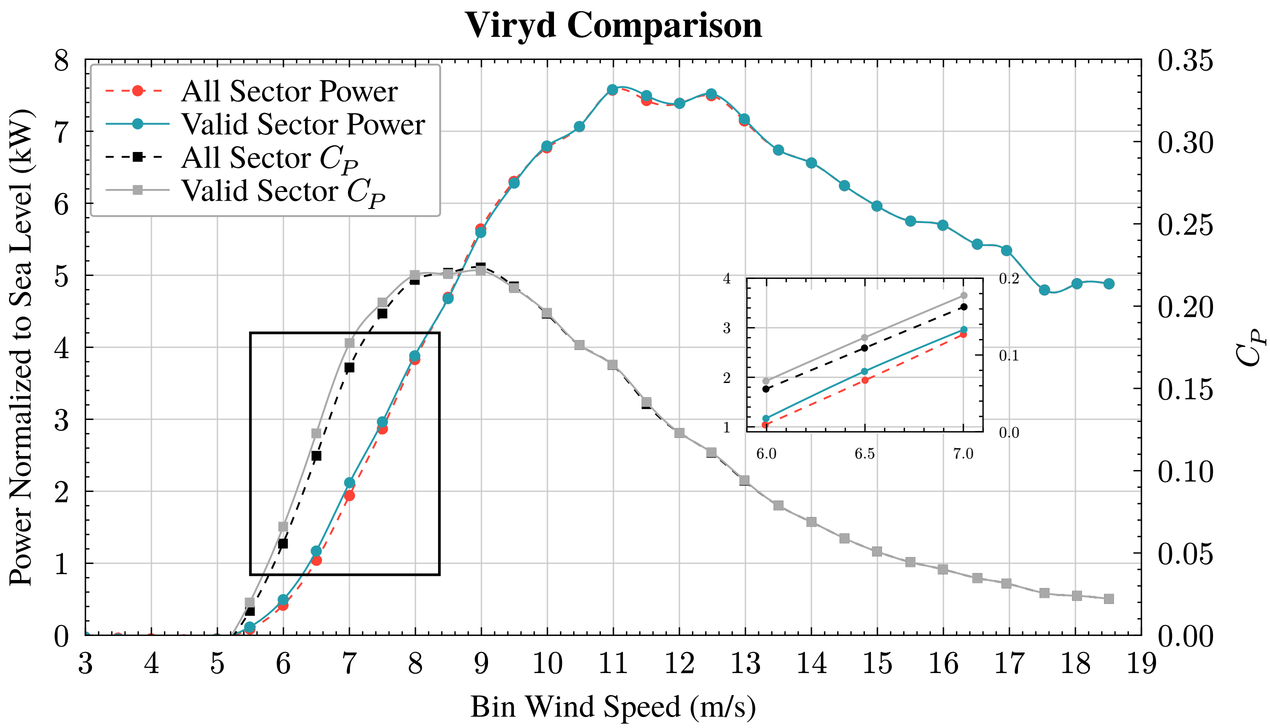


Figure 8: Viryd power plotted as a function of wind speed

Viryd IEC Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	4.05
5	10.13
6	17.01
7	23.21
8	27.99
9	31.17

Table 2: Viryd AEP measured using wind data from the IEC sector only (211 to 38° true)

Viryd All Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	3.93
5	9.94
6	16.79
7	22.99
8	27.78
9	30.97

Table 3: Viryd AEP measured using wind data from all wind directions (excluding $79 \text{ to } 150^\circ \text{ true}$)

The analysis tool calculated annual energy production to be similar, with the IEC sector data having slightly better performance. Moreover, from Figure 8, the IEC sector appears to be shifted higher than the all sector data when it comes to both power production and C_P, which is the turbine's efficiency, derived from:

$$\text{Efficiency } (C_P) = \frac{\text{Power Generated by Turbine}}{\text{Energy in the Wind}} = \frac{P_{\text{Generated}}}{\frac{1}{2}\rho A V^3} \tag{2}$$

Because of the increase in wind data points for the lower wind speed bins and the test site topology, data from the bin lower bounds could have reduced the power average per bin. The binning procedure groups wind data together to average power values. The bin numbers are denoted by Equation 3:

$$\text{Bin Number} = \text{Round } [2 * (\text{Wind Speed})] \tag{3}$$

where "Round" is rounding to the nearest even number. Each wind speed bin is 0.5 m/s wide, which is how the standard normalizes power output (averages power for every wind speed within the bin). Moreover, the plot supports the hypothesis that some turbulence was produced by neighboring turbines such as the Skystream or Alstrom—in which the turbulent wind would be yielding less power for the same speed bins in the non-obstructed IEC test. Yet, because the high wind bins were filled in a constant direction for both tests, other turbines with high wind events from obstructed sectors are needed.

During the IEC test, combined uncertainty (from both statistical and fixed for instruments) was determined to range from 0.1 to 0.4 kW. The largest power discrepancy between the two tests was approximately 0.17 kW. Ultimately, subtle changes in performance could be the result of many factors including random variation in the data, wind gusts that induce intensive yawing of the turbine, abnormal weather events, or other extraneous factors. However, the small changes in efficiency and power production do accrue on the annual scale, with 0.22 MWh at an average wind speed of 6 m/s being the largest difference. When compared at scale, the less than one MWh change appears relatively insignificant, as encapsulated in Figure 9:

