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Are Lidars Good Enough for Resource Assessments?

– Accuracy of AEP predictions in flat terrain generated from measurements by conically scanning lidars

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Summary
Commercially available conically scanning lidars have been rigorously assessed over the last three years. The accuracy has increased due to improvements of signal processing, cloud correction algorithms and cone angle accuracy. The standard deviation of a pulsed lidar's error in horizontal wind speed, as compared to mast-mounted cup anemometers, has in a three-month campaign in flat terrain been lower than 0.1 m/s, even at measuring heights exceeding 100 m. Biases are small for winds assessed over flat terrain and mean lidar errors have typically not exceeded 0.1 m/s.

Although price and reliability might not yet be satisfactory, the precision of lidar anemometry seems to have matured to a level where stand-alone resource assessment in flat terrain can be considered. In this paper, boundaries of the required precision of remote sensors for bankable resource assessments are estimated. The impact on AEP predictions based on measurements with Windcubes, with current measurement uncertainties, is estimated. Furthermore, case studies from simultaneous lidar and mast-mounted cup measurements are compared to predictions from WAsP modelling from shorter masts.

The current cup-traceable Windcube accuracy is estimated to lie within ± 1.5 % and ± 5 m. This is possibly sufficient for resource assessment in certain wind climates and hub-heights, for example offshore where hub-height wind shear is relatively small. It is estimated that with further advances, traceability can be improved to lie within ± 1 % and ± 3 m.

Introduction
Commercially available conically scanning lidars have been rigorously assessed over the last three years. The accuracy has increased due to improvements of signal processing, cloud correction algorithms and cone angle accuracy. Although price and reliability might not yet be satisfactory the precision of lidar anemometry seems to have matured to a level where stand-alone resource assessment in flat terrain can be considered.

If lidars are to become the preferred choice for wind resource assessment in flat terrain for turbines with hub-heights above 60 m they have to be able to assess a wind climate with sufficient accuracy for economic decisions, i.e. be bankable. It also has to be proven that lidar anemometry is a better option than other cheaper methods, like sodars or flow models based on measurement with sub hub-height tilt-up masts. Especially flow models have high potential to be competitive since they are expected to give relatively precise results in flat terrain.

Lidar accuracy estimations can be approached in different ways, in this paper traceability to cup anemometers has been chosen. Wind tunnel calibration, as is done for cup anemometers, is difficult due to the large sample and scan volumes, and will probably not be more dependable than tests in well known flat terrain. Calibrations on a moving solid target (hard-target) can not reveal all uncertainties which are associated with measurements in a dispersed medium, such as the atmosphere, but are important tests during manufacturing. Describing the uncertainties of each sub element, e.g. the cone angle, is important but it will be difficult to precisely define the uncertainties of e.g. the estimator which picks one velocity from the sensed wind speed distribution.

In this paper the impact on AEP predictions based on measurements with remote sensors, with likely uncertainties, is estimated and case studies from simultaneous lidar and mast-mounted cup measurements are compared to predictions from WAsP modelling from shorter masts.

Cup traceability

Verification of lidar accuracy and the influence of the uncertainty on different applications will be vital for a successful introduction of the technology. Lidars can not be accepted as substitutes for cup anemometers unless we can verify their accuracy using calibrated and traceable instruments. Linear correlations between the cup measurements and lidars are often reported as measures of lidar accuracy. However, this analysis method is not sufficient for highly precise lidar, or sodar, anemometry testing, but is a historic residue from cup anemometer testing.

Lidars have been observed to suffer from errors which are proportional to other factors than the wind speed [1]. The result from a linear regression analysis of the wind speed sensed with cup and lidar will during these circumstances depend on the correlation between the error source and the wind speed in the comparative data set. For example, it is an intrinsic difficulty in any remote sensing application to know the sensing distance, i.e. the altitude a remote sensor retrieves the wind speed from. If a lidar makes limited errors in sensing range it will make errors which are to a first approximation linearly proportional to the wind shear, here defined as the wind speed increase in meter per seconds per meter height [2]. If a lidar measures below the intended height it will typically underestimate the wind velocity, especially at low heights. Since the wind shear and the wind speed typically are correlated to some degree, the linear regression of cup and lidar measurements will for this case therefore typically be lower than 1 and with high correlation. However, how much lower depends on the wind shear in the data set and this remote sensor will behave differently in different climates. If the lidar is tested with cups at several altitudes it will see different regression results at each height, which should not be the case if the lidar uniquely suffered from an error which was proportional to the wind speed, e.g. an uncertainty in the cone angle.

