Uncertainty estimations for offshore wind resource assessment and power verification

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1. Introduction

The scope of the work is the uncertainty estimation of the annual energy production (AEP) calculations, based on a variety of offshore wind potential measurements techniques.

Photo 1: FloatMast at Lavrion port – Beginning of the deployment phase.

The current and upcoming versions of the IEC 61400-12-1 standard [1], [2] were considered as the basic reference methodology for the uncertainty estimation. Although these documents do not cover all the cases examined herein, they provide a commonly established and recognized basis for the calculations.

For the scope of the present work, the NREL offshore 5-MW baseline wind turbine [3] is used. It is a model widely employed in several research projects as a typical offshore turbine, being well documented with all the detailed technical specifications publicly available [3].

2. Offshore measurement options

The following measurement options, listed in Table 3, were considered for offshore wind potential and power curve measurements.

Case	Method	Short Name	Comments
A	Fixed permanent full rotor height meteorological mast (150m)	RHMM	**+** High accuracy & TI measurements (cup/sonic) **+** High data availability **+** Rotor equivalent wind speed **-** Very high installation cost **-** Significant flow disturbance
B	Fixed permanent hub height meteorological mast (90m) with remote sensing device (RSD)	HHMM+RSD	**+** High accuracy & TI measurements (cup/sonic) **+** High data availability **+** Rotor equivalent wind speed **+** RSD continuously verified against cups **-** High installation cost **-** Flow disturbance
C	Fixed permanent below hub height mast (40m) with remote sensing device (RSD)	BHMM+RSD	**+** High accuracy & TI measurements (cup/sonic) **+** High data availability **+** Rotor equivalent wind speed **+** RSD continuously verified against cups **-** High installation cost
D	Remote sensing device (RSD) on floating vessel (i.e. floating LIDAR)	flRSD	**+** Low installation cost **+** Rotor equivalent wind speed **+** No flow disturbance **-** Lower data availability **-** Strong effects from structure movements
E	Temporary TLP mast (40m) with remote sensing device	FloatMast	**+** Good accuracy & TI measurements (cup/sonic) **+** High data availability **+** Rotor equivalent wind speed **+** RSD continuously verified against cups **+** Low installation cost **-** Limited effects from structure movements

Cases A, B, C are explicitly defined in [2]

Table 1. Measuring options for offshore wind potential and power curve measurements.

It is beyond the scope of this work to comment in detail the pros and cons of each method. All of them have some strong advantages and none has no disadvantages. As an example, consider the issues of met mast height and atmospheric stability.

Despite the belief that the higher the met mast the better is, flow distortion becomes an important factor since self-supporting met mast are huge structures that affect shear measurements (higher effect at lower anemometers, especially if a helicopter platform is present).

Atmospheric stability, on the other hand, can only be measured accurately by a met mast (by two or more ultrasonics and/or differential thermometers at different heights), in contrary to floating lidars which can only deduce it empirically (from the vertical wind profile).

Also, it is worth mentioning the advantage of floating lidars concerning their ability to be redeployed at another point of the wind farm site, while met mast platforms must use a horizontally scanning lidar to cover the wind potential of the site.

Research and testing is on-going so the performance of the various options is expected to be improved with time.

3. Typical Virtual offshore WT

The selected wind turbine for the AEP uncertainty calculations is the well-documented and widely used in research projects 5MW offshore wind turbine from NREL [3]. Below the main technical specifications are presented.

NREL WT specifications [3]	
Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º

Table 2. Technical specifications for the chosen fictitious WT type.

Figure 1 presents the binned power curve along with the standard deviation of power in each wind speed bin (0.5m/s). Table 2 shows tabulated data in form of a typical power curve campaign.

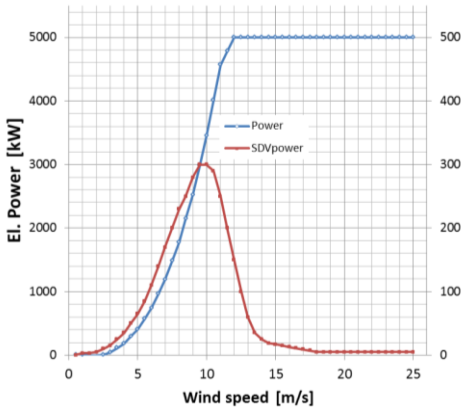

Figure 1. Power curve of the NREL offshore 5-MW wind turbine.