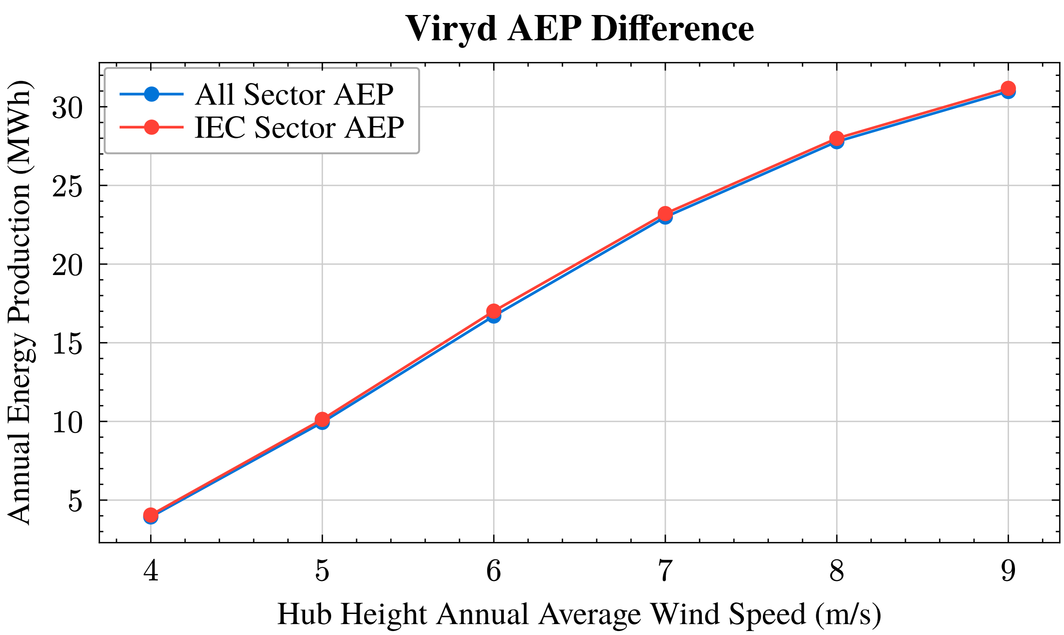


Figure 9: AEP as a function of wind speed for both IEC and All sector analysis

B. SWIFT

The SWIFT was a five-bladed, 1kW-rated turbine with fixed blade pitch angles. The SWIFT had a passive yaw control via a tail fin and was stall-power regulated—like the Viryd. This turbine had more obstacles of note, including two three meter high shipping containers less than 50 m away and a 3.5 meter high data shed 26 meters away. From the SWIFT site assessment, an IEC measurement sector was identified between 178 to 311° true.[11]

The wind data resource for the SWIFT is shown in Figure 10. The IEC sector is rotated in comparison to the Viryd to exclude the data shed at 360° true. Moreover, for the SWIFT and the other turbines, wake effects from the wind turbine on the meteorological tower are included in the “all sector” analysis. The decision to include turbine wake effects on the met tower are unimportant in the scope of the study as long as the conditions are consistent within the analysis for each individual turbine (i.e. considered for both stages of Viryd, disregarded for both stages of SWIFT). Nonetheless, similar to Viryd, the Eldorado Canyon venturi caused high winds to be from the IEC direction range. However, there were multiple data points over 10 m/s, which may have generated a wake from the data shed. The resulting power performance plot and annual energy production estimates are shown below in Figure 11, Table 4, and Table 5:

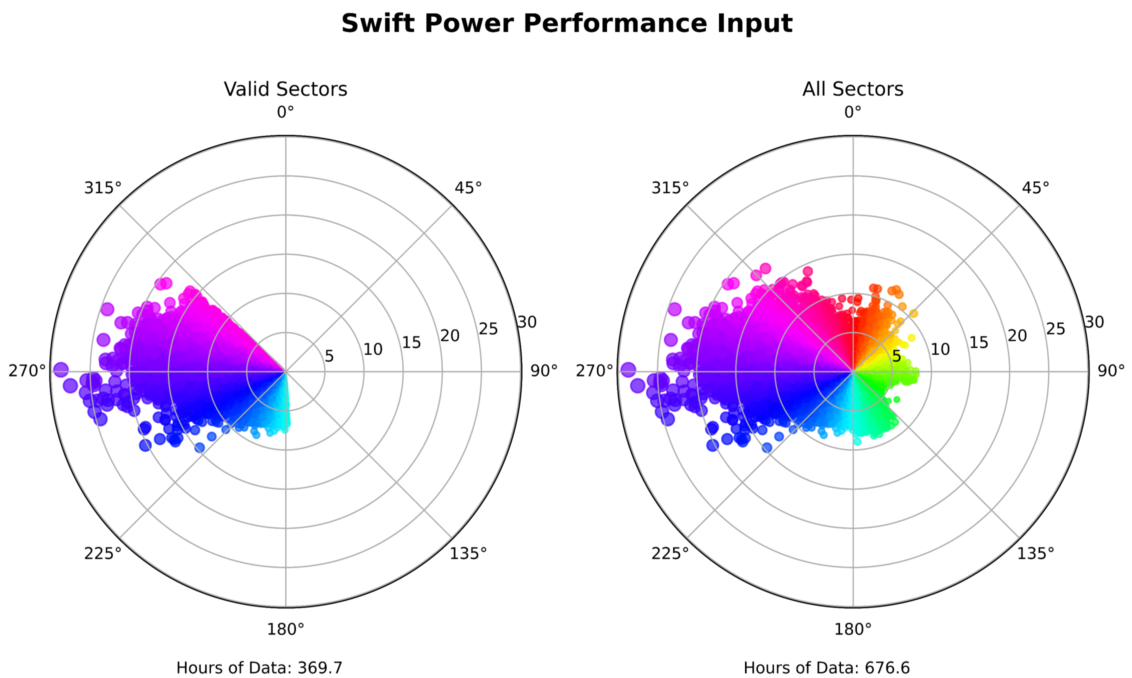
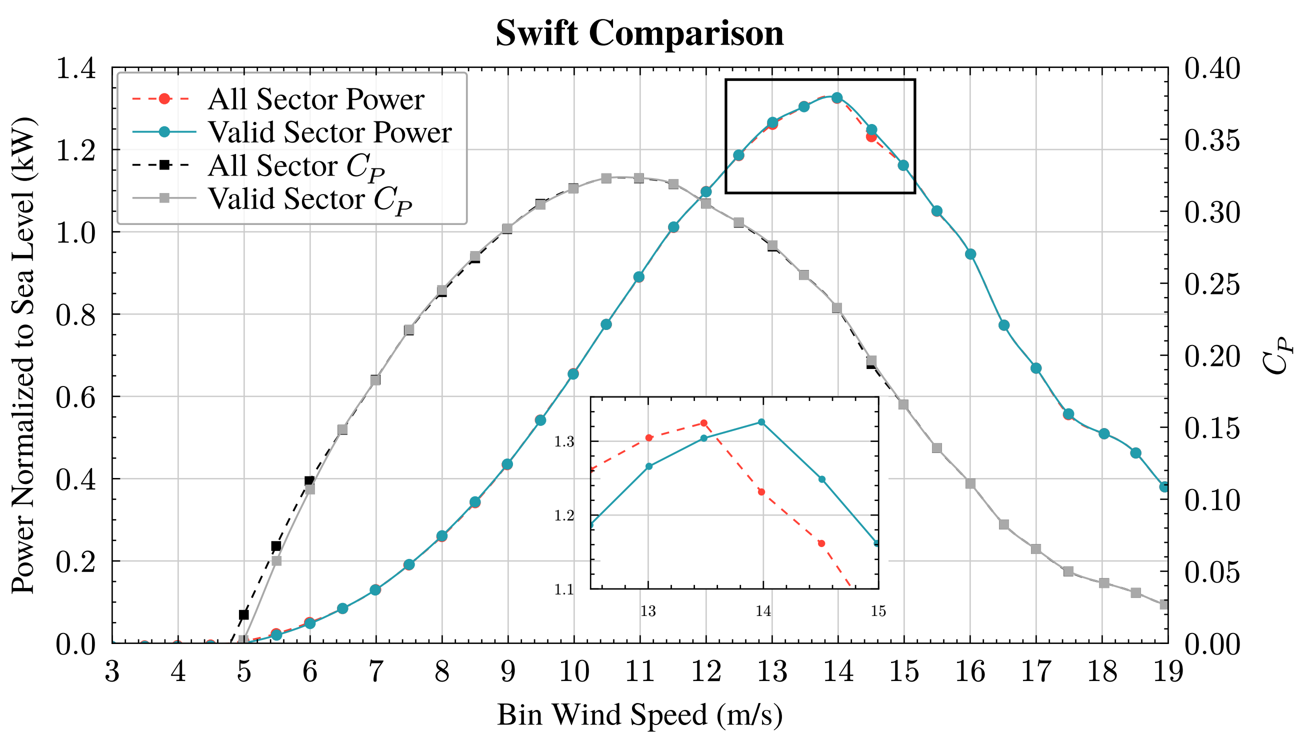