At Risø DTU we have developed analysis strategies which consider several possible lidar errors, see Figure 1 [1]. Several of the lidar errors have been resolved or mitigated and also the reference measurements have been improved. As can be seen in Table 1 cup-traceable lidar accuracy can already lie within the ±1 % and ± 3 m. It is believed that this can become a consistent result for Windcubes [3] within the coming year. A higher precision will probably be difficult to document using mast-mounted cup anemometers that themselves have combined calibration and mast/boom uncertainties already approaching 0.5% at the test site. However, in a slightly conservative approach, the cup-traceable accuracy is considered to be lower at present, taking into account the spread in current systems quality and the accuracy of shorter test periods. It is estimated that the uncertainties of an acceptance-tested Windcube can be traced to a calibrated cup anemometer with errors which lie within ±1.5 % and ±5 m in sensing height. It is also fair to question what cup-traceable lidar accuracy that corresponds to the current “in field” cup anemometer precision, since cup anemometer precision in practice often leaves much to be desired.

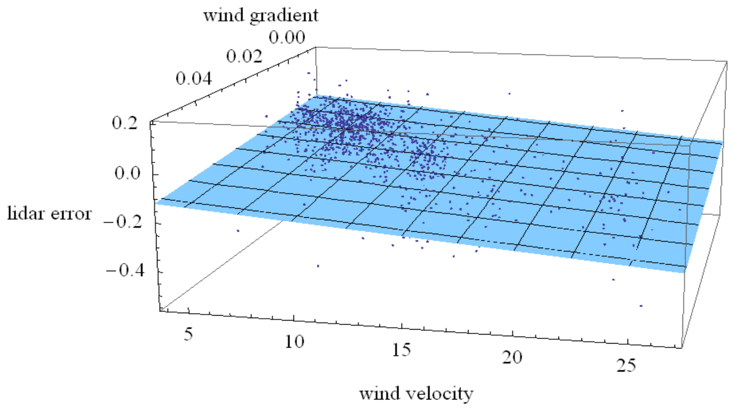

Figure 1 : Two parametric linear regression analysis of lidar-cup as function of wind speed and wind shear for evaluation of altitude and cone angle errors.

Height [m]	Regression offset [m/s]	Gain [%]	Altitude error [m]	STDEV [m/s]	Mean [m/s]
116	0.00 ± 0.01	-0.7 ± 0.1	-2.2 ± 0.3	0.09	-0.11
100	-0.02 ± 0.01	-0.7 ± 0.1	-1.4 ± 0.3	0.09	-0.12
80	-0.03 ± 0.01	-0.4 ± 0.1	-1.6 ± 0.3	0.09	-0.12
60	-0.09 ± 0.01	-0.2 ± 0.1	0.5 ± 0.2	0.09	-0.09

Table 1 : Results from a two parametric linear regression analysis based on 2600 ten minute averages. The ± indicates the 90% confidence intervals of the analysis.

AEP predictions with lidars in flat terrain

Since it is expensive and logistically complex to erect masts to the hub-height of modern turbines, it is important to asses the required accuracy of stand-alone lidars for AEP predictions in flat terrain. AEP predictions are in practice very uncertain since the chain of predictions is long, covering the wind measurement, correlation to long term climate, flow modelling of the site, power curve uncertainties to shear and turbulence as well as turbine availability. Studies of AEP predictions as compared to actual production have shown both large biases, up to 10 % and large uncertainties, with standard deviations above 15 %.

In this paper only the uncertainty of the wind assessment, either by using hub-height lidar measurements or WAsP models using lower cup measurements, according to current AEP prediction practice is considered. Hub-height measurement with calibrated class 1 Risø cup anemometers is used as the reference value [4].

A sensitivity analysis of the impact of sensor inaccuracy on the AEP predictions is made for typical coastal and inland high wind climates by considering winds measured during three years, 2006-2009, in the sector between 255-285°, inflow over water, and 75-105°, wind coming in over flat terrain, see wind climate estimates in Figure 2 and reference [1] for information on site roughness.