Artificial Power curve data for typical 5MW WT (NREL type)							
Average wind speed (m/s)	Average Power (kW)	SDV Power (kW)	Numer of samples	Power minimum (kW)	Power maximum (kW)	Average density (kg/m3)	Average temperature (oC)
0.5	0.0	0.01	5	0.00	0.00	1.225	21.1
1.0	0.0	3.00	5	-20.00	0.00	1.225	21.1
1.5	-3.0	3.00	5	-20.00	6.00	1.225	21.1
2.0	-5.0	5.00	10	-20.00	10.00	1.225	21.1
2.5	0.0	10.00	20	-30.00	30.00	1.225	21.1
3.0	40.5	15.00	50	-30.00	85.50	1.225	21.1
3.5	109.1	25.00	70	34.10	184.10	1.225	21.1
4.0	177.7	35.00	75	72.70	282.70	1.225	21.1
4.5	290.8	50.00	80	140.80	440.80	1.225	21.1
5.0	403.9	65.00	85	208.90	598.90	1.225	21.1
5.5	570.8	85.00	90	315.75	825.75	1.225	21.1
6.0	737.6	110.00	90	407.60	1067.60	1.225	21.1
6.5	962.4	140.00	90	542.40	1382.40	1.225	21.1
7.0	1187.2	170.00	80	677.20	1697.20	1.225	21.1
7.5	1479.2	200.00	80	879.15	2079.15	1.225	21.1
8.0	1771.1	230.00	70	1081.10	2461.10	1.225	21.1
8.5	2144.9	250.00	70	1394.85	2894.85	1.225	21.1
9.0	2518.6	280.00	60	1678.60	3358.60	1.225	21.1
9.5	2983.5	300.00	60	2083.50	3883.50	1.225	21.1
10.0	3448.4	300.00	55	2548.40	4348.40	1.225	21.1
10.5	4005.5	290.00	55	3135.45	4875.45	1.225	21.1
11.0	4562.5	250.00	50	3812.50	5020.00	1.225	21.1
11.5	4781.3	200.00	50	4181.25	5020.00	1.225	21.1
12.0	5000.0	150.00	45	4550.00	5020.00	1.225	21.1
12.5	5000.0	100.00	45	4700.00	5020.00	1.225	21.1
13.0	5000.0	60.00	40	4820.00	5020.00	1.225	21.1
13.5	5000.0	35.00	40	4895.00	5020.00	1.225	21.1
14.0	5000.0	25.00	35	4925.00	5020.00	1.225	21.1
14.5	5000.0	19.00	35	4943.00	5020.00	1.225	21.1
15.0	5000.0	17.00	30	4949.00	5020.00	1.225	21.1
15.5	5000.0	15.00	30	4955.00	5020.00	1.225	21.1
16.0	5000.0	13.00	20	4961.00	5020.00	1.225	21.1
16.5	5000.0	11.00	19	4967.00	5020.00	1.225	21.1
17.0	5000.0	9.00	20	4973.00	5020.00	1.225	21.1
17.5	5000.0	7.00	20	4979.00	5020.00	1.225	21.1
18.0	5000.0	5.00	15	4985.00	5015.00	1.225	21.1
18.5	5000.0	5.00	15	4985.00	5015.00	1.225	21.1
19.0	5000.0	5.00	10	4985.00	5015.00	1.225	21.1
19.5	5000.0	5.00	10	4985.00	5015.00	1.225	21.1
20.0	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
20.5	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
21.0	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
21.5	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
22.0	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
22.5	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
23.0	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
23.5	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
24.0	5000.0	5.00	5	4985.00	5015.00	1.225	21.1
24.5	5000.0	5.00	3	4985.00	5015.00	1.225	21.1
25.0	5000.0	5.00	2	4985.00	5015.00	1.225	21.1

Table 3: Artificial power curve data in 0.5m/s bins for AEP calculations.

4. Uncertainty components

The uncertainty estimation follows the methodology described in [1] and [2]. For the scope of this application (no measurement campaign data), the default recommended values in these documents were applied (or typical ones from similar test campaigns).