Figure 10: SWIFT analysis resource with wind speed as a function of wind direction



Swift All Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	0.31
5	0.91
6	1.73
7	2.59
8	3.35
9	3.91
10	4.27
11	4.45

Table 4: SWIFT AEP measured using wind data from all directions

Swift IEC Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	0.30
5	0.90
6	1.72
7	2.59
8	3.35
9	3.91
10	4.27
11	4.45

Table 5: SWIFT AEP measured using wind data from the IEC sector only ($178 \text{ to } 311° \text{ true}$)

Opening the analysis to all sectors resulted in 306.9 more hours of data. The performance was more similar between iterations than the Viryd, which was unexpected considering the increased prevalence of obstacles. The all sector data had a better efficiency (C_P) than the IEC until the 6 m/s bin, which corresponds to roughly 3 m/s true wind speed (normalizations were computed for wind speed, including wind shear and density corrections). This could appear for various reasons, including data from other sectors coming in at the top of the 0.5 m/s wide bin—thereby increasing the average for those bins. There is some divergence in power production, however, it is relatively small and within the combined uncertainty margins, which range from 0.02 to 0.1, depending on the bin.

The AEP tables illustrate a similar result, showing equal estimates to three significant figures in most cases, with a maximum difference of 0.02 MWh (when rounded up. Thus, the SWIFT results did not reveal any trends from obstacle-induced wakes, instead demonstrating significant similarity between tests as shown in Figure 12.

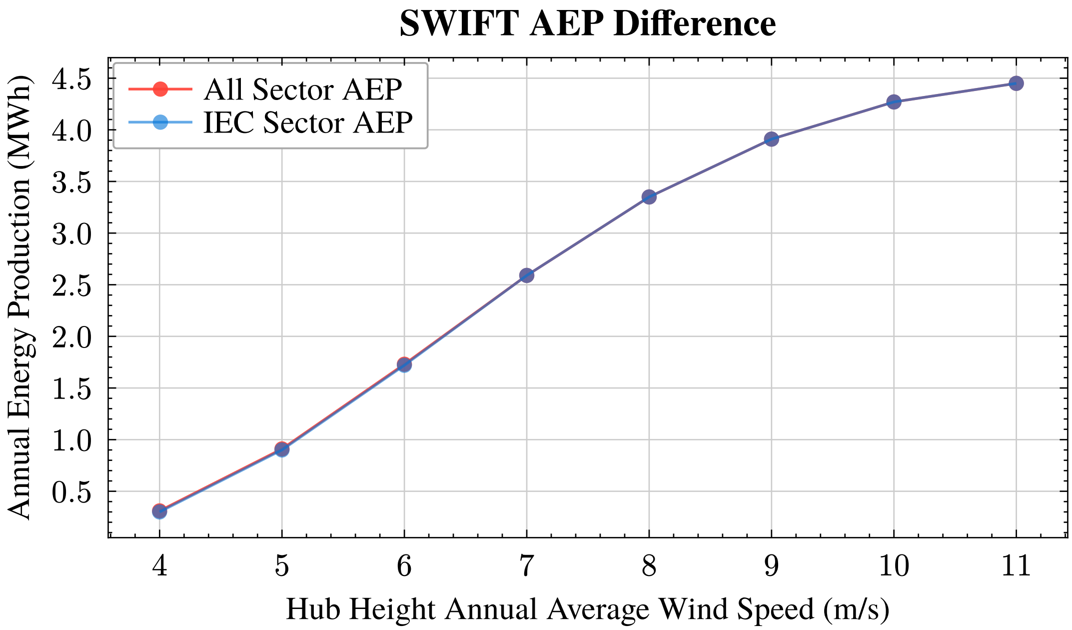


Figure 12: AEP as a function of wind speed for both IEC and All sector analysis

3. Entegrity EW50

The Entegrity EW50 was a pitch-fixed (5.14 to $5.17°$ at 75% span) three-bladed turbine, stall regulated to a rated power of 50 kW. From the IEC site assessment, the EW50 was positioned relatively close to large buildings, including the eight meter high NREL structural testing laboratory 137 meters from the turbine. The IEC test considered wind data from 272 to $350°$ true.[12] The IEC valid sector is narrower than the other turbines considered in this study, shown in Figure 13. As such, expanding the analysis to all directions nearly triples the data resource, with 926.27 more hours of wind data considered.