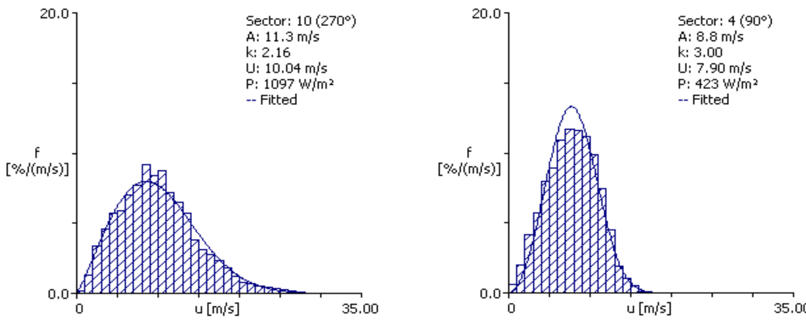

Figure 2 : Wind climate for the westerly sector (255-285°), left, and easterly sector (75-105°), right. A and k are the fitted Weibull parameters and U is the average wind speed.

A 100 m hub-height 2 MW turbine and a 60 m hub-height 1.5 MW turbine with power curves according to figure 3 have been used in this example.

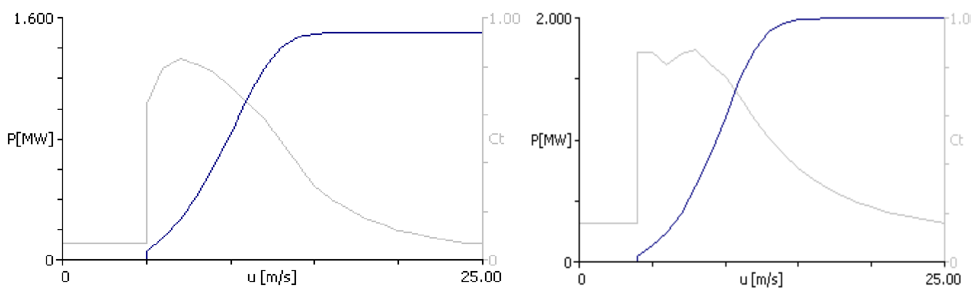

Figure 3 : Power curves of the 1.5 MW turbine, left, and the 2 MW turbine, right.

A sensitivity analysis of the impact of sensor uncertainty on the AEP prediction is done by imposing errors, from -3 to 3 % in wind speed gain and from -10 to + 10 m in height, on the wind measured at hub-height. The wind climate above and below hub-height has been calculated from a polynomial fit to the winds measured at 10, 40, 60, 80, 100 and 116 m. The results for a 100 m hub-height, 2 MW turbine in a flat inland site can be seen in Figure 4.

The wind shear over inland terrain is considerable and significant errors are inflicted by a remote sensor which makes a height error, i.e. makes a measurement which statistically best compares with an erroneous height. For this northern European site, with limited heat flux and low roughness, an error of 4 m in height at 100 m corresponds to an error of 1 % in gain. AEP predictions in these conditions are very sensitive to sensor errors. The current cup-traceable lidar accuracy of ±1.5 % and ±5 m would then ensure AEP predictions within ±6.5 % for this height and climate. Such uncertainties are probably not sufficient for investment decisions.

The results for a 100 m hub height, 2 MW turbine in a coastal site can be seen in Figure 5. In the coastal wind climate the wind shears are much lower and the speeds higher. Errors of up to 10 m in height are here comparable to a 1 % gain error. Note that the AEP prediction sensitivity also depends on the wind speed distribution. If the wind distribution is centered at speeds where the power curve is most dynamic the sensitivity to sensor gain is high. The current cup traceability ensures AEP predictions within 2.5 % for typical coastal/offshore conditions, which already might be an acceptable compromise considering the extreme costs for offshore hub-height masts.