4.1 Combined uncertainties

The uncertainty components regard the instrumentation (cup anemometry and remote sensing devices), the reference wind speed estimation (cup anemometer or rotor equivalent wind speed REWS) and their statistical variation.

Two additional components are considered in order to describe the operation of options of the floating LIDAR and FloatMast, namely structure movement effects and data availability.

The detailed uncertainty components for each applicable measured quantity are shown in Table 4. They are grouped as required in the Annex E of [2]

Statistical uncertainties and the power measurement uncertainties are assumed common for all 5 cases.

4.2 Effect of the structure motions

In the luck of measured data for floating lidars and FloatMast motions, published material (conference presentations, papers, etc) was used to define the corresponding uncertainty component. Four such publications [8], [9], [10], [11] were taken into account in order to deduce an average value of **1.4%**.

Photo 2: CMR's experimental setup [8] for motion induced errors in wind speed: Two fixed lidars against two identical ones on a moving platform.

Perhaps, the most known publication comes from the Norwegian Christian Michelsen Research (CMR) performing comparisons between two sets of identical ZephIRs and Windcubes lidars, the first one fixed and the other on a moving platform with 6 degrees of freedom. The only inconvenient of this campaign was the somehow low average wind speed (5m/s), since it was performed close the Company's buildings. As expected, the results for the horizontal speed deviation depend not only to the motion type (yaw, tilt, surge, heave, roll, pitch, circular, etc) and the corresponding frequency and amplitude, but also to the lidar type (pulsed- or continuous-wave).

T. Rogers from DNV [9] modeled three different floating vessels movements (barge, spar buoy and disk buoy) and reports errors from 0.2% (barge) 1% (spar buoy) and 2% (disk buoy). In the assessment of the SeaWatch floating lidar [10] DNV reports in average wind speed deviations of 1.4%, for the 4 investigated heights. Correction algorithms are already implemented in some floating lidars but few papers are published, showing promising results though. Anyhow, a common practice is to add half of the correction as additional uncertainty, therefore uncertainties do not become zero.

FloatMast's motion amplitude and frequency, by design, cannot reach those of a floating lidar and is considered as a significantly more stable foundation. Nevertheless, for the scope of this work, it is (conservatively) safe to use the half of uncertainty of the floating lidar. If floating lidars with motion correction algorithms are considered, this assumption remains true because simpler correction algorithms would be required (if any) for a FloatMast platform.

5. Effect of the data availability

Although the data availability component does not affect directly the power curve uncertainty, it does affect the uncertainty of the wind speed, measured within a specific campaign duration (i.e.: site assessment study).

LIDARs data availability is affected by harsh environmental conditions such as fog, mist, low clouds, etc. Therefore, lower annual data availabilities are expected, even in onshore deployments. As an example, the latest revision of the German TR6 guideline for Wind Resource Assessment [6], for LIDAR standalone operation, requires 12 consecutive months of measurement, with minimum data availability of 80%. Similar requirements appear in Carbon Trust's Offshore Roadmap for the commercial acceptance of floating LIDAR technology [12], where the monthly and overall data availabilities are set to 80% and 85%.

The following procedure [4] was applied in order to investigate the effect of LIDAR's lower data availability within a 1-year campaign[1]. A high-quality offshore wind dataset was selected and 14 scenarios were examined, simulating several patterns of data losses, reaching 20% for each scenario. The deduced uncertainty of the average wind speed was found to be **1.0%**.

[1] It should not be confused with the data availability of multi-years campaign, for long-term wind resource assessment.