While the highest wind speeds were from Eldorado Canyon, there were significant (greater than 15 m/s) wind events coming from roughly 190° true, which coincides with a data shed (not explicitly mentioned in the test report. The power performance plot and AEP tables are shown below respectively as Figure 14, Table 6, and Table 7.

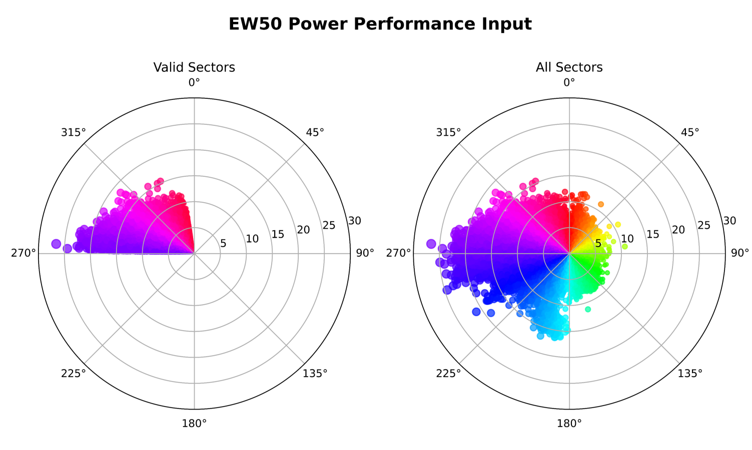


Figure 13: Entegrity EW50 wind resource input, where wind speed is a function of direction

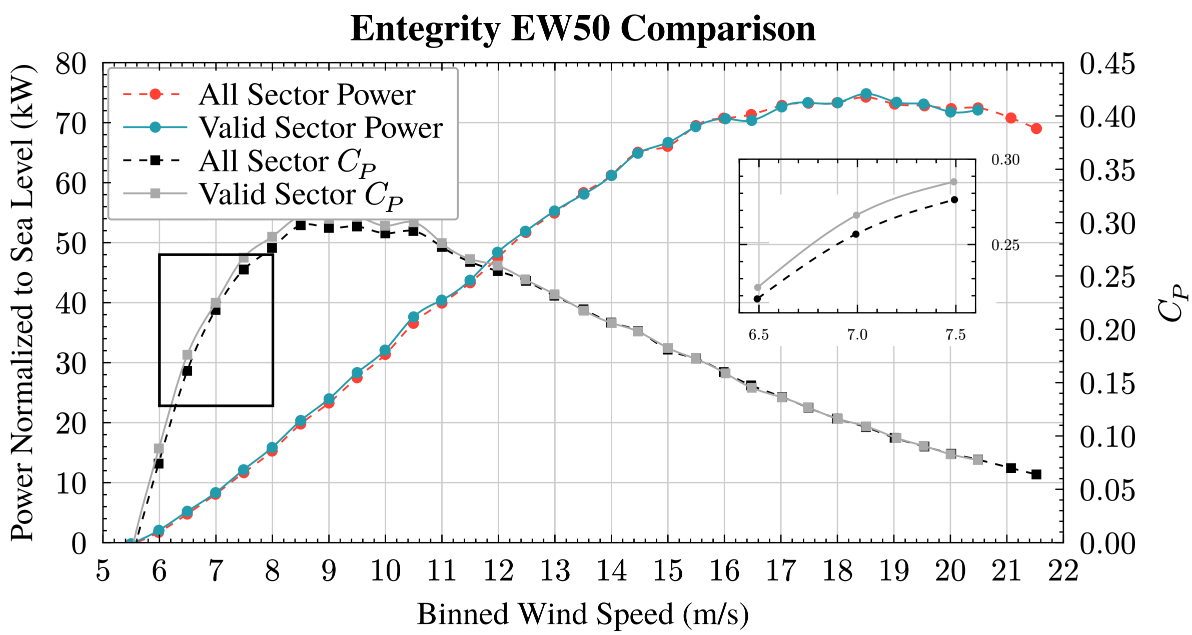


Figure 14: EW50 Power Performance and Efficiency Comparison

EW50 All Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	11.36
5	41.86
6	83.89
7	130.49
8	177.77
9	220.49

Table 6: EW50 AEP derived from all direction wind data

EW50 IEC Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	10.85
5	42.28
6	84.58
7	131.78
8	177.85
9	217.72

Table 7: EW50 AEP derived from wind within 272 to 350° true

The power curve illustrates a similar result to the Viryd, in which the IEC data yielded a higher efficiency and power production compared to the all sector. This could be the result of averaging on the lower end for each bin range as mentioned previously for the all sector data. Or some wake effects could exist on the turbine, such that the meteorological tower records a higher wind speed than the turbine physically receives (due to vortices). The power production had a combined uncertainty ranging from 0.45 to 2.78 kW, depending on the wind bin. The two plots were reasonably around this margin, with slight exceeds occurring at 16.5 m/s, for example. The marginal differences manifested themselves on the projected annual scale, however, all AEP discrepancies remained less than one MWh shown in Figure 15.