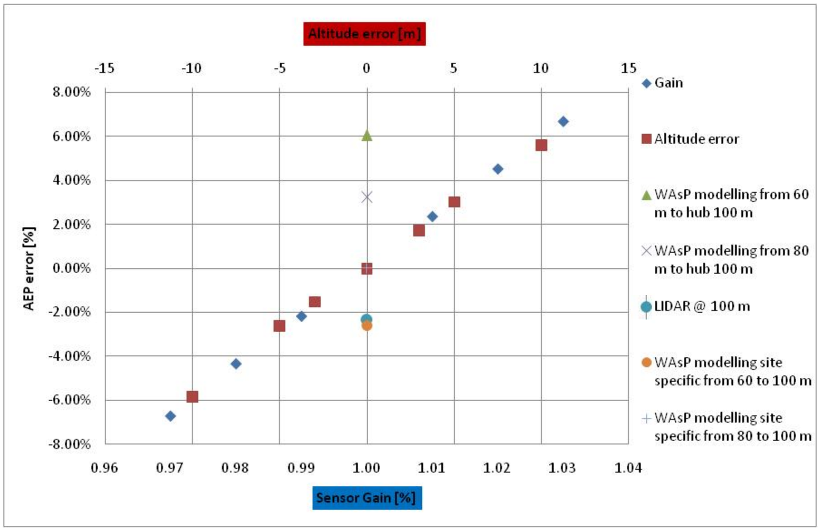

Figure 4 : AEP prediction results for a 100 m hub-height, 2 MW turbine in a flat land site. Blue diamonds indicate the errors due to sensor gain, red squares the influence from altitude errors. The light blue circle is the result from the lidar measurements while cross and plus sign is a WAsP model result from a measurement at 80 m and the orange circle and green triangle is the WAsP result from 60 m, explained in a following chapter.

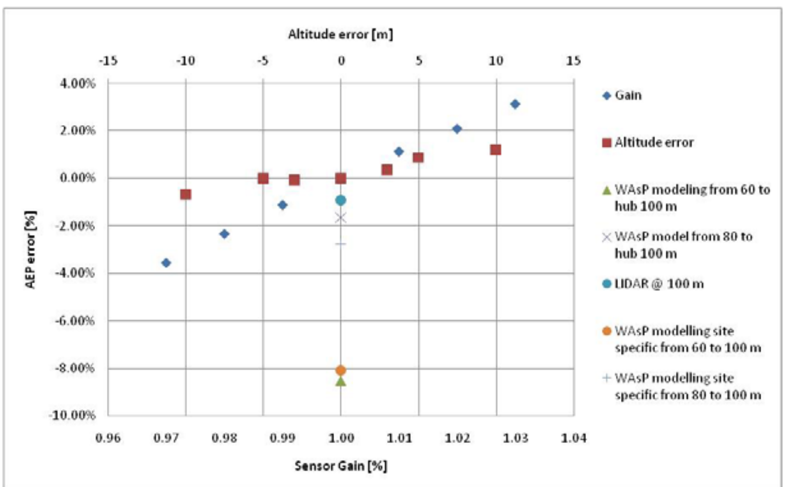

Figure 5 : AEP prediction results for a 100 m hub-height, 2 MW turbine in a coastal site. Colors and symbols are the same as described in Figure 4.

Resource assessment by hub-height measurements for lower turbines, e.g. on 60 m towers, are economically and logistically obtainable with tilt-up masts. The shears at lower heights are much higher and the sensitivity to altitude errors is therefore great. Remote sensing at these heights is therefore not the immediate choice. To illustrate this, results of a sensitivity analysis of the AEP prediction of a 60 m hub 1.5 MW turbine is given in figure 6.