Abbreviation	Uncertainty description	RHMM	HHMM + RSD	BHMM + RSD	flRSD	FloatMast
UNCERTAINTY ITEMS FOR WIND SPEED						
RUV1(4) [4. m/s]	standard uncertainty cup PRE-calibration 4-16M/S	0.1	0.1	0.1	0	0.1
RUV2[m/s]	uncertainty due to in-situ or post calibration	0.1	0.1	0.1	0	0.1
RUV3[]	sensor classification k	1.7	1.7	1.7	0	1.7
RUV4[%]	uncertainty due to mounting - mast shadowing effects (0.5:top, 1.0:top-s	0	0	0	0	0
RUV5[%]	uncertainty due to lightning finial [%]	0	0	0	0	0
RUV6[%FR],CRUV6	uncertainty of DAQ as per cent of full range & full range [m/s]	0.1	0.1	0.1	0	0.1
UNCERTAINTY ITEMS FOR AIR DENSITY DUE TO TEMPERATURE						
RUT1[oK]	uncertainty of temperature sensor calibration	0.5	0.5	0.5	0.5	0.5
RUT2[oK]	uncertainty due to imperfect radiation shield	1.5	1.5	1.5	1.5	1.5
RUT3[oK]	uncertainty due to mounting effects	0.3	0.3	0.3	0.3	0.3
RUT4[%FR],CRUT4	uncertainty of DAQ as per cent of full range & full range [oK]	0.2	0.2	0.2	0.2	0.2
UNCERTAINTY IN AIR DENSITY DUE TO PRESSURE						
RUB1[hPa]	uncertainty of air pressure sensor calibration	3	3	3	3	3
RUB2[], DH_RUB2	uncertainty due to mounting effects (=10%), height difference	0.1	0.1	0.1	0.1	0.1
RUB3[%FR],CRUB3	uncertainty of DAQ as per cent of full range & full range [hPa]	0.1	0.1	0.1	0.1	0.1
UNCERTAINTY IN AIR DENSITY DUE TO RELATIVE HUMIDITY						
RUH1[%]	uncertainty of air humidity sensor calibration	2	2	2	2	2
RUH2[%]	uncertainty due to mounting effects (%)	0.2	0.2	0.2	0.2	0.2
RUH3[%FR],CRUH3	uncertainty of DAQ as per cent of full range & full range [%]	0.1	0.1	0.1	0.1	0.1
UNCERTAINTY ITEMS FOR WIND SPEED FROM REMORE SENSING DEVICES U_rsd		**0.00**	**2.74**	**2.74**	**3.44**	**2.74**
RURSD1[%]	E.7.2 uncertainty related to device verification E.7.2	0	0	0	0.3	0
RURSD2[%]	E.7.3 uncertainty related to in situ device check E.7.3	0	0	0	1.5	0
RURSD3[%]	E.7.4 uncertainty for operational characteristics (classification)	0	1.5	1.5	1.5	1.5
RURSD4[%]	E.7.5 uncertainty for mounting of the device	0	1	1	1	1
RURSD5[%]	E.7.6 uncertainty of flow variation in different probe volumes	0	2	2	2	2
RURSD6[%]	E.7.7 uncertainty due to the monitoring test	0	0.5	0.5	1.5	0.5
RURSD7[%]	uncertainty due to data acquisition of wind speed signal	0	0.1	0.1	0.1	0.1
UNCERTAINTY ITEMS FOR ROTOR EQUIVALENT WIND SPEED		**2.24**	**1.12**	**2.29**	**1.58**	**2.29**
RUREWS1[%]	RSD only	0	0	0	1.5	0
RUREWS2[%]	E.8.2.2 uncertainty wind shear: met mast significantly above hub height	2	0	0	0	0
RUREWS3[%]	E.8.2.3 uncertainty wind shear: RSD + lower than hub height met mast	0	0	2	0	2
RUREWS4[%]	E.8.2.4 uncertainty wind shear: hub height met mast + RSD for shear	0	1	1	0	1
RUREWS5[%]	E.8.3 uncertainty wind veer	1	0.5	0.5	0.5	0.5
UNCERTAINTY COMPONENTS FOR METHODOLOGY						
UM_SHEAR [%]	missing information for wind shear	0	0	0	0	0
UM_VEER [%]	missing information for wind veer	0	0	0	0	0
UM_UPFLOW [%]	missing information for upflow	0	0	0	0	0
UM_TI [%]	missing information for turbulence (no hub height met mast)	0	0	0	0.4	0
UM_SEASON [%]	unquantifiable seasonal influences	0	0	0	0	0
UM_TINORM [%]	turbulence normalization	0	0	0	0	0
UM_SHEARNORM [	shear normalization	0	0	0	0	0
UM_CC [%]	cold climates	0	0	0	0	0
SPECIFIC UNCERTAINTY COMPONENTS						
RUREST1[%]	uncertainty due to system availability losses	0	0	0	1	0
RUREST2[%]	uncertainty due to mast/LIDAR movement effects	0	0	0	1.4	0.7

Table 4: Detailed uncertainty components for the calculations, following [2]]

AEP calculations are performed for average wind speeds ranging from 4m/s up to 14m/s. Table 5 shows the AEP calculations and the associated uncertainty depending the measurement scenarios.