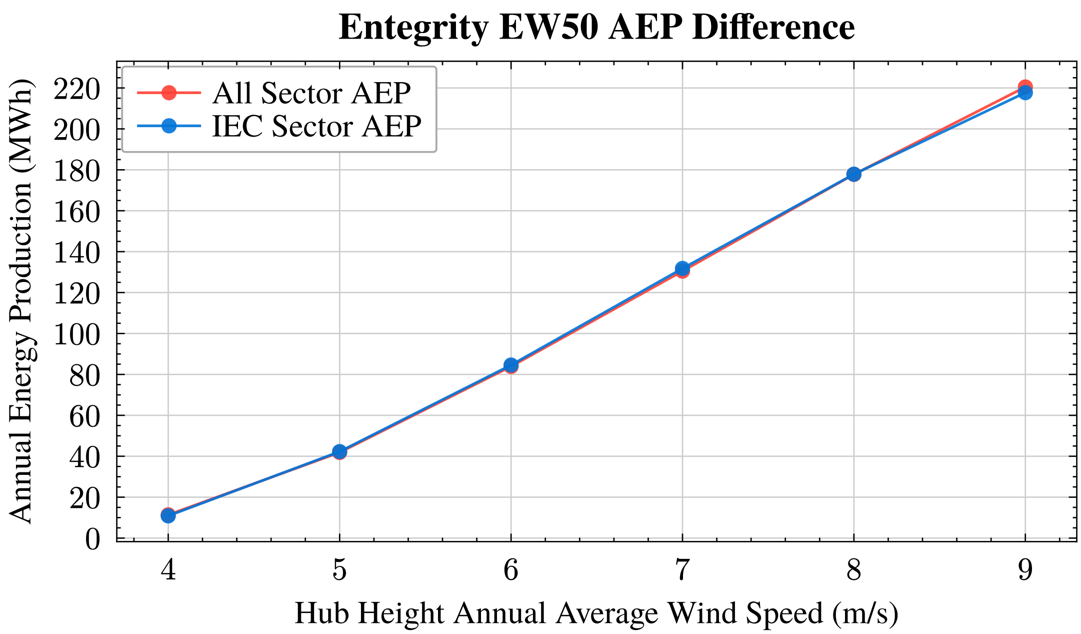


Figure 15: AEP as a function of wind speed for both IEC and All sector analysis

Unexpectedly, opening the analysis to all directions resulted in the analysis tool filling out two higher wind bins than for the IEC sector. This is because the standard requires at least 10 minutes of data per wind speed bin, which was satisfied with the additional data. The EW50 was the first analyzed turbine to demonstrate a consistent trend, which indicates wake effects could be at work. However, from the site assessment, the EW50 was relatively unaffected by terrain and obstacles, easily avoiding a site calibration.

4. ARE 442

The ARE 442 was a three-bladed, fixed pitch turbine rated to 10 kW. Like the other turbines, the ARE had a tail fairing for passive yaw control. However, at high wind speeds, the rotational inertia from the blades induced a 90° yaw out of the wind (known as furling).[13] In addition to yawing out of the wind, the ARE was equipped with an active voltage “clamp,” which dumped a resistive load on the generator to regulate power.[14]

From the IEC test report, the measurement sector was identified to be between 214 and 74° true. As shown in Figure 16, nearly all high wind events were captured within the

IEC sector excluding a few 10 m/s data points near 135°, which is unobstructed. Opening all sectors to analysis resulted in 139.11 more hours of data. The results from the power performance comparison are shown below in Figure 17, Table 8, and Table 9.

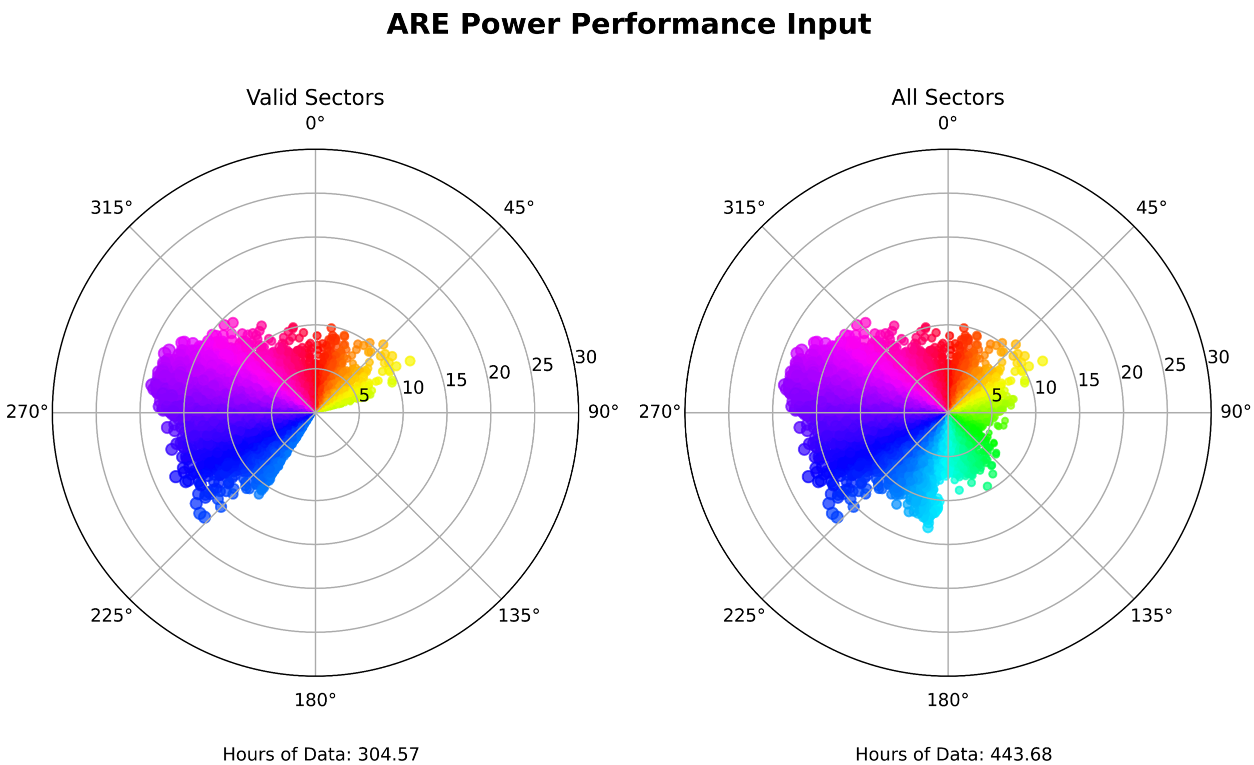


Figure 16: ARE 442 wind resource input, where wind speed is a function of direction