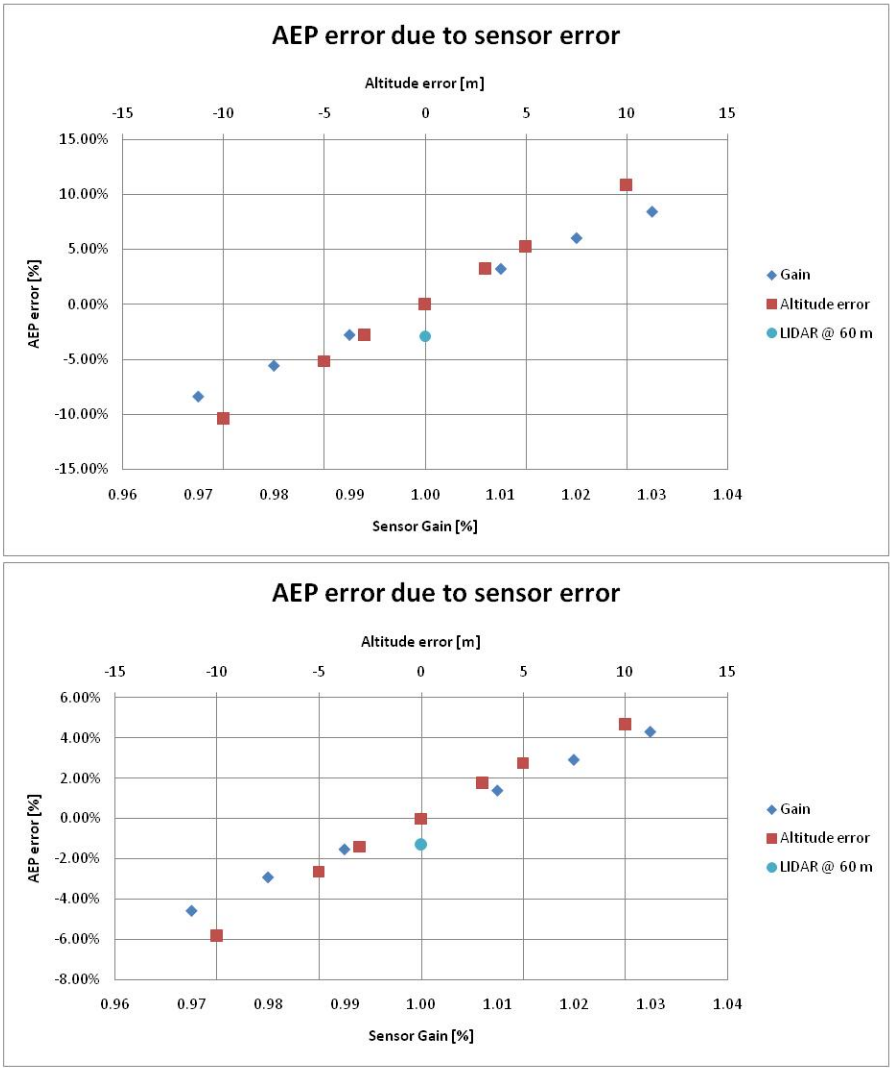

Figure 6 : Sensitivity analysis of sensor uncertainty on AEP predictions of a 1.5 MW turbine with 60 m hub-height. Results from the inland climate, top graph. Results for the coastal climate, bottom graph.

The impact of altitude errors are very large at 60 m since the shear is often strong both in coastal and inland climates. Less than 3 m height error is here comparable to a 1% gain error. The errors made by a ±1.5 % and ±5 m lidar could induce AEP prediction errors of 5 % for the coastal climate and 9.5 % for the inland climate.

A test case of AEP prediction using lidar

A Windcube was installed 15 m from the meteorology tower in Høvsøre and measured from December 2008 to March 2009 with two shorter stops. The data set from the lidar and well synchronized cup measurements was screened so that only the free wind sector, i.e. without wakes from nearby turbines and the measurement tower, were included. Further screening was done for periods with frozen cups and finally for periods where the lidar was unavailable both due to the shorter stop and due to low CNR levels, for about 6% of the data set. Note that precipitation and low wind speeds were included in the screened data sets, which is often not the case when lidar errors are being inspected.

Again we look at two sectors with different wind climates. The sector 150-180° gives a good representation of a flat inland climate while the 255-285° still represents a coastal climate. The coastal data set includes 941 ten minute averages while the inland set includes 873.

Due to the short measurement period AEP predictions where calculated directly from the wind measurements from the cups and the lidar. That is, no wind climate fit was made to the data set. The very small positive bias in the lidar AEP prediction due to making the calculation directly from the individual wind measurement with a non-negligible measurement standard deviation has been neglected.

The difference in the AEP prediction of the 2MW turbine with 100 m hub-height with cup and lidar hub-height measurements is -1.1 % and -2.3 % for the coastal and inland climate respectively. This is a good example of the potential of lidar anemometry for resource assessment offshore but also in flat inland terrain.

Comparison with WAsP extrapolation from lower masts

A test case was also made to compare the accuracy of vertical extrapolation using WAsP modeling based on 60 and 80 m cup anemometer measurements. Cup anemometer measurements in sector 255-285° and 75-105° from 2006 to 2009 was used for these AEP predictions. The data set was screened for frozen cups.

With 60 m measurements and default settings of heat flux, the WAsP model gave AEP predictions which differed with +6.1% and -8.5%, for the inland and coastal climate respectively, from those calculated with the 100 m cup anemometer. The extrapolation of 80 m measurements were as expected more precise and differed with +3.2% and -1.7%, for the inland and coastal climate respectively.

Since the yearly average heat flux is measured at 100 m in Høvsøre these parameters were also used as input in the WAsP model [5]. The predictions improved considerably to -2.6% and 0.0% for the inland conditions using 60 and 80 m measurements respectively. As for the costal conditions the results only changed slightly to - 8.1 % and -2.8 %. The sensitivity to heat flux is notably high in WAsP modeling.