AEP uncertainty indicative calculations for NREL type 5MW offshore WT for various wind speed measurement scenarios											
Umean (m/s) - Rayleigh	AEP [MWh]	Case A: Full rotor met mast		Case B: Hub-height met mast + RSD		Case C: Below-hub met mast + RSD		Case D: Floating RSD		Case E: FloatMast	
		AEP uncertainty [MWh]	AEP uncertainty %	AEP uncertainty [MWh]	AEP uncertainty %	AEP uncertainty [MWh]	AEP uncertainty %	AEP uncertainty [MWh]	AEP uncertainty %	AEP uncertainty [MWh]	AEP uncertainty %
4	3493.7	484.4	13.9	542.7	15.5	596.8	17.1	969.6	27.8	603.0	17.3
5	6758.4	677.5	10.0	782.3	11.6	878.3	13.0	1406.6	20.8	889.2	13.2
6	10692.7	832.8	7.8	975.6	9.1	1105.7	10.3	1736.3	16.2	1120.5	10.5
7	14735.0	919.2	6.2	1083.5	7.4	1232.5	8.4	1904.3	12.9	1249.5	8.5
8	18491.1	945.9	5.1	1117.0	6.0	1271.9	6.9	1939.1	10.5	1289.5	7.0
9	21747.8	933.2	4.3	1101.3	5.1	1253.4	5.8	1889.2	8.7	1270.6	5.9
10	24397.1	898.0	3.7	1057.8	4.3	1202.2	4.9	1793.7	7.4	1218.6	5.0
11	26397.4	851.6	3.2	1000.6	3.8	1135.1	4.3	1677.9	6.4	1150.3	4.4
12	27761.5	800.7	2.9	938.0	3.4	1061.9	3.8	1556.5	5.6	1075.9	3.9
13	28545.4	749.0	2.6	874.7	3.1	988.2	3.5	1437.5	5.0	1001.1	3.5
14	28832.0	698.5	2.4	813.5	2.8	917.1	3.2	1324.9	4.6	928.9	3.2

Table 5. AEP calculations and uncertainty estimations.

AEP uncertainty indicative calculations for NREL type 5MW offshore WT for various wind speed measurement scenarios										
Umean (m/s) - Rayleigh	Case A: Full rotor met mast		Case B: Hub-height met		Case C: Below-hub met		Case D: Floating RSD		Case E: FloatMast	
	Umean uncertainty [m/s]	Umean uncertainty %	Umean uncertainty [m/s]	Umean uncertainty %	Umean uncertainty [m/s]	Umean uncertainty %	Umean uncertainty [m/s]	Umean uncertainty %	Umean uncertainty [m/s]	Umean uncertainty %
4	0.166	4.1	0.186	4.7	0.206	5.1	0.439	11.0	0.208	5.2
5	0.184	3.7	0.211	4.2	0.237	4.7	0.462	9.2	0.240	4.8
6	0.203	3.4	0.237	4.0	0.269	4.5	0.487	8.1	0.273	4.5
7	0.223	3.2	0.264	3.8	0.302	4.3	0.513	7.3	0.306	4.4
8	0.243	3.0	0.292	3.6	0.336	4.2	0.541	6.8	0.340	4.3
9	0.262	2.9	0.318	3.5	0.368	4.1	0.568	6.3	0.373	4.2
10	0.280	2.8	0.342	3.4	0.397	4.0	0.593	5.9	0.403	4.0
11	0.294	2.7	0.362	3.3	0.421	3.8	0.613	5.6	0.428	3.9
12	0.305	2.5	0.376	3.1	0.439	3.7	0.626	5.2	0.446	3.7
13	0.311	2.4	0.385	3.0	0.451	3.5	0.632	4.9	0.458	3.5
14	0.313	2.2	0.389	2.8	0.455	3.3	0.630	4.5	0.463	3.3

Table 6. AEP calculations and uncertainty estimations.