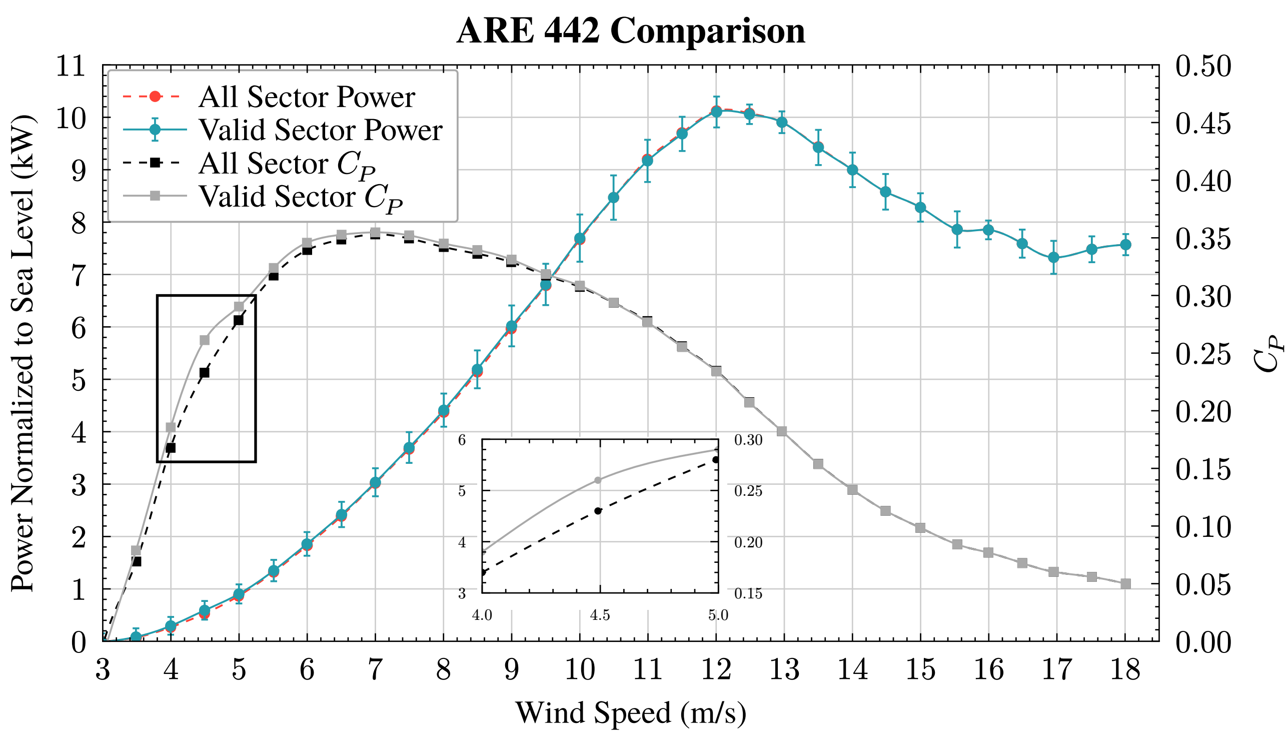


Figure 17: ARE 442 Comparison

ARE 442 All Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	7.75
5	15.16
6	23.34
7	30.81
8	36.58

Table 8: ARE AEP derived from all wind data

ARE 442 IEC Sector estimated annual energy production	
Hub height annual average wind speed m/s	AEP-measured MWh
4	7.88
5	15.32
6	23.51
7	30.96
8	36.71

Table 9: ARE AEP derived from wind within $214 \text{ to } 74°$ true

The ARE 442 demonstrated a slight increase in power production for the IEC sector for the low wind bins. However, The all sector power data were well within the combined uncertainty values for the IEC sector data, which is depicted by the error bars in Figure 17 (error bars were omitted from the other turbines for clarity). The difference in efficiency was more pronounced, with a maximum advantage of $C_P(\text{IEC}) - C_P(\text{All}) = 0.03$ at a wind speed of 4.94 m/s. The bin averaging of the data was likely responsible for the difference, as the added data points from $75 \text{ to } 213°$ true lowered the average bin power reading (more data on the lower end of the bin width). However, without any significant obstacles in the considered directions, the changes in performance and efficiency cannot be attributed to mechanical wake effects.

The AEP comparison echoed the power performance plots. The largest discrepancy was at 5 m/s with a variation of 0.15 MWh. Figure 18 shows the AEP as a function of wind speed, in which the IEC sector demonstrated a marginal advantage over the all sector result for all wind speeds. However, all variations are within 1 MWh and 10% of each other. The ARE 442 illustrates that opening all sectors for analysis can introduce alternative uncertainty considerations and potential measurement error at the expense of quicker and easier tests.