Bankability

An important question is whether lidar wind resource data can be accepted by commercial banks on the same footing as cup anemometer data. Since there is no formal standard for resource assessment, the ‘rules’ are much less rigid than for power performance verification [6]. This gives the freedom (and requirement) for projects and their supporting wind measurements to be assessed on a case-by-case basis. It is very likely that with coming improvements well-documented lidar measurements for hub-heights above 60 m in flat terrain will be similar in precision to many “in field” cup anemometer set ups. Furthermore, the avoidance of vertical extrapolation is likely to reduce the overall AEP estimate uncertainty.

It is important to emphasise that large biases are typically introduced when lidars are used in complex terrain since the intrerpolation method used in current lidar systems only is suited for wind flows which are horizontally homogeneous on average [7]. Lidars will need assistance of flow models to provide a wind vector from the measured radial wind velocities, i.e. the wind speed projected on lidar’s line of sight [8]. A general traceability to cup or sonic anemometers will for this case be much more difficult to provide. Another approach is to use three lidars which sample one volume from three different directions, however, price and complexity then increases.

Our advice is to make early contact to the banker's consultant – the organization who will perform a 'due diligence' analysis on the measurement project. By a process of lidar verification against a well documented measurement mast before and preferably also after the measurement campaign, it should be possible to assess the accuracy of the lidar measurements. It is also clear that a code of practice for this process is required.

Conclusions

Due to logistical difficulties and economic viability it is still common to use flow models and sub hub-height masts when predicting Annual Energy Production, especially in flat terrain where models are expected to give relatively precise results.

Predictions of Annual Energy Production are uncertain. Already the sensitivity of the wind assessment is high. To be able to obtain an accuracy within 3 % it is currently needed to use hub-height measurements with class 1 cup anemometers, however this is not always economically or logistically viable. Current cup-traceable Windcube accuracy, ±1.5 % on wind speed and ±5 m on height, is likely to provide AEP predictions well within ±10 % in flat terrain at hub-heights exceeding 60 m.

Cup-traceable lidar accuracy in flat terrain is likely to be further improved to ensure ±1 % on wind speed and ±3 m on height. In this case lidars could provide AEP prediction results well within 5 % as compared to that given from hub-height cup measurements. Such accuracy is comparable to many hub-height cup measurements in practice and for certain climates they are probably likely to be sufficient for an investment decisions, i.e. be bankable.

The results of one test case show that the uncertainty obtained by hub-height LIDAR anemometry is lower than that from a WAsP extrapolation from a 60 m mast.

A summary of comparative performances is given in table 2.

Sensor	**Sensor error**	**AEP error [%]** **Coastal site**	**AEP error [%]** **Inland site**
Calibrated and well maintained class 1 cup anemometer	± 0.5% on U	± 0.5% at 100 m ± 0.75% at 60 m	± 1% at 100 m ± 1.5% at 60 m
Lidar traceable to cup anemometer	± 1.5% on U ± 5 m on height	± 2.5 % at 100 m ± 5.0 % at 60 m	± 6.5% at 100 m ± 9.5 % at 60 m
Extraction from mast measurement, default heat flux setting	± 0.5% on U + WAsP	-8.5 % 60 to 100 m -1.7 % 80 to 100 m	6.1 % 60 to 100 m 3.2 % 80 to 100 m
Extraction from mast measurement, site specific heat flux	± 0.5% on U + WAsP	-8.1 % 60 to 100 m -2.8 % 80 to 100 m	-2.6 % 60 to 100 m 0.0 % 80 to 100 m
Test case LIDAR anemometry at hub-height	-0.6% on U -0.7 m on height	-1.1 % at 100 m -1.3 % at 60 m	-2.3 % at 100 m -3.0 % at 60 m

Table 2 : Summary of the AEP prediction uncertainties for the different methods and sensors used in this paper.

Nevertheless, even if lidar anemometer accuracy has matured sufficiently to be considered for stand alone resource assessments in flat terrain, it is still uncertain whether reliability and price has, not forgetting the cost and complication of the lidar's power supply.

For future turbine sizes it will become increasingly more difficult and expensive to build masts to hub height. At the same it is likely that wind speed information up to hub-height will be insufficient for accurate AEP predictions. In these circumstances the lidar case grows stronger and the highest AEP prediction accuracy will probably be provide by hub-height towers supplemented by shear studies to blade tip by lidar.

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