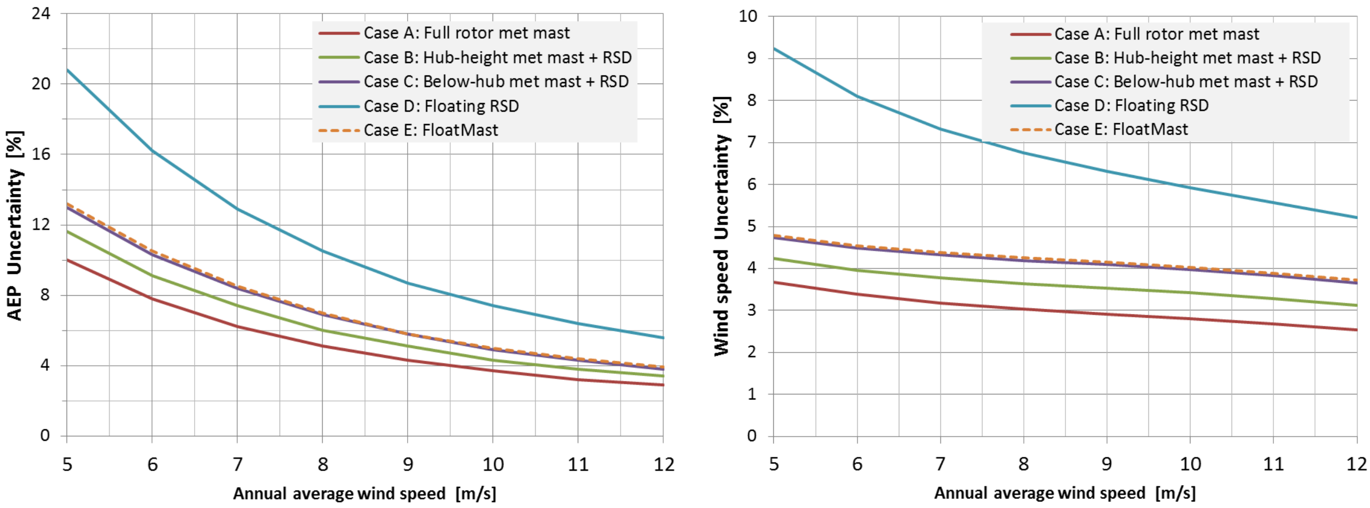

Figure 2. AEP (*left*) and wind speed (*right*) uncertainties for various Rayleigh distributions.

6. Conclusions

In this work five common configurations for offshore wind resource assessment were examined, regarding the uncertainty of their methodology.

All the individual uncertainties components were categorized and assessed following the corresponding requirements of the IEC 61400-12-1 standard [2]. In the cases, where no information is available for a specific uncertainty component (i.e.: uncertainty due to mounting effects of a device), the recommended default values were adopted.

Case E configuration (a short met mast on a floating platform) differs from the IEC compliant Case C, only in respect to the movement of the TLP platform. It might be potentially regarded as such, only if the dynamics of the motion do not affect wind flow results. In that case, measurements will provide the extra uncertainty values to be included, if needed.

Case	Method	Wind speed uncertainty	AEP	AEP uncertainty
A	Fixed permanent full rotor height meteorological mast (150m)	2.9 %	21.7GWh	4.3 %
B	Fixed permanent hub height meteorological mast (90m) with remote sensing device (RSD)	3.5 %		5.1 %
C	Fixed permanent below hub height mast (40m) with remote sensing device (RSD)	4.1 %		5.8 %
D	Remote sensing device (RSD) on floating vessel (i.e. floating LIDAR)	6.4 %		8.8 %
E	Temporary TLP mast (40m) with remote sensing device (FloatMast)	4.2 %		5.9 %

Table 7: AEP uncertainty vs measurement method
typical **5MW** HAWT at a site with **9m/s** annual average wind speed.

Concluding, when strict compliance to IEC 61400-12-1:20017 is unachievable (deep waters, floating wind farms) or requires high financial costs, the proposed methodology introduces two offshore configurations and compares the resulting uncertainties.

7. References

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