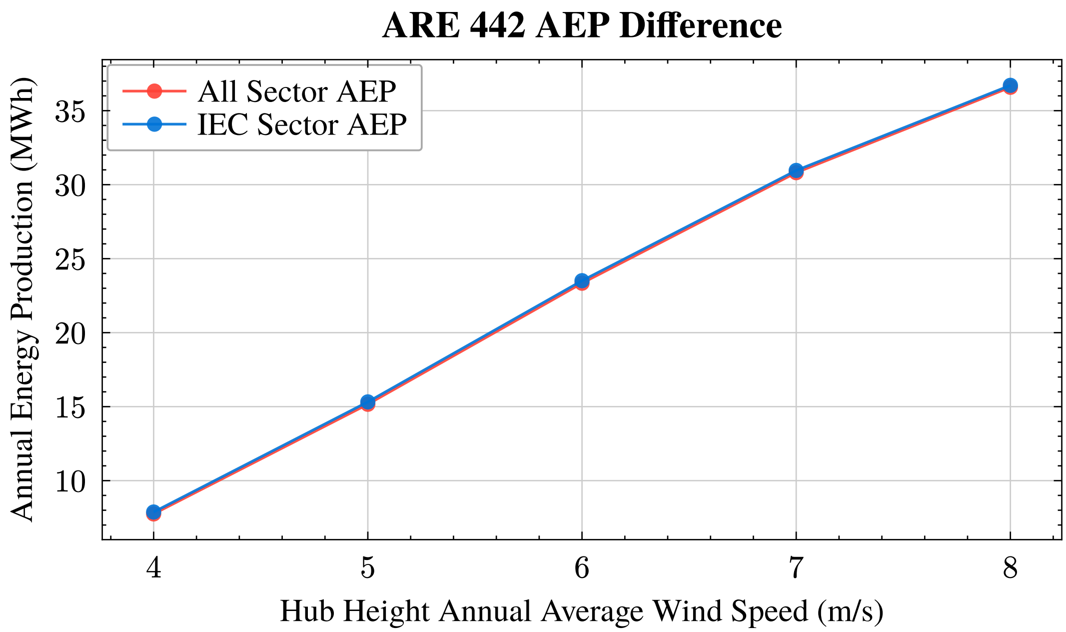


Figure 18: AEP as a function of wind speed for both IEC and All sector analysis

IV. CONCLUSIONS

This report discussed the single parameter analysis of four wind turbines measured during the NREL small distributed wind project in the early 2000s sponsored by the DOE to help reduce the barriers of wind energy. Power performance, efficiency, and annual energy production was measured with respect to wind coming exclusively from the sectors defined in the IEC site assessment and from all directions. Despite different site configurations and obstacle orientations for each turbine, performance remained largely consistent between sector tests, with the existence of slight variations. The differences seen by the ARE 442, Entegrity EW50, and Viryd were in favor of the IEC sector test, with slight increases in power production, efficiency, and AEP over the all sector results. The subtle differences can be explained by various phenomena, including a down averaging of bin data, in which the all sector data lowers a power average by including wind events at the lower end of a wind speed bin. Alternatively, with passive yaw control, some vortices may have formed off the tail fairing in directionally gusty conditions—which can introduce some inconsistency as the turbine rapidly yaws. Lastly, mechanical turbulence induced by upwind obstacles may reduce the all sector power averages, as the meteorological tower reads a higher wind speed than the turbine physically encounters. However, with respect to this study, all data sheds and obstacles were sufficiently far away such that the discrepancies between the IEC and All sector performance is within the calculated uncertainty margins. The uncertainty is the likely explanation for the Swift turbine results, in which the sector analysis resulted in near-equivalent performance.

Amending or removing the IEC small turbine site assessment requirements, combined with a higher likelihood of avoiding a site calibration would dramatically reduce a turbine validation time. Moreover, in sites that do not experience high wind events, opening analysis to all sectors may be the only method to achieve test completion—reducing the test barriers and potentially increasing the amount of competitive manufacturers on the market. However, opening all sectors increases the amount of uncertainty components in each wind speed bin, thereby increasing the overall uncertainty. Thus, in situations that involve opening all sectors for analysis, care should be given with respect to gust rates (turbulence intensity) and directional wind shears. Any revision to the standard must then weigh the cost and convenience against uncertainty and statistical error.

V. APPENDIX A

The Gaia turbine was also analyzed in the study, however, confounding events were present in the data interpreted by the power performance code. Thus, the result is largely invalid. Unfortunately, the Gaia turbine had an interesting site layout, with some potential for significant turbulent effect. Figure 19 shows the overall site layout for the Gaia in addition to the considered sectors for the IEC test (shaded green and blue). The obstacles are categorized in Table 10, with both the ARE and the Mariah with large obstruction widths. The resource comparison is shown in Figure 20, which has an unreasonably large amount of data (most of which includes “bad” data values such as grid faults and icing information). The Gaia had some high wind events outside of the IEC sector, particularly from the direction of the Mariah turbine relative to the Gaia.

Figure 20 indicated interesting potential for a turbulence study. However, with the invalid data, the power performance plot (shown in Figure 21) showed significant divergence between values, especially at the higher wind speeds. To better understand the data, the anemometer sector was excluded as an experiment to see if convergence between values could be improved, as the majority of high wind speeds originate from Eldorado Canyon. Indeed, the anemometer-excluded sector captured the nuances of the the power plot behavior at high wind speeds, yet remained significant differences between the plots. Moreover, the anemometer lies within the IEC sector, disproving the usefulness of much of the analysis. Nonetheless, the Gaia remains an interesting turbine for future study.

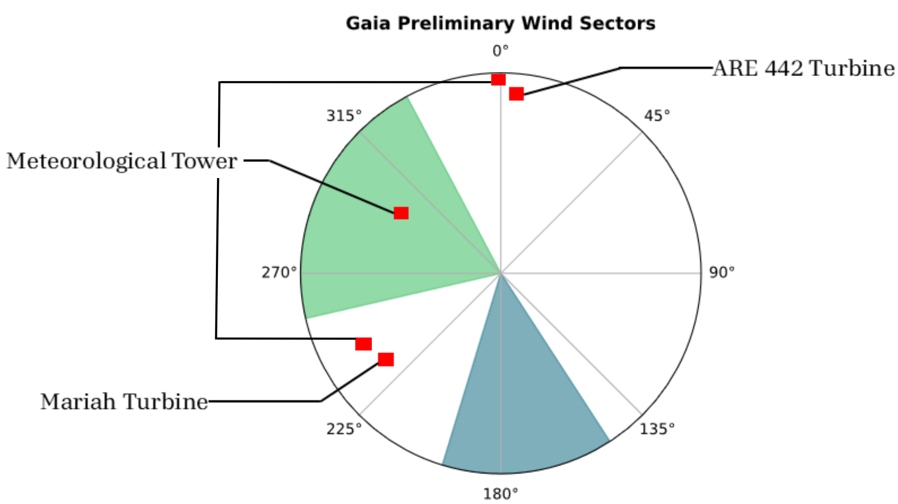


Figure 19: Wind directions considered after site assessment

Designation	Bearing from Test Turbine (° true)	Distance from Test Turbine (m)	Obstruction Height (m)	Rotor Diameter or Obstruction Width (m)
Met B	290	107.5	18.2	0.4
Data Shed	292	207.5	3.1	7.0
ARE	2	157.6	31.0	7.3
Met A	344	184.9	31.0	0.4
Mariah	227	168.9	6.1	1.2
Met C	236	184.5	4.6	0.4

Table 10: Structural assessment for Gaia

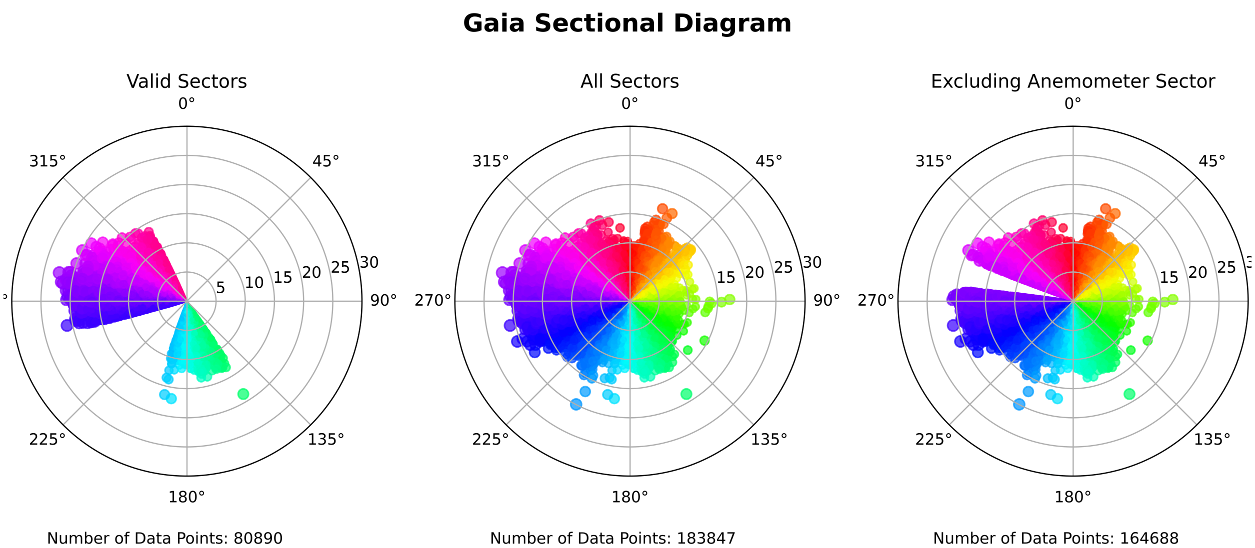


Figure 20: Plots of wind speed (radial) as a function of wind direction (azimuth)

Gaia IEC Sector estimated annual energy production				
Hub height annual average wind speed (Rayleigh)	AEP-measured MWh	Standard Uncertainty in AEP-measured		AEP-extrapolated
m/s	MWh	MWh	%	MWh
4	14.12	1.47	0.10	14.12
5	29.57	1.89	0.07	29.58
6	39.18	2.18	0.06	39.39
7	50.00	2.39	0.05	51.08

Table 11: Gaia IEC Sector AEP Table

Gaia All Sector estimated annual energy production				
Hub height annual average wind speed	AEP-measured MWh	Standard Uncertainty in AEP-measured		AEP-extrapolated
m/s	MWh	MWh	%	MWh
4	16.09	1.58	0.10	16.09
5	29.64	2.00	0.07	29.65
6	43.28	2.22	0.05	43.39
7	55.22	2.30	0.04	66.74

Table 12: Gaia All Sector AEP Table

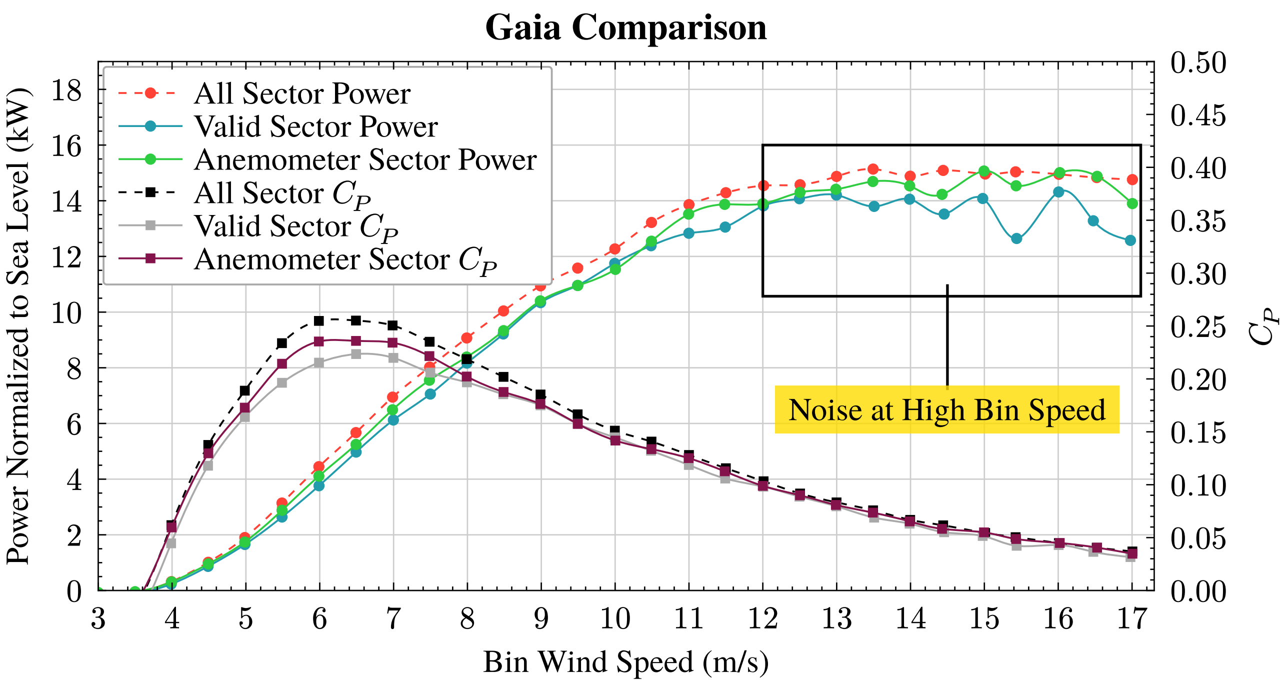


Figure 21: Gaia Power Performance

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VII. NOMENCLATURE

Units:
m = meters
MW = megawatt
kW = kilowatt
In the order of appearance:
D_e = equivalent rotor diameter,
l_h = height of an obstacle,
l_w = width of an obstacle,
ρ = air density,
A =swept area of the wind turbine blades,
V = wind velocity,